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Effects of maxillary molar distalization using clear aligners during the mixed dentition and early permanent dentition with 3 types of Class II traction: a three-dimensional finite element analysis

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Abstract

Background Impacts of the developmental stages of maxillary second molars, methods for distalization of the maxillary first molars, Class II traction application, and different traction modes on three-dimensional molar movements, anchorage tooth displacement, and stress distribution remains poorly understood.

Method Patients with maxillary second molars in Nolla 4–6 and 7–8 stages were selected for 3D finite element modeling. We analyzed three-dimensional movements and stress distribution in maxillary and mandibular dentitions after unilateral and bilateral distalization of maxillary first molars using clear aligners, with no traction and three types of Class II traction.

Results In Nolla 4–6 and 7–8 stages, after bilateral molar distalization, maxillary anterior labial inclination, tooth, periodontal membrane and alveolar bone stress were more significant. Movements of maxillary first molars were greater in Nolla 7–8 stages regardless of unilateral or bilateral molar distalization. Either unilateral or bilateral molar distalization, Angel button group provided better anchorage control for central incisors. Precision incision group provided superior anchorage control for lateral incisors and achieved the largest distal movements of maxillary first molars. Lingual button group provided anchorage control for deciduous or permanent canines. Molar distalization modes had no effect on mandibular dentition. Movements and maximum periodontal membrane stress values of mandibular dentition were the smallest in the Angel button group.

Conclusion When moving molars distally, it's necessary to consider the development of maxillary second molar and evaluate the distalization modes, Class II traction modes and the influence on anchorage teeth, to design personalized treatment plan.

Keywords Clear aligners, Maxillary first molar distalization, Mixed dentition, Early permanent dentition, Class II traction, Three-dimensional finite element

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Translational impact statements

In this study, the three-dimensional finite element models of distalization of the maxillary first molars with clear aligners combined with different Class II traction modes in mixed dentition and early permanent dentition were constructed. We found that when moving the maxillary first molar distally, it is necessary to take into account the development of the patients'maxillary second molar, and comprehensively consider the methods of distalization of the maxillary first molars, Class II traction modes and the influence on the anchorage teeth, to design a personalized treatment plan.

Introduction

Angle Class II malocclusion adversely affects dental and facial development, oral health, and function, with potential implications for facial aesthetics and systemic health [1–4]. These effects are particularly pronounced in children during mixed and early permanent dentition stages. Maxillary first molar distalization is a widely used non-extraction orthodontic technique in early childhood, enabling bite correction and creating space for dental alignment. Clear aligners, which fully encapsulate the tooth surface, offer precise control over tooth movement [5–8]. By utilizing the entire dental arch as anchorage, clear aligners effectively distalize maxillary molars. It is reported that Clear aligners are mostly recommended in simple malocclusions. Bodily distalization of maxillary molar within 1.5 mm revealed the highest predictability (88%). In addition, their aesthetic appeal, comfort, and oral health benefits provide unique advantages in orthodontic treatment, making them a preferred choice for both clinicians and patients [9–11].

Existing evidence suggests optimal timing for maxillary first molar distalization occurs during mixed or early permanent dentition stages, typically corresponding to ages 7–12 years [12]. Based on the Nolla classification [13], permanent tooth development timelines [14, 15], and radiographic findings, we categorized maxillary second molar development in early orthodontic patients into two stages using Insil Kim et al.'s method [16]: Nolla 4–6 stages (complete crown formation without root development) and Nolla 7–8 stages (unerupted with 1/3–2/3 root formation). These developmental phases correspond to distinct clinical presentations—Nolla 4–6 stages typically manifest as mixed dentition, while Nolla 7–8 stages represent early permanent dentition. The potential differential impacts of these developmental stages on first molar distalization efficacy remain underexplored. In clinical practice, clear aligners are commonly used for unilateral or bilateral maxillary first molar distalization in Class II malocclusion cases during these stages. However, limited evidence exists regarding the efficacy of clear aligners with different developmental stages and differences between unilateral and bilateral distalization approaches.

Class II elastic traction enhances anterior support and promotes molar distalization through sagittal force application [17–19]. This technique connects maxillary canine elastics to mandibular molar lingual buttons, generating sagittal forces that simultaneously induce lingual anterior retraction and molar distal movement. Three distinct clear aligner-based traction designs are currently implemented [20]: ① Lingual button + Class II traction: a buccal window is created at the canine neck of the clear aligner, and a lingual button (a small metal attachment traditionally used on lingual surfaces of teeth. Now, it is now also effectively employed for buccal surface attachment with clear aligners) is bonded to the buccal surface. When the elastic band is attached to the lingual button and stretched, the traction force directly acts on the canine, using the bonded area as a fulcrum to transfer force to the incisor and molar regions. Unlike Precise incisions or Angel buttons, this design delivers force directly to the tooth, potentially altering force transmission dynamics. ② Precise incision + Class II traction: a precise incision is created at the canine tooth's aligner neck. When the elastic band is hung on this incision and stretched, the clear aligner's precise incision serves as the fulcrum. The elastic traction force acts directly on the clear aligner and is transferred to the incisor and molar areas. ③ Angel button + Class II traction: an angel button (a protruding structure) is fabricated on the clear aligner between the lateral incisor and canine. When the elastic band is hung on this button, it serves as a fulcrum, transmitting elastic traction force directly to both incisor and molar regions. Compared to lingual buttons and precise incisions, the angel button's unique positioning—closer to incisors and more distant from canines and molars—may lead to distinct orthodontic force distribution patterns. While all three modalities achieve Class II traction, they differ in force fulcrum location and aligner-tooth contact areas. Their differential effects on anterior anchorage control and molar movement during maxillary first molar distalization remain unclear, particularly across Nolla 4–6 and 7–8 stages. Furthermore, given the interarch connection established by Class II traction, investigating modality-specific impacts on both maxillary and mandibular dentitions is essential.

The three-dimensional finite element method enables comprehensive analysis of biomechanical changes in oral structures. We constructed 3D finite element models of patients with maxillary second molars at Nolla 4–6 and 7–8 stages, analyzing three-dimensional movements and stress distribution patterns during maxillary first molar distalization using clear aligners. The study incorporated unilateral and bilateral molar distalization and with no traction and three Class II traction modalities. These findings provide a theoretical foundation for optimizing Class II traction selection during maxillary first molar distalization in mixed and early permanent dentition phases.

Methods

Objects of study

This study excluded patients with maxillary second molars at Nolla 1–3 stages (ages 2–6 years, unsuitable for early orthodontic intervention) and Nolla 9–10 stages (ages 13–16 years, the maxillary second molars eruption completely). Two volunteers exhibiting unerupted maxillary second molars at Nolla 4–6 and 7–8 stages, respectively, along with Angle Class II malocclusion, were selected for the study. Inclusion criteria comprised: complete dentition (excluding third molars), bilateral dental arch symmetry, healthy periodontal status, normal dental anatomy without defects, and absence of temporomandibular disorders. Both participants provided informed consent, and the study protocol was approved by the Medical Ethics Committee of the Affiliated Stomatology Hospital of Kunming Medical University (Approval No. KYKQ2023MEC0115).

Research methods

Model construction

Digital Cone-Beam CT scans (New Tom VG, Verona, Italy) were performed on volunteers, with acquired images stored in DICOM format. These data were processed through Mimics 21.0 (Materialise, Belgium) to generate STL files of maxillomandibular structures using thresholding and region growing algorithms. Subsequent refinement in Geomagic Wrap 2015 (Geomagic, USA) involved feature removal and hole filling. Using 3-matic (Materialise, Belgium), we created initial aligner and periodontal membrane models by uniformly offsetting tooth crowns and roots by 0.75 mm and 0.25 mm, respectively. Attachment design specifications included: vertical rectangular attachments (3 ×2 ×1 mm) on canines and horizontal rectangular attachments (2 ×3 ×1 mm) on primary molars, premolars, and first molars. All models were adaptively meshed with C3D4 elements in 3-matic and exported as INP files for finite element analysis in Abaqus 2020 (Dassault SIMULIA, USA) (Fig. 1).

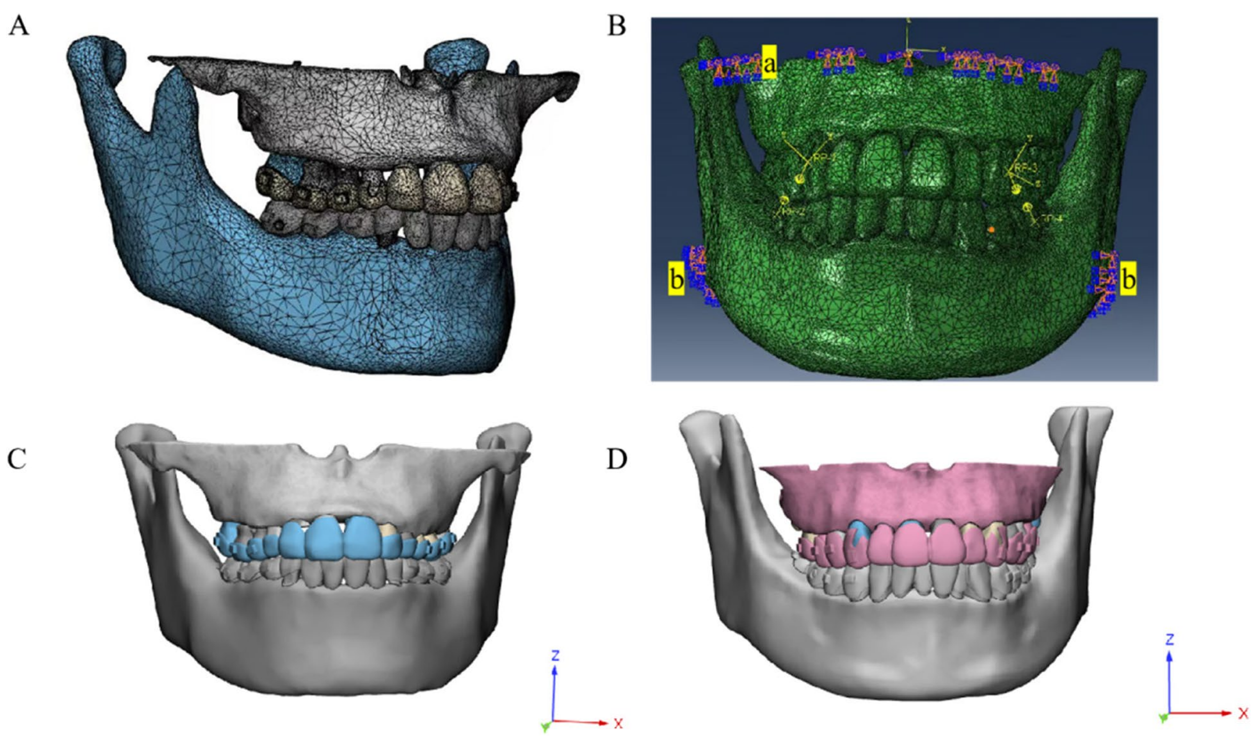

Fig. 1 Illustrates the grid diagram, boundary conditions, and coordinate setting. **A** Grid diagram; **B** Boundary condition setting, where the maxillary margin of the maxilla (as shown in a) and the lateral angles of the mandible (as shown in b) are designated as fixed surfaces to constrain the position of the maxilla and mandible during loading application; **C** Coordinate setting for the finite element model of Nolla 4–6 stages; **D** Coordinate setting for the finite element model of Nolla 7–8 stages

Parameter setting

The elasticity modulus and Poisson ratio of the teeth, periodontal ligament, alveolar bone, orthodontic appliance, and attachments obtained from previous studies are listed in Table 1 [21–24]. The top surface of the maxilla is constrained with fixed boundary conditions, setting the degrees of freedom in all directions to zero. Contact relationships between the jawbone and periodontal ligament, between the periodontal ligament and teeth, between teeth and attachments are defined as fixed contacts; meanwhile contact between teeth is set to be frictionless. The contact between the orthodontic appliance and teeth, as well as between orthodontic appliances and attachments is established as a frictional contact with a coefficient of friction of 0.2.

Coordinate axis setting

Establish a Cartesian coordinate system. The X-axis represented the coronal direction, with positive values assigned to the lingual direction of the right canine and posterior teeth. The Y-axis represented the sagittal direction and took the distal direction as positive. The Z-axis represents the vertical direction, with the positive values were associated with the gingival side of maxillary jaw dentition.

Design scheme

In accordance with Invisalign's clinical protocols, we established a maxillary first molar distalization parameter of 0.25 mm. We named Group 1 and Group 2 as the finite element models of maxillary second molar development to Nolla 4–6 and 7–8 stages respectively. According to the different ways of maxillary first molar, Group 1 was divided into Group 1-U (unilateral molar distalization, which refers to the distal movement of only the right maxillary first molar) and Group 1-B (bilateral molar distalization, which involves simultaneous distal movement of both the right and left maxillary first molars). Taking Group 1-U as an example, Group 1-U was compared with No traction and three Class II traction modes. For readability, we named each group separately by G1-U + N T, G1-U + T I, G1-U + T II and G1-U + T III (N T: No traction. T I: Traction I, Lingual button + Class II traction. T II: Traction II, Precise incision + Class II traction. T III: Traction III, Angel button + Class II traction). Group 1-B and Group 2 followed the same subgrouping scheme and naming method as Group 1. Therefore, the finite element models in this study were divided into 2 groups, each group of 8 sub-models, for a total of 16 groups. Figure 2 demonstrated the Class II traction configurations, with experimental group details presented in Table 2. For both unilateral and bilateral distalization protocols, bilateral Class II traction was applied at 120 g per side, achieved through spring deformation design to accurately simulate clinical elastic traction conditions [24, 25].

Table 1 Material properties

Material	Young's modulus (MPa)	Poisson ratio
Dental hard tissue	84,100	0.3
Dental pulp	2	0.45
Periodontal ligament	0.67	0.45
Cancellous bone	345	0.31
Cortical bone	13,800	0.26
Clear aligners	816	0.3
Attachment	12,500	0.36

Measuring mark points

Our study followed the guidelines of the International Dental Federation for identifying primary and permanent teeth. Therefore, we named the teeth with numeric notation so that each tooth could be accurately and concisely positioned. The midpoint of the central and lateral incisors, the apex of the canines and deciduous canines, as well as the mesio-buccal tip of the first and second deciduous molars, first and second premolars, and first molar were identified as the designated measurement points for dental analysis.

Results

Three-dimensional movements of maxillary and mandibular dentitions following unilateral and bilateral molar distalization using clear aligners with no traction and three Class II traction modes in Nolla 4–6 and 7–8 stages

In Nolla 4–6 and 7–8 stages, both unilateral and bilateral distalization of the maxillary first molars resulted in significant Y-axis movements and intrusion of the maxillary dentition. The three-dimensional movements of the maxillary anterior and posterior teeth are detailed in Table 3 and Fig. 3.

Three-dimensional movements of maxillary anterior teeth

Irrespective of the Class II traction use or not, we found that on the X-axis, bilateral molar distalization resulted in smaller movements for teeth 12, 53, 22, and 63 in Nolla 4–6 stages, and for teeth 13 and 23 in Nolla 7–8 stages compared to unilateral distalization (Figs. 3, 4A-B, 5A-B). And on the Y-axis, bilateral molar distalization caused more significant movements for teeth 11, 12, 21, and 22 in both Nolla 4–6 and 7–8 stages than unilateral molar distalization (Figs. 3, 4C-D, 5C-D). On the Z-axis, anterior teeth exhibited intrusion

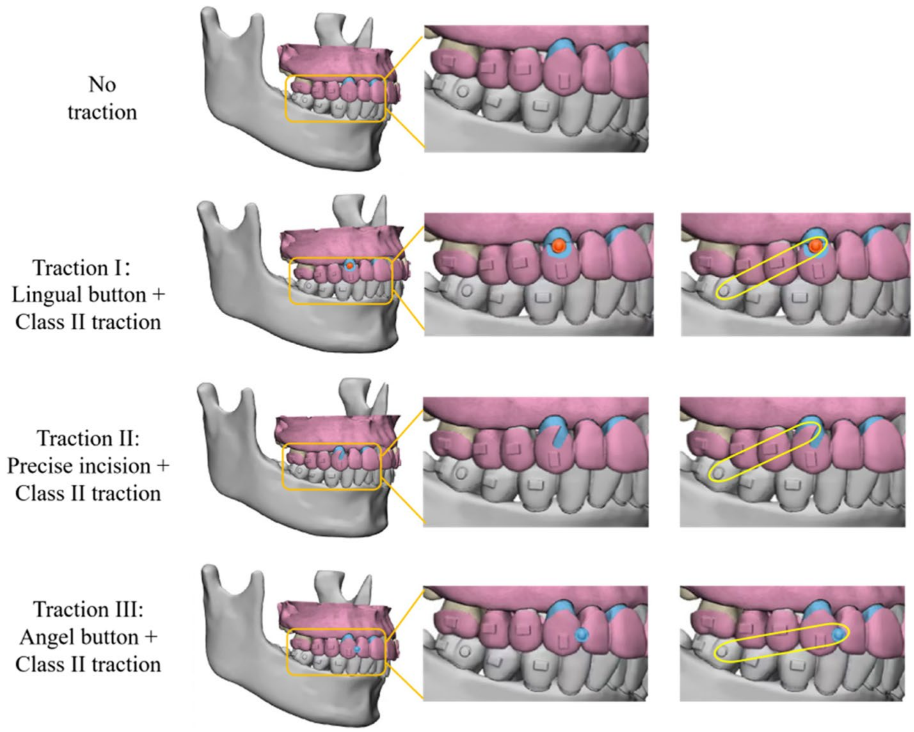

Fig. 2 Taking the finite element model of the maxillary second molars in Nolla 7–8 stages as an example, the diagram showed No traction and three Class II traction modes (Lingual button + Class II traction, Precise incision + Class II traction and Angel button + Class II traction)

Table 2 Experimental groups

Groups		Class II traction modes
Group 1 (*n* = 8) (The development of maxillary second molars was in Nolla 4–6 stages)	Group 1-U (*n* = 4) U: Unilateral molar distalization	G1-U + N T (Group 1- U + No traction)
		G1-U + T I (Group 1- U + Traction I)
		G1-U + T II (Group 1- U + Traction II)
		G1-U + T III (Group 1- U + Traction III)
	Group 1-B (*n* = 4) B: Bilateral molar distalization	G1-B + N T (Group 1- U + No traction)
		G1-B + T I (Group 1- U + Traction I)
		G1-B + T II (Group 1- U + Traction II)
		G1-B + T III (Group 1- U + Traction III)
Group 2 (*n* = 8) (The development of maxillary second molars was in Nolla 7–8 stages)	Group 2-U (*n* = 4) U: Unilateral molar distalization	G2-U + N T (Group 1- U + No traction)
		G2-U + T I (Group 1- U + Traction I)
		G2-U + T II (Group 1- U + Traction II)
		G2-U + T III (Group 1- U + Traction III)
	Group 2-B (*n* = 4) B: Bilateral molar distalization	G2-B + N T (Group 1- U + No traction)
		G2-B + T I (Group 1- U + Traction I)
		G2-B + T II (Group 1- U + Traction II)
		G2-B + T III (Group 1- U + Traction III)

movements in both Nolla 4–6 and 7–8 stages. Bilateral distalization resulted in greater intrusion for most teeth, except for 53 in Nolla 4–6 and 13 in Nolla 7–8 stages than unilateral molar distalization (Figs. 3, 4E-F, 5E-F).

Three-dimensional movements of the maxillary posterior teeth

Regardless of Class II traction use or not, we found that on the X-axis, bilateral molar distalization resulted in smaller movements for teeth 54 and 55 in Nolla 4–6

Table 3 Three-dimensional movement of the anterior and posterior maxillary teeth with unilateral and bilateral molar distalization

	Nolla 4–6 stages	Nolla 7–8 stages
X-axis	**·Unilateral molar distalization:** 11 and 12 exhibited mesial movements 53 demonstrated lingual movement 21 and 22 showed distal movements 63 displayed buccal movement 54 and 55 exhibited lingual movement 64, 65, 16, and 26 demonstrated buccal movements **·Bilateral molar distalization:** 11 and 21 exhibited distal movements 12 and 22 demonstrated mesial movements 53 and 63 displayed buccal movements 54, 55, 64, and 65 showed lingual movements 16 and 26 displayed buccal movements	**·Unilateral molar distalization:** 11 and 12 exhibited mesial movements 13 demonstrated lingual movement 21 and 22 showed distal movements 23 displayed buccal movement 14 and 15 showed lingual movements 24, 25, 16 and 26 exhibited buccal movements **·Bilateral molar distalization:** 11, 12, 21, and 22 exhibited mesial movements 13 showed lingual movement 23 presented buccal movement 14, 15, 24 and 25 demonstrated lingual movements 16 and 26 still presented buccal movements
Y-axis	**·Unilateral molar distalization:** 11, 12, 21 and 22 presented labial movements 53 showed mesial movement 63 displayed distal movement 54 and 55 exhibited mesial movements 64, 65, 16 and 26 showed distal movements **·Bilateral molar distalization:** 11, 12, 21, 22 showed labial movements; 53, 63 exhibited mesial movements 54, 55, 64 and 65 presented mesial movements 16 and 26 displayed distal movements	**·Unilateral molar distalization:** 11, 12, 21, and 22 exhibited labial movements 13 showed mesial movement 23 presented distal movement 14 and 15 showed mesial movements 24, 25, 16 and 26 exhibited distal movements **·Bilateral molar distalization:** 11, 12, 21, 22 showed labial movements 13, 23 displayed mesial movements 14, 15, 24 and 25 exhibited mesial movements 16 and 26 exhibited distal movements
Z-axis	All anterior teeth and posterior teeth demonstrated intrusion movements following both unilateral and bilateral molar distalization	

stages than unilateral molar distalization. In Nolla 7–8 stages, maxillary first molars showed smaller movements compared to Nolla 4–6 stages (Figs. 3, 5A-B). On the Y-axis, bilateral distalization caused smaller movements for teeth 54 and 55 in Nolla 4–6 stages and for teeth 14 and 15 in Nolla 7–8 stages than unilateral molar distalization. The interesting finding was that the movements for maxillary first molars were smaller after unilateral or bilateral molar distalization in Nolla 4–6 stages than that in Nolla 7–8 stages (Figs. 3, 5C-D). On the Z-axis, all posterior teeth exhibited intrusion movements. Bilateral molar distalization resulted in smaller intrusion for teeth 54 and 55 in Nolla 4–6 stages and for teeth 14 and 15 in Nolla 7–8 stages. And following bilateral molar

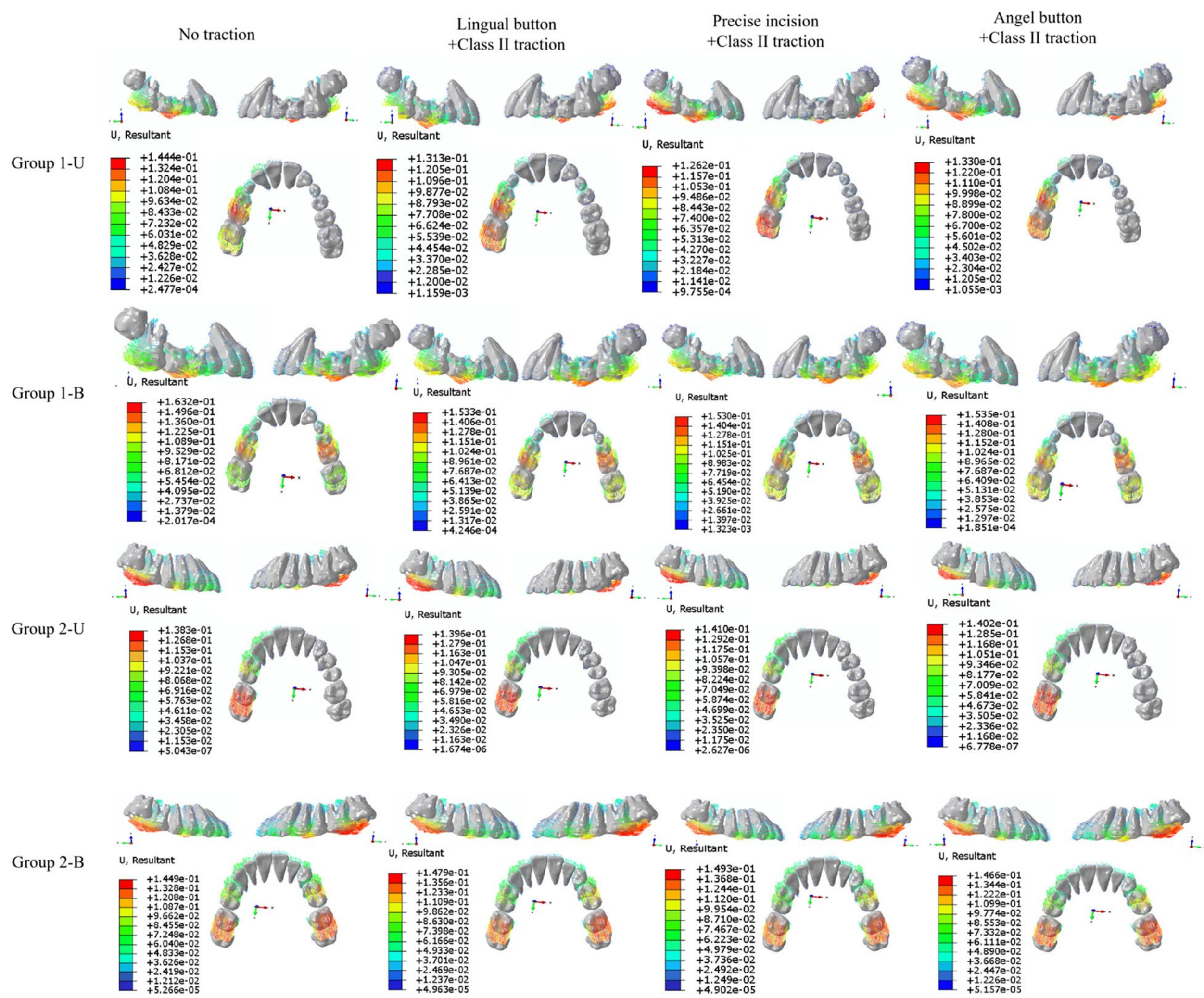

Fig. 3 Moving arrow diagram of the maxillary dentition. The bodily movements of the maxillary dentition in Group 1and 2 were shown in the figure. The movements of each maxillary dentition in each model was shown from the left side, right side and maxillary occlusal surface. The maximum value of the forward movement along the axis was shown in red, and the maximum value of the reverse movement along the axis was shown in blue

distalization, the intrusion of tooth 16 exhibited comparable movement to unilateral distalization in Nolla 4–6 and 7–8 stages (Figs. 3, 5C-D).

Effect of different traction modes on the maxillary dentition

The left and right maxillary homonymous tooth movements along the X, Y, and Z-axes were compared in the Group 1-U, Group 1-B, Group 2-U and Group 2-B respectively. The results demonstrated that regardless of distalization methods (unilateral and bilateral molar distalization), the influence of Class II traction on tooth movement remained consistent and were described together in both Nolla 4–6 and 7–8 stages. Additionally, the movements were ranked from maximum to minimum in Table 4 and illustrated in Figs. 4–5.

Three-dimensional movements of mandibular teeth and influence of different traction modes

In the three groups of Class II traction, unilateral or bilateral molar distalization had no effect on mandibular dentition movements. In all submodels, mandibular dentition movements were consistent, demonstrating mesial inclination of the first molar, mesial displacement of deciduous molars, canines, premolars, and permanent canines, along with labial inclination and

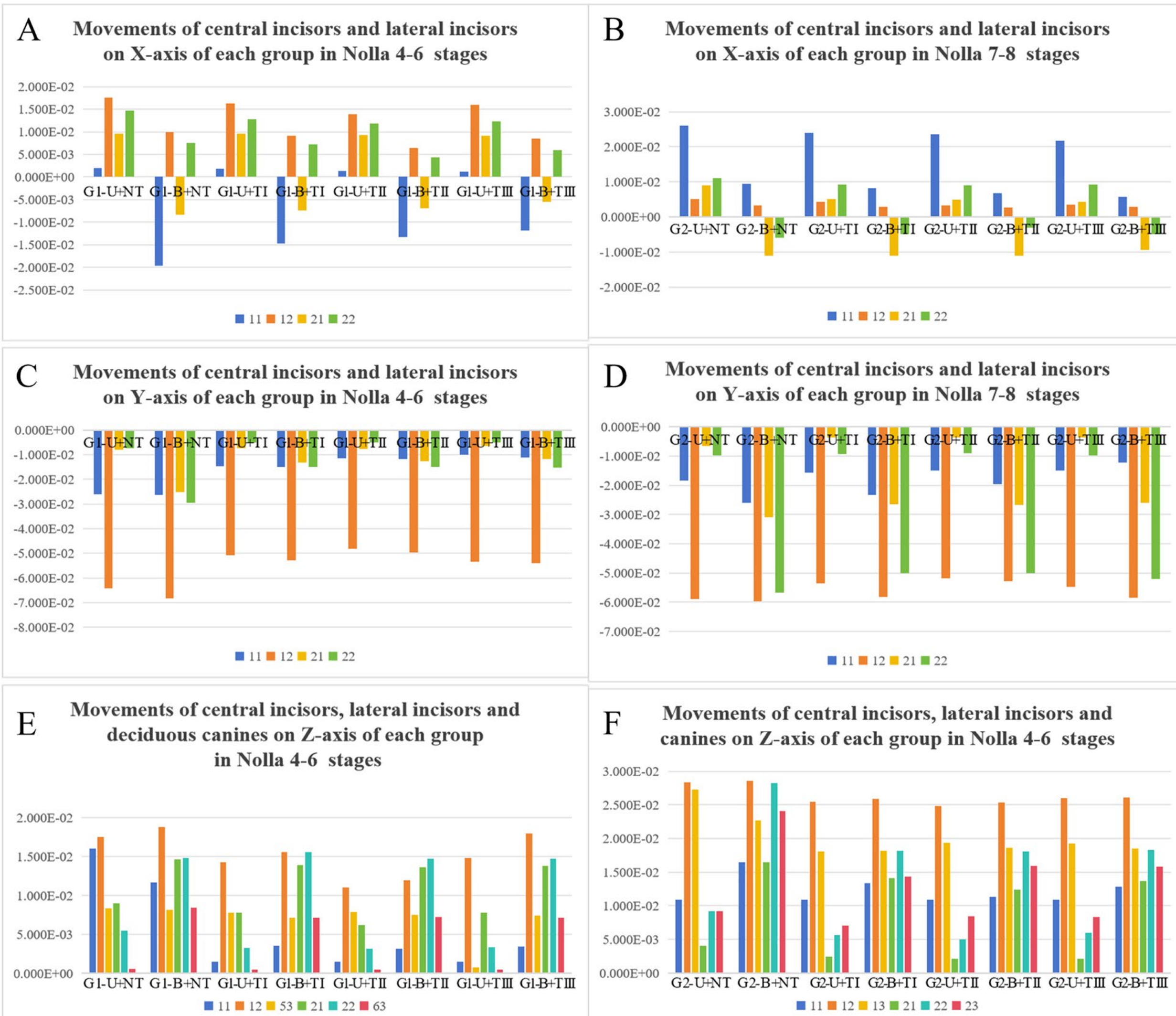

Fig. 4 Statistical diagrams of maxillary anterior tooth movements. The horizontal coordinate represented the experimental groups, and the vertical coordinate represented the movement (mm). **A**-**B** Movements of the central incisors and lateral incisors in X-axis of each group in Nolla 4–6 and 7–8 stages; **C**-**D** Movements of central incisors and lateral incisors in Y axis of each group in Nolla 4–6 and 7–8 stages; **E** Movements of central incisors, lateral incisors and deciduous canines in Z-axis of each group in Nolla 4–6 stages; **F** Z-axis movements of central and lateral incisors and canines in each group in Nolla 7–8 stages

intrusion of anterior teeth. The maximum movement values of dentition were ordered from largest to smallest: Traction II group > Traction I group > Traction III group (Fig. 6).

Stress distribution of teeth, periodontal membrane, and alveolar bone following unilateral and bilateral molar distalization using clear aligners with no traction and three Class II traction modes in Nolla 4–6 and 7–8 stages

Stress distribution and stress values for maxillary and mandibular dentitions, ranked from largest to smallest, are detailed in Appendix Tables 5, 6 and 7 for each group.

For the maxillary dentition, bilateral molar distalization resulted in greater stress on teeth, periodontal membrane and alveolar bone. The stress primarily concentrated on the mesiobuccal crown, distal root surface, root and cervical periodontal membranes, and distal-lingual alveolar bone of the maxillary first molars (Fig. 7A, C, E). For the mandibular dentition, stress distribution remained unaffected by unilateral or bilateral molar distalization. However, with three Class II traction, stress primarily concentrated on the mesiobuccal crown, buccal and distal periodontal membranes, and distal-lingual-buccal alveolar bone of the maxillary first molars (Fig. 7B, D, F).

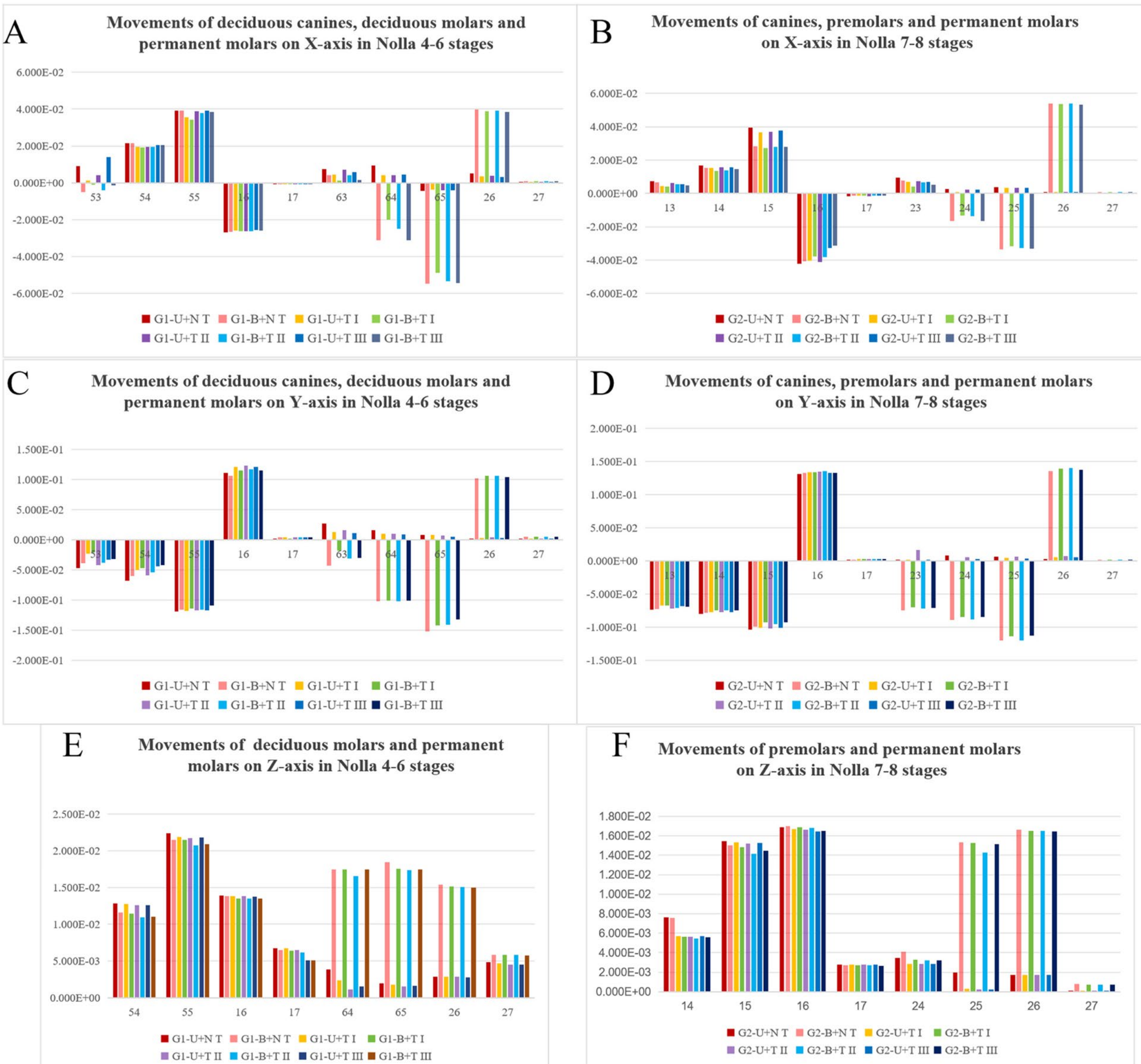

Fig. 5 Statistical diagrams of maxillary posterior tooth movements, abscissa represented tooth position, and ordinate represented movement (mm). **A** Movements of deciduous canines, deciduous molars and permanent molars in X-axis of each group in Nolla 4–6 stages; **B** Movements of canines, premolars and molars in X-axis of each group in Nolla 7–8 stages; **C** Movements of deciduous canines, deciduous molars and permanent molars in Y-axis of each group in Nolla 4–6 stages; **D** Movements of canine, premolars and molars in Y-axis of each group in Nolla 7–8 stages; **E** Movements of deciduous molars and permanent molars in the Z-axis of each group in Nolla 4–6 stages; **F** The movements of premolars and molars in Z-axis of each group in Nolla 7–8 stages

Discussion

The use of invisible early treatment in childhood has become the focus of orthodontic research. One common non-extraction mode in early childhood orthodontic treatment is distalization of the maxillary first molars by using clear aligners [26–28]. However, the crowns and (or) roots of the maxillary second molars that do not erupt are in different stages of growth and development, which may have an effect on maxillary first molar distalization. Therefore, we selected a patient who was in Nolla 4–6 stages (aged 8–10 years old) of maxillary second molar development, as well as another patient in Nolla 7–8 stages (aged 10–12 years old) as our subjects. In our study, the quantities of distal movements of the maxillary first molars in Nolla 7–8 stages were greater than that in Nolla 4–6 stages This discrepancy likely stems from advanced alveolar bone maturation, longer root formation, and a broader periodontal membrane

Table 4 In Nolla 4–6 and 7–8 stages, the left and right maxillary tooth movements were ranked from maximum to minimum without and with 3 types of Class II traction

Nolla 4–6 and 7–8 stages			
	X-axis	**Y-axis**	**Z-axis**
Left and right central incisors	No traction group > Traction I group > Traction II group > Traction III group		No traction group > Traction I group > Traction III group > Traction II group
Left and right lateral incisors	No traction group > Traction I group > Traction III group > Traction II group	No traction group > Traction III group > Traction I group > Traction II group	
Left and right deciduous and permanent canines	No traction group > Traction II group > Traction III group > Traction I group		
Left and right deciduous molars and premolars	No traction group > Traction III group > Traction II group > Traction I group	No traction group > Traction II group > Traction I group > Traction III group	No traction group > Traction I group > Traction III group > Traction II group
Left and right first molars	No traction group > Traction II group > Traction I group > Traction III group	Traction II group > Traction I group > Traction III group > No traction group	No traction group > Traction I group > Traction II group > Traction III group

Take the No traction group for example, No traction group included Group 1- U + No traction, Group 1- B + No traction, Group 2- U + No traction and Group 2- B + No traction. Traction I group, Traction II group and Traction III group followed the same subgrouping scheme as No traction group

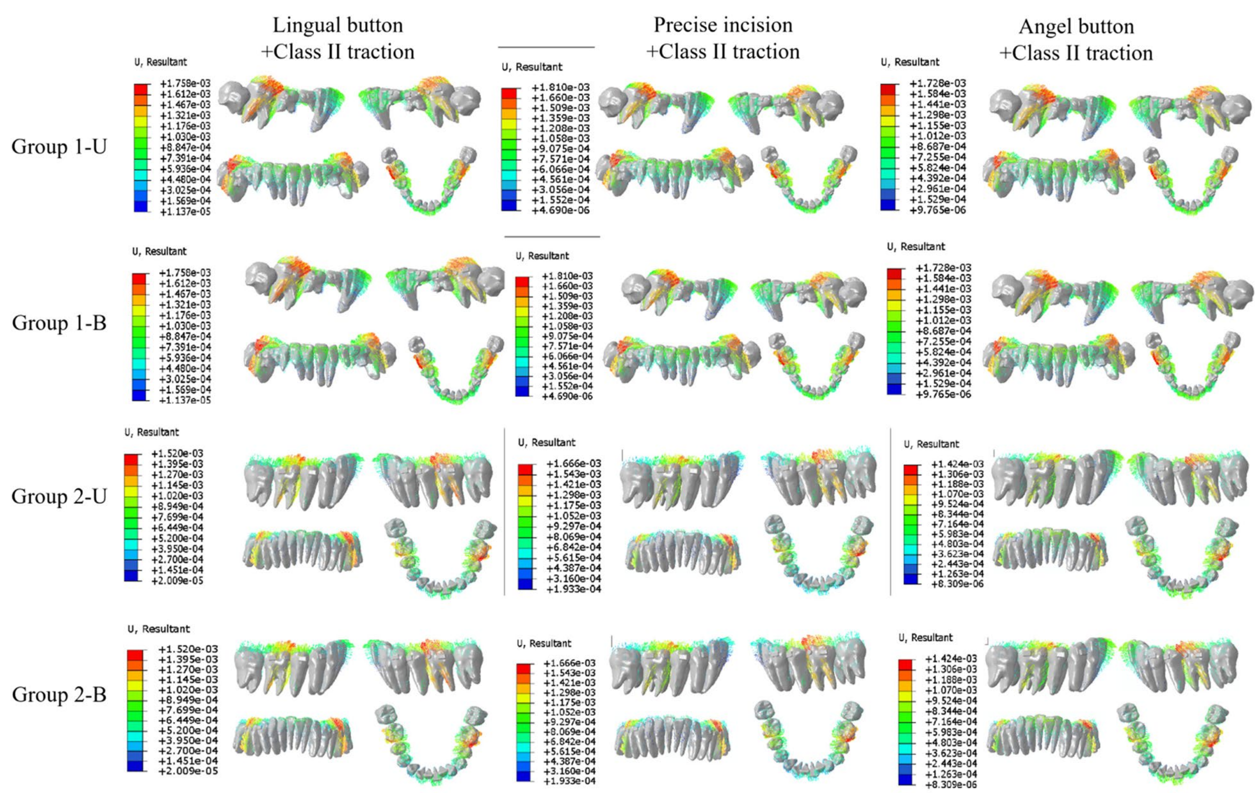

Fig. 6 The moving arrow diagrams of the mandibular dentition were presented and the movements of Group 1 and 2 were illustrated. The figure displayed the movement of each tooth in the mandibular dentition in each model from various perspectives including left side, right side, front side and mandibular occlusal surface. The maximum value of forward movement along the axis was highlighted in red, while the maximum value of reverse movement along the axis was indicated in blue

area in Nolla 7–8 stages, which enhance anchorage support. Conversely, Nolla 4–6 stages are characterized by shorter dental arches, mixed dentition with primary teeth undergoing root resorption, and immature permanent tooth roots, resulting in reduced anchorage capacity. Furthermore, complete arch engagement by aligners in Nolla 7–8 stages strengthens anchorage, whereas shorter primary tooth crowns in younger patients limit aligner coverage and stability. In different development stages of the maxillary second molar, the maxillary crown height, root length, periodontal ligament area and maxillary alveolar bone development are different, which may be factors affecting the coverage and stability of clear aligners during the molar distalization. Then these factors may affect the distal movements of the maxillary first molars. Notably, the magnitude of maxillary first molar distalization varied significantly across traction modalities in both Nolla 4–6 and 7–8 stages. The Precision incision + Class II traction group demonstrated the greatest distal displacement, followed by Lingual button + Class II and Angel button + Class II groups, with minimal movement observed in the No traction group. This hierarchy suggests that reduced fulcrum-to-molar distances under Class II traction enhance distalization efficiency. However, our findings contrast with Lili Ji et al. [32], who reported superior distal movement with Angel button + Class II traction in adults. This discrepancy likely arises from developmental distinctions: our study focused on mixed/early permanent dentition (Nolla 4–8 stages), where alveolar bone and teeth immaturity and transitional dentition dynamics alter biomechanical responses. Consequently, adult-derived protocols for molar distalization and traction modality selection are not directly applicable to mixed/early permanent dentition patients. Clinicians must instead tailor strategies to individual developmental stages and dentition status.

Bilateral molar distalization resulted in greater labial movement of anterior teeth and reduced mesial movement of deciduous molars and premolars compared to unilateral distalization. This phenomenon can be attributed to the force superposition mechanism in bilateral molar distalization: two labial moving forces acting on anterior teeth, while deciduous molars and premolars experienced a combination of larger mesial and smaller distal movement forces. Clinically, these findings emphasize the necessity for precise treatment planning based on individual patients'oral conditions and distalization patterns to optimize anchorage preparation. Moreover, bilateral molar distalization induced greater stress on teeth and periodontal membranes than unilateral approach, and the stress of alveolar bone was observed concentration primarily at maxillary first molars. This underscores the importance of meticulous monitoring of teeth and alveolar bone development during treatment planning, particularly in mixed and early permanent dentition stages. While early treatment coincides with active development of the teeth, periodontal membrane, and alveolar bone [30, 31], the long-term effects of corrective forces on their development and remodeling remain unclear, warranting extended clinical follow-up studies for comprehensive evaluation.

Currently, the primary modalities for Class II traction encompass Lingual button, Precise incision, and Angel button techniques combined with Class II traction [21, 32]. In this study, we observed labial inclination and anterior tooth support loss during maxillary first molar distalization with clear aligners, irrespective of the traction method employed. These findings are consistent with previous reports by Jiayu Cui and Xulin Liu et al. [20, 33]. Notably, our analysis identifies stage-specific anchorage control patterns: Angel button + Class II traction optimally stabilizes maxillary central incisors during Nolla 4–6 and 7–8 stages, while Precise incision and Lingual button approaches preferentially regulate lateral incisor and canine/deciduous canine anchorage, respectively. These findings resonate with Chunlei Xun et al.'s finite element analysis [34], which demonstrated superior anterior tooth protection when applying Class II traction directly to aligners rather than targeting canines. Mechanistic differences explain these variations: Lingual button systems localize force application to canine regions, whereas Precise incision and Angel button configurations distribute forces through the aligner itself, counteracting deformation and enhancing anterior anchorage. Notably, Precise incision + Class II traction achieves greater molar displacement with reinforced anterior stability, likely due to direct force transfer to aligners without intermediary energy dissipation—contrasting with Angel button systems where force transmission through the button may reduce efficiency. It is worth noting that the use of

(See figure on next page.)

Fig. 7 Stress distribution. **A**-**B** The stress distribution of the maxillary and mandibular teeth in Group 1 and 2 was shown in the figure. The maximum stress value was shown in red, and the minimum stress value was shown in blue. **C**-**D** Stress distribution of the periodontal membrane of the maxillary and mandibular dentition, with the maximum stress shown in red and the minimum stress shown in blue. **E**–**F** The distribution of stress in the maxillary and mandibular alveolar bone was presented for Group 1 and 2 in the figure. This depiction showcases the stress distribution in the alveolar bone for each model from maxillary and mandibular occlusal surface

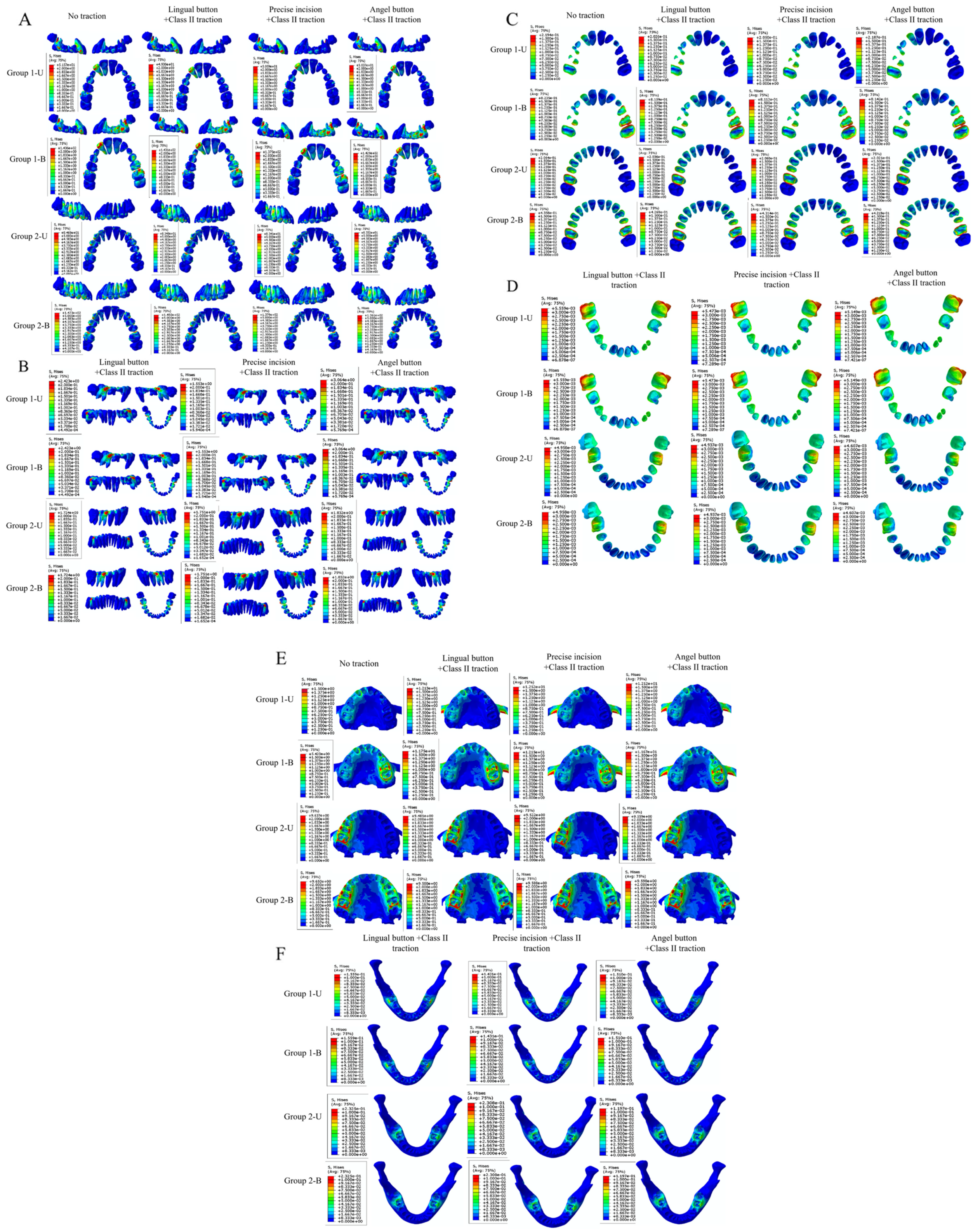

Fig. 7 (See legend on previous page.)

Class II traction during maxillary molar distalization may induce undesirable labial inclination of the mandibular anterior teeth and increase periodontal ligament stress, potentially compromising periodontal health, even though Angel button + Class II traction minimizes mandibular dentition displacement and periodontal stress. Furthermore, long-term use of Class II traction exacerbates these adverse effects. This emphasizes the necessity for maxillary and mandibular dental arches biomechanical considerations in treatment planning. Clinicians must strategically balance maxillary anchorage requirements with mandibular stability when selecting traction modalities.

Conclusion

(1) In both Nolla 4–6 and 7–8 stages, bilateral molar distalization demonstrated greater maxillary anterior labial inclination, maxillary tooth stress and periodontal membrane and alveolar bone stress compared to unilateral distalization.

(2) Maxillary first molar movement was greater in Nolla 7–8 stages than in Nolla 4–6 stages, irrespective of unilateral or bilateral distalization. At different developmental stages of the maxillary second molar, variations in maxillary crown height, root length, periodontal ligament area and maxillary alveolar bone may influence the coverage and stability of clear aligners during molar distalization. Then these factors affect the distal movements of the maxillary first molars.

(3) Either unilateral or bilateral molar distalization, Angel button + Class II traction offered superior anchorage control for maxillary central incisors. Precision incision + Class II traction provided better anchorage control for maxillary lateral incisors and resulted in the greatest distal movement of maxillary first molars. Lingual button + Class II traction enhanced anchorage control for maxillary deciduous or permanent canines.

(4) Mandibular dentition movement and stress distribution were minimally affected by unilateral or bilateral molar distalization. Although among the three traction modes, Angel button + Class II traction resulted in the least movement and periodontal membrane stress of mandibular dentition, we need to pay attention to the negative effect of Class II traction use.

(5) This study offers an experimental foundation for clear aligner application in mixed and early permanent dentition, enriches biomechanical understanding, and aims to inform clinical treatment planning. Future research will include clinical case tracking to validate these findings.

Appendix

Table 5 The primary stress distribution areas and corresponding stress magnitude rankings of maxillary and mandibular teeth

	The areas with more obvious stress distribution and stress magnitude rankings of teeth in the maxillary dentition	The areas with more obvious stress distribution and stress magnitude rankings of teeth in the mandibular dentition
Group 1-U	• The middle and distal adjacent contact points of 54 • The distal and lingual sides of 12 • No traction group > Traction II group > Traction III group > Traction I group	• The mesial buccal crowns of 36 and 46 • The mesial and distal proximal contact points and mandibular occlusal surfaces of deciduous molar and premolar teeth • Traction III group > Traction I group > Traction II group
Group 1-B	• The middle and distal adjacent contact points of 54 • The distal and lingual sides of 12 • The contact point of 64 and 65 • No traction group > Traction I group > Traction III group > Traction II group	
Group 2-U Group 2-B	• The stress distribution on the maxillary dentition teeth was relatively uniform, mainly concentrated in the proximal and distal contact points and the distal crown buccal side of the maxillary teeth, and the proximal and distal roots of the canine and premolars • No traction group > Traction I group > Traction II group > Traction III group	• The mesial buccal crowns of 36 and 46 • The mesial and distal proximal contact points and mandibular occlusal surfaces of deciduous molar and premolar teeth • Traction III group > Traction II group > Traction I group

Take the No traction group for example, No traction group included Group 1-U + No traction, Group 1- B + No traction, Group 2- U + No traction and Group 2-B + No traction. Traction I group, Traction II group and Traction III group followed the same subgrouping scheme as No traction group

Table 6 The primary stress distribution areas and corresponding stress magnitude rankings of maxillary and mandibular periodontal membrane

	The areas with more obvious stress distribution and stress magnitude rankings of the periodontal membrane in the maxillary dentition	The areas with more obvious stress distribution and stress magnitude rankings of the periodontal membrane in the mandibular dentition
Group 1-U	• The tooth necks of 12, 53, 54, 55 and 16 • No traction group > Traction III group > Traction II group > Traction I group	• The buccal and distal areas of 36 and 46 • The proximal and distal areas of the deciduous canines and deciduous molars • The labial area of the mandibular anterior teeth • Traction I group > Traction II group > Traction III group
Group 1-B	• The lingual neck of 54 • The buccal mesial of 64 • The proximal distal area of 65 and the proximal distal area of 26 • No traction group > Traction III group > Traction II group > Traction I group	
Group 2-U	• The teeth necks of 12, 13, 14, 15 and 16 • The distal and proximal distal areas of 15 and 16 • No traction group > Traction II group > Traction I group > Traction III group	• The buccal side of 36 and 46 • The buccal area as well as the proximal and distal areas of the premolars and canines • The labial area of the mandibular anterior teeth • Traction I group > Traction II group > Traction III group
Group 2-B	• The distal area of 15 • The proximal distal area and the buccal neck of 16 • The distal area of 25 and the proximal distal area of 26 • No traction group > Traction II group > Traction I group > Traction III group	

Take the No traction group for example, No traction group included Group 1-U + No traction, Group 1- B + No traction, Group 2- U + No traction and Group 2-B + No traction. Traction I group, Traction II group and Traction III group followed the same subgrouping scheme as No traction group

Table 7 The primary stress distribution areas and corresponding stress magnitude rankings of maxillary and mandibular alveolar bone

	The areas with more obvious stress distribution and stress magnitude rankings of the maxillary alveolar bone	The areas with more obvious stress distribution and stress magnitude rankings of the mandibular alveolar bone
Group 1-U	• The distal surface and lingual side of alveolar bone in 16 • No traction group > Traction II group > Traction I group > Traction III group	• The proximal–distal surface and along the buccal-lingual side in 36 and 46 • Traction I group > Traction III group > Traction II group
Group 1-B	• The distal and buccolingual side of the alveolar bone in 65 • The distal surface and lingual side of alveolar bone in 16 and 26 • No traction group > Traction II group > Traction I group > Traction III group	
Group 2-U	• The buccolingual side of alveolar bone in 14 and 15 • The distal surface and lingual side of alveolar bone in 16 • No traction group > Traction III group > Traction II group > Traction I group	• The proximal–distal surface and along the buccal-lingual side in 36 and 46 • Traction I group > Traction II group > Traction III group
Group 2-B	• The buccolingual side of alveolar bones in 14 and 15 • the distal and lingual side of alveolar bones in 16, 25 and 26 • No traction group > Traction III group > Traction II group > Traction I group	

Take the No traction group for example, No traction group included Group 1-U + No traction, Group 1- B + No traction, Group 2- U + No traction and Group 2-B + No traction. Traction I group, Traction II group and Traction III group followed the same subgrouping scheme as No traction group

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Authors' contributions
C.C.S designed the research. Y.L, M.Y.W and X.Y.X conducted the experiment. Y.L, Y.M.C, C.L.Z and J.H.H analyzed the data and Y.L wrote the paper. All authors read and approved the final manuscript.

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Data availability
All the data are provided within the manuscript.

Declarations

Ethics approval and consent to participate
This study adhered to the Declaration of Helsinki principles for medical research involving human subjects and was approved by the Medical Ethics Committee of the Affiliated Stomatology Hospital of Kunming Medical University, and the approval number is KYKQ2023MEC0115. The participants and their parents were asked to sign that they agreed to participate in the study. Informed consent to participate and their parents was obtained from all the participants in this study.

Consent for publication
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Competing interests
The authors declare no competing interests.

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