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The effect of canine lingual attachments during maxillary arch distalization with clear aligner: a 4D finite element analysis and in vitro simulator study

Bochun Mao[1†], Yajing Tian[2†], Hanzhang Zhou[1] and Yan Gu[1*]

Abstract

Objective During the maxillary premolar distalization process in clear aligner (CA) therapy, anterior aligner misfit and mesial displacement of the molars are two common challenges. This study aims to propose a novel attachment design to address these issues and to investigate the biomechanical effects of varying canine tipping angles during treatment.

Method A dual-methodological approach was employed: 1) A four-dimensional finite element model (4D FEM) incorporating automated staging simulation was developed, utilizing iterative computations for long-term tooth movement prediction and thermal expansion algorithms for CA morphology adaptation; 2) An electromechanical orthodontic simulator (OSIM) was implemented for in vitro validation. The study analyzed three canine inclination groups in FEM simulations versus eleven groups in OSIM experiments, with particular focus on lingual attachment biomechanics. The A t-test was used to compare the forces and moments of each tooth between the groups with the same canine tipping angle.

Results The findings from the 4D FEM analysis demonstrated that distally inclined canines provided greater anchorage during premolar distalization (0.27 mm mesial movement for the first molar in -10° group), while mesially inclined canines contributed to more pronounced anchorage loss (0.34 mm mesial movement for the first molar in 10° group). The use of lingual attachments on canines improved the average distalization efficacy of premolars by 1%, 6%, and 7% in the -10°, 0°, and 10° canine tipping groups, respectively. Similarly, the in vitro orthodontic simulator (OSIM) experiment showed a comparable trend in force and moment variations.

Conclusion Both the 4D FEM and OSIM analyses indicted that during the distalization process of premolars, canine lingual attachment significantly reduces the mesial displacement of molars by alleviating the unfitness of CA at anterior teeth area to enhance anterior anchorage. The efficiency of the attachment increased with the greater mesial tipping of canine. Based on the results of this study, it is clinically recommended to place lingual attachments during premolar distalization when the canine mesially tipped more than 4°.

Keywords Clear aligner, Molar distalization, Orthodontic biomechanics, Finite element analysis

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Introduction

Clear aligners (CAs) have gained widespread adoption in orthodontic practice due to their superior esthetics and improved patient comfort compared to conventional fixed appliances. Molar distalization with CAs has been demonstrated as a feasible and convenient method, making it a research hotspot for several years [1–3]. Previous studies primarily focused on the efficiency and movement patterns of molar distalization, the design of attachments and anchorage, and staging protocols [1–5]. However, while the predictability of molar distalization during the distalization phase was as high as 88%, it dropped to 42% after the following anterior teeth retraction process [6, 7]. Moreover, many studies have overlooked issues such as off-tracking and labial movement of the anterior teeth, which occur due to reciprocal forces. Our previous studies suggested that the 'reversed bow effect', which characterized as the flared anterior teeth and distal tipping of molars that caused increased overjet and shallow overbite, was common during the dentition distalization with CA, which may cause potential periodontal risks, such as alveolar bone dehiscence and root resorption [4, 5].

It is noticed that during the distalization of premolars, the unfitness of CA at anterior teeth area, the 'reverse bow effect', and the mesial displacement of molars were commonly noticed problems [5, 8]. Clinical observations suggest that the mesiodistal tipping of the canines may affect the anterior fit of the aligner. Moreover, the precise cut of the CA is frequently designed at the maxillary canine area for retraction, which further reduce the wrapping of the canine, leading to potential track-off [9].

With a thorough understanding of the biomechanics of clear aligners (CAs), orthodontists can achieve treatment outcomes that are not only safe but also predictable and long-lasting. In recent years, the finite element method (FEM) has been widely used to simulate CA treatments in various studies [4, 5, 10]. However, all the previous studies published thus far have been confined to examining the initial displacement during CA wear, overlooking biological changes, i.e. alveolar bone remodeling, which are fundamental to orthodontic tooth movement. This limitation hinders accurate modeling of long-term orthodontic effects. Recent advancements introduced 4D FEM to simulate orthodontic tooth movement by integrating periodontal tissue responses as another dimension [4, 5, 8], Additionally, the temperature-changing method (TCM) has been applied to automatically remodel the CA during long-term simulations [4, 5, 8]. TCM operates on the principle that heat induces expansion while cold induces contraction. By defining parameters such as thermal expansion/shrinkage coefficients, temperature variations, and expansion directions, the CA—especially at interdental regions—can be updated automatically with high accuracy and without the need for manual remeshing. This enables iterative morphological changes of the aligner to be simulated efficiently. With 4D FEM, which could simulate constant changing interrelationships among all components within a simulation model, orthodontists can gain more significant results for long-term orthodontic treatment.

Nevertheless, several simplifications—such as assuming uniform thickness for the aligner and the periodontal ligament (PDL)—are typically made during FEM simulations, which may compromise result accuracy. To address these limitations, an in vitro electro-mechanical orthodontic simulator (OSIM) was employed in this study to complement the FEM analysis. The OSIM is a force/moment measurement system capable of capturing, in real time, the forces exerted by CAs on a representative 14-tooth maxillary or mandibular dentition. It has been demonstrated to be an effective tool for simulating tooth displacement in orthodontic research [11–13]. The system employs multiple six-axis force sensors connected to each tooth in the dental arch, enabling the measurement of three-dimensional (3D) forces delivered at the level of individual dental crowns. Although the experimental model does not incorporate an in vitro representation of the PDL, it remains effective for analyzing the biomechanics of clinically applied clear aligners, regardless of their design complexity or material properties.

Therefore, to enhance the predictability of molar distalization and to minimize anterior aligner misfit during premolar distalization, this study aimed to design and evaluate the efficacy of a novel canine lingual attachment. Additionally, the biomechanical effects of varying canine tipping angles during premolar distalization were assessed. The null hypotheses were as follows: (1) the incorporation of the canine lingual attachment would have no effect on treatment outcomes, and (2) there would be no differences among the groups with different canine tipping angles.

Method

4D finite element analysis

This research was approved by the Institutional Review Board of Peking University School and Hospital of Stomatology (PKUSSIRB-202059154), and all experiments were performed in accordance with relevant guidelines and regulations. The FEM model contained teeth, PDL, attachments, and CA (Fig. 1a), following the methodologies outlined in previous publications [4, 5]. The canine was moved to gain the same angulation as Andrews occlusion in respect of the mesiodistal and labiolingual angulation. For computational efficiency, the model was constructed for the right side only, with symmetrical boundary conditions applied to the median section of the

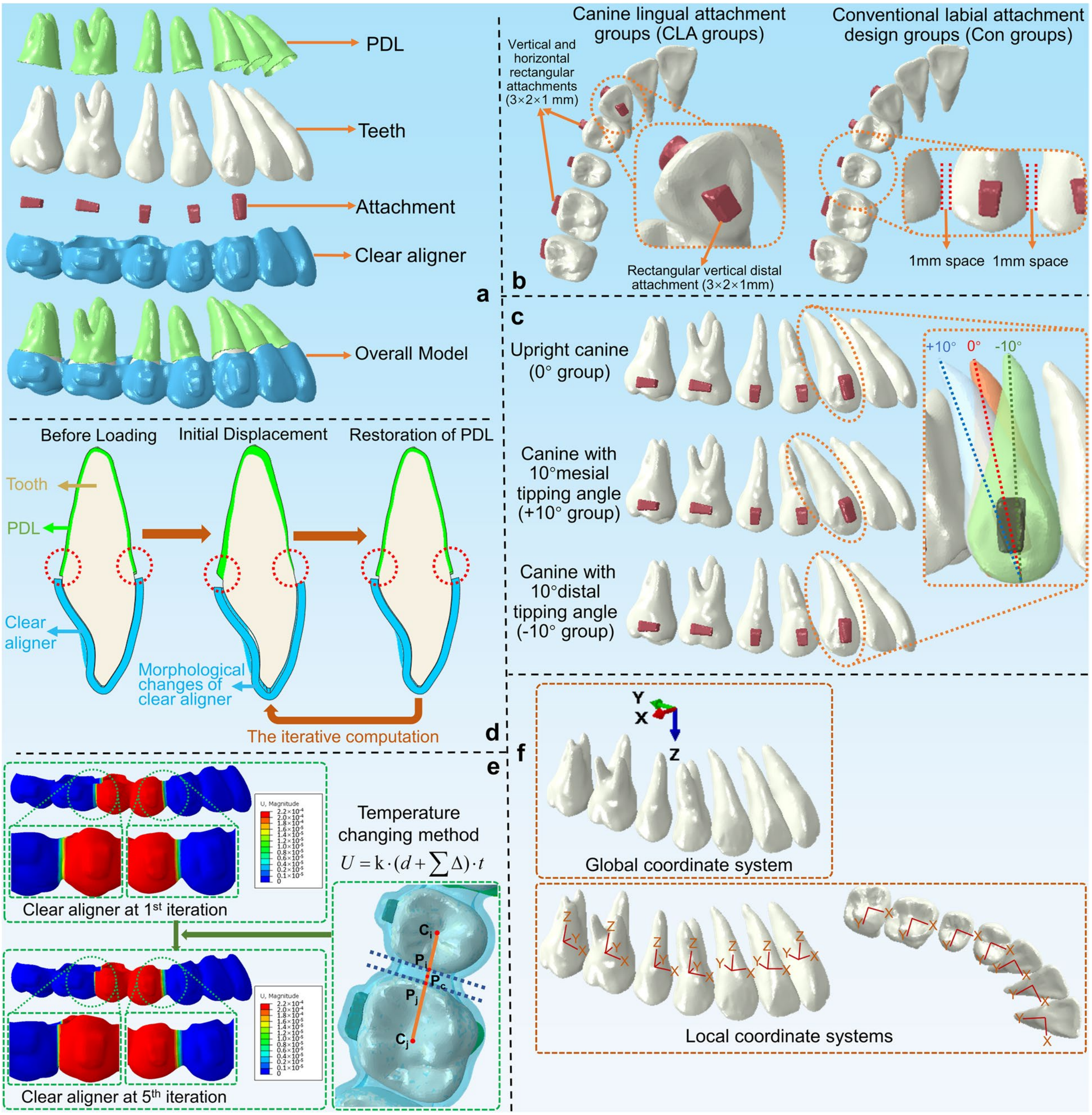

Fig. 1 **a** The components of the model; **b** The attachment designs of different groups; **c** Three different set of canine tipping angles; **d** Diagram of the bone remodeling simulation method (Notice the deformation of periodontal ligament in the red circles); **e** The automatic clear aligner morphology changing method based on the temperature changing method: the process began with the determination of the center point of dental crowns in the occlusal view, denoted as (Ci, Cj). Margin points of dental crowns on the line connecting Ci and Cj were established as (Pi, Pj), and the center point of Pi-Pj (Pc) was then calculated. A selected area, both mesial and distal to Pc, perpendicular to the Ci–Cj line, was identified as the deformation region during staging. Deformation within this area was constrained along the Ci–Cj line. Where in the formula U refers to the preset deformation quantity, k refers to the coefficient of linear expansion, Δ refers to the amount of deformation in previous steps, d refers to the width of the area, and t refers to the change of temperature. **f** Two coordinate systems were used in this study to evaluate tooth displacements. PDL, periodontal ligament

CA. The PDL was represented by a 0.30 mm shell element [4, 5]. Conventional vertical and horizontal rectangular attachments (3 ×2 ×1 mm) were designed according to manufacturer's suggestion. The material parameters for involved models were detailed in Supplementary Table 1 [14]. The crowns were uniformly thickened to a thickness of 0.7 mm and underwent preprocessing to create the initial CA model [15]. The assembly of all models was performed using Hypermesh 14.0 software (Altair, Troy, Mich). Unstructured four-noded tetrahedral elements were selected. Subsequently, the models were imported into Abaqus/CAE software (SIMULIA, Providence, RI) for FEM study. The PDLs and tooth roots were considered position constraint. The relationship between aligners and crowns was designated as small-sliding surface-to-surface with the friction coefficient set to 0.2 [16]. In this study, a convergence study was carried out to determine the optimal element size. The effect of element size on the maximum von Mises stress and maximum displacement was investigated. The results showed that both stress and displacement values converged when the element size was reduced below 0.2 mm. Therefore, an element size of 0.2 mm was selected for subsequent simulations.

Both 1 mm spaces were set anteriorly and posteriorly of the second premolar (Fig. 1b), simulating the scenario where the two molars had completed distalization during total arch distalization with the common V-pattern teeth movement strategy. In addition to the conventional labial attachment design of the control groups (Con groups), rectangular vertical distal attachment (3 ×2 ×1 mm) was added in ClinCheck (Align Technology, Inc.) at the lingual surface of the canine in the canine lingual attachment groups (CLA groups) (Fig. 1b). Three different canine tipping angles were set (Fig. 1c): 1) upright canine (0°); 2) canine with 10° mesial tipping angle (+ 10°); 3) canine with 10° distal tipping angle (−10°). In total, 6 FEM models were included: 2 (Con and CLA groups) ×3 (three different canine tipping angles).

As previous studies revealed, an iteration method was employed to simulate the bone remodeling process during CA treatment, assuming teeth and the alveolar bone to be rigid bodies throughout this simulation (Fig. 1d) [4, 5, 17]. The TCM, as previously elucidated, was utilized to automatically remodel the CA during long-term orthodontic simulation (Fig. 1e, Supplementary Video 1) [4, 5]. Employing TCM, five steps of distal body movement of the first and the second premolars were designed, with a 0.2 mm movement for each step. Each CA staging step was paired with 2 iterations of PDL to replicate the clinical scenario where the CA was adequately worn over a sufficient duration. These procedures are executed automatically using custom-developed subroutines with Python for ABAQUS.

The occlusion plane and the global coordinate system were defined according to previous method (Fig. 1f) [18]. Local coordinate systems were used to illustrate the displacement of the teeth. The crown point (CP), root point (RP), resistance center (RC), and the long axis (LA) of each tooth were determined as shown in Supplementary Table 3. The gap between the CP of the central incisor and the corresponding point on CA was recorded. As for the local coordinate systems for each tooth, the Z-axis was set the same as the global coordinate system, but the X- and Y-axes represented the mesial/distal, labial/lingual directions, respectively (Fig. 1f). The 3D displacement of the crown points and the rotation of the LA at each step were recorded.

In vitro experimental study

The in vitro OSIM used in this study is capable of measuring the 3D forces and moments acting on each individual tooth, and has been employed in previous studies [11, 12]. The OSIM system consisted of 14 high-precision six-axis force sensors (Nano17-E, ATI Industrial Automation, Apex, NC, USA), each connected to an isolated 3D-printed resin tooth via a connecting rod (DM15, Shining 3D, Hangzhou, China) (Fig. 2a). The coordinate system of each sensor was provided by the manufacturer. Jacobian transformation matrices between the sensors and the local coordinate system of each tooth were calculated following the method described in previous studies [19, 20]. A custom software package developed in the MATLAB programming environment was used to interpret and process the force and moment data collected from the 14 sensors.

The same digital dentition model was used in the OSIM study as the FEM study. The canine lingual attachments were designed for the CLA groups same as the FEM study (Fig. 2b). According to the 4D FEM study design, the first step of teeth movement design was simulated in the OSIM study, i.e. 0.2 mm distal movement was prescribed for both premolars. Models with more finely distributed canine tipping angles were included: +10°, +8°, +6°, +4°, +2°, 0°, −2°, −4°, −6°, −8°, −10° (Fig. 2c). In total, 22 models were included: 2 (Con and CLA groups) ×11 (eleven different canine tipping angles). Each 3D-printed resin tooth, together with its connecting rod, was scanned using an optical scanner (D2000, 3Shape). The scanned models were aligned with the corresponding original 3D designs using Geomagic Qualify 2013 (Geomagic, 3D Systems), and geometric discrepancies were evaluated via 3D deviation analysis. The average deviation of all models was less than 0.07 mm, confirming the acceptable accuracy of the 3D-printed components.

The process of the OSIM test is shown in Fig. 2d. The dentitions were 3D-printed for the production of the corresponding CA by thermoforming with 0.80 mm diaphragms (Erkodent, Pfalzgrafenweiler, Germany). The initial force (F) and moment (M) components of each tooth were recorded. Six CAs were thermoformed for each group, and each CA was tested for 6 times. Data

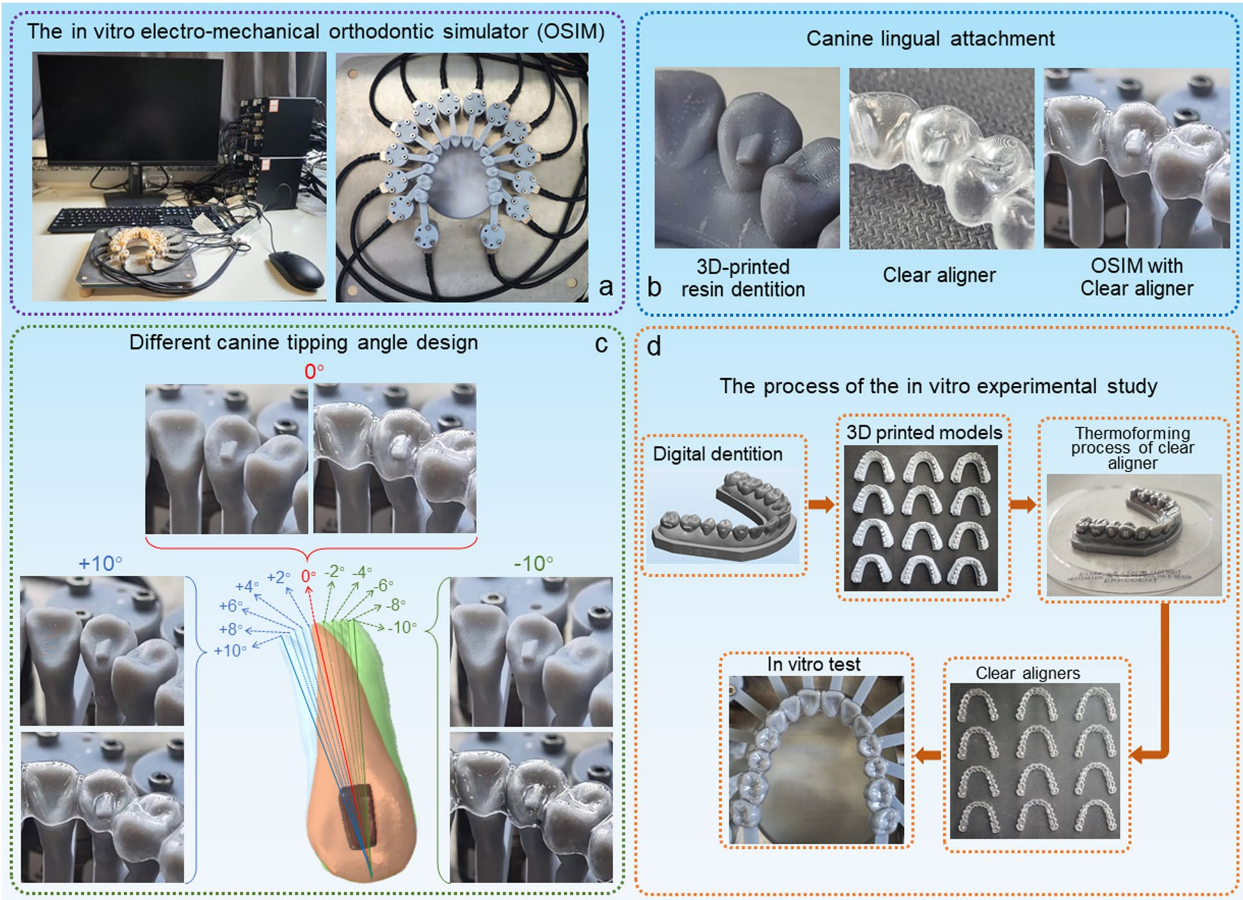

Fig. 2 The in vitro electro-mechanical orthodontic simulator (OSIM) test: **a** the OSIM; **b** The canine lingual attachment design; **c** Different canine tipping angle design; **d** The process of the in vitro experimental study

were exported to SPSS 19.0 (IBM, Chicago, USA) for statistical analysis. After the Shapiro–Wilk test was used to verify the normal distribution of data, a t-test was used to compare the forces and moments of each tooth between the groups with the same canine tipping angle. $P < 0.05$ was considered statistically significant.

Results

4D finite element analysis results

Figure 3 illustrates the displacement of dental crowns and rotation of teeth across the five simulation steps, while Table 1 presents the corresponding quantitative results at the conclusion of each simulation. Comparing the three control groups with varying canine tipping angles, the −10° canine tipping group exhibited the largest labial displacements and labial torques for incisors and canines, along with the most pronounced distal movement of premolars and the least mesial movement of molars. In comparisons between corresponding CLA and control groups with identical canine tipping angles, the CLA groups showed greater labial displacement for incisors, more distal movement of premolars, and reduced mesial movement of molars. The most significant anterior tooth torque was observed in the CLA group with 10° canine tipping (−2.33°), followed by the corresponding control group (−1.74°).

As shown in Table 2, the largest gap between the central incisor CP and the corresponding CA point was observed in the 10° canine tipping control group (0.51 mm), which decreased to 0.31 mm with the incorporation of lingual attachments on canines. The smallest gaps were observed in the −10° canine tipping groups (0.26 mm for the control group, 0.24 mm for the CLA group). Regarding premolar distalization efficacy (Table 2), the first premolars exhibited greater distalization efficacy than the second premolars across all groups. The use of lingual attachments on canines improved the average distalization efficacy of premolars by 1%, 6%, and 7% in the −10°, 0°, and 10° canine tipping groups, respectively. Additionally, all groups showed molar width expansion, as indicated by buccal displacement and buccal torque of the molars.

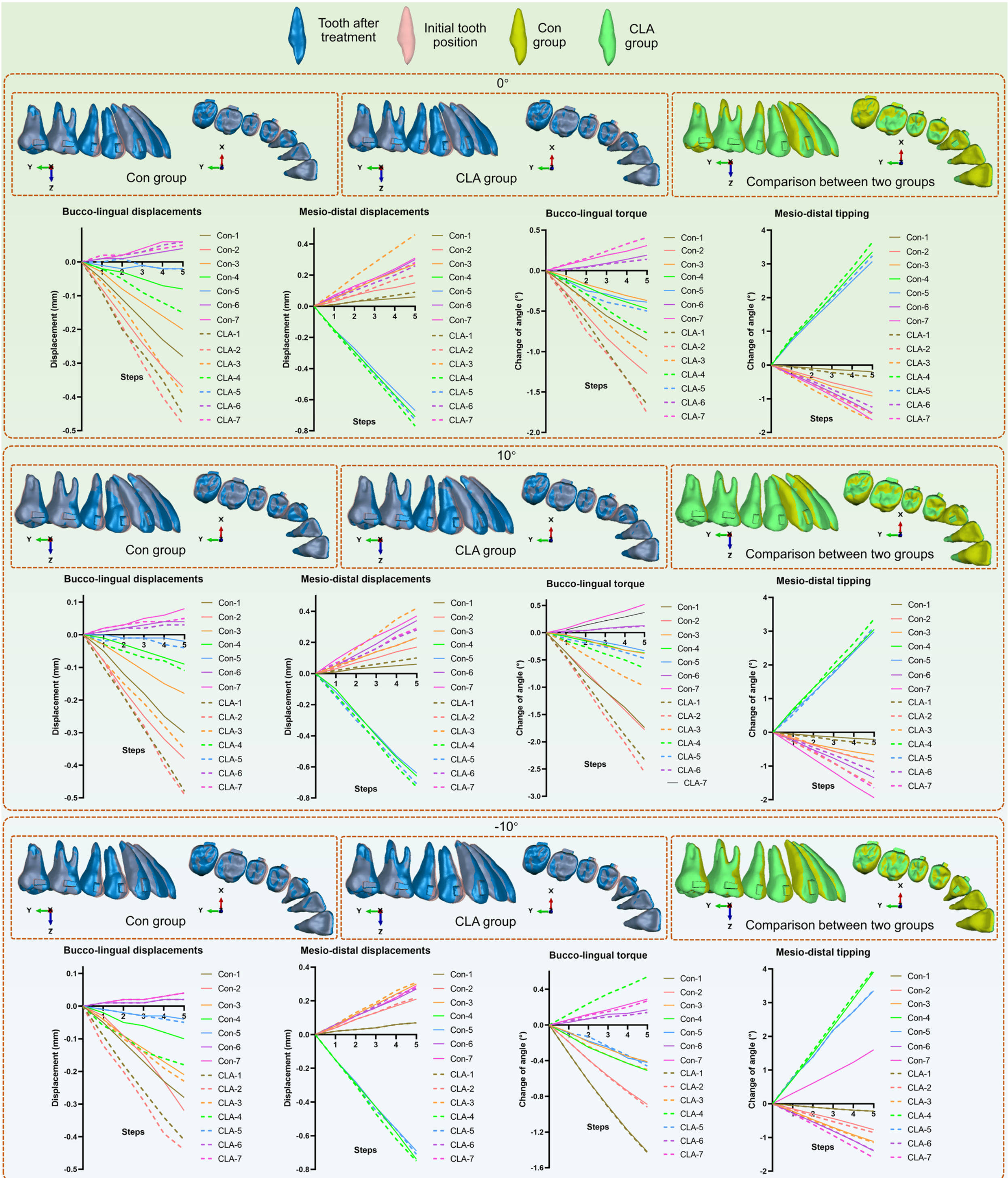

Fig. 3 Within the local coordinate systems of each tooth, the displacements of crown points and rotation of teeth were shown. Tooth numbering according to the FDI tooth numbering system. Con, conventional attachment design. CLA, canine lingual attachment design. 0°, upright canine group. 10°, canine with 10°mesial tipping angle group. –10°, canine with 10°distal tipping angle group

Table 1 The displacements of crown points and rotation of long axis of each tooth at the end of the simulations under the local coordinate systems

Displacement (mm)/Rotation (°)		Groups		Teeth						
		Canine tipping angle	Attachment design	1	2	3	4	5	6	7
Displacement of crown point	Mesio-distal (X)	0°	Con	0.06	0.15	0.27	−0.71	−0.67	0.30	0.31
			CLA	0.09	0.20	0.46	−0.77	−0.73	0.26	0.28
		10°	Con	0.06	0.17	0.23	−0.66	−0.64	0.34	0.37
			CLA	0.10	0.23	0.42	−0.73	−0.71	0.28	0.29
		−10°	Con	0.07	0.21	0.30	−0.74	−0.69	0.27	0.29
			CLA	0.07	0.22	0.31	−0.75	−0.71	0.27	0.28
	Bucco-lingual (Y)	0°	Con	−0.28	−0.37	−0.20	−0.08	−0.02	0.04	0.06
			CLA	−0.45	−0.48	−0.39	−0.15	−0.02	0.06	0.05
		10°	Con	−0.30	−0.38	−0.18	−0.9	−0.02	0.04	0.08
			CLA	−0.48	−0.49	−0.35	−0.11	−0.04	0.03	0.05
		−10°	Con	−0.28	−0.32	−0.21	−0.10	−0.04	0.02	0.04
			CLA	−0.41	−0.44	−0.23	−0.18	−0.05	0.02	0.04
Rotation of long axis	Buccal/lingual torque (X)	0°	Con	−0.86	−1.27	−0.37	−0.47	−0.39	0.19	0.31
			CLA	−1.65	−1.76	−1.06	−0.77	−0.50	0.14	0.41
		10°	Con	−1.74	−1.78	−0.38	−0.37	−0.33	0.13	0.52
			CLA	−2.33	−2.56	−0.98	−0.65	−0.47	0.12	0.37
		−10°	Con	−1.42	−0.89	−0.41	−0.51	−0.42	0.17	0.29
			CLA	−1.43	−0.92	−0.5	−0.54	−0.46	0.14	0.27
	Mesial/distal tipping (Y)	0°	Con	−0.2	−0.81	−0.92	3.35	3.07	−1.42	−1.63
			CLA	−0.35	−1.45	−1.64	3.64	3.24	−1.25	−1.43
		10°	Con	−0.21	−0.88	−0.67	3.05	2.98	−1.35	−1.94
			CLA	−0.36	−1.56	−0.87	3.36	3.13	−1.16	−1.65
		−10°	Con	−0.22	−0.77	−1.12	3.91	3.35	−1.4	−1.60
			CLA	−0.22	−0.85	−1.15	3.97	3.37	−1.39	−1.60

Tooth numbering according to the FDI tooth numbering system. Mesio-distal displacement: mesial (-) and distal (+); Bucco-lingual displacement: bucco (-) and lingual (+); Buccal/lingual torque: buccal (-) and lingual (+); Mesial/distal tipping: mesial (-) and distal (+). *Con* Conventional attachment design, *CLA* Canine lingual attachment design. 0°, upright canine group. 10°, canine with 10°mesial tipping angle group. −10°, canine with 10°distal tipping angle group

Table 2 In the 4D finite element analysis, the gap between the CA and the medial incisor margin and the distalization efficacy of both premolars under the local coordinate systems

	Canine tipping angle	Attachment design	Gap between the CA and the central incisor margin (mm)	Efficacy of first premolar distalization (%)	Efficacy of second premolar distalization (%)
Groups	0°	Con	0.36	71%	67%
		CLA	0.28	77%	73%
	10°	Con	0.51	66%	64%
		CLA	0.31	73%	71%
	−10°	Con	0.26	74%	69%
		CLA	0.24	75%	71%

0°, upright canine group. 10°, canine with 10°mesial tipping angle group. −10°, canine with 10°distal tipping angle group

CA clear aligner, *Con* conventional attachment design, *CLA* canine lingual attachment design

In vitro experimental study results

The FEM results demonstrated that the canine tipping angle significantly influences anchorage, highlighting the importance of using canine lingual attachments. Based on these findings, further in vitro experiments were conducted to refine the groupings. Figure 4 presents the forces and moments experienced by each tooth across all groups.

Firstly, it was observed that the more mesially tipped the canine, the greater the difference between the CLA and Con groups. Conversely, as the canine becomes more distally upright, the differences between the CLA and Con groups diminish. Secondly, both molars experienced mesial forces in all groups, with the −10° canine tipping group showing the smallest forces and the +10° group the largest. In each comparison, the forces in the Con groups exceeded those in the CLA groups, and within each group, the first molar consistently experienced less mesial force than the second molar.

Additionally, both premolars exhibited distal forces, with the −10° group demonstrating the greatest force and the +10° group the smallest. The forces observed in the Con groups were lower than those in their respective CLA groups. Within the same group, the first premolar experienced less force than the second premolar. Statistically significant differences between the Con and CLA groups were observed in groups with a canine tipping angle greater than 0° ($P < 0.05$).

Furthermore, the canine experienced mesial forces across all groups, with the −10° group showing the highest force and the +10° group the lowest. For groups with a canine tipping angle exceeding 0°, the Con groups demonstrated significantly smaller forces compared to the corresponding CLA groups. Moment analysis indicated that in CLA groups, canines experienced significantly larger mesial tipping moments compared to Con groups when the canine tipping angle exceeded 4°, with statistical significance ($P < 0.05$).

Finally, both incisors experienced labial forces, with the −10° canine tipping group showing the largest forces and the +10° group the smallest. Although no statistically significant differences were found between the Con and CLA groups for the incisors, the CLA groups exhibited a trend towards larger forces. The moment results revealed that CLA groups experienced significantly larger labial tipping moments on the incisors in cases where the canine tipping angle was 2° or more compared to the corresponding Con groups ($P < 0.05$).

Discussion

Previously, it was believed that high efficacy, ranging from 73 to 87%, could be achieved during maxillary arch distalization using CA [3, 6]. However, the tooth movements in these studies were evaluated at the end of treatment, where any inadequate control of movements during the initial set of aligners could be corrected in subsequent refinements. In recent years, to minimize potential confounding factors, several studies have focused on assessing tooth movements after the first series of aligners. Liu et al. [21] conducted a retrospective study, concluding that distalization efficiency ranged from 36.2% to 43.9% for posterior teeth and from 36.9% to 49.4% for anterior teeth. Similarly, Li et al. [7] reported that, following the initial aligner treatment, the efficacy rates for maxillary first and second molar distalization were 36.48% and 41.94%, respectively.

During the distalization of the dentition, a phenomenon known as the"reversed bow effect"—characterized by flaring of the anterior teeth and distal tipping of the molars—has been previously observed [4, 5, 22]. A recent review concluded that across all published studies on molar distalization, the range of maxillary first molar distalization was 0.5 to 6.4 mm, with distal tipping ranging from 18.5° to bodily distalization [23]. For second molars, a smaller amount of distal movement and more pronounced crown tipping were typically observed. Relapse of molar distalization may occur during premolar distalization and anterior tooth retraction. Notably, none of the published studies have examined the off-tracking of anterior teeth or the influence of mesial canine inclination during the distalization process.

In this study, two approaches—FEM analysis and in vitro experimentation—were employed, and both yielded results that exhibited similar trends. However, in the FEM simulations, the thickness of the CAs was assumed to be uniform and exhibited idealized stretching during deformation, which differs from the mechanical behavior of actual aligners. To address this limitation, realistic CAs were used in the in vitro experiment to better represent their true biomechanical behavior. It should be noted that the in vitro model did not include a representation of the PDL, which may have influenced the biomechanical outcomes in comparison to the FEM simulations. Due to these inherent methodological differences, direct numerical comparison between the two approaches was not feasible. Nevertheless, the FEM and in vitro methods complemented each other and consistently demonstrated the same overall biomechanical trends. In this study, the FEM analysis revealed the biomechanical effects of canine tipping angle and the application of canine lingual attachments during maxillary arch distalization over five treatment steps. The OSIM experiment further refined the subgrouping, resulting in outcomes with greater clinical relevance. Recently, Jin et al. [11] investigated the biomechanical performance of a novel localized thickened structure of CA during space

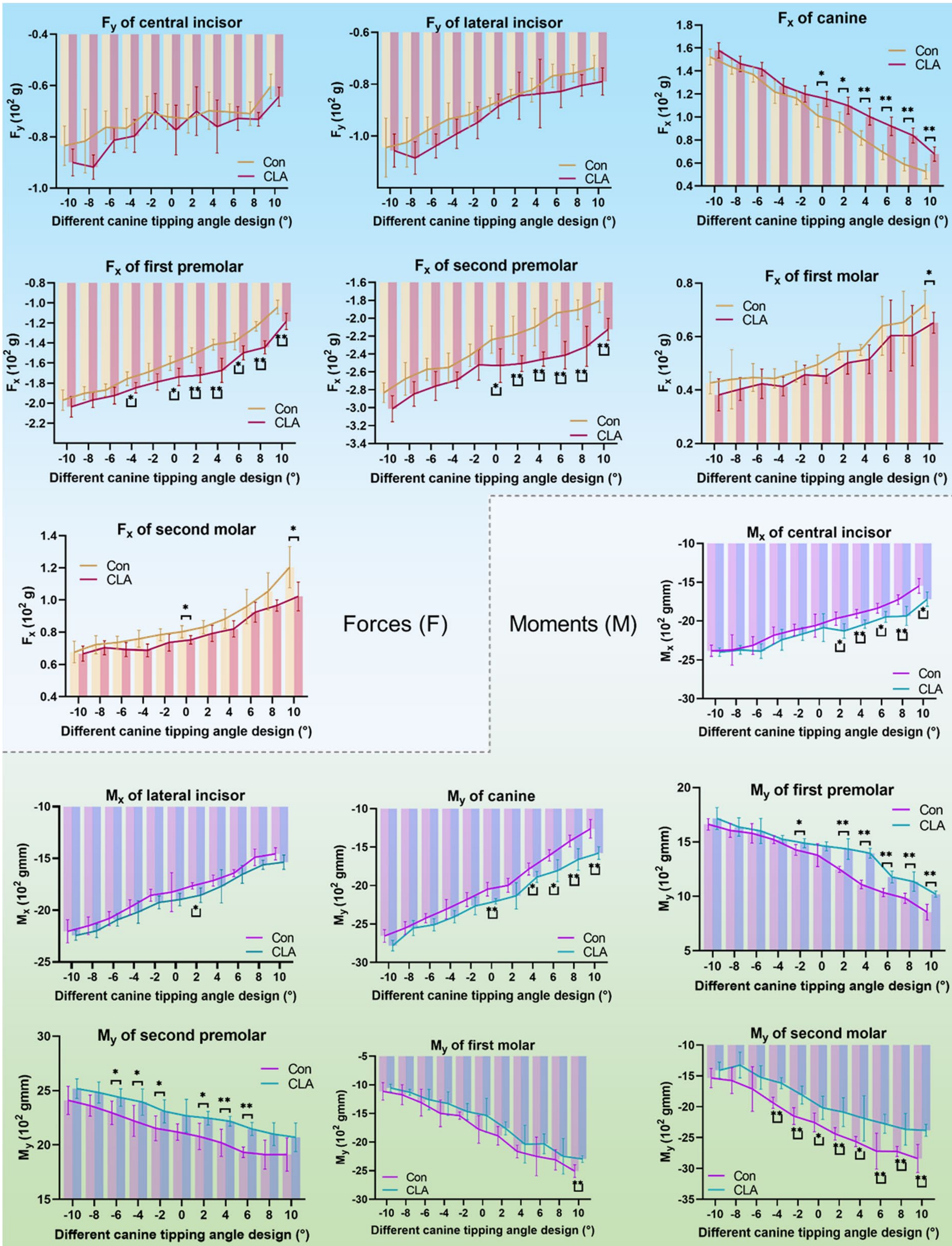

Fig. 4 The initial forces (F) and moments (M) of each teeth of the in vitro experimental study. F, force; M, moment; Con, control group; CLA, canine lingual attachment group; *, $P < 0.05$; **, $P < 0.01$

closure in CA treatment. In their study, both FEM analysis and the OSIM experiment were carried out, and the results from the vitro experiment demonstrated similar trend in force variation with the FEM results. Likewise, Liu et al. [12] investigated different intrusion patterns of incisors with CA using the same OSIM. Likewise, Zhu et al. [13] also utilized the OSIM to demonstrate that the"bowing effect"during en-masse anterior retraction in CA treatment was pronounced but could be mitigated through anterior teeth intrusion. Kaur et al. [24] investigated the effect of material selection on CA during different designed tooth movement with OSIM.

The common V-pattern teeth movement strategy was recommended by different aligner companies. While anchorage preparation for molars is commonly recommended in extraction cases, no relevant preparation is generally not suggested during maxillary total arch distalization. However, based on the results of this study, we recommend preparing canine anchorage, particularly through distal uprighting of canines, prior to initiating premolar distal movement. Our findings demonstrate that the use of canine lingual attachments significantly mitigated molar anchorage loss while improving premolar distalization efficacy. Notably, the degree of canine mesial inclination was found to be directly proportional to the clinical significance of incorporating lingual attachments. Concurrently, anterior teeth were subjected to stronger anteriorly directed forces, resulting in increased anchorage loss and labial tipping. Previous studies have suggested that palatal temporary anchorage devices (TADs) may enhance molar distalization efficacy while reducing anterior labial tipping through improved torque control [5, 25]. However, to maintain consistency between FEM and OSIM results, we intentionally excluded additional anchorage reinforcement, including buccal TADs, from this study. Additionally, we observed that the second molar, being fully covered by the aligner distally, experienced more pronounced mesial pulling forces compared to the first molar [8].

The largest labial inclinations were observed during the premolar distalization phase of maxillary arch distalization [5]. As Fig. 5 demonstrates, this phase is characterized by the occlusal and labial inclined distal-lingual surfaces of canines serving as primary force application areas. This alignment correlates with the direction of aligner dislocation, potentially leading to misfit issues and subsequent anchorage loss. Moreover, mesially tipped canines can exacerbate these problems. Current canine labial attachments, typically aligned along the dislocation path, often fail to provide adequate retention strength during this process. Furthermore, a mesially tipped canine may cause the aligner's dislocation direction to shift more labially, thereby increasing labial torque on incisors. Therefore, we propose that canine

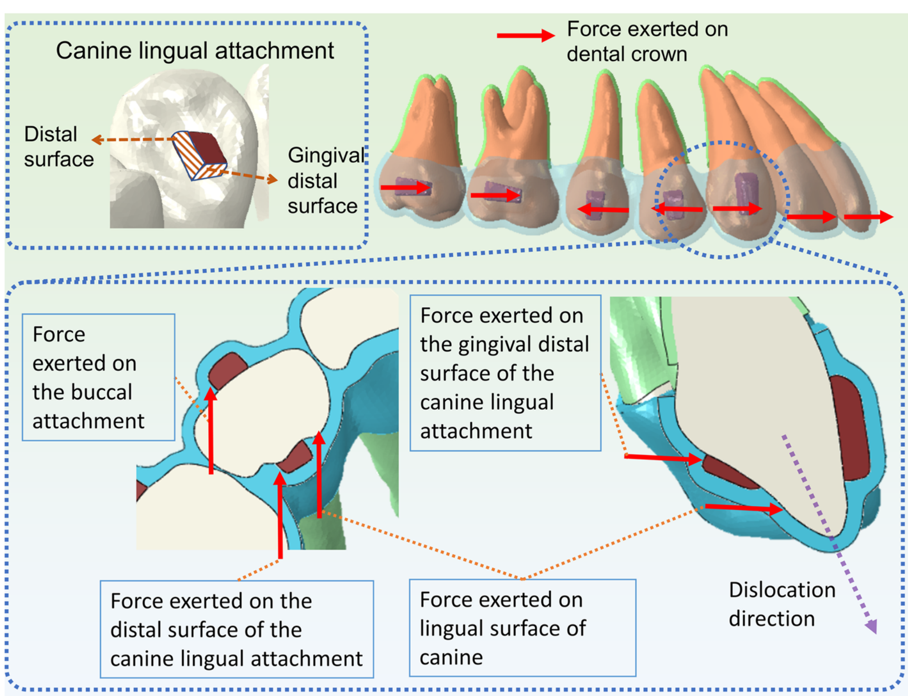

Fig. 5 Mechanism of the biomechanical effect of the canine lingual attachment during the distalization of premolars in the maxillary distalization process of clear aligner treatment

lingual attachments should incorporate two essential features: 1) adequate retention strength during distalization, requiring a gingival surface; and 2) effective accommodation of aligner push forces, necessitating a distal surface.

Although significant lingual inclination of incisors has been reported following maxillary total arch distalization with CAs [8], it is crucial to minimize labial inclination of incisors during molar and premolar distalization to reduce undesirable back-and-forth movements. Labial movement of anterior teeth during molar distalization may increase periodontal risks, including alveolar bone dehiscence and root resorption. Therefore, clinicians should exercise caution during treatment. We recommend incorporating torque compensation for anterior teeth during the premolar distalization phase to address these concerns.

The tipping of the canines plays a crucial role in orthodontic treatment. During anterior teeth retraction, a deeper overbite can be achieved if the canines tilt distally with inadequate root control. Fan et al. [26] analyzed the influence of initial canine tips of canine to the distalization of canine during CA treatment with an OSIM study, and the results demonstrated that initial distal angle of the canines increased the risk of deepening the anterior overlap. Yan et al. [27] conducted a retrospective study involving 51 Angle Class II division 2 patients treated with clear aligners. Their findings indicated that patients with mesially tipped canines experienced an average increase of 1.8° in labial inclination of the incisors compared to those with non-proclined canines.

CA attachments, as essential auxiliary components in CA treatment, play a key role in transmitting forces from the aligner to the dentition. The shape and position of attachments are strategically designed to enhance aligner retention and to facilitate various types of tooth movement. Among existing designs, ellipsoid attachments are currently considered the least effective due to their small size and lack of a well-defined active surface [28]. Conventional rectangular attachments—whose dimensions, prominence, beveling angle, and placement can be customized by clinicians via treatment planning software—are widely utilized in clinical practice. Optimized attachments have been introduced with the aim of generating more precise biomechanical forces. However, a recent retrospective study demonstrated that optimized attachments provide clinical outcomes comparable to those of conventional attachments [29]. In terms of canine bodily movement, Kawamura et al. [30] conducted a FEM study to examine the influence of different labial attachment designs on the bodily movement of the maxillary canine. Three attachment types were analyzed: semicircular, vertical rectangular, and horizontal rectangular. Their results suggested that while labial attachments are essential for controlling canine movement, differences among the three designs in achieving bodily movement were minimal. Based on these findings, a conventional vertical rectangular labial attachment was selected for the canine in this study. Regarding maxillary arch distalization, prior studies have focused primarily on molar attachment design during distalization [31, 32], while little research has addressed the design and biomechanical role of canine attachments in this context.

O In one of our earlier studies, we examined various anchorage enhancement methods during maxillary total arch distalization with CAs, including Class II elastics, buccal TADs, and palatal TADs [7]. The results indicated that the use of Class II elastics can cause side effects such as mesialization and extrusion of the mandibular molars, along with lingual tipping and extrusion of the maxillary incisors. Additionally, while palatal TADs may provide the best anterior anchorage maintenance, arch expansion was observed across all groups, with the palatal TADs group showing the greatest expansion, as confirmed by a subsequent clinical retrospective study [33]. In contrast, for this study, we found it challenging to precisely control the elastic forces during the in vitro experiments, which led us to exclude these methods to ensure consistent experimental conditions for both the FEA and in vitro studies.

The results revealed that upright canines provided greater anchorage during premolar distalization, whereas distally tipped canines had a limited effect on strengthening anchorage. Conversely, mesially inclined canines led to more significant anchorage loss. It is crucial to emphasize that, regardless of the initial labial inclination of the incisors or the degree of mesial tipping of the canines prior to treatment, as molar distalization progresses and the space gained is transferred anteriorly, the canines—serving as anchorage—continue to lose anchorage and tip mesially. Thus, the study's focus is not on the canines'initial mesial tipping angle but rather on their inclination as the space between the canines and first premolars expands.

However, this study has several limitations. First, the lingual positioning of attachments on the maxillary canine may result in occlusal interferences, which should be carefully considered and avoided during clinical application. Second, alternative anchorage reinforcement strategies, such as the use of TADs, were not investigated. This is because achieving up to 2 mm of maxillary arch distalization without additional anchorage is generally considered clinically acceptable [2]. Nevertheless, from a theoretical perspective, the distal and lingual traction forces provided by TADs may enhance anterior aligner fit, warranting further exploration in future studies. Additionally, although both the FEM and in vitro results demonstrated consistent trends, direct numerical comparison between the two approaches was not feasible due to methodological differences. Furthermore, several simplifications were introduced in the current PDL modeling approach to balance computational efficiency and accuracy, which may have led to the accumulation of errors during the iterative process. Ultimately, further clinical trials are necessary to validate the clinical significance and efficacy of the proposed canine lingual attachment design.

Conclusion

This study innovatively proposed the use of canine lingual attachment during the distalization of premolars in CA treatment. Based on the results from the 4D FEM and OSIM experiments, two key conclusions can be drawn:

1) Clinical Recommendations for Canine Lingual Attachments: It is recommended to use canine lingual attachments during premolar distalization when the canine is tipped mesially by more than 4°to reduce the off-track movement of anterior teeth, enhance anchorage control, and improve the efficiency of molar distalization. Care should be taken to avoid occlusal interferences during the placement of these attachments.
2) Impact of Canine Tipping Angle on Anchorage Control: The canine tipping angle significantly influences anchorage control during the premolar distalization phase of total maxillary arch distalization with CAs. Mesially tipped canines may lead to off-track movements of anterior teeth, weakening anchorage and increasing the mesial movement of molars, thereby diminishing the overall efficiency of molar distalization. Mesially tipped canines can cause greater labial inclination of incisors compared to upright canines. Therefore, it is advisable to prepare the canine anchorage, specifically by distal uprighting the canines, prior to initiating the distal movement of premolars.

Abbreviations

CA	Clear aligner
OSIM	In vitro electro-mechanical orthodontic simulator
FEM	Finite element method
4D	Four-dimensional
PDL	Periodontal ligament
Con	Control
CLA	Canine lingual attachment
TCM	Temperature changing method
CP	Crown point
RP	Root point
RC	Resistance center
LA	Long axis
F	Forces
M	Moments
TAD	Temporary anchorage device

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s12903-025-06109-9.

Additional file 1: Supplementary Table 1. The parameters of materials.

Additional file 2: Supplementary Table 2. Number of nodes and elements.

Additional file 3: Supplementary Table 3. The definition of the measurement indicators of each tooth during the analysis.

Additional file 4: Supplementary Video 1. The morphology of clear aligner automatically changes in this study.

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Authors' contributions
BM, YT, and HZ contributed to investigation. BM and YT contributed to methodology. BM contributed to drafted the manuscript. YG contributed to supervision, drafted and critically revised the manuscript. All authors gave their final approval and agree to be accountable for all aspects of the work.

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Data availability
Data availability statements: The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate
This research was approved by the Institutional Review Board of Peking University School and Hospital of Stomatology (PKUSSIRB-202059154). Written informed consent was obtained from the participant. The ethics approval and the written informed consent included the permission of using the raw data of CBCT of the patient. The study adhered to the Declaration of Helsinki.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

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