

Biomechanical effect of en-masse versus substep extraction space closure on posterior teeth using clear aligners: a finite element study

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Objective: To evaluate the biomechanical effects of en-masse versus substep extraction space closure on posterior teeth during clear aligner treatment and to provide guidelines for optimising anti-tipping designs.

Methods: Twenty-four maxillary finite element models incorporating first premolar extractions treated by clear aligners were constructed. The models were divided into two groups: en-masse closure (I_{o_1} , en-masse retraction; II_{o_1} , en-masse mesialisation), and substep closure (I_{a_1} , canine distalisation; I_{b_1} , incisor retraction; II_{a_1} , premolar mesialisation; II_{b_1} , molar mesialisation). Within each group, different anti-tipping designs (1° , 2° , 3°) were applied to the posterior teeth.

Results: Compared to I_{o_1} groups I_{a_1} , I_{b_1} , and I_{a+b_1} exhibited less crown mesial displacement, root distal displacement, and mesial tipping of the posterior teeth. In contrast, groups II_{a_1} , II_{b_1} , and II_{a+b_1} demonstrated more crown mesial displacement, root distal displacement, and mesial tipping. Of note, II_{a_1} increased the mesial movement of the premolars and generated a distal force on the molars, mitigating their mesial inclination. II_{b_1} had a similar effect. Consequently, I_{a_1} , I_{b_1} , and I_{a+b_1} required significantly less anti-tipping design to maintain the pretreatment mesiodistal angulation of the posterior teeth. Conversely, II_{a_1} , II_{b_1} , and II_{a+b_1} necessitated more anti-tipping design to achieve bodily movement of the posterior teeth.

Conclusion: Substep retraction may reduce the mesial tipping and anti-tipping design of the posterior teeth. Substep mesialisation, however, may increase crown displacement, posterior mesial tipping, and the anti-tipping design; nevertheless, the reaction forces from adjacent teeth can partially alleviate these effects. Further clinical validation is necessary to confirm these findings.

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Introduction

In recent years, clear aligner treatment (CAT) has gained popularity due to its aesthetic appeal, comfort, and convenience.¹⁻³ However, extraction cases often encounter the “roller coaster effect” during space closure, characterised by distal tipping of the canines, mesial tipping of the posterior teeth, and deepening of an anterior overbite.⁴⁻⁶ Digital design plays a

crucial role in CAT. A previous clinical retrospective study demonstrated that appropriate distal crown tipping designs for posterior teeth could effectively prevent mesial tipping during en-masse retraction in first premolar extraction cases requiring maximum anchorage.⁷ The recommended anti-tipping values for second premolars (PM2), first molars (M1), and second molars (M2) were 9.5° , 8.7° , and 7.8° ,

respectively, to maintain pre-mesiodistal angulation.⁷ A finite element analysis (FEA) revealed that in Class II elastic traction cases involving mandibular first premolar (PM1) extractions, a distal-tipping design of 3°/0.25 mm on the posterior teeth resulted in mesial bodily movement of the mandibular first molars with mesial cutouts.⁸ For distal and lingual cutout groups, a 1.7°/0.25 mm anti-tipping design was sufficient.⁸ These findings suggest a relatively large anti-tipping design is necessary to control posterior tooth angulation in extraction cases. However, an excessive anti-tipping design can lead to aligner “off-tracking”, uncontrolled mesial tipping of the posterior teeth, and increased treatment complexity.^{9–13}

Staging might be used to optimise the anti-tipping design for the posterior teeth during CAT. Staging involves the step-by-step progression of tooth movement from the initial to the final position.¹⁰ An *in vitro* study suggested that with the same level of intrusion (0.2 mm), simultaneous intrusion of all mandibular anterior teeth resulted in lower forces on incisors compared to the canines.¹⁴ However, individual intrusion of the canines or incisors leads to increased forces on those specific teeth.¹⁴ While there are no current clinical *in vivo* studies comparing overall intrusion and alternating intrusion, traditional fixed orthodontic treatment commonly employs en-masse retraction (simultaneous retraction of the entire anterior segment) and two-step retraction (sequential retraction of canines and incisors) to close extraction spaces.^{15,16} Randomised controlled trials have shown no significant differences in anchorage control between the two retraction methods.¹⁶ The two-step approach is generally considered a more sophisticated and time-consuming technique.^{15–18} However, the mechanics of extraction space closure using clear aligners differ from the sliding mechanics of fixed orthodontics,¹⁹ as CAT relies on aligner deformation to move teeth.²⁰ To date, there has been no research on the mechanical effects of posterior mesial tipping between en-masse and substep space closure. Therefore, it is hypothesised that en-masse and substep tooth movement using CAT may have different effects on the mesial tipping of the posterior teeth during space closure.

The present study conducted a series of finite element analyses to investigate the potential biomechanical effects on the posterior teeth of en-masse and substep closure patterns in combination with various anti-tipping designs (0°, 1°, 2°, 3°). Overall, the findings provide biomechanical guidance for optimising the

clinical anti-tipping digital design in CAT, potentially preventing unnecessary treatment detours.

Materials and methods

Creating an original FEA model

The study was approved by the Ethical Committee of the Affiliated Stomatology Hospital, Zhejiang University School of Medicine (No. 2024033). The patients comprehensively understood the study's objectives and voluntarily provided the CT and oral scan data. A single consenting patient wearing clear aligners was selected to construct the finite element model. The inclusion criteria required the permanent dentition, a symmetrical maxillary arch without crowding, normal labial tipping of the upper incisors (U1-SN = 105°), a normal crown-root ratio, no tooth defects nor fillings, healthy periodontal tissue, and complete cone-beam computed tomography (CBCT) and intraoral scan data. Three-dimensional geometric surface models of the maxillary dentition were generated by CBCT and intraoral scan data using Mimics Research 21.0 (Materialise, Leuven, Belgium) and Geomagic Wrap 2021 (3D Systems, Rock Hill, SC, USA). In SOLIDWORKS 2017 (Dassault Systems, Massachusetts, USA), buccal attachments were designed for M2 (3 mm × 2 mm × 1 mm), M1 (double 3 mm × 2 mm × 1 mm),²¹ PM2 (3 mm × 2 mm × 1 mm), canines (4 mm × 2 mm × 1 mm), and the lateral incisors (optimised attachments). The periodontal ligament (PDL) was modelled as a 0.3 mm extension from the root surfaces.²² Premolar extractions were simulated by removing the maxillary PM1. The aligner model was developed by creating an external offset of 0.5 mm around the dentition with attachments.²³ In this model, the mesiodistal angulation was defined as the angle formed by the long axis of the tooth and the Z-axis of the global coordinate system. PM2, M1, and M2 exhibited 1.3° of crown distal tipping, 2.7° of crown mesial tipping, and 2° of crown distal tipping, respectively. To enhance aligner coverage and simulate clinically alternating anterior retraction or posterior mesialisation patterns, a 1 mm space was introduced between the canines and incisors, as well as between the PM2 and molars.

Material properties and contact conditions

All components (Figure 1A) were imported into Abaqus/CAE (2016; SIMULIA, Providence, RI)

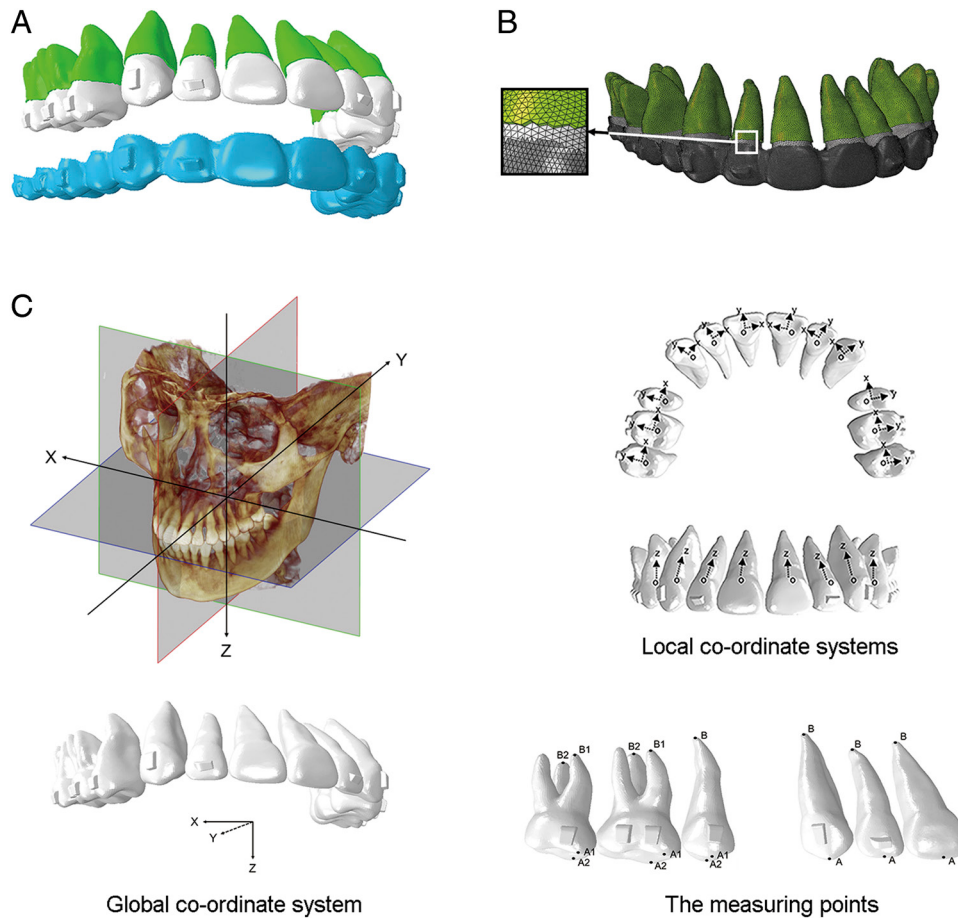


Figure 1. FEA models, co-ordinate systems, and the measuring points. (A) Maxillary dentition with attachments^{21,24} in white color, PDL in green color, and aligners in blue color; (B) Meshing process and discretization; (C) Co-ordinate systems and the measuring points.

to generate a 3D finite element model through a meshing process and discretisation (Figure 1B). As shown in Table I, the discretisation process resulted in 220,356 nodes and 364,170 elements. To simplify the model, the teeth, alveolar bone, PDL, attachments, and aligner were assumed to be homogenous and isotropic. Table II lists the material properties of these components, which were obtained from previous studies.^{11,23,25–29} Fixed boundaries were

set at the outer surface of the PDL to prevent bodily motion when forces were applied. Given that the alveolar bone's modulus of elasticity was significantly higher (over 3 orders of magnitude) than the PDL, it was considered as a rigid boundary. Bonding contacts were established between the inner surfaces of the PDL and teeth. Surface-to-surface contact was used between the aligner surface and teeth, as well as between the aligner surface and attachment surfaces, with a Coulomb friction coefficient of $\mu=0.2$.²⁷

Table I. Number of nodes and elements of the components of finite element models

Component	Elements	Nodes
Teeth	133300	66734
PDL	72914	73866
Attachment	81836	40942
Clear aligners	76120	38814

Experimental designs and loading method

A series of FEA aligner models were designed. Test 1 included six aligner models: 0.25 mm en-masse retraction (I_0), substep retraction (I_a , 0.25 mm distalisation of the canines; I_b , 0.25 mm incisor retraction), en-masse mesialisation (II_0), and substep mesialisation (II_a , 0.25 mm mesialisation of PM2; II_b ,

Table II. Material properties

Component	Young's modulus (MPa)	Poisson's ratio
Teeth	19600	0.3
PDL	0.67	0.45
Attachment	12500	0.36
Clear aligners	528	0.36

0.25 mm mesialisation of the molars) (Figure 2A). En-masse retraction was simulated by reducing the aligner length from the distal aspect of the canine by 0.25 mm to represent the overall retraction of the anterior teeth. Posterior mesialisation was achieved by shortening the aligner from the mesial area of the second premolar by 0.25 mm to simulate the overall movement of the posterior teeth. Test 2 involved three aligner models with different anti-tipping degrees (1°, 2°, 3°) for each of the six aligner models in Test 1 (Figure 2B). Various aligner anti-tipping designs were created by rotating the maxillary canines mesially and the posterior teeth (PM2, M1, M2) distally around rotation axes defined as lines connecting the buccal and lingual cervical points. All 24 models were prepared for force loading.

To simulate the mechanical effects of alternating movement modes commonly seen in clinical practice, I_a and I_b were combined through calculation. The final mesial tipping resulting from I_{a+b} and II_{a+b} was calculated by combining the effects of the individual steps. For example, consider PM2 in the I_{a+b} combination (Figure 2C). After canine distalisation (I_a), PM2 was inclined mesially by x° . When the incisors were retracted (I_b), the original aligner, designed for the pre-mesially tipped PM2, effectively acted as an x° anti-tipping design on the now mesially inclined PM2. This resulted in two opposing forces on PM2: the incisor retraction that caused further mesial inclination (z°), and the original aligner's distal tipping force (x°). The net mesial inclination of PM2 was y° , in which $y^\circ = z^\circ - x^\circ$. Therefore, the total mesial tipping for $I_{a+b} = x^\circ + y^\circ$. The same calculation applied to II_{a+b} . Since the FEA did not simulate mesially tipped teeth, the data were obtained through mathematical calculations, which may serve as a reference for clinical digital design. The calculations do not

precisely represent the actual clinical situation and require further validation through clinical research.

Co-ordinate systems

Two co-ordinate systems were applied in the present study (Figure 1C). A global co-ordinate was set based on the orientation of the skull. The coronal plane was obtained by the overlapping of the two orbits in the lateral view. The horizontal plane was set parallel to the Frankfort Horizontal plane. The sagittal plane was designed to bisect the skull using a symmetry calliper. On this basis, the occlusal plane of the FEA model was then finely adjusted to be the horizontal plane. The X -axis represents the line intersecting the horizontal and coronal planes. The Y -axis represents the line intersecting the horizontal and sagittal planes, and the Z -axis represents the line intersecting the sagittal and coronal planes. Using the global co-ordinate system has been shown to be relatively accurate in analysing tooth vertical movement.³⁰ Local co-ordinates were set on each tooth for calculating 3D movements comprehensively and accurately. The origins of each co-ordinate system were set at the dental cervix of the corresponding tooth. The x -, y -, and z -axis represented the mesiodistal, labiolingual, and tooth long-axis directions, respectively. The local co-ordinates enabled direct clarification of the displacement tendency of each tooth by its 3D co-ordinates and further determined how to add anti-tipping designs in the current CA design system, which would provide the study more clinical validity.³⁰

Outcomes

The incisal point (A) and apical point (B) of the anterior teeth, the buccal cusp (A1) and apical point (B) of the premolars, and the mesiobuccal cusp (A1) and mesiobuccal root apex (B1) of the molars were taken as the measuring points (Figure 1C). Tooth displacement tendencies of the measuring points and the force and moment at the resistance centre of each tooth were analysed. The moment was obtained by taking the force on the tooth relative to the centre of resistance. The moment/force (M/F) ratio was the distance from the resultant force on the teeth to the centre of resistance, and this resultant force was applied by the aligners. d was the distance between

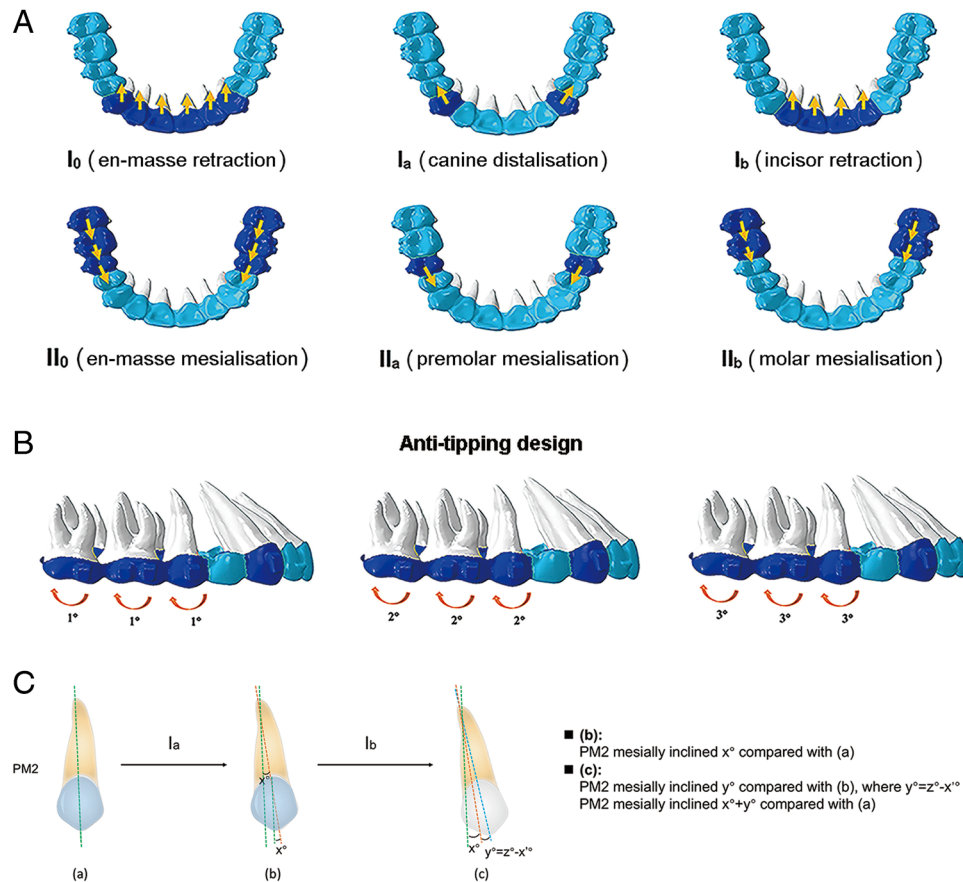


Figure 2. Grouping Diagrams. (A) Test 1: I_0 and II_0 represented en-masse TM; I_a and I_b represented substep anterior TM, while II_a and II_b represented substep posterior TM; (B) Test 2: three aligner models were established on each of the six aligner models of Test 1 according to different anti-tipping degrees (1° , 2° , 3°). All these 24 aligners in the above tests were made on tooth models for force loading; (C) To illustrate the combined effect of I_a and I_b , consider PM2. Initially, the tooth axis was aligned with the green dashed line. After I_a , the axis shifted to the red dashed line. Subsequently, I_b applied forces in two directions: an incisor retraction force that inclined PM2 mesially by z° and a crown distal tipping force from the original aligner that inclined PM2 distally by x° . The net mesial inclination of PM2 after I_b was y° , in which $y^\circ = z^\circ - x^\circ$. If we neglect the impact of axial inclination on the anti-tipping design effect, y° can be calculated as shown in Figure 4B. After I_b , the tooth axis shifted to the blue dashed line.

the crown and root of each tooth. The mesiodistal tipping (α) of PM2, M1, and M2 was calculated by $\tan \alpha = \frac{x_{\text{crown}} - x_{\text{root}}}{d}$. The labiolingual tipping (β) of CI was calculated by $\tan \beta = \frac{y_{\text{crown}} - y_{\text{root}}}{d}$.

Results

All groups exhibited varying degrees of mesial tipping of the posterior teeth (Figure 3A).

Compared with en-masse retraction (I_0), the distalisation of the canines (I_a) significantly reduced the force and moment, the crown mesial displacement and root distal displacement of the posterior teeth, including premolars and molars, as well as their mesial inclination (Table III; Figure 3B). Incisor retraction (I_b) yielded similar results with decreased

crown and root displacement of the posterior teeth and reduced mesial tipping (Figure 3B). Combined substep patterns demonstrated that, compared to en-masse anterior retraction I_0 (PM2, 0.373° ; M1, 0.402° ; M2, 0.452°), I_{a+b} slightly reduced the mesial tipping of the posterior teeth (PM2, 0.301° ; M1, 0.360° ; M2, 0.434°) (Figure 3B).

Compared with en-masse mesialisation of the posterior teeth (II_0), II_a exhibited greater mesial crown movement and mesial tipping of PM2 (Figure 3). Notably, in II_a , as PM2 migrated mesially, the molars experienced distal reaction forces rather than mesial forces, thereby mitigating their mesial tipping (Table III; Figure 3). A comparable phenomenon was observed in the II_b group (Table III; Figure 3). In comparison to en-masse posterior mesialisation II_0 (PM2, 0.333° ; M1, 0.430° ; M2, 0.596°), II_{a+b} slightly

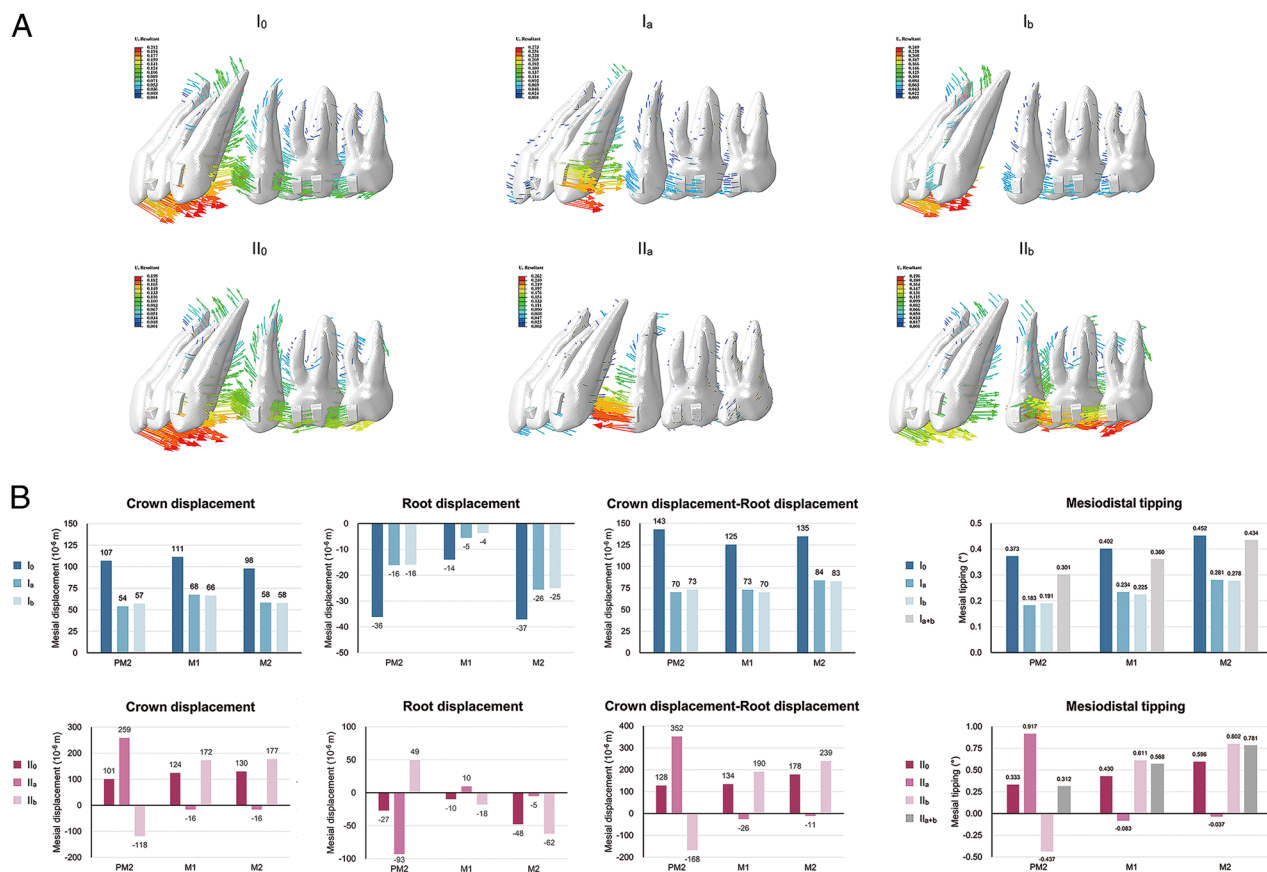


Figure 3. Comparison between en-masse and substep space closure in Test 1. (A) Vector diagrams of tooth displacement; (B) The displacement tendencies of PM2, M1, and M2.

reduced the mesial tipping of PM2 (PM2, 0.312°) but augmented the mesial tipping of the molars (M1, 0.568°; M2, 0.781°) (Figure 3B).

As the anti-tipping design (1°, 2°, 3°) increased, the posterior teeth exhibited reduced mesial tipping but a gradual distal-to-mesial root movement occurred (Figure 4A). Compared to en-masse retraction (I_0), substep retraction (I_a , I_b) significantly decreased the necessary anti-tipping design to maintain pretreatment mesiodistal angulation (Figure 4C). Conversely, substep mesialisation (II_a , II_b) required a significantly higher anti-tipping design than en-masse mesialisation (II_0) to achieve bodily movement of the posterior teeth (Figure 4C).

Additionally, both en-masse posterior mesialisation (II_0) and en-masse retraction (I_0) resulted in comparable levels of incisor lingual tipping (Figure 5) and similar anti-tipping effects on the posterior teeth (Figure 4C). Substep mesialisation of the posterior teeth, however, reduced incisor lingual inclination

(Figure 5). Conversely, the increased anti-tipping design on the posterior teeth enhanced the lingual tipping of the incisors (Figure 5).

Table III presents the mesiodistal forces and moments acting on the resistance centres of each tooth in the local co-ordinate system during en-masse and substep space closure.

The en-masse and substep tooth movement techniques (I_0 , II_0 vs. I_a , I_b , II_a , II_b , I_{a+b} , II_{a+b}) have distinct biomechanical effects on the posterior teeth during extraction space closure with clear aligners, as illustrated in Figure 6.

Discussion

The present study found that when posterior teeth were actively engaged in movement, the substep technique (II_a , II_b) enhanced their anti-tipping design, likely by increasing the crown displacement at each step (Figure 3B). The reciprocal force exerted by PM2 during mesial movement resulted in distal tipping of

Table III. Mesiodistal force and moment at the resistance centre of each tooth in the local coordinate system under en-masse and substep space closure

		I _o			I _b			II _o			II _b		
		F	M	M/F	F	M	M/F	F	M	M/F	F	M	M/F
0°	PM2	1.56	5.53	3.54	0.76	2.01	2.63	0.87	2.31	2.64	1.47	3.37	2.29
	M1	1.89	6.59	3.49	0.75	4.19	5.62	0.95	3.67	3.88	1.93	7.16	3.71
	M2	1.47	6.19	4.2	0.82	4.06	4.99	0.83	3.92	4.7	1.59	8.77	5.51
1°	PM2	0.63	-4.29	-6.78	-0.18	-7.63	43.41	0.03	-7.74	-238.72	0.92	-6.07	-6.61
	M1	2.37	-5.23	-2.2	1.24	-7.48	-6.03	1.51	-8.42	-5.57	2.31	-4.61	-1.99
	M2	1.35	-1.55	-1.15	0.71	-3.64	-5.09	0.75	-3.98	-5.28	1.14	2.16	1.89
2°	PM2	-0.22	-13.15	59.23	-1.13	-17.58	15.59	-0.77	-16.77	21.71	0.26	-14.2	-53.96
	M1	2.65	-15.76	-5.94	1.74	-19.18	-11.04	1.94	-19.49	-10.04	2.47	-16.48	-6.68
	M2	1.16	-7.06	-6.1	0.45	-9.67	-21.47	0.6	-9.74	-16.33	1.2	-6.49	-5.39
3°	PM2	-0.88	-21.76	24.79	-1.82	-26.58	14.64	-1.34	-25.03	18.74	-0.42	-22.57	54.12
	M1	2.55	-23.48	-9.2	1.69	-27.34	-16.17	1.89	-26.99	-14.29	2.46	-25.09	-10.2
	M2	1.08	-11.44	-10.58	0.42	-14.43	-34.51	0.59	-14.08	-23.95	1.19	-12.56	-10.6

Note. PM2, second premolar; M1, first molar; M2, second molar. +F, mesially; -F, distally; +M, mesially; -M, distally. F (N), M (N.mm).

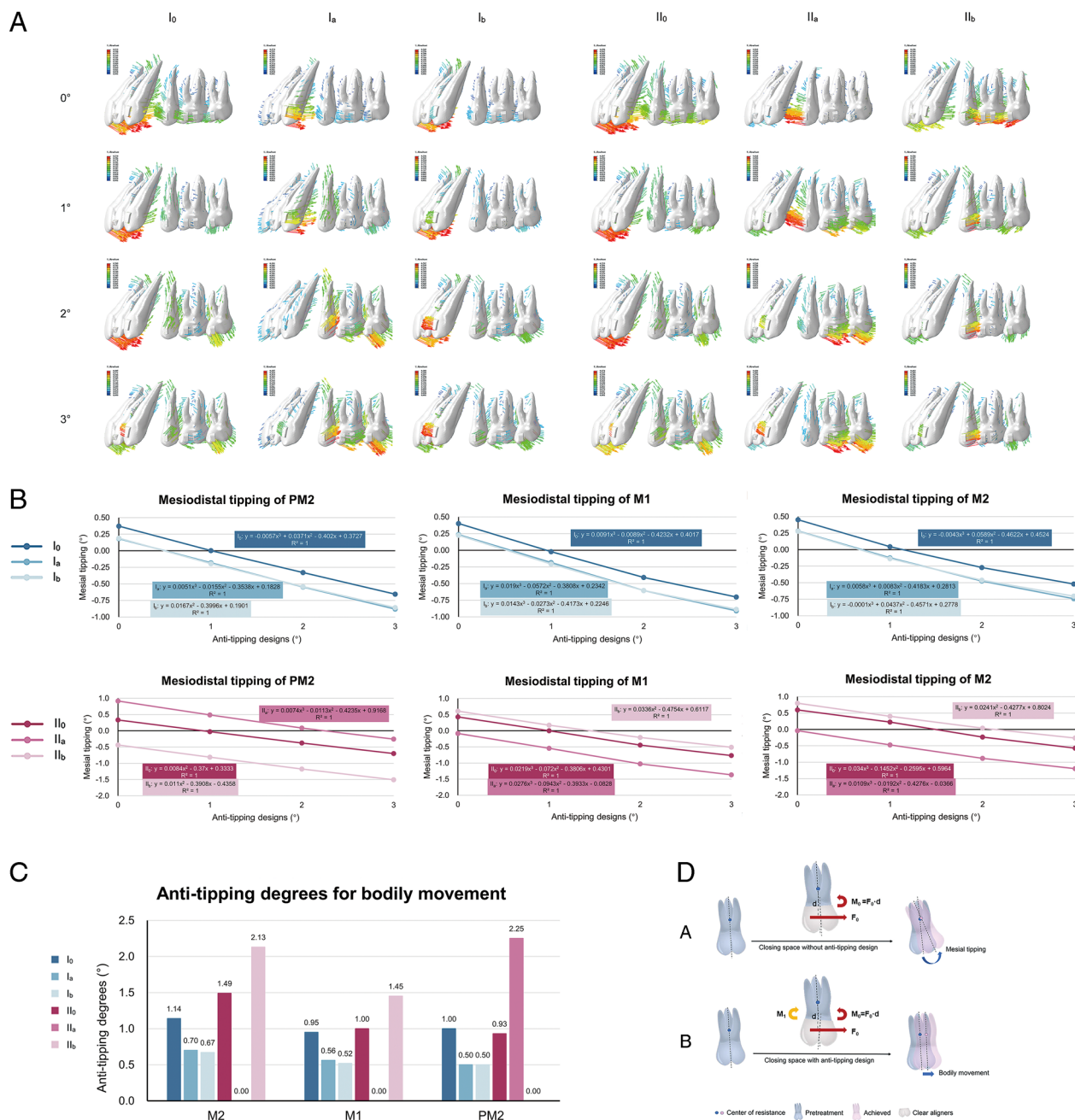


Figure 4. Anti-tipping designs were added to the clear aligners of canines, PM2, M1, and M2 during Test 2. (A) Vector diagrams of tooth displacement; (B) Mesial tipping of posterior teeth; (C) The anti-tipping degrees for bodily movement of posterior teeth; (D) Schematic diagram of mechanical systems on M1: the red arrows indicated the force (F_0) and moment (M_0) produced by displacement of the aligner; the yellow arrow indicated the moment (M_1) produced by aligner' anti-tipping design.

the molars, and conversely, mesialisation of the molars led to distal tipping of PM2 (Figure 3A). Substep mesial movement generated a distal force on adjacent posterior teeth, thereby counteracting mesial tipping. This phenomenon, known as the “physiological anti-tipping effect”, is attributed to the reaction force produced by the deformation of the aligners during

alternating movements. The necessary anti-tipping design is influenced by the total amount of movement and the specific alternating movement patterns of the teeth involved. Thus, more frequent alternating movements correlate with more frequent occurrences of this reaction force. The cumulative effect of these forces may optimise the anti-tipping design for the designated

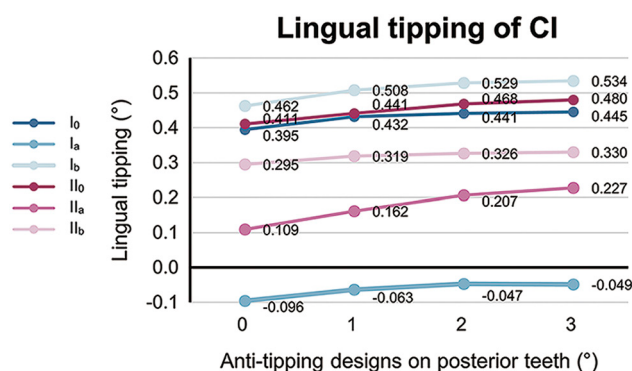


Figure 5. Effects of en-masse and substep space closure on lingual tipping of the central incisor.

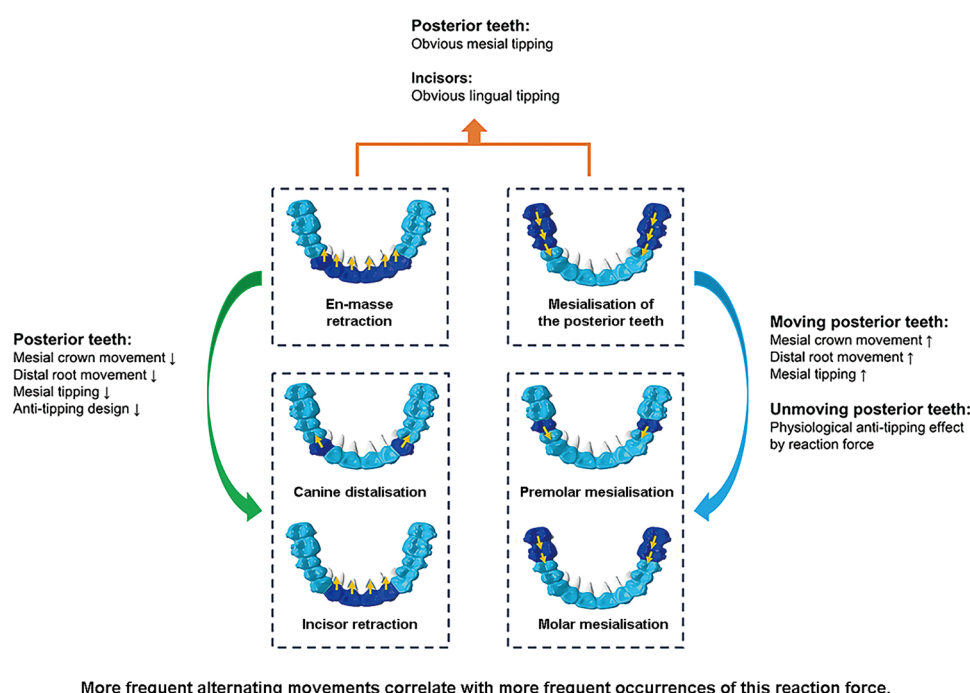


Figure 6. Biomechanical effect for en-masse space closure versus substep space closure in extraction cases using clear aligners.

moving teeth. However, further clinical studies are warranted to validate this effect.

Notably, the anti-tipping design effectively prevented mesial tipping of the posterior teeth but may not mitigate the overall anchorage loss. However, the design may reduce the additional anchorage loss typically associated with crown mesial tipping. Specifically, the design facilitates a controlled movement, with the crown gradually shifting away from the extraction space while the root progressively moves towards it (Figure 4A). The total mesialisation achieved of the

anchorage teeth is influenced by incisor retraction, canine distalisation, and posterior mesialisation. In fixed orthodontics, studies have consistently shown that 2-step retraction techniques do not outperform en-masse retraction related to reducing anchorage loss.^{15–17} Therefore, the anti-tipping design may not alleviate the anchorage loss stemming from the bodily movement of the posterior teeth.

In the present study, I_a and II_a demonstrated uniquely distinct biomechanical effects on terminal teeth compared to the I_0 , I_b , II_0 , and II_b groups. In I_a

(distalisation of the canines), the incisors experienced a labial force, while a mesial force on the posterior teeth was minimal. Conversely, in II_a (mesialisation of PM2), the posterior teeth were subjected to a distal force with minimal lingual force on the incisors (Figure 3; Table III). This phenomenon is intriguing as the two groups (I_a , II_a) resulted in the maintenance of a constant dental arch length during space closure. In contrast, en-masse retraction (I_0), incisor retraction (I_b), mesialisation of the posterior teeth (II_0), and mesialisation of the molars (II_b) resulted in shorter aligners. These findings suggest that a “roller coaster effect” might not occur when the dental arch length remains constant while the extraction space is reduced. However, a discernible “roller coaster effect” may be observed once the dental arch length shortens.

En-masse mesial movement of the posterior teeth resulted in a pronounced lingual inclination of the incisors, nearly identical to that observed during en-masse retraction (Figure 5). Despite the distinct approaches, both ultimately achieved a reduction of the aligner in the extraction space by 0.25 mm, leading to comparable outcomes. Moreover, given the larger periodontal ligament area of posterior teeth compared to the anterior teeth, the intraoral application of the two types of aligners exerts significant force on the anterior teeth. This action force is equal in magnitude to the reaction force, resulting in greater anterior retraction and reduced posterior mesial movement. This observation underscores the potential inefficiency of posterior mesialisation in achieving substantial mesial movement, as it often leads to anterior retraction instead. Therefore, increasing the torque of the anterior teeth during posterior mesialisation should be a priority.

In an FEA study of traditional fixed orthodontics for upper central incisors, the M/F ratio was -9.53 for root movement (Co at the incisal edge), -8.39 for translation, and -6.52 for tipping around the apex.³¹ The present study examined how M/F changes with different closing methods and anti-tipping designs. As illustrated in the line graph of Figure 4B, PM2 and M1 exhibited near-translation behaviour in group I_0 and group II_0 associated with a 1° anti-tipping design, while M2 displayed similar behaviour in group I_0 with a 1° anti-tipping design and in group II_b with a 2° anti-tipping design. Analysing the M/F values in Table III,

a reference range could be established for the M/F required for posterior tooth translation during CAT. Specifically, the M/F values for PM2, M1, and M2 to achieve translation were approximately -6.78 to -6.61, -2.2 to -1.99, and -1.38 to -1.15, respectively. These variations may be attributed to the differing resistance centre positions of these teeth. Further research is necessary to determine the precise ratios needed for translation.

The present study was limited by constraints inherent to FEA. Firstly, clinical biological individuals are complex and exhibit characteristic variations that cannot be fully captured by FEA models. Secondly, the FEA simulations were restricted to the mechanical effects of routine 0.25 mm increments in CAT. The differential effects between en-masse movement and substep movement following the complete closure of the extraction spaces by a single case require further confirmation through clinical studies. Additionally, the extent to which the “physiological anti-tipping effect” resulting from reaction forces during frequent alternating movements can offset tipping caused by designed movements remains to be determined by clinical verification. Finally, while the mechanical mechanisms explored in the present study may serve as a reference for clinical design and further clinical research, the finite element models employed were primarily applicable to typical scenarios.

Conclusions

1. Substep anterior retraction decreased posterior tooth mesial tipping and anti-tipping design. In contrast, substep posterior mesialisation increased crown displacement and could enhance posterior mesial tipping and anti-tipping design.
2. Substep posterior mesialisation in tooth movement mode for space closure created a physiological anti-tipping force on the adjacent teeth.
3. Space closure using aligners with constant lengths (I_a , II_a) exhibited significantly less “roller coaster effect” compared to shorter aligners (I_0 , I_b , II_0 , II_b).

Conflict of interest

The authors declare that there is no conflict of interest.

Authors' contribution

Y.J.: contributed to searching the literature, designing experiments, methodology, data curation, data analysis, and original draft; L.M.: contributed to manuscript review and editing; L.X.: contributed to funding acquisition; J.W.: contributed to revision of the article; X.F.: contributed to designing experiments, revision of the article, funding acquisition, and supervising the overall project; and X.C. contributed to conceptualization, supervision, and project administration.

Ethics approval

This study was approved by the Ethical Committee of the Affiliated Stomatology Hospital, Zhejiang University School of Medicine (No. 2024033).

Data availability statement

The authors confirm that the data supporting the findings of this study are available within the article and its supplementary materials.

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Supplementary 1. Crown and root displacement in the global co-ordinate system under en-masse and substep space closure

Anti-tipping design		0°			1°			2°			3°		
Local coordinate system		X	Y	Z	X	Y	Z	X	Y	Z	X	Y	Z
En-masse retraction	CI Crown (mm)	0.023	0.153	0.076	0.020	0.164	0.087	0.017	0.164	0.094	0.010	0.161	0.103
	Root (mm)	-0.016	-0.051	-0.048	-0.012	-0.062	-0.049	-0.010	-0.068	-0.045	-0.008	-0.075	-0.039
LI	Crown (mm)	0.059	0.175	0.067	0.055	0.184	0.075	0.051	0.180	0.079	0.045	0.175	0.084
	Root (mm)	-0.015	-0.039	-0.098	-0.018	-0.046	-0.102	-0.021	-0.050	-0.098	-0.021	-0.056	-0.092
Canine	Crown (mm)	0.060	0.193	0.040	0.125	0.113	0.011	0.196	0.021	-0.018	0.276	-0.069	-0.053
	Root (mm)	-0.008	-0.047	-0.091	-0.046	-0.009	-0.071	-0.087	0.031	-0.044	-0.132	0.074	-0.022
PM2	Crown (mm)	0.029	-0.100	-0.050	0.001	-0.005	-0.076	-0.025	0.079	-0.095	-0.064	0.155	-0.097
	Root (mm)	-0.013	0.036	-0.032	0.003	-0.003	-0.076	0.019	-0.038	-0.109	0.041	-0.075	-0.124
M1	Crown (mm)	0.027	-0.106	-0.031	0.021	-0.019	-0.010	0.012	0.062	0.010	0.016	0.122	0.025
	Root (mm)	-0.003	0.015	-0.014	0.009	-0.028	-0.009	0.019	-0.066	-0.004	0.028	-0.097	0.002
M2	Crown (mm)	0.027	-0.096	0.008	0.041	-0.005	0.069	0.067	0.064	0.120	0.099	0.121	0.163
	Root (mm)	-0.011	0.034	0.021	-0.009	-0.002	0.073	-0.008	-0.032	0.118	-0.010	-0.057	0.157
Canine distalisation	Crown (mm)	0.021	-0.045	-0.010	0.020	-0.038	0.003	0.016	-0.037	0.013	0.010	-0.039	0.018
	Root (mm)	-0.015	0.014	0.025	-0.016	0.004	0.027	-0.016	-0.004	0.031	-0.014	-0.008	0.036

Supplementary 1. Crown and root displacement in the global co-ordinate system under en-masse and substep space closure

Anti-tipping design		0°			1°			2°			3°		
Local coordinate system		X	Y	Z	X	Y	Z	X	Y	Z	X	Y	Z
LI	Crown	0.036	-0.024	0.006	0.034	-0.017	0.013	0.030	-0.016	0.016	0.026	-0.017	0.020
	Root (mm)	-0.012	-0.024	-0.002	-0.013	-0.029	-0.005	-0.013	-0.035	-0.004	-0.011	-0.037	-0.001
Canine	Crown	-0.151	0.209	0.041	-0.085	0.121	0.009	-0.021	0.026	-0.024	0.054	-0.050	-0.055
	Root (mm)	0.067	-0.062	-0.072	0.026	-0.019	-0.051	-0.013	0.024	-0.024	-0.054	0.059	-0.011
PM2	Crown	0.009	-0.051	-0.037	-0.014	0.045	-0.068	-0.043	0.138	-0.092	-0.086	0.214	-0.091
	Root (mm)	-0.004	0.017	-0.028	0.009	-0.021	-0.076	0.028	-0.058	-0.116	0.051	-0.096	-0.127
M1	Crown	0.004	-0.066	-0.020	-0.001	0.020	-0.001	-0.014	0.108	0.023	-0.011	0.171	0.038
	Root (mm)	0.003	0.008	-0.012	0.014	-0.035	-0.008	0.024	-0.075	0.000	0.034	-0.107	0.006
M2	Crown	-0.002	-0.060	-0.004	0.012	0.030	0.058	0.037	0.108	0.114	0.067	0.168	0.159
	Root (mm)	-0.003	0.025	0.003	-0.002	-0.010	0.056	0.000	-0.043	0.105	-0.002	-0.069	0.146
Incisor retraction	Crown	0.028	0.194	0.064	0.024	0.207	0.081	0.020	0.211	0.091	0.015	0.209	0.101
	Root (mm)	-0.013	-0.046	-0.081	-0.012	-0.060	-0.079	-0.010	-0.067	-0.076	-0.008	-0.074	-0.068
LI	Crown	0.067	0.220	0.049	0.064	0.231	0.059	0.057	0.232	0.068	0.050	0.225	0.081
	Root (mm)	-0.009	-0.018	-0.134	-0.008	-0.025	-0.135	-0.008	-0.032	-0.131	-0.009	-0.042	-0.119

Canine	Crown	0.064	-0.034	0.023	0.151	-0.090	-0.010	0.230	-0.149	-0.040	0.317	-0.204	-0.074
	Root	-0.019	-0.008	0.027	-0.067	0.027	0.027	-0.110	0.059	0.032	-0.157	0.093	0.032
PM2	Crown	0.032	-0.049	-0.024	0.004	0.049	-0.048	-0.026	0.135	-0.061	-0.069	0.206	-0.059
	Root	-0.017	0.013	-0.017	0.000	-0.029	-0.058	0.019	-0.067	-0.086	0.044	-0.103	-0.096
M1	Crown	0.025	-0.062	-0.014	0.017	0.025	0.010	0.005	0.108	0.032	0.006	0.165	0.046
	Root	0.000	0.004	-0.003	0.012	-0.041	0.003	0.022	-0.080	0.011	0.032	-0.110	0.016
M2	Crown	0.016	-0.056	0.001	0.027	0.035	0.064	0.050	0.107	0.117	0.080	0.161	0.159
	Root	-0.007	0.023	0.010	-0.004	-0.012	0.062	-0.003	-0.043	0.109	-0.005	-0.068	0.148
Mesialization of the posterior teeth	Crown	0.014	0.168	0.073	0.010	0.176	0.084	0.005	0.185	0.093	0.002	0.185	0.103
	Root	-0.008	-0.048	-0.057	-0.007	-0.058	-0.057	-0.005	-0.065	-0.057	-0.003	-0.072	-0.050
LI	Crown	0.025	0.180	0.071	0.021	0.188	0.075	0.018	0.201	0.081	0.013	0.200	0.089
	Root	-0.001	-0.050	-0.098	0.000	-0.054	-0.102	0.003	-0.058	-0.107	0.003	-0.067	-0.103
Canine	Crown	0.014	0.182	0.048	0.091	0.102	0.009	0.177	0.045	-0.021	0.262	-0.022	-0.055
	Root	0.008	-0.056	-0.075	-0.035	-0.010	-0.063	-0.080	0.023	-0.061	-0.125	0.060	-0.054
PM2	Crown	0.064	-0.082	-0.060	0.018	0.000	-0.073	-0.015	0.089	-0.077	-0.055	0.166	-0.080
	Root												

Supplementary 1. Crown and root displacement in the global co-ordinate system under en-masse and substep space closure

Anti-tipping design		0°			1°			2°			3°		
Local coordinate system		X	Y	Z	X	Y	Z	X	Y	Z	X	Y	Z
Premolar mesialisation	Root	-0.029	0.023	-0.048	-0.001	-0.016	-0.075	0.019	-0.050	-0.095	0.039	-0.085	-0.110
	(mm)												
	M1 Crown	0.058	-0.114	-0.027	0.040	-0.025	-0.001	0.021	0.067	0.015	0.011	0.135	0.030
	(mm)												
	Root	-0.003	0.010	-0.005	0.012	-0.031	0.002	0.023	-0.073	0.001	0.032	-0.103	0.004
	(mm)												
M2	Crown	0.059	-0.122	0.007	0.082	-0.037	0.059	0.058	0.059	0.119	0.061	0.134	0.167
	(mm)												
	Root	-0.022	0.042	0.027	-0.025	0.010	0.070	-0.012	-0.024	0.117	-0.007	-0.052	0.157
	(mm)												
	Crown	0.018	0.052	0.012	0.013	0.068	0.028	0.010	0.085	0.039	0.005	0.088	0.052
	(mm)												
LI	Root	-0.011	-0.001	-0.020	-0.009	-0.014	-0.022	-0.007	-0.023	-0.026	-0.005	-0.032	-0.021
	(mm)												
	Crown	0.027	0.065	0.027	0.023	0.081	0.034	0.018	0.096	0.040	0.012	0.097	0.049
	(mm)												
	Root	-0.007	-0.026	-0.044	-0.004	-0.032	-0.052	-0.002	-0.036	-0.058	-0.003	-0.044	-0.054
	(mm)												
Canine	Crown	0.016	0.058	0.022	0.098	-0.007	-0.015	0.177	-0.063	-0.052	0.258	-0.126	-0.088
	(mm)												
	Root	0.001	-0.019	-0.020	-0.044	0.020	-0.016	-0.085	0.055	-0.019	-0.128	0.091	-0.016
PM2	(mm)												
	Crown	0.076	-0.246	-0.026	0.035	-0.144	-0.047	-0.004	-0.044	-0.061	-0.054	0.033	-0.064
	(mm)												
M1	Root	-0.037	0.085	0.018	-0.011	0.037	-0.023	0.015	-0.005	-0.056	0.042	-0.041	-0.071
	(mm)												
	Crown	-0.009	0.014	0.009	-0.024	0.110	0.034	-0.045	0.208	0.065	-0.051	0.280	0.081
	(mm)												

Molar mesialisation	M2	Root	0.008	-0.009	0.005	0.020	-0.053	0.012	0.033	-0.100	0.026	0.043	-0.133	0.031
		Crown	-0.031	0.012	-0.015	-0.021	0.108	0.048	-0.002	0.198	0.108	0.022	0.268	0.159
		Root	0.006	0.008	-0.017	0.008	-0.029	0.036	0.012	-0.066	0.087	0.012	-0.096	0.133
		Crown	0.014	0.122	0.053	0.008	0.127	0.064	0.004	0.128	0.070	0.000	0.125	0.080
	Cl	Root	-0.009	-0.032	-0.041	-0.007	-0.041	-0.038	-0.005	-0.046	-0.034	-0.003	-0.052	-0.027
		Crown	0.026	0.136	0.058	0.021	0.142	0.065	0.018	0.145	0.070	0.012	0.140	0.079
	I1	Root	-0.004	-0.043	-0.075	-0.002	-0.049	-0.076	-0.001	-0.053	-0.074	-0.001	-0.061	-0.068
		Crown	0.015	0.134	0.043	0.095	0.058	0.010	0.180	-0.009	-0.018	0.263	-0.072	-0.051
	Canine	Root	0.004	-0.044	-0.050	-0.041	-0.004	-0.037	-0.086	0.030	-0.027	-0.131	0.065	-0.021
		Crown	-0.030	0.117	-0.033	-0.051	0.212	-0.056	-0.077	0.303	-0.066	-0.107	0.382	-0.068
	PM2	Root	0.012	-0.045	-0.053	0.026	-0.089	-0.093	0.043	-0.130	-0.116	0.060	-0.169	-0.130
		Crown	0.064	-0.160	-0.049	0.047	-0.071	-0.024	0.032	0.007	-0.005	0.028	0.069	0.012
M1		Root	-0.003	0.020	-0.021	0.010	-0.024	-0.015	0.022	-0.060	-0.011	0.030	-0.091	-0.004
		Crown	0.074	-0.167	0.003	0.089	-0.079	0.063	0.076	0.001	0.115	0.083	0.068	0.163
	M2	Root	-0.026	0.056	0.030	-0.024	0.021	0.079	-0.019	-0.005	0.121	-0.016	-0.031	0.162
		Crown												

Cl, central incisor; I1, lateral incisor; +X, right; -X, left; +Y, posteriorly; -Y, anteriorly; +Z, extrusion; -Z, intrusion.

Supplementary II. Crown and root displacement in the local coordinate system under en-masse and substep space closure

Anti-tipping
design

0°		1°			2°			3°		
Local coordinate system		X	Y	Z	X	Y	Z	X	Y	Z
En-masse retraction	Cl Crown	-0.007	-0.171	0.018	-0.013	-0.186	0.015	-0.017	-0.189	0.008
	(mm)									
	Root	-0.004	0.005	0.013	0.002	0.007	0.009	0.004	0.008	0.002
	(mm)									
II	Crown	-0.009	-0.187	0.061	-0.016	-0.196	0.060	-0.019	-0.195	0.054
	(mm)									
	Root	0.005	0.094	0.051	0.005	0.102	0.050	0.003	0.103	0.044
	(mm)									
Canine	Crown	-0.112	-0.163	0.060	-0.006	-0.161	0.052	0.114	-0.157	0.039
	(mm)									
	Root	0.058	0.063	0.058	0.001	0.065	0.055	-0.062	0.066	0.047
	(mm)									
PM2	Crown	0.107	-0.004	0.043	0.010	-0.005	0.076	-0.077	-0.006	0.100
	(mm)									
	Root	-0.036	-0.001	0.035	0.009	-0.008	0.075	0.049	-0.016	0.105
	(mm)									
M1	Crown	0.111	-0.011	0.018	0.024	-0.018	0.005	-0.059	-0.022	-0.007
	(mm)									
	Root	-0.014	-0.002	0.015	0.030	-0.005	0.006	0.068	-0.006	-0.004
	(mm)									
M2	Crown	0.098	-0.008	-0.016	0.007	-0.038	-0.071	-0.061	-0.075	-0.117
	(mm)									
	Root	-0.037	0.005	-0.018	-0.006	0.010	-0.072	0.020	0.016	-0.120
	(mm)									

Canine distalisation	CI	Crown (mm)	0.029	0.039	-0.015	0.025	0.026	-0.022	0.021	0.021	-0.030	0.015	0.021	-0.036
		Root (mm)	-0.019	-0.004	-0.014	-0.018	-0.002	-0.021	-0.018	0.000	-0.029	-0.015	-0.001	-0.035
II	Crown	(mm)	0.041	0.002	-0.013	0.037	-0.006	-0.014	0.033	-0.008	-0.017	0.029	-0.007	-0.021
	Root	(mm)	-0.003	0.022	-0.015	-0.001	0.028	-0.016	0.000	0.032	-0.020	0.003	0.030	-0.023
Canine	Crown	(mm)	-0.256	-0.008	0.052	-0.142	-0.001	0.044	-0.023	0.011	0.032	0.087	0.003	0.029
	Root	(mm)	0.110	0.006	0.039	0.047	0.007	0.037	-0.017	0.005	0.031	-0.072	0.015	0.034
PM2	Crown	(mm)	0.054	0.003	0.034	-0.042	-0.004	0.071	-0.138	-0.004	0.101	-0.223	0.015	0.107
	Root	(mm)	-0.016	-0.003	0.029	0.027	-0.009	0.074	0.071	-0.019	0.110	0.115	-0.031	0.117
M1	Crown	(mm)	0.068	0.005	0.014	-0.020	-0.003	0.002	-0.111	-0.003	-0.012	-0.173	-0.015	-0.023
	Root	(mm)	-0.005	-0.006	0.012	0.038	-0.009	0.003	0.078	-0.009	-0.009	0.110	-0.012	-0.019
M2	Crown	(mm)	0.058	0.013	-0.001	-0.032	-0.016	-0.056	-0.108	-0.055	-0.106	-0.166	-0.094	-0.148
	Root	(mm)	-0.026	-0.001	-0.001	0.004	0.004	-0.056	0.034	0.010	-0.108	0.055	0.018	-0.151
Incisor retraction	Crown	(mm)	-0.009	-0.200	0.051	-0.016	-0.218	0.043	-0.021	-0.227	0.037	-0.026	-0.230	0.026
	Root	(mm)	0.001	0.007	0.044	0.004	0.009	0.035	0.007	0.009	0.028	0.009	0.009	0.018
II	Crown	(mm)	-0.016	-0.210	0.104	-0.024	-0.224	0.102	-0.031	-0.228	0.095	-0.036	-0.229	0.079
	Root	(mm)	0.001	0.007	0.044	0.004	0.009	0.035	0.007	0.009	0.028	0.009	0.009	0.018

Supplementary II. Crown and root displacement in the local coordinate system under en-masse and substep space closure

Anti-tipping

Local coordinate system	0°			1°			2°			3°		
	X	Y	Z	X	Y	Z	X	Y	Z	X	Y	Z
Root (mm)	0.005	0.099	0.093	0.008	0.104	0.090	0.010	0.106	0.083	0.012	0.107	0.067
	0.057	-0.040	-0.032	0.162	-0.066	-0.023	0.263	-0.086	-0.019	0.367	-0.112	-0.009
Canine (mm)	0.057	-0.015	-0.029	-0.070	0.029	-0.016	-0.121	0.043	-0.008	-0.175	0.062	0.005
	0.057	-0.018	0.019	-0.042	-0.021	0.049	-0.132	-0.018	0.068	-0.212	0.003	0.074
PM2 (mm)	-0.016	0.011	0.019	0.032	0.004	0.057	0.075	-0.006	0.081	0.117	-0.021	0.087
	0.066	-0.015	0.005	-0.023	-0.020	-0.010	-0.108	-0.020	-0.024	-0.165	-0.030	-0.033
M1 (mm)	-0.004	-0.001	0.004	0.042	-0.004	-0.008	0.081	-0.006	-0.020	0.111	-0.009	-0.029
	0.058	-0.006	-0.006	-0.034	-0.032	-0.062	-0.105	-0.067	-0.110	-0.157	-0.106	-0.148
M2 (mm)	-0.025	0.003	-0.007	0.006	0.008	-0.062	0.033	0.013	-0.112	0.053	0.020	-0.152
	-0.019	-0.181	0.028	-0.025	-0.192	0.024	-0.032	-0.204	0.020	-0.036	-0.209	0.011
Mesialisation of the posterior teeth												
Root (mm)	0.004	0.003	0.022	0.006	0.005	0.017	0.010	0.005	0.013	0.012	0.006	0.004

II	Crown	-0.043	-0.183	0.056	-0.050	-0.189	0.057	-0.058	-0.201	0.059	-0.062	-0.204	0.051
	(mm)												
Canine	Root	0.021	0.097	0.047	0.024	0.102	0.048	0.029	0.107	0.050	0.031	0.111	0.042
	(mm)												
	Crown	-0.135	-0.124	0.044	-0.018	-0.128	0.046	0.086	-0.154	0.051	0.198	-0.173	0.055
	(mm)												
	Root	0.068	0.049	0.040	0.006	0.054	0.049	-0.047	0.071	0.059	-0.103	0.084	0.067
	(mm)												
PM2	Crown	0.101	-0.042	0.051	0.010	-0.022	0.071	-0.085	-0.017	0.082	-0.169	0.000	0.092
	(mm)												
	Root	-0.027	0.017	0.051	0.020	0.000	0.074	0.059	-0.011	0.090	0.100	-0.021	0.102
	(mm)												
M1	Crown	0.124	-0.039	0.009	0.032	-0.035	-0.007	-0.063	-0.031	-0.013	-0.133	-0.032	-0.021
	(mm)												
	Root	-0.010	0.000	0.007	0.032	-0.006	-0.006	0.075	-0.009	-0.010	0.106	-0.011	-0.017
	(mm)												
M2	Crown	0.130	-0.035	-0.019	0.046	-0.072	-0.065	-0.057	-0.066	-0.115	-0.134	-0.082	-0.158
	(mm)												
	Root	-0.048	0.014	-0.023	-0.021	0.024	-0.068	0.012	0.018	-0.118	0.036	0.020	-0.161
	(mm)												
Premolar mesialisation	Crown	0.008	-0.053	0.018	0.000	-0.074	0.013	-0.007	-0.093	0.012	-0.013	-0.102	0.004
	(mm)												
	Root	-0.009	-0.004	0.017	-0.005	-0.002	0.011	-0.002	0.000	0.010	0.002	0.000	0.001
	(mm)												
II	Crown	0.001	-0.072	0.022	-0.008	-0.087	0.025	-0.018	-0.100	0.029	-0.025	-0.104	0.021
	(mm)												
	Root	0.005	0.048	0.018	0.010	0.056	0.021	0.013	0.063	0.024	0.015	0.067	0.016
	(mm)												
Canine	Crown	-0.038	-0.051	0.009	0.071	-0.067	0.016	0.172	-0.087	0.028	0.279	-0.104	0.036
	(mm)												

Supplementary II. Crown and root displacement in the local coordinate system under en-masse and substep space closureAnti-tipping
design

Local coordinate system	0°			1°			2°			3°		
	X	Y	Z	X	Y	Z	X	Y	Z	X	Y	Z
PM2	Root	0.020	0.016	0.009	-0.037	0.029	0.021	-0.086	0.043	0.037	-0.139	0.056
	(mm)											0.048
	Crown	0.259	-0.005	0.009	0.151	0.004	0.037	0.045	0.011	0.060	-0.043	0.037
	(mm)											0.070
	Root	-0.093	0.013	-0.011	-0.037	-0.002	0.025	0.013	-0.017	0.054	0.055	-0.034
	(mm)											0.065
M1	Crown	-0.016	0.008	-0.007	-0.115	0.008	-0.021	-0.218	0.014	-0.041	-0.291	0.009
	(mm)											-0.051
	Root	0.010	-0.005	-0.007	0.054	-0.008	-0.019	0.101	-0.010	-0.038	0.135	-0.013
	(mm)											-0.047
M2	Crown	-0.016	0.028	0.017	-0.114	0.001	-0.039	-0.203	-0.033	-0.092	-0.272	-0.069
	(mm)											-0.137
	Root	-0.005	-0.007	0.018	0.027	-0.002	-0.038	0.060	0.003	-0.093	0.085	0.009
	(mm)											-0.141
Molar mesialisation	Crown	-0.010	-0.131	0.021	-0.017	-0.141	0.014	-0.022	-0.144	0.009	-0.026	-0.146
	(mm)											0.000
	Root	0.000	0.000	0.017	0.002	0.002	0.010	0.005	0.001	0.004	0.007	0.001
	(mm)											-0.005
I	Crown	-0.026	-0.142	0.039	-0.033	-0.149	0.037	-0.037	-0.154	0.034	-0.041	-0.154
	(mm)											0.024
	Root	0.015	0.079	0.032	0.019	0.083	0.030	0.022	0.085	0.027	0.024	0.087
	(mm)											0.017
Canine	Crown	-0.099	-0.097	0.026	0.015	-0.108	0.025	0.125	-0.129	0.024	0.233	-0.149
	(mm)											0.028

PM2	Root	0.050	0.038	0.024	-0.011	0.046	0.028	-0.067	0.060	0.032	-0.121	0.074	0.040
	(mm)												
	Crown	-0.118	-0.007	0.040	-0.213	-0.015	0.069	-0.307	-0.017	0.085	-0.391	-0.010	0.094
	(mm)												
M1	Root	0.049	-0.003	0.050	0.098	-0.007	0.086	0.144	-0.013	0.106	0.187	-0.019	0.117
	(mm)												
	Crown	0.172	-0.039	0.026	0.080	-0.036	0.012	-0.001	-0.033	0.001	-0.064	-0.039	-0.011
	(mm)												
M2	Root	-0.018	-0.003	0.022	0.026	-0.008	0.011	0.064	-0.011	0.003	0.095	-0.013	-0.007
	(mm)												
	Crown	0.177	-0.041	-0.019	0.088	-0.071	-0.072	0.003	-0.073	-0.117	-0.065	-0.091	-0.160
	(mm)												
	Root	-0.062	0.016	-0.024	-0.032	0.021	-0.077	-0.009	0.022	-0.120	0.013	0.024	-0.163
	(mm)												

+x, mesially; -x, distally; +y, buccally; -y, lingually; +z, intrusion; -z, extrusion.