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En masse maxillary dentition distalization with clear aligners using infrazygomatic mini-implants: A finite element study

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Objective: Considering the success of infrazygomatic mini-implants in conjunction with traditional braces, this study aimed to evaluate the efficacy of infrazygomatic mini-implants in *en masse* maxillary distalization utilizing clear aligner therapy. **Methods:** In a three-dimensional finite element study, we evaluated the *en masse* maxillary dental distalization through the use of infrazygomatic mini-implants equipped with varying force-application arm lengths (0 mm, 4 mm, and 8 mm). Vertical, sagittal, and horizontal displacements were quantified. **Results:** Intrusion was observed in the incisors at all force application arm lengths (0 mm, 4 mm, and 8 mm), with similar sagittal displacement tendencies and labial crown tipping. Among all maxillary teeth, only the canine exhibited distalization of both the crown and root. Distalization of the posterior teeth was achieved, with the greatest magnitude of distalization occurring at the 0-mm force application arm length, which was characterized by minimal tipping and reduced vertical movements compared to the other force application arm lengths. **Conclusions:** The findings indicate that infrazygomatic mini-implants represent a viable approach for facilitating targeted tooth movement in clear aligners across various force-application arm lengths. These results may inform orthodontic treatment strategies in non-extraction cases.

Key words: Finite element method, Distalization, Orthodontic mini-implants, Aligners

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INTRODUCTION

Since the introduction of clear aligners by Align Technology (San Jose, CA, USA) in 1997, a transformative shift has occurred within the field of orthodontics, transitioning from fixed appliances to aligners. The aesthetic advantage of clear aligners positions them as the preferred orthodontic option for patients, notably adults.¹ Initially, clear aligner therapy (CAT) was utilized for uncomplicated orthodontic cases. Recent advancements have explored the effectiveness of CAT in managing more complex malocclusions. However, the inherent flexibility of aligners has been associated with unintended tooth movements.^{2,3} To mitigate reactions associated with intramaxillary forces, intermaxillary forces or auxiliary devices, such as mini-implants, are necessary to provide a high degree of skeletal anchorage, particularly for *en masse* distalization of anterior teeth.⁴ The complexity of managing mild to severe malocclusions has been addressed through mini-implants, leading to a reduced necessity for premolar extractions.⁵

The infrazygomatic (IZ) crest of the maxilla is considered an optimal site for the insertion of temporary anchorage devices. Due to its high bone density, mini-implants positioned in this extra-radicular area demonstrate increased stability and the capacity to provide reliable anchorage during *en masse* maxillary dentition distalization.^{6,7} Specifically, when mini-implants are inserted in the IZ crest, a loading force of 220 to 340 g (approximately 8 to 12 ounce) effectively induces *en masse* maxillary dentition distalization, akin to outcomes observed with fixed braces.⁶ Current literature supports the use of short mini-implants measuring 2.0 mm × 12.0 mm.⁸ For optimal stability, insertion angles between 50 and 60 degrees, alongside insertion heights of 11 mm from the alveolar crest or up to 15 mm from the occlusal plane, have been recommended to ensure secure engagement with the buccal bone.^{7,9} Furthermore, the biomechanical implications of varying lever arm heights with IZ mini-screws have been investigated, comparing 0 mm, 4 mm, and 8 mm lever heights.⁷ However, data pertaining to IZ mini-implants utilized in CAT remains sparse.

An extensive review of the literature revealed a lack of similar studies investigating the efficacy of IZ mini-implants in non-extraction cases during CAT. However, Shaikh et al.⁹ assessed the effectiveness of IZ mini-implants with braces, revealing encouraging results in a clinical cohort of 10 patients presenting with malocclusions. Thus, the successful application of IZ mini-implants with braces highlights the imperative need for studies addressing displacement patterns and force systems generated by IZ mini-implants within the context of CAT.

In orthodontics, the finite element (FE) model serves as a comprehensive virtual platform for predicting treatment outcomes in a non-invasive preclinical environment. FE models facilitate the calculation of tooth movements and simulation of displacement patterns following force application, while simultaneously depicting stress distribution among various tissues involved in orthodontic treatment, such as the periodontal ligament (PDL), teeth, and alveolar bone.^{2,7} Notably, FE analyses have demonstrated efficacy in accurately evaluating stress distribution associated with bodily movements in fixed brackets,⁸ as well as analyzing surface-to-surface contact in clear aligners.¹⁰

To date, no FE studies have specifically examined the use of mini-implants inserted into the IZ crest for *en masse* maxillary dentition distalization via clear aligners. Existing studies on CAT include an FE study by Bai et al.,¹¹ which explored the effect of mini-implants in conjunction with clear aligners for anterior retraction following first premolar extractions. Thus, the primary objective of the present study was to evaluate the biomechanical effects of IZ mini-implants on *en masse* maxillary dentition distalization using clear aligners.

MATERIALS AND METHODS

Modeling was conducted utilizing SolidWorks version 2019 (Dassault Systems, Paris, France). The models were designed with reference to the methodology established by Geramy and Ebrahimi.¹² The three-dimensional FE models encompassed the maxilla, maxillary teeth, PDL, spongy bone, cortical bone, and the clear aligner (inclusive of the lever arm). Material properties for the maxilla, maxillary teeth, PDL, and alveolar bone were derived from average values reported in the literature (Table 1). The dentition was designed according to Ash's dental anatomy, with the PDL thickness determined to be uniformly 0.25 mm, as reported by Schmidt and Lapatki.¹³ A mini-implant was modeled in the IZ area, and a clear aligner was incorporated in all three models. The differentiating factor among the models was the length of

Table 1. Mechanical properties of the materials used in the models

Material	Young's modulus (MPa)	Poisson's ratio
Spongy bone	13,400	0.38
Cortical bone	34,000	0.26
Tooth	20,300	0.26
Periodontal ligament	0.667	0.49
Titanium (mini-implant)	96,000	0.36
Clear aligner (Duran)	2,227	0.36

the lever arm used as the force application point. During the loading of the various configurations of the maxillary model, *en masse* maxillary dentition distalization via CAT was simulated from the IZ mini-implants, utilizing three distinct lever arm heights (Figure 1):

- Model 1: at the level of the cemento-enamel junction (0 mm)
- Model 2: at 4 mm above the cemento-enamel junction
- Model 3: at 8 mm above the cemento-enamel junction

IZ mini-implants were positioned between the maxillary first and second molars, at a height of 15 mm from the occlusal plane, angled at 60 degrees inferior to the horizontal plane to maximize engagement with the buccal bone.⁷ A distalizing force of 2.8 N, decomposed into three spatial planes according to the geometric relationship between the hook and the mini-implant in each model, was applied to facilitate safe distalization of the entire arch.^{6,9} The lever arms were loaded in accordance with their orientation relative to the mini-implant position. This defined the force applied on the hook, with the line of action passing through the other point of

force application (the mini-implant); these forces were defined as elastic tensions connecting the two points.

The models were subsequently transferred to the FE method software ANSYS Workbench V15.0 (ANSYS Inc., Canonsburg, PA, USA) for simulation. The mechanical properties of the materials were evaluated (Table 1). All models generated in this study were simulations of the full-arch Class II malocclusion of the maxillary dentition. The mechanical properties of the aligner employed corresponded with those of a Duran aligner (SCHEUDENTAL, Iserlohn, Germany) having a thickness of 1 mm.¹⁴ All materials utilized in the FE model study were regarded as isotropic, homogeneous, and linearly elastic.

Following the assignment of properties to the components, the models underwent meshing, dividing them into smaller three-dimensional elements featuring a series of nodes (Figure 1). Approximately 190,000 nodes and 90,000 elements were utilized in the meshing process. In this phase, contact elements were defined, and the base of the models was constrained against displacements in all three directions, serving as the boundary condition.

No statistical tests were applied to this study due to

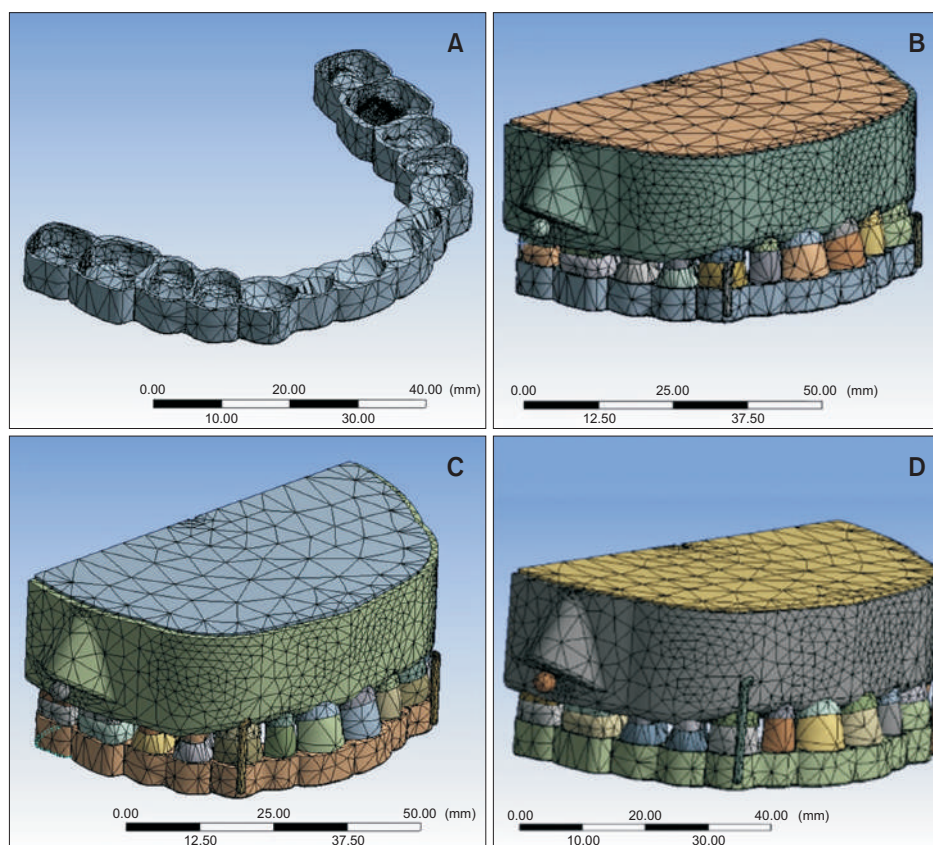


Figure 1. Meshed three-dimensional models of the **A**, Aligner without hook; **B**, Model 1 with aligner and IZ mini-implant at 0 mm; **C**, Model 2 with aligner and IZ mini-implant at 4 mm; **D**, Model 3 with aligner and IZ mini-implant at 8 mm. IZ, infrazygomatic.

the singular patient population. A static analysis approach was employed, indicating that reactions were assessed at the moment of force application.

The endpoints assessed included the three-dimensional movements of all maxillary teeth across the three planes:

- Vertical displacement along the Z-axis: intrusion and extrusion displacements of all maxillary teeth;
- Horizontal/transverse displacement along the X-axis: contraction and expansion in the apical and occlusal areas only for maxillary premolars and molars; and
- Sagittal/anteroposterior displacement along the Y-axis: distalization and mesialization of the apical and incisal/occlusal areas of all maxillary teeth.

To evaluate tooth movements, measurements were taken at the midpoint of the incisal edges of the central and lateral incisors, the cusp tips of the canines, the mesiobuccal or palatal cusp tips for the molars (using both buccal and palatal cusps), and the central grooves of the premolars. Specifically, displacements were assessed as follows:

- Central and lateral incisors: along a path connecting the apical node of the root to the midpoint of the incisal edge;
- Canines: along a path connecting the apical node to the canine cusp tip;
- Premolars: along a path connecting the apical node to the central groove of the occlusal surface; and
- Molars: for sagittal displacement, measurements were taken along a path connecting the apical node

of the mesiobuccal root to the mesiobuccal cusp tip, with vertical and transverse displacements evaluated along the mesiodistal occlusal path connecting the mesial and distal fossae on the occlusal surface.

RESULTS

The results of the three-dimensional FE displacement analysis for the maxillary teeth are expressed across vertical (Figures 2 and 3), horizontal (Figures 4 and 5), and sagittal (Figures 6 and 7) planes.

Vertical displacement (intrusion/extrusion)

Table 2 summarizes the vertical displacements of all maxillary teeth across the three models. An anti-

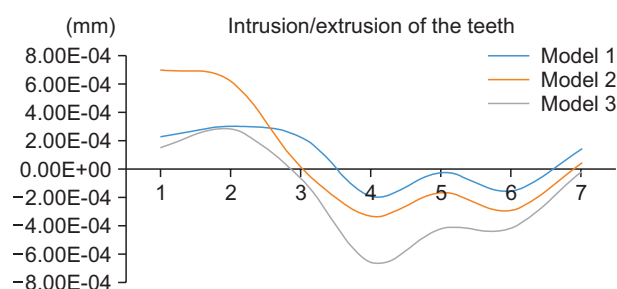


Figure 2. Vertical displacement in the three models. The numbers denote the maxillary teeth: 1, central incisor; 2, lateral incisor; 3, canine; 4, first premolar; 5, second premolar; 6, first molar; 7, second molar.

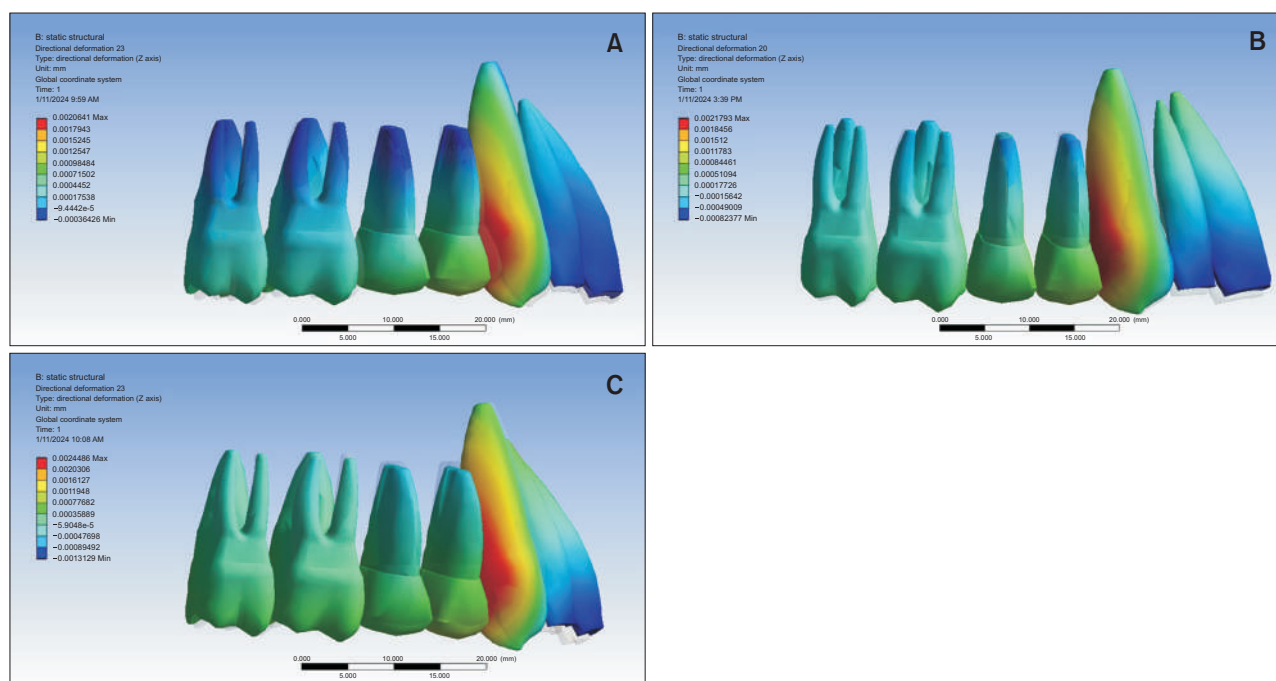


Figure 3. Vertical displacement in the buccal view for A, Model 1; B, Model 2; C, Model 3.

clockwise rotation of the occlusal plane was observed, resulting from the intrusion of the maxillary incisors and the extrusion of the premolars and first molars across all models. In Model 1, the anterior teeth were nearly equally intruded. Similarly, the second molar displayed intrusion, while all other posterior teeth were extruded. Among the three models, the most significant intrusion occurred in Model 2 for both the central (6.94×10^{-4} mm) and lateral incisors (6.14×10^{-4} mm). All teeth exhibited similar behaviors across models, with the exceptions of the canine and second molars. Unlike Models 1 and 2, where the canine was intruded, extrusions of 7.03×10^{-5} mm were noted for the canine in Model 3. The second molar displayed intrusion in Models 1 and 2, with an extrusion of 2.20×10^{-5} mm recorded in Model 3. The greatest posterior extrusion was observed in the first premolar, registering an extrusion of 6.59×10^{-4}

mm in Model 3.

Horizontal displacement (expansion/contraction)

Table 3 details the horizontal displacements of the posterior teeth across the three models. The most significant mediolateral displacement was noted in the premolars. Across all models, posterior teeth exhibited contraction in the occlusal area, with the first premolar demonstrating the largest contraction (-1.36×10^{-3} mm in Model 3). Overall, crown displacement increased from Models 1 to 3. For instance, the second premolar illustrated an apical expansion from 3.70×10^{-4} mm in Model 1 to 5.75×10^{-4} mm in Model 3. The first premolar also showed a considerable apical expansion (5.43×10^{-4} mm), coinciding with substantial contraction in

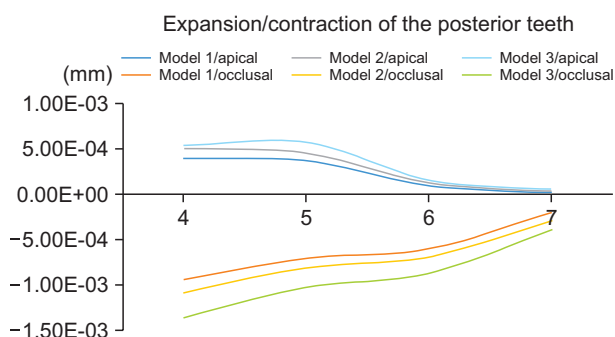


Figure 4. Horizontal displacement in the three models. The numbers denote the maxillary teeth: 4, first premolars; 5, second premolars; 6, first molars; 7, second molars.

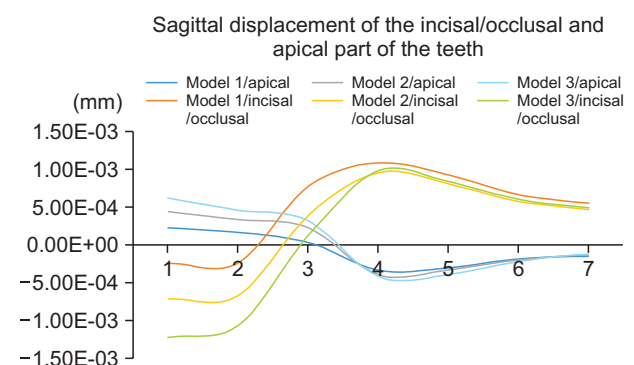


Figure 6. Sagittal displacement in the three models. The numbers denote the maxillary teeth: 1, central incisor; 2, lateral incisor; 3, canine; 4, first premolar; 5, second premolar; 6, first molar; 7, second molar.

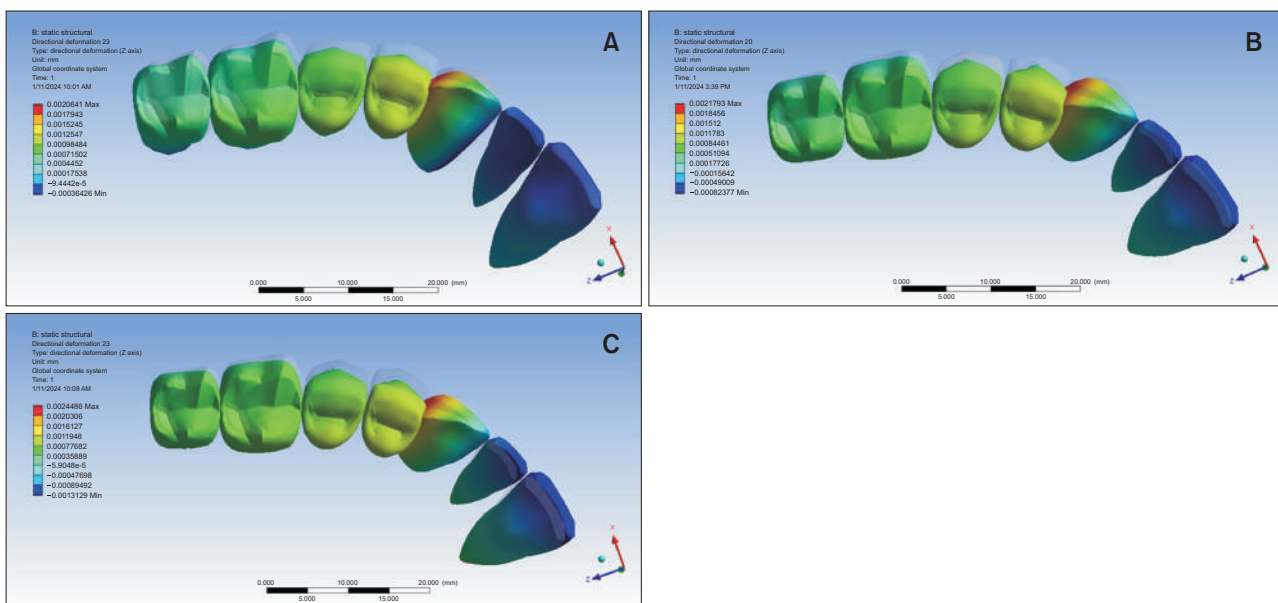


Figure 5. Horizontal displacement in the occlusal view for A, Model 1; B, Model 2; C, Model 3.

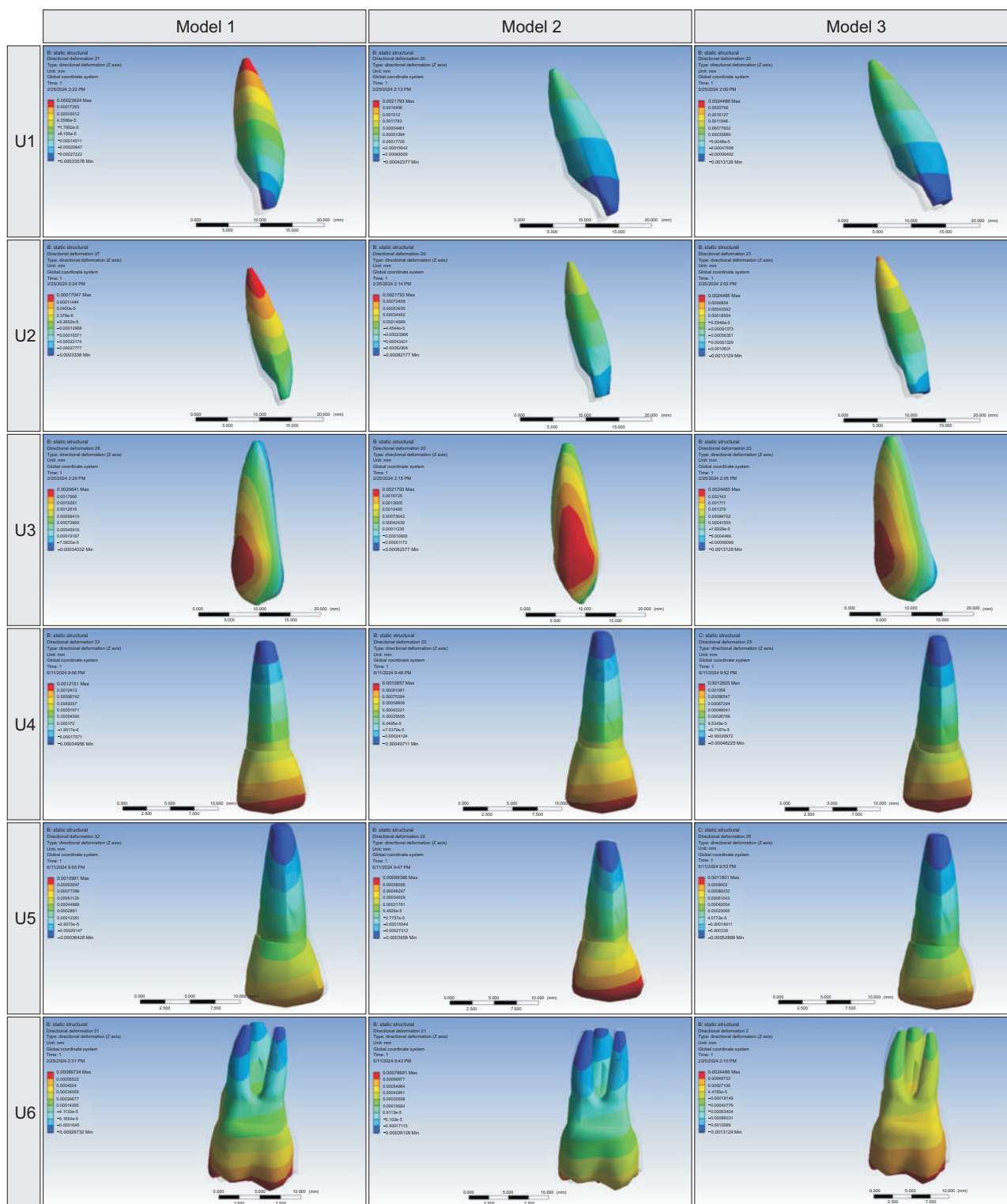


Figure 7. Sagittal displacement of the maxillary teeth across the three models.

the occlusal area of the first premolar (-1.36×10^{-3} mm) observed in Model 3.

Sagittal displacement (distalization/mesialization)

Table 4 presents sagittal displacement data for all maxillary teeth across the three models. Labial crown tipping of the anterior teeth occurred in all models. The

Table 2. Vertical displacement

	Central incisor (mm)	Lateral incisor (mm)	Canine (mm)	First premolar (mm)	Second premolar (mm)	First molar (mm)	Second molar (mm)
Model 1	2.29×10^{-4}	2.98×10^{-4}	2.24×10^{-4}	-1.93×10^{-5}	-2.71×10^{-5}	-1.58×10^{-4}	1.36×10^{-4}
Model 2	6.94×10^{-4}	6.14×10^{-4}	9.25×10^{-6}	-3.32×10^{-4}	-1.66×10^{-4}	-2.94×10^{-4}	3.53×10^{-5}
Model 3	1.53×10^{-4}	2.77×10^{-4}	-7.03×10^{-5}	-6.59×10^{-4}	-4.20×10^{-4}	-4.17×10^{-4}	-2.20×10^{-5}

Positive values indicate intrusion, and negative values indicate extrusion.

Table 3. Horizontal displacement

	First premolar (mm)	Second premolar (mm)	First molar (mm)	Second molar (mm)
Model 1/apical	3.98×10^{-4}	3.70×10^{-4}	9.47×10^{-5}	1.30×10^{-5}
Model 1/occlusal	-9.37×10^{-4}	-7.07×10^{-4}	-6.01×10^{-4}	-2.00×10^{-4}
Model 2/apical	5.09×10^{-4}	4.56×10^{-4}	1.26×10^{-4}	3.83×10^{-5}
Model 2/occlusal	-1.08×10^{-3}	-8.15×10^{-4}	-6.93×10^{-4}	-2.96×10^{-4}
Model 3/apical	5.43×10^{-4}	5.75×10^{-4}	1.60×10^{-4}	5.70×10^{-5}
Model 3/occlusal	-1.36×10^{-3}	-1.03×10^{-3}	-8.74×10^{-4}	-3.94×10^{-4}

Positive values indicate expansion, and negative values indicate contraction.

Table 4. Sagittal displacement

	Central incisor (mm)	Lateral incisor (mm)	Canine (mm)	First premolar (mm)	Second premolar (mm)	First molar (mm)	Second molar (mm)
Model 1/apical	2.27×10^{-4}	1.62×10^{-4}	3.62×10^{-5}	-3.35×10^{-4}	-3.04×10^{-4}	-1.92×10^{-4}	-1.42×10^{-4}
Model 1/incisal/occlusal	-2.37×10^{-4}	-2.36×10^{-4}	7.75×10^{-4}	1.09×10^{-3}	9.26×10^{-4}	6.68×10^{-4}	5.58×10^{-4}
Model 2/apical	4.40×10^{-4}	3.35×10^{-4}	2.28×10^{-4}	-3.89×10^{-4}	-3.28×10^{-4}	-1.99×10^{-4}	-1.24×10^{-4}
Model 2/incisal/occlusal	-7.12×10^{-4}	-6.71×10^{-4}	3.92×10^{-4}	9.59×10^{-4}	8.11×10^{-4}	5.79×10^{-4}	4.72×10^{-4}
Model 3/apical	6.16×10^{-4}	4.58×10^{-4}	3.15×10^{-4}	-4.25×10^{-4}	-3.97×10^{-4}	-2.25×10^{-4}	-1.26×10^{-4}
Model 3/incisal/occlusal	-1.22×10^{-3}	-1.07×10^{-3}	1.20×10^{-4}	9.83×10^{-4}	8.44×10^{-4}	6.07×10^{-4}	4.95×10^{-4}

Positive values indicate distalization, and negative values indicate mesialization.

largest crown displacement of the anterior teeth was recorded in Model 3 (10^{-3} mm displacement compared to 10^{-4} mm displacements in Models 1 and 2). Crown movements of the incisors were labial, while roots exhibited lingual movement. In all models, distalization of the crowns and mesialization of the roots were observed for the posterior teeth. The most pronounced occlusal distalization for these posterior teeth occurred in Model 1; for instance, the second molar exhibited an occlusal distalization of 5.58×10^{-4} mm in Model 1 versus 4.72×10^{-4} mm in Model 2 and 4.95×10^{-4} mm in Model 3. Distal movements of both crown and root in the same direction (both distally) were noted solely for the canines across the three models. Figure 7 illustrates sagittal displacement of the maxillary teeth across the models.

DISCUSSION

In our three-dimensional FE study, we evaluated the *en masse* maxillary dentition distalization utilizing varying force application arm lengths from the aligners to the mini-implants positioned in the IZ crest (0 mm, 4 mm, and 8 mm corresponding to Models 1, 2, and 3, respectively). Displacement tendencies for the anterior teeth exhibited similarities across all force application arm lengths in all three dimensions (vertical, horizontal, and sagittal), with the exception of the canine, which displayed a distinct vertical displacement in the model with an 8 mm arm length. The posterior teeth experienced distalization, with the greatest magnitude observed at the 0 mm force application arm length, characterized by minimal tipping and less vertical movement compared to the 4 mm and 8 mm arm lengths.

Vertical displacement

In all three models, the incisors demonstrated intrusion while all posterior teeth were extruded, excluding the second molar at the 0- and 4-mm arm lengths where intrusion occurred. The canine exhibited intrusion at the 0- and 4-mm arm lengths and extrusion at the 8-mm arm length. Similar patterns of nonuniform displacement for the canine and posterior teeth have been documented in clear aligner studies.^{3,15} Kwak et al.¹⁵ hypothesized that deformation of the clear aligner would lead to intrusion of the canine and extrusion of the molars. Conversely, the results from this study revealed divergent patterns of intrusion and extrusion for the canine and molars across various force application arm lengths. A potential explanation for the differing vertical displacements of the canine lies in the positioning of the IZ mini-implant relative to the lever arm length on the aligner, with the IZ mini-implant positioned more apically for the 0- and 4-mm lever arm lengths resulting in canine intrusion. In a comparable analysis, Ji et al.¹⁶ evaluated maxillary dentition behavior using clear aligners and inter-radicular mini-screws; they found, that all anterior teeth exhibited intrusion regardless of the traction device employed.

Similar vertical displacement trends were observed in a recent FE analysis by Schwertner et al.,¹⁷ which utilized varying power arm heights of 4 mm, 7 mm, and 10 mm supported on IZ mini-implants with braces, where the incisors and canines displayed distinct displacements corresponding to power arm height variations. In alignment with the current study's findings, the maxillary canine was extruded at power arm heights of 10 mm and 7 mm but displayed intrusion at a height of 4 mm. In contrast, this study found that incisors consistently exhibited intrusion across all tested heights, with the most significant intrusion at 4 mm. This discrepancy in incisor movement may be attributable to the differing mechanics of the orthodontic appliances used: braces versus aligners.¹⁷

Owing to the inherent elasticity of CAT, the potential for deformation poses a risk. Jiang et al.² elucidated that aligners, in general, lack the requisite strength to maintain vertical stability for the teeth; hence, intrusions manifest when forces are applied below the centers of resistance of the tooth during the distalization process.² Contrastingly, extrusions occur with forces acting above these centers, as observed in the 8 mm arm length scenario where the IZ mini-implant assumes a more occlusal position relative to the other arm lengths, leading to canine extrusion. Consequently, the magnitude of extrusion escalates for the posterior teeth when the 8-mm arm length is employed, correlating to an increase in posterior tooth extrusion with heightened lever arm heights.⁷

Horizontal displacement

Identical horizontal displacement patterns were noted for all premolars and molars across the different force application arm lengths, where all crowns exhibited contraction and all roots demonstrated expansion. The largest occlusal displacement was achieved at the 8-mm arm length, leading to expectations of a concurrent increase in apical displacement at this length, which was confirmed by the numerical data. The posterior crowns experienced contraction due to the line of action of the resultant force vector, which acted in front of the premolars and molars, resulting in a moment tending to contract the posterior segment while simultaneously promoting distalization. Transitioning from the 0-mm to 8-mm arm lengths elicited alterations in reaction, particularly for the posterior crowns, which can be attributed to the varying distance between the force application point and the IZ, thereby influencing the moment established within the force system.

Sagittal displacement

Each maxillary tooth exhibited analogous sagittal displacement patterns across the various force application arm lengths, albeit with differing magnitudes. Of all the maxillary teeth, only the canine displayed distalization involving both crown and root, with the crowning achievement observed at the 0-mm arm length (7.75×10^{-4} mm). Corresponding with established treatment protocols, an FE study conducted by Sanap et al.¹⁸ demonstrated that IZ mini-screws in different placements effectively facilitated maxillary arch distalization in Class II malocclusions, with the most substantial distalization achieved via IZ mini-screws positioned between the upper first and second molars (mean $\pm$ standard deviation of $1.199 \pm 0.904 \times 10^{-4}$ mm).¹⁸

Regarding the posterior teeth, crown distalization and root mesialization were uniformly noted. The highest occlusal distalization for the posterior teeth occurred at the 0-mm arm length, potentially attributed to deformation of the clear aligner in the region of the premolars. Observations indicate that deformation was evident in all models but was most pronounced at the 0-mm arm length due to the alignment of the force vector relative to the premolar area. In contrast to the posterior teeth, the incisors exhibited mesial crown movement with contemporaneous distalization of their roots, with the highest magnitude recorded at the 8-mm arm length. Despite the occurrence of anterior teeth mesialization—a phenomenon explicable through Newton's third law, which posits that every action (distalization of posterior teeth) produces an equal and opposite reaction (mesialization of anterior teeth)—the magnitude of mesialization for the anterior teeth remained inferior to that of distalization for the posterior teeth, attributable to the

anchorage control provided by the IZ mini-implant.

Labial crown tipping was observed for the anterior teeth in all models, with an increasing magnitude correlating to the transition from 0 to 8 mm. Given that the most significant posterior distalization was recorded at the minimum lever arm length, and that the entirety of the dentition behaves as a singular unit, the resultant anterior teeth exhibited minimized mesialization at this arm length. For the 0-mm arm length, the incisor tip distanced further from the center of resistance than at the 4-mm length. As a result, an increment in moment associated with this distance translated into enhanced clockwise lingual tipping forces on the crowns. With the application of a 4-mm arm length, force vectors shifted closer to the center of resistance, leading to reduced control of the crowns. At 8 mm, the force vector placement above the center of resistance for the incisors produced a counterclockwise moment affecting the incisors.

Previous studies have validated the use of IZ mini-implants with fixed braces through both FE model evaluations and clinical investigations.^{9,18} Notably, within the clinical domain, successful full-arch maxillary distalization was achieved in 10 patients with Class II malocclusions through the implementation of IZ implants situated between the first and second molars.⁹ Considerable magnitudes of anterior tooth distalization (4.6 mm) and intrusion (≥ 3.8 mm) were found to be statistically and clinically significant.⁹ It is vital to highlight that, as this study is an FE analysis, the results cannot be directly compared to those from clinical settings.

Currently, no FE research has assessed the *en masse* distalization of the entire maxillary dentition under non-extraction conditions utilizing IZ mini-implants and clear aligners. This limitation implies that findings from this study cannot be directly compared with other FE studies on clear aligners, as much of the available research is based on extraction conditions employing various attachments and anchorage devices. Nonetheless, this study corroborates the effectiveness of IZ mini-implants and clear aligners in achieving maxillary distalization while minimizing undesirable effects, aligning with the findings from Ji et al.,¹⁶ who demonstrated distalization of molars alongside labial inclination of anterior teeth through different traction devices.

Limitations

While FE analysis provides invaluable insights into predicting the biomechanical behavior of orthodontic appliances, certain limitations inherent in FE methodologies must be recognized when interpreting study outcomes. FE models represent simplified constructs of the intricate structures and tissues present within the human body, and may not fully encompass the complexities involved in orthodontic treatment. Additionally,

FE models typically operate under the assumption of static loading conditions, which may not accurately reflect the dynamic and continually evolving forces experienced during orthodontic therapy. Therefore, although FE models serve as useful tools for comprehending orthodontic biomechanics, careful interpretation of results is essential. Given that the present study employed a static analysis approach, it would be prudent to explore long-term displacement in future investigations.

CONCLUSIONS

Within the limitations of this FE study, the following conclusions were drawn:

- IZ mini-implants with force application arm lengths of 0 mm, 4 mm, and 8 mm exhibited potential in supporting maxillary dentition distalization with clear aligners.
- Incisors demonstrated intrusion with comparable sagittal displacement tendencies, revealing mesial tipping.
- The crowns of all molars and premolars underwent contraction during distalization, accompanied by mesial root movement. The maximum magnitude of distalization was observed with the 0-mm force application arm length, characterized by minimal tipping and fewer vertical movements compared to the 4-mm and 8-mm arm lengths.
- Among all maxillary teeth, only the canine showed distalization of both the crown and root.

The findings of this analysis may inform orthodontic treatment planning and assist clinicians in making informed decisions regarding the integration of clear aligners and IZ mini-implants for effective maxillary distalization. However, the validation of these findings via clinical trials is essential to ensure their applicability within real-world orthodontic scenarios.

AUTHOR CONTRIBUTIONS

Conceptualization: NN, RK, JB. Formal analysis: All authors. Investigation: All authors. Methodology: NN, AG, RK, PS. Project administration: NN. Resources: AG. Supervision: JB. Validation: All authors. Visualization: NN, RK, PS, JB. Writing—original draft: All authors. Writing—review & editing: All authors.

CONFLICTS OF INTEREST

No potential conflict of interest relevant to this article was reported.

FUNDING

None to declare.

SUPPLEMENTARY VIDEO

A video presentation of this article is available at <https://youtu.be/deunxAR-Msl>

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