REVIEW

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Different Maxillary Molar Intrusion Mechanics Supported By Mini-Screws: A Finite Element Method

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Abstract

To evaluate and compare the biomechanical effects of three different maxillary molar intrusion mechanics supported by mini-screws using finite element analysis. A three-dimensional maxillary model, including cortical bone, trabecular bone, teeth, and periodontal ligaments, was constructed from high-resolution cone-beam computed tomography data (0.1 mm slice thickness). Three intrusion mechanics were simulated: (1) a cast appliance with a palatal bar, (2) a prefabricated "Mousetrap" appliance with a transpalatal arch, and (3) an appliance with both buccal and palatal mini-screw anchorage. In each scenario, an intrusive force of 100 g was applied, and displacement patterns were analyzed in the transverse, sagittal, and vertical directions. Material properties, mesh characteristics, and boundary conditions were standardized across all simulations. Buccally placed mini-screws effectively minimized transverse displacement of posterior teeth. Palatal anchorage alone resulted in greater transverse tipping, especially in the second molars. Combined buccal-palatal mini-screw anchorage produced controlled tooth movement in all three spatial dimensions and reduced tipping compared to other scenarios. Occlusal wing extensions transmitted forces but did not adequately prevent transverse tipping of the second molar. Dual buccal-palatal anchorage offers superior three-dimensional control during maxillary molar intrusion, whereas palatal-only anchorage compromises transverse stability.

Keywords: Finite element analysis, orthodontic anchorage procedures, tooth movement techniques

INTRODUCTION

Tooth movement apically along its long axis within the alveolar socket is defined as intrusion.[1] Intrusion mechanics are used in cases of Class I, II, or III open bites and in situations where a molar tooth elongates toward an extraction space.[1-3] Traditional approaches include active vertical correctors[1], springs and magnets in bite blocks[2,4], occipital headgear[3,5], and maxillary traction devices.[5,6] Despite good patient compliance, achieving absolute anchorage control with these conventional methods is often challenging.[7]

Skeletal anchorage involves enhancing the anchorage of the reactive unit by temporarily placing devices into the bone, thereby reducing or eliminating the need for dental or soft tissue support.[8] These devices, including mini-implants, miniplates, and microscrews, can be placed transosteally, subperiosteally, or endosteally, and can be attached mechanically or through osseointegration.[8,9] Skeletal anchorage has been widely applied to maxillary molar intrusion.[6-29]

Finite element analysis (FEA) allows for the creation of models incorporating the physical properties of structures to calculate stresses, strains, and displacements under applied forces.[30,31] This method, widely used in engineering, has become an important tool in dental research for simulating craniofacial structures and visualizing tooth displacement in response to applied forces.[32]

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Although previous studies have evaluated molar intrusion with skeletal anchorage using FEA[22], no published work has comprehensively compared the specific modern methods assessed in this study.

Understanding the biomechanics of molar intrusion has direct clinical implications for the management of vertical discrepancies. Patients with anterior open bite or excessive lower facial height often present with functional problems, such as incomplete incisor contact, impaired mastication, and an increased risk of temporomandibular joint dysfunction. Aesthetically, these patients may also be dissatisfied because of increased gingival display or elongated facial proportions. Successful molar intrusion can address these concerns by inducing counterclockwise mandibular autorotation, thereby improving both occlusion and facial balance.

However, the effectiveness of intrusion is largely dependent on the stability of anchorage. Uncontrolled tipping or asymmetric displacements may not only compromise treatment efficiency but also increase the risk of root resorption, periodontal damage, or relapse. Identifying which anchorage configuration-palatal, buccal, or combined-provides the most favorable biomechanical environment is therefore of critical importance. By clarifying these differences under standardized conditions through finite element modeling, this study offers valuable guidance for clinicians seeking to optimize treatment mechanics, minimize complications, and improve long-term stability.

Therefore, the aim of this study was to compare the biomechanical effects of three distinct maxillary molar intrusion protocols supported by skeletal anchorage. Displacements in transverse, sagittal, and vertical dimensions were assessed using FEA to determine which method provides superior three-dimensional control and minimizes unwanted side effects.

MATERIALS AND METHODS

A digitally reconstructed cone-beam computed tomography (CBCT) dataset, not associated with a real patient, was used to construct the 3D finite element model; therefore, neither ethics committee approval nor informed consent was required. Figure 1 illustrates the stepwise process, from CBCT data acquisition and 3D model reconstruction through finite element meshing, intrusion scenarios, loading conditions, and output analysis. The dataset had a voxel size of 0.1 mm and was processed using 3D Slicer (v4.11) and Mimics (v21.0, Materialise, Leuven, Belgium). The maxilla, teeth, and periodontal ligament (PDL) were segmented and reconstructed according to Hounsfield unit (HU) thresholds (teeth >1200 HU, cortical bone >450 HU, and trabecular bone 150-450 HU). The PDL was modeled as a 0.2 mm uniform layer surrounding the tooth roots. The models were imported into ANSYS Workbench (v19.2, ANSYS Inc., USA) for mesh generation and FEA.

The maxilla, dentition, PDL, and mini-screws were meshed with 10-node tetrahedral elements (SOLID187). The average element size was 0.3-0.5 mm, resulting in approximately 450,000 nodes and 1,600,000 elements. Mesh convergence was verified by ensuring that changes in displacement remained below 5%. Linear elastic, isotropic material properties were assigned based on previous studies. The elastic modulus and Poisson's ratio for cortical bone, trabecular bone, teeth, PDL, stainless steel, titanium, and acrylic are summarized in Table 1.

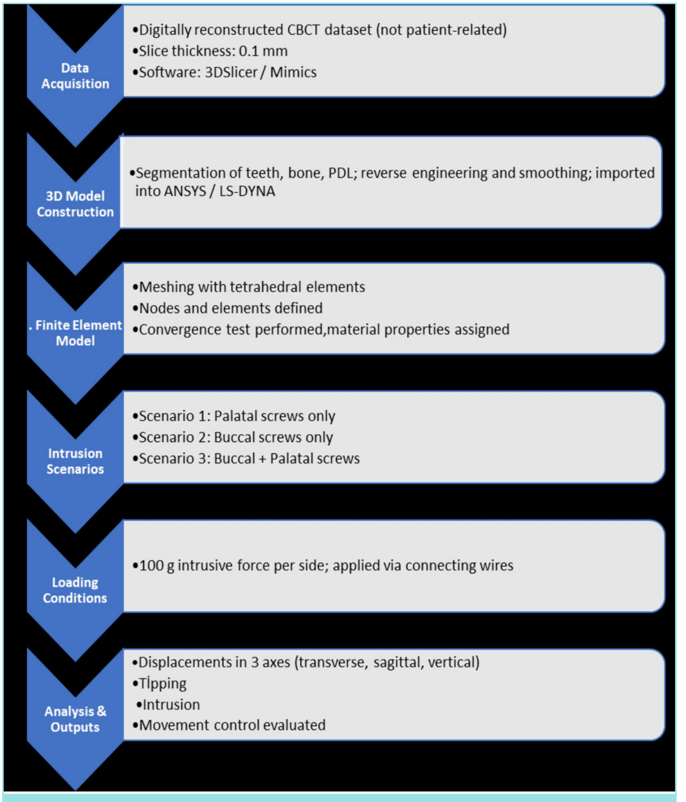

Figure 1. Flowchart summarizing the study design. The process included CBCT dataset reconstruction, 3D segmentation, finite-element meshing, simulation of three intrusion scenarios (palatal screws, buccal screws, and combined anchorage), application of a 100-g intrusive force per side, and evaluation of displacement, tipping, and intrusion patterns.

CBCT: Cone-beam computed tomography, PDL: Periodontal ligament.

Table 1. Linear elastic, isotropic material properties were used for all components

Material	Elastic modulus (MPa)	Poisson's ratio (ν)
Cortical bone	13,700	0.26
Trabecular bone	1,370	0.30
Tooth	19,613.3	0.15
Periodontal ligament	69	0.49
Stainless steel	200,000	0.30
Titanium	110,000	0.33
Acrylic	1,800	0.35

Three different intrusion scenarios were simulated :

- Scenario 1: palatal screws only (Figure 2)
- Scenario 2: buccal screws only (Figure 3)
- Scenario 3: buccal and palatal screws combined (Figure 4)

In all scenarios, a total intrusive force of 100 g per side was applied. In Scenarios 1 and 3, the force was delivered via elastic chains, while in Scenario 2 it was generated through lever arm activation. Displacements were measured along the transverse, sagittal, and vertical planes, and tooth movements were evaluated accordingly. Boundary conditions were defined by constraining all degrees of freedom at nodes in the inferior and posterior bone regions, with symmetry about the Y-Z plane. Bonded contacts were assigned between all contacting surfaces, assuming no relative motion during loading.

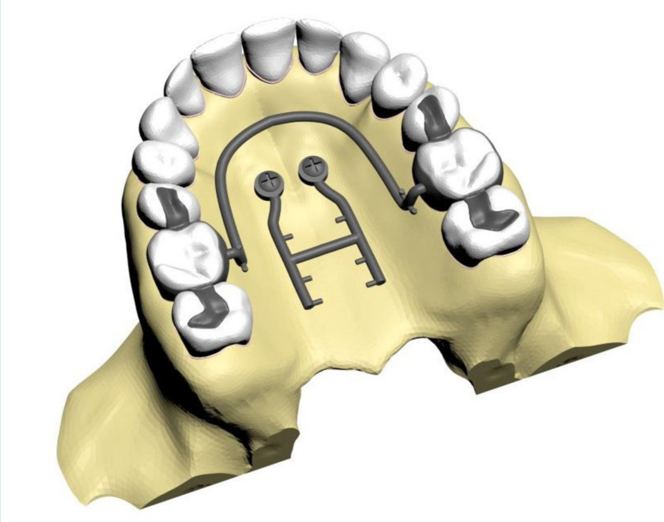

Figure 2. Cast appliance with palatal bar design used in Scenario 1.

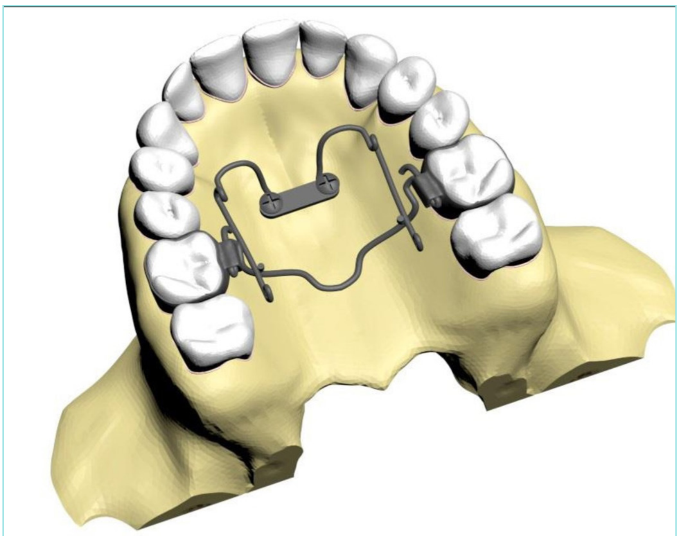

Figure 3. Prefabricated "Mousetrap" appliance used in Scenario 2. The appliance includes a transpalatal arch with hooks positioned near the molars' center of resistance and connected to lever arms to apply force.

RESULTS

In the transverse direction, all scenarios showed palatal tipping of the crowns and buccal tipping of the roots, though the degree varied among teeth. In the first scenario, the second molar exhibited the greatest tipping, the first premolar the least, and the second premolar and the first molar tipped at similar levels. In the second scenario, the greatest tipping was observed in the first molar, whereas the first premolar and the second molar exhibited less pronounced tipping. In the third scenario, all crowns tipped palatally, but the movements were more parallel overall, with the first premolar exhibiting the least tipping and the first molar exhibiting slightly more tipping than the second premolar (Table 2).

In the sagittal direction, crowns tended to tip distally while roots tipped mesially. The second premolar was generally the most affected, showing the greatest distal tipping in the first and second scenarios, while the second molar showed the least distal tipping. In the third scenario, the first premolar demonstrated the most distal tipping, whereas the second molar was the only tooth showing mesial tipping, resulting in the least overall distal tipping among the three scenarios (Table 3).

Vertically, the greatest intrusion occurred in the second molar (first scenario), the first molar (second scenario), and the second premolar (third scenario). Palatal aspects exhibited greater intrusion than buccal aspects. Across all scenarios, the smallest overall intrusion was observed in the third scenario, while values in the first and second scenarios were similar, with slightly greater intrusion in the second (Table 4).

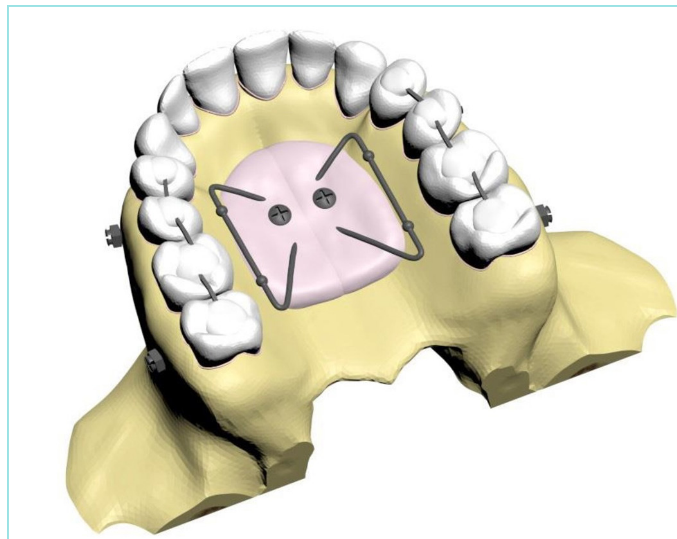

Figure 4. Acrylic palatal plate with buccal and palatal mini-screw anchorage used in Scenario 3. The occlusal wire unites posterior teeth to distribute forces evenly.

Table 2. Values of transversal displacement of crown and root (mm)

Transversal (X) axis	1. Premolar crown	1. Premolar apex	2. Premolar crown	2. Premolar apex	1. Molar crown	1. Molar apex	2. Molar crown	2. Molar apex
Scenario 1	-0.0003852	0.00005408	-0.0006454	0.0002388	-0.0007383	0.0001318	-0.0000729	0.0001559
Scenario 2	-0.0001833	0.00002587	-0.0003448	0.0001283	-0.0004060	0.0001039	-0.0003579	0.00009886
Scenario 3	-0.00003386	0.00001535	-0.0003581	-0.0000864	-0.0003841	-0.00002589	-0.0004106	-0.00005892

Table 3. Values of sagittal displacement of crown and root (mm)

Sagittal (Y) axis	1. Premolar crown	1. Premolar apex	2. Premolar crown	2. Premolar apex	1. Molar crown	1. Molar apex	2. Molar crown	2. Molar apex
Scenario 1	0.0004302	-0.00006298	0.0001064	-0.00008342	0.00008934	-0.00004438	0.00008108	0.0001124
Scenario 2	0.0006166	-0.00004377	0.0001012	-0.00006024	0.00006620	-0.00005821	0.00005440	0.0001073
Scenario 3	0.00009224	-0.00004807	0.00003437	0.00002330	0.00008432	-0.00002454	-0.00001158	0.00001198

Table 4. Values of vertical displacement of crown and root (mm)

Vertical (Z) axis	1. Premolar crown	1. Premolar apex	2. Premolar crown	2. Premolar apex	1. Molar crown	1. Molar apex	2. Molar crown	2. Molar apex
Scenario 1	0.0001144	0.0001716	0.0001289	0.0002071	0.0002078	0.0003980	0.0002402	0.0004097
Scenario 2	0.0001067	0.0001313	0.0001528	0.0001874	0.0002091	0.0003313	0.0002035	0.0002862
Scenario 3	0.0003373	0.0002145	0.0003495	0.0002391	0.0002586	0.0002230	0.0001782	0.0001664

DISCUSSION

Intrusion of posterior teeth has historically been challenging because traditional methods provide limited anchorage.[1-5] The advent of temporary anchorage devices has allowed clinicians to apply forces from multiple directions, improving control.[6-9] However, the mechanical differences between various appliances require further investigation.[33,34] This highlights the importance of FEM-based comparative analyses, which provide valuable theoretical guidance when clinical experimentation is limited.

In Scenario 1, all posterior crowns tipped palatally and roots tipped buccally due to the palatal-occlusal position of the application of force relative to the center of resistance (Figure 2). The first premolar tipped the least because it was excluded from the appliance design. The palatal bar effectively minimized the palatal tipping of the first molars, consistent with the findings of Wilmes et al.[33] Occlusal wing extensions transmitted intrusive forces to the second molars and the second premolars, but did not sufficiently prevent palatal movement of the second molars.[33] Sagittally, second premolars tipped more than molars, partly due to having a single root and smaller mesiodistal root surface area, reducing resistance to tipping forces.[33,35] Occlusal wing extensions had minimal effect on distal tipping control of second premolars.[35] Greater vertical intrusion of the second molars was observed, likely due to a higher trabecular bone content in that region combined with force transmission via the occlusal wing.[35] These findings suggest that palatal anchorage and occlusal extensions can partially improve control but remain insufficient for comprehensive 3D stability.

In Scenario 2, tipping patterns were similar to those in Scenario 1, but greater tipping occurred in the first molars due to the reduced rigidity of the 0.9 mm transpalatal arch (TPA) compared with the cast palatal bar in Scenario 1 (Figure 3). This finding aligns with previous studies showing that a TPA alone provides insufficient transverse anchorage.[35] In the sagittal plane, second premolars tipped more than molars, consistent with their single-rooted morphology and reduced resistance to tipping.[33,35] Occlusal wing extensions again showed minimal effect in controlling the distal tipping of the second premolars.[34] Vertically, intrusion was greatest in the first molars, consistent with Kawamura et al.[30], who reported that palatal-only forces favor intrusion of the first molars.[35] There fore, palatal anchorage alone may achieve localized intrusion but lacks the multidimensional control required for clinical predictability.

In Scenario 3, palatal tipping was least pronounced overall, likely due to force application from both buccal and palatal mini-screws (Figure 4). This dual anchorage reduced transverse movement compared with Scenarios 1 and 2, consistent with other studies in which labio-palatal or mesio-distal mini-implant placement helped prevent molar tipping.[34,35] In the sagittal plane, mesial tipping of the second molar and an overall reduction in distal tipping may be attributed to the unifying occlusal wire and bidirectional force application.[33,34] Similar mesial tipping of second molars when forces are applied between the first and second molars has been reported by Wilmes et al.[33] Second premolars intruded most in the vertical dimension, possibly because single-rooted teeth are more susceptible to intrusion when equal forces are applied.[31] Across all scenarios, Scenario 3 achieved the least intrusion while providing the best three-dimensional movement control.[34,35] A force of 100 g per side is consistent with literature recommendations of 100-250 g for upper posterior intrusion.[35] This demonstrates that dual anchorage offers the most balanced and clinically relevant biomechanics for posterior intrusion.

CONCLUSION

Although this study provides valuable insights into the biomechanics of maxillary molar intrusion, several methodological limitations should be considered. The model was based on a digitally reconstructed CBCT dataset not associated with a real patient, allowing standardization but limiting clinical representativeness. The PDL was modeled as a uniform, linearly elastic layer, although its true behavior is non-linear and viscoelastic. Bonded contacts were assumed between all interfaces, which may underestimate micromovements; the analysis was performed under static, linear conditions and did not account for time-dependent biological changes such as bone remodeling. Moreover, the study lacked experimental or clinical validation and was limited to a single anatomical model, thereby reducing generalizability. Despite these simplifications, the displacement patterns were consistent with previous FEM and clinical studies, supporting the method's usefulness as a theoretical framework and highlighting the need for future in vivo validation.[12,30,35]

This FEA provided valuable insights into the biomechanics of maxillary molar intrusion with different skeletal anchorage systems. Although methodological limitations-such as using a digitally reconstructed CBCT dataset not linked to a real patient, simplified PDL modeling, bonded contact assumptions, and absence of biological time-dependent factors-restrict direct clinical translation, the overall displacement patterns were consistent with previous FEM and clinical studies, supporting the model's predictive validity.

In conclusion, our data support the conclusion that buccal miniscrews reduce the transverse displacement of the posterior teeth, while palatal-only anchorage provides less transverse control. Dual buccal-palatal anchorage yielded the most favorable three-dimensional control, minimizing tipping and enhancing stability. Occlusal wing extensions contributed to the transmission of intrusive forces but were insufficient to fully prevent transverse tipping of second molars. Taken together, these findings indicate that dual anchorage may be an effective biomechanical strategy for posterior intrusion and that it provides a sound basis for future experimental and clinical investigations.

MAIN POINTS

- Mini-screws placed buccally minimized transverse displacement of the posterior teeth.
- Palatal anchorage alone reduced control of transverse movements.
- Combined buccal-palatal mini-screws provided superior three-dimensional control and reduced tipping.
- Occlusal wing extensions alone did not adequately prevent transverse tipping of second molars.

Footnotes

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Authorship Contributions

Concept: T.T., Design: T.T., Data Collection and/or Processing: D.K., Analysis and/or Interpretation: D.K., Literature Search: D.K., Writing: D.K.

DISCLOSURES

Conflict of Interest: No conflict of interest was declared by the authors.

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