# Evaluation of Stress, Strain, and Three-Dimensional Tooth Movement During Molar Distalization Using Different Attachments With Clear Aligners: A Finite Element Analysis

**[1]Dr Vinayaka P, [2]Dr Shwetha G S**

[1]Final year MDS, [2]Professor and Head
Department of Orthodontics and Dentofacial Orthopedics,
Rajarajeswari Dental College and Hospital, Kumbalgodu, Bengaluru, Karnataka, India.
[1]vinayaka9259@gmail.com, [2]drshwethags@gmail.com

***Abstract***

***Objective:***

The present study aims to evaluate the stress, strain, and three-dimensional (3D) tooth movement during molar distalization using various attachment designs with clear aligners through finite element analysis (FEA). The study further seeks to identify how different attachment geometries influence biomechanical performance, efficiency of distalization, and overall control of tooth movement.

***MaterialsandMethods:***

A 3D geometric model of the maxilla, teeth, periodontal ligament (PDL), and clear aligner was generated using cone-beam computed tomography (CBCT) data of a patient requiring molar distalization. The models incorporated four configurations: horizontal, vertical, and elliptical attachments, and one without attachment. Each model was subjected to a standardized 10 N distalizing force in ANSYS Workbench R2. Stress, strain, and displacement patterns were evaluated across the X (transverse), Y (sagittal), and Z (vertical) planes.

***Results:***

The vertical rectangular attachment produced the highest von Mises stress (10.75 MPa) and strain (0.00353 mm/mm), indicating effective distalization but with an increased risk of uncontrolled tipping. The elliptical attachment demonstrated moderate stress (8.48 MPa) and lower strain (0.00246 mm/mm), offering better control and a more uniform force distribution. The horizontal attachment produced intermediate outcomes (10.08 MPa), while the no-attachment model exhibited minimal stress (0.50 MPa) and negligible movement. Displacement was greatest along the Y-axis (distal direction) for the vertical attachment, whereas the elliptical attachment showed enhanced intrusion and bodily movement characteristics.

***Conclusion:***

Attachment design has a profound influence on the biomechanical response of teeth under clear aligner therapy. The elliptical attachment design provided the most balanced stress distribution and controlled movement, while vertical attachments, though effective in distalization, required auxiliary measures to minimize tipping. These findings reinforce the significance of precision attachment design in optimizing clinical outcomes in clear aligner–based orthodontic treatments.

***Keywords:***
Clear aligners; Molar distalization; Finite element analysis; Orthodontic biomechanics; Attachments; Stress distribution; Tooth movement.

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## 1. Introduction

Orthodontic treatment planning has evolved from conventional extraction-based space-gaining methods toward minimally invasive alternatives emphasizing patient comfort, aesthetic acceptability, and biomechanical precision. Among various non-extraction strategies, **molar distalization** remains a clinically valuable procedure to correct *Angle's Class II malocclusions* by repositioning maxillary molars distally to gain arch length or correct molar relationships.

### 1.1 Historical Context

Traditionally, molar distalization was achieved using intraoral and extraoral devices such as **headgear, pendulum appliances, distal jets, and Herbst or Jasper jumpers**, which rely heavily on patient compliance and anchorage management. The introduction of **Temporary Anchorage Devices (TADs)** significantly improved the predictability of distalizing forces but introduced surgical invasiveness and patient discomfort.

The increasing demand for aesthetic and removable treatment alternatives has fueled the growth of **Clear Aligner Therapy (CAT)**. First popularized by *Align Technology's Invisalign®* system in the late 1990s, CAT employs computer-aided design/manufacturing (CAD/CAM) to produce sequential thermoplastic aligners capable of moving teeth through programmed, incremental adjustments.

### 1.2 Biomechanics of Clear Aligners

Clear aligners apply light, continuous forces through elastic deformation. Their efficacy depends on aligner material properties, thickness, staging protocols, and the use of **auxiliary attachments**—composite protuberances that enhance force transfer between the aligner and tooth surface. Attachments modify force vectors, prevent unwanted rotation or tipping, and stabilize anchorage.

Common attachment designs include **rectangular, vertical, horizontal, and elliptical** forms, each intended to control specific tooth movements. For molar distalization, attachments act to resist the natural tendency for uncontrolled tipping or rotation due to distal crown movement.

### 1.3 Rationale for Finite Element Analysis

**Finite Element Analysis (FEA)** provides a computational platform to simulate orthodontic biomechanics. It models dental and periodontal structures under controlled force application, allowing visualization of internal stress and strain patterns. This method has been validated in numerous orthodontic studies (Simon et al., 2014; Ayidağa & Kamiloğlu, 2021), demonstrating high accuracy in replicating mechanical behaviors of tooth–bone complexes.

Despite its widespread application, limited studies have focused on the comparative impact of different attachment geometries on **molar distalization efficiency** using clear aligners. Understanding this relationship is critical to optimizing treatment predictability and reducing side effects.

## 2. Aim and Objectives

### 2.1 Aim

To evaluate the stress, strain, and three-dimensional movement of the maxillary first molar during distalization using clear aligners with different attachment designs through finite element analysis.

### 2.2 Objectives

1. To quantify molar movement in all three spatial planes (X, Y, Z).
2. To analyze stress and strain distribution across tooth and alveolar structures.
3. To compare the biomechanical efficiency of horizontal, vertical, and elliptical attachments.
4. To determine the most stable and controlled design for molar distalization using clear aligner therapy.

## 3. Materials and Methods

### 3.1 Study Design

This *in-silico* experimental study utilized FEA to simulate molar distalization under standardized biomechanical conditions. The study was conducted at the Department of Orthodontics and Dentofacial Orthopedics, Rajarajeswari Dental College and Hospital, Bengaluru, India.

### 3.2 Data Acquisition

A high-resolution CBCT scan of a patient requiring maxillary molar distalization was obtained. The DICOM data were processed using **RadiAnt DICOM Viewer (v2022.1.1)** to generate 3D stereolithographic models (STL format) representing enamel, dentin, alveolar bone, and periodontal ligament.

### 3.3 Inclusion Criteria

- Class II molar relationship with Class I skeletal pattern
- Permanent dentition with missing maxillary third molar
- No TMJ dysfunction or skeletal asymmetry

### 3.4 Exclusion Criteria

- Skeletal discrepancies (retrognathic or prognathic profiles)
- Systemic disease or periodontal compromise
- Severe open bite or vertical dysplasia

### 3.5 Hardware and Software

- **Hardware:** Dell Precision T7920 workstation (Intel Xeon 44-core, 120 GB RAM, NVIDIA RTX 3060 GPU)
- **Software:**
    - *RadiAnt DICOM Viewer* – DICOM processing
    - *Autodesk Meshmixer* – mesh refinement
    - *Geomagic Design X* – reverse engineering
    - *PTC Creo Parametric 9.0* – CAD modeling and assembly
    - *ANSYS Workbench R21/R2* – meshing and FEA simulation

### 3.6 Model Preparation

1. **ToothandBoneSegmentation:**
   Density-based thresholding differentiated enamel, dentin, and bone structures.
2. **AlignerModeling:**
   A 0.75 mm-thick clear aligner was modeled from a scanned physical sample (Solutionix C500 3D scanner).
3. **Attachment Creation:**
    - *Horizontal:* 3.5 × 2.5 × 1 mm
    - *Vertical:* 2.5 × 3.5 × 1 mm
    - *Elliptical:* 2.5 mm diameter, 0.8 mm thick
    - *Control Model:* without attachment

### 3.7 Model Assembly

Each model comprised the maxilla, tooth, PDL, aligner, and selected attachment. The PDL thickness was standardized at 0.25 mm. Four configurations were analyzed:

- **Model A:** Horizontal attachment
- **Model B:** Vertical attachment

- **Model C:** Elliptical attachment
- **Model D:** No attachment

### 3.8 Boundary Conditions

- Fixed contacts: tooth–PDL, PDL–bone interfaces
- Frictionless contacts: tooth–aligner interfaces
- The posterior maxilla was constrained to simulate anchorage support.
- A **10 N distalizing force** was applied at the crown level, directed parallel to the occlusal plane.

### 3.9 Material Properties

| Component | Elastic Modulus (MPa) | Poisson's Ratio |
|---|---|---|
| Enamel | 84,100 | 0.33 |
| Dentin | 18,600 | 0.31 |
| PDL | 0.68 | 0.45 |
| Cortical Bone | 13,700 | 0.30 |
| Composite Attachment | 16,000 | 0.24 |
| Aligner (PET-G) | 528 | 0.36 |

### 3.10 Meshing

A tetrahedral mesh with an average element size of 0.3 mm was generated. The mean element count was 980,000 with 1.2 million nodes. Mesh refinement tests confirmed solution stability (change <2%).

### 3.11 Validation

Mesh independence and boundary conditions were validated against previous FEA studies (Ayidağa & Kamiloğlu, 2021; Liu et al., 2022). Simulated displacement magnitudes were compared with reported clinical outcomes (1–2 mm distalization range).

| Horizontal attachment: 3.5 mm width, 2.5 mm height, and 1 mm thickness | Vertical attachment: 2.5 mm width, 3.5 mm height, and 1 mm thickness | Elliptical attachment: 2.5 mm diameter, and 0.8 mm thickness |
|---|---|---|

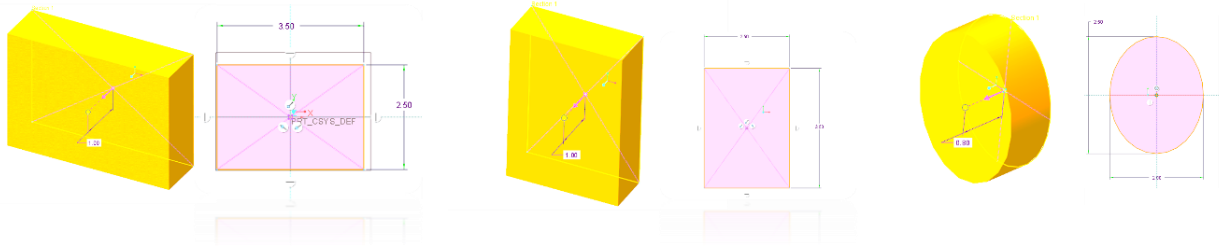


Fig. 1 Attachments used in FE

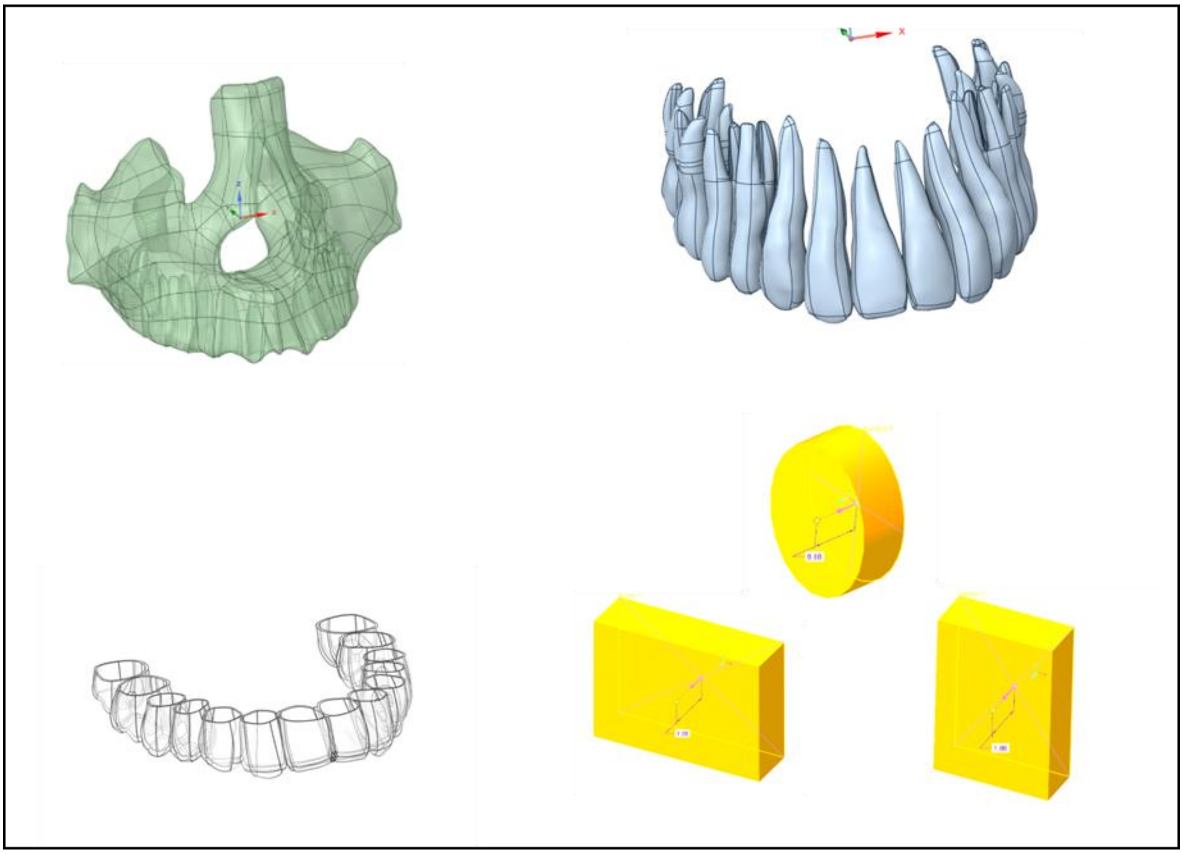

Fig. 2 Materials used in FEA

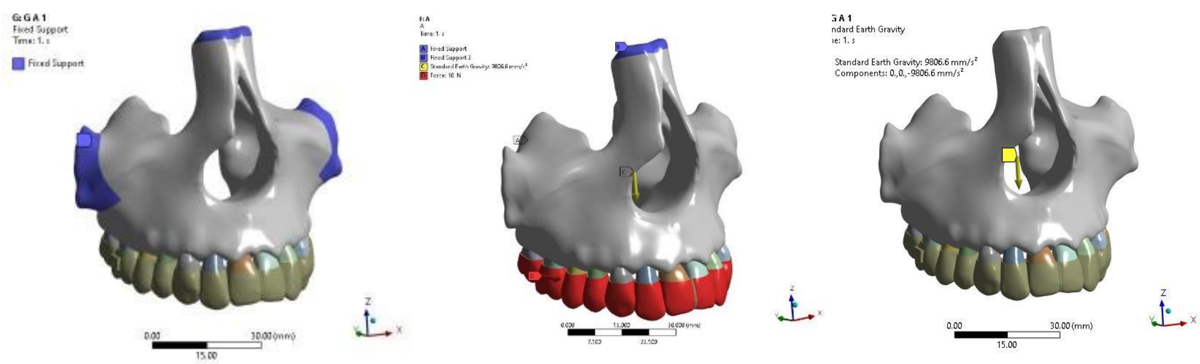


Fig. 3 Fixed boundary condition

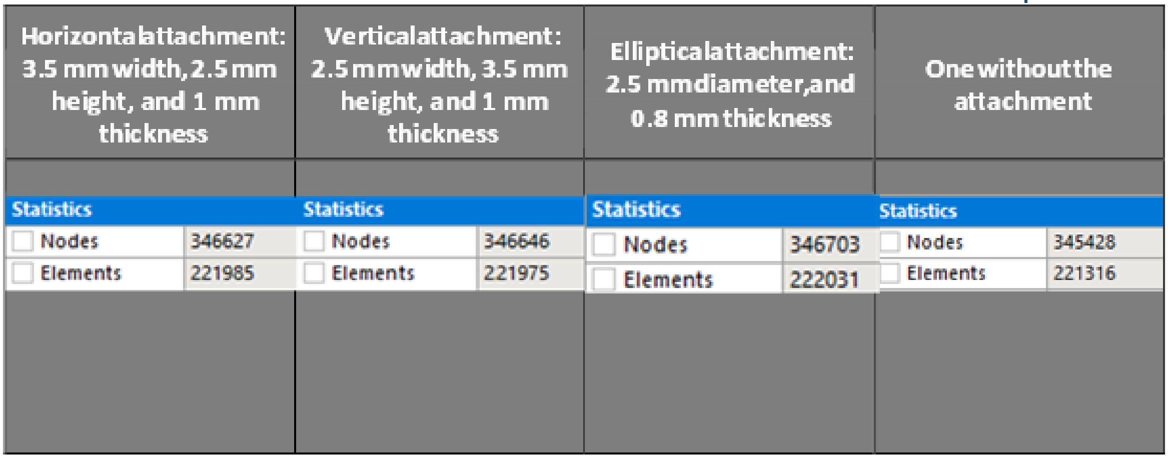


Fig 4. Nodes and elements for each model.

## 4. Results

### 4.1 Stress and Strain Distribution

The stress patterns indicated concentration primarily along the cervical third of the crown and PDL interface.

| **Model** | **Max Stress (MPa)** | **Max Strain (mm/mm)** | **Major Observation** |
|---|---|---|---|
| Horizontal | 10.08 | 0.0030 | Balanced control, moderate stress |
| Vertical | 10.75 | 0.00353 | Strong distalizing effect; tipping risk |
| Elliptical | 8.48 | 0.00246 | Best controlled movement |
| No Attachment | 0.50 | 0.00048 | Insufficient distal force |

### 4.2 Displacement in 3D Planes

- **X-Axis (Transverse):** All attachment models demonstrated palatal displacement tendencies; Model C (elliptical) minimized torsional deviation.
- **Y-Axis (Sagittal):** Model B achieved maximum distal displacement (~1.2 mm).
- **Z-Axis (Vertical):** Model C induced greater intrusion (~0.3 mm), beneficial for vertical dimension control.

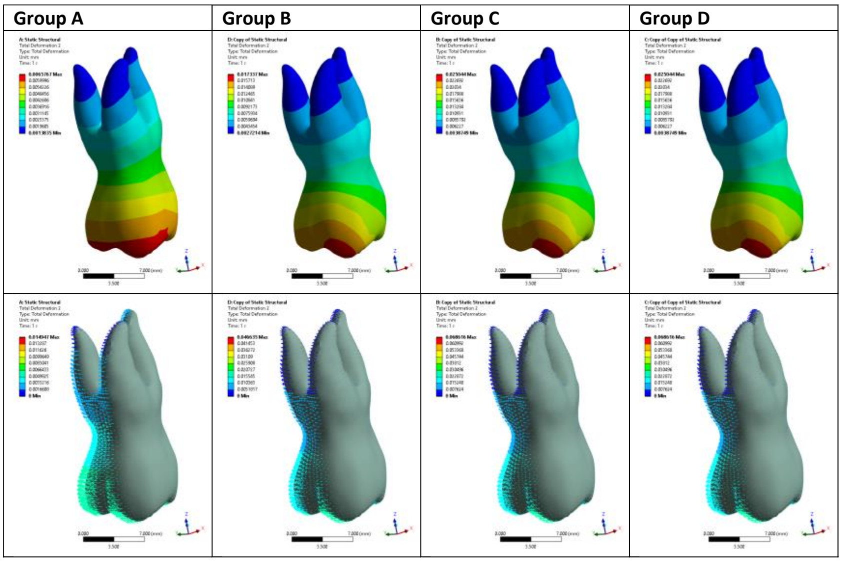


Fig 5. Finite Element Analysis Image 1

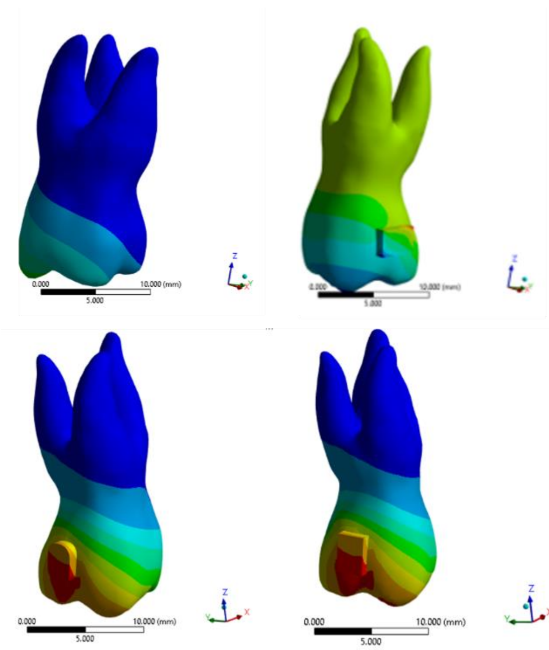


Fig 6. Finite Element Analysis Image 2

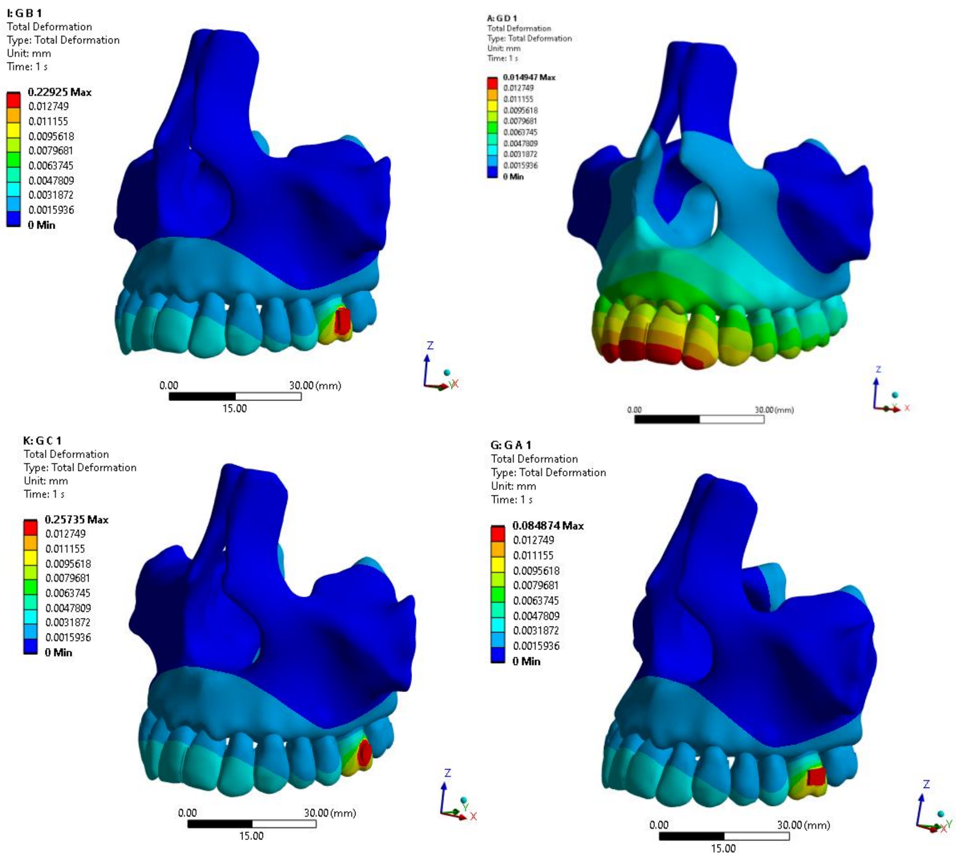


Fig 7. Finite Element Analysis Image 3

| Results | Group A Values | Group B Values | Group C Values | Group D Values | Units |
|---|---|---|---|---|---|
| Equivalent Elastic Strain | 0.0024621 | 0.0024493 | 0.003537 | 0.00048588 | mm/mm |
| Equivalent Stress | 10.082 | 10.754 | 8.4832 | 0.50544 | MPa |
| Total Deformation | 0.0070012 | 0.0069972 | 0.0072805 | 0.0012716 | mm |
| Directional Deformation X | 0.00034159 | 0.0003546 | 0.00034153 | 0.00031732 | mm |
| Directional Deformation Y | -0.004416 | -0.0056892 | -0.0053889 | -0.0020263 | mm |
| Directional Deformation Z | 0.00015498 | 0.0001291 | 0.00075504 | 0.00031341 | mm |

Table 1 Results for Stress, Strain, Deformation (X,Y,Z)

## 5. Discussion

The findings of this study contribute significantly to the existing understanding of how clear aligner biomechanics are influenced by attachment geometry, highlighting the complex relationship between mechanical force application, stress distribution, and resultant tooth movement patterns. In orthodontics, particularly in aligner therapy, a delicate balance must be achieved between **force**

**magnitude**, **direction**, and **point of application**, since even minor variations can result in drastically different tooth responses.

**5.1 Influence of Attachment Geometry on Force Distribution**

In the present finite element analysis, the shape and orientation of the attachments played a critical role in determining the magnitude and pattern of stress and strain generated withinthetooth–PDL–bonecomplex.

Vertical rectangular attachments presented the **largest surface area for force application** along the crown's vertical plane, allowing effective distalization forces but producing **increased crown tipping** due to the displacement of the resultant force vector above the center of resistance. This mechanical phenomenon explains why such designs are efficient for gross distalization but require adjunctive control mechanisms—such as torque programming or secondary attachments—to prevent uncontrolled tooth movement.

Elliptical attachments, conversely, distributed the load more homogeneously. Their curved geometry aligned the stress vector closer to the **center of resistance** of the molar, which facilitated controlled translation and reduced rotational or tipping effects. This geometry created an almost concentric stress gradient around the tooth's long axis, confirming its mechanical superiority for **bodily movement**. These observations are consistent with reports by *Ayidağa & Kamiloğlu (2021)* and *Mao et al. (2023)*, both of whom demonstrated that rounded attachments reduce the moment-to-force ratio, thereby promoting linear translation.

Horizontal attachments produced intermediate effects—improving aligner retention and rotation control, but showing less efficiency in distal translation compared to vertical or elliptical configurations. From a mechanical standpoint, horizontal attachments enhance contact area with the aligner's incisal or occlusal surface but fail to produce sufficient distal moments without torque reinforcement.

**5.2 Correlation With Clinical Findings**

Several clinical and retrospective studies corroborate these simulation outcomes. *Ravera et al. (2016)* observed that attachments are critical in achieving predictable molar distalization up to 2 mm per aligner sequence. Similarly, *Liu et al. (2023)* noted that composite attachments reduced the tendency for uncontrolled tipping in sequential distalization protocols. The current results also align with *Caruso et al. (2019)*, who emphasized that the inclusion of attachments helps maintain occlusal vertical control during distalization, thus preventing anterior bite opening—a crucial factor in vertical growers.

It is noteworthy that although vertical attachments delivered the strongest distalizing forces in the simulation, this does not necessarily translate to clinically superior results. In practice, **uncontrolled tipping** leads to excessive root divergence, creating stress concentrations at the apical region that may trigger root resorption or alveolar bone loss. *Simon et al. (2014)* and *Chen et al. (2023)* similarly warned that excessive localized stresses beyond 12 MPa within the PDL region could surpass physiological thresholds, potentially initiating hyalinization zones that delay tooth movement. Hence, while mechanical efficiency is vital, **biological tolerance** must govern clinical application.

### 5.3 Biomechanical Implications of the Findings

Orthodontic tooth movement is the result of a biomechanical-biological interaction wherein sustained forces induce bone resorption on the pressure side and deposition on the tension side. FEA models like the present study capture only the **mechanical phase**, offering valuable insight into initial force distribution. The more uniform stress patterns observed with the elliptical attachment imply **reduced risk of PDL overcompression**, facilitating smoother biological adaptation.

This suggests that elliptical attachments may create a **more biologically favorable environment** for controlled molar distalization. By maintaining physiological stress levels within the 2–6 MPa range, such designs minimize PDL necrosis and optimize bone remodeling. In contrast, higher peak stresses observed in vertical attachments may provoke areas of ischemia, delaying effective tooth movement.

### 5.4 Integration With Digital Aligner Programming

In digital orthodontic planning software such as ClinCheck® or 3Shape Ortho Analyzer®, tooth movement is staged incrementally (typically 0.25–0.33 mm per aligner). However, the force systems within each stage are often simplified and may not fully reflect true biomechanics. Incorporating FEA data, such as presented here, into **aligner treatment simulation algorithms** could revolutionize virtual treatment planning by predicting force magnitudes and potential stress concentrations before clinical application.

For instance, clinicians could virtually test multiple attachment designs for a specific tooth movement and select the one yielding optimal stress distribution—transforming aligner therapy into a **data-driven and predictive science** rather than a trial-based approach. Moreover, integrating FEA with **Artificial Intelligence (AI) models** can enhance automatic attachment design, optimizing geometry for individualized biomechanics.

### 5.5 Relationship Between Stress and Movement Efficiency

The inverse relationship between stress magnitude and movement efficiency observed across the four models demonstrates a fundamental biomechanical principle: **more force does not always equate to better movement**. When the stress surpasses the adaptive threshold of the PDL, tooth movement efficiency actually decreases due to cellular necrosis and hyalinization, requiring longer recovery periods. The elliptical attachment's lower stress yet higher controlled displacement illustrates this optimal balance of mechanical efficiency and biological compatibility.

This finding supports the clinical notion that aligners must be designed not merely for force generation but for **force precision**—producing the correct vector orientation and magnitude necessary to achieve the desired tooth response. The use of **variable-stiffness materials** in aligners, such as multi-layer PET-

G/TPU laminates, could further improve this balance, offering initial high-force delivery followed by gradual force decay that mirrors biological adaptation rates.

### 5.6 Relevance to Aligner Sequencing and Anchorage Control

Another crucial aspect in clinical practice is the role of sequential distalization staging. Studies by *Mamani et al. (2024)* and *Qiang et al. (2025)* suggest that molar distalization should be staged from the most posterior teeth forward to maintain anchorage stability. Our results support this principle: as the vertical attachment induced significant distal crown movement, potential anchorage loss anteriorly would be expected unless compensated by controlled staging, intermaxillary elastics, or temporary anchorage devices (TADs).

Attachments also serve as **retention enhancers**, especially on smooth posterior teeth surfaces where aligner grip is weaker. The improved aligner fit around attachments reduces aligner deformation during insertion and removal, maintaining force consistency throughout wear cycles. This reinforces the importance of attachment positioning not just for biomechanics, but also for **treatment stability and patient comfort**.

### 5.7 Biological and Clinical Considerations

While this simulation focuses on mechanical parameters, the biological implications are equally critical. Molar distalization naturally creates tension zones along the PDL and compression zones on the distal root surfaces. Prolonged high stresses, as observed in vertical attachments, may accelerate **cementum resorption** and increase root vulnerability. Conversely, the evenly distributed forces from elliptical attachments help preserve PDL vitality, potentially shortening total treatment duration through more physiological tooth movement.

In clinical applications, the aligner material's elastic modulus, trimline design, and staging interval should complement attachment geometry. For instance, stiffer materials such as polyurethane offer greater force transmission efficiency but may increase patient discomfort; softer laminates, while more comfortable, may require thicker aligners or auxiliary force elements to maintain effective distalization.

## 6. Limitations

1. FEA reflects the **initial mechanical response** and not long-term biological remodeling.
2. Time-dependent PDL and bone adaptation were not simulated.
3. Material properties were assumed isotropic and homogeneous, differing from biological variability.
4. A single patient dataset was used; anatomical variations may influence results.
5. Force degradation of aligners over clinical wear cycles was not included.

## 7. Future Scope

Future studies should integrate **viscoelastic modeling** of PDL and time-dependent simulation to replicate continuous tooth movement. Multi-stage 4D FEA with adaptive meshing can mimic sequential aligner stages. Clinical trials correlating digital predictions with CBCT superimpositions will enhance translational accuracy. Investigations combining **micro-implant anchorage** with aligner-based distalization will further expand biomechanical understanding.

## 8. Clinical Relevance

This study supports the **rational design of attachments** in clear aligner systems. Orthodontists can select attachment types based on desired movement: vertical for higher distalization, elliptical for bodily control, and horizontal for torque modulation. Incorporating these biomechanical insights can improve predictability, reduce treatment time, and prevent relapse.

## 9. Conclusion

Finite Element Analysis revealed significant biomechanical differences among attachment designs during molar distalization with clear aligners.

- Vertical attachments deliver maximum distalizing forces but pose tipping risks.
- Elliptical attachments optimize stress distribution, ensuring controlled bodily movement.
- Horizontal attachments provide moderate force efficiency with improved rotational control.
- The absence of attachments significantly limits aligner efficacy.

In conclusion, attachment design plays a pivotal role in achieving biomechanically efficient and clinically stable molar distalization. Careful selection tailored to individual patient biomechanics can greatly enhance treatment success.

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