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**Initial Biomechanical Response to Different Attachment Configurations and Class II
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Extraction: A Three-Dimensional Finite Element Analysis**

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Abstract

Objectives: To compare the initial biomechanical responses generated by different attachment configurations and button-cut Class II intermaxillary elastic mechanics during a single 0.25-mm programmed activation for maxillary canine distalization with clear aligners following first premolar extraction.

Methods: A patient-specific three-dimensional finite element model comprising the maxillary dentition, periodontal ligament (PDL), alveolar bone, clear aligner, attachments, and orthodontic button was constructed from cone-beam computed tomography data. Six attachment configurations were analyzed, including one incorporating button-cut Class II intermaxillary elastic mechanics. A single 0.25-mm programmed distalization step was simulated through geometric mismatch between the activated aligner and pretreatment dentition, generating the initial force system through aligner deformation and elastic recovery. Initial three-dimensional crown and root displacements and principal and equivalent (von Mises) stress distributions within the aligner and PDL were evaluated.

Results: Attachment configuration influenced initial stress distribution, force transmission, and canine displacement patterns. The attachment-free model demonstrated the greatest overall initial canine displacement, extrusive component, and PDL stress. The optimized attachment produced a more balanced initial crown–root displacement pattern with a smaller extrusive component, although the initial response remained tipping-dominant across all configurations. Incorporation of Class II elastic mechanics into the angulated rectangular attachment configuration reduced initial canine displacement and slightly modified force transmission and

PDL stress distribution without increasing distal crown displacement. Aligner stresses were concentrated around the activated canine and attachment–aligner interfaces, whereas cervical PDL stress concentrations accompanied the tipping-dominant initial displacement pattern.

Conclusions: Attachment configuration and button-cut Class II elastic mechanics produced configuration-dependent differences in the initial biomechanical response to a single programmed activation. The optimized attachment produced a more balanced initial crown–root displacement pattern, whereas Class II elastic mechanics modified initial displacement and PDL stress without increasing distal displacement. These findings characterize the immediate mechanical response at aligner engagement and should not be interpreted as evidence of cumulative attachment effectiveness or tooth-movement control over successive aligner stages.

Clinical trial registration: Not applicable.

Keywords: Attachment configuration; Canine distalization; Clear aligner; Class II elastic; Finite element analysis

Background

Clear aligner therapy has evolved from a treatment modality primarily indicated for mild malocclusions to an effective option for increasingly complex orthodontic tooth movements owing to continuous advances in digital treatment planning, thermoplastic materials, and biomechanical auxiliaries. Consequently, its clinical application has expanded to include premolar extraction cases and other treatments requiring complex three-dimensional tooth movements [1]. Unlike fixed orthodontic appliances, in which orthodontic forces are generated through archwire activation, force generation in clear aligner therapy originates from the elastic deformation of the thermoplastic appliance caused by the geometric mismatch between the digitally prescribed tooth position and the existing dentition. Upon aligner insertion, elastic recovery generates an initial force system that is transmitted to the teeth through aligner–tooth and aligner–attachment interactions [2, 3]. The magnitude, direction, and distribution of this initial mechanical response are therefore influenced by material properties, aligner geometry, contact conditions, and auxiliary design [4]. Characterizing this initial force system is important for understanding how different biomechanical configurations modify force transmission at the onset of aligner engagement.

Maxillary canine distalization following first premolar extraction represents a particularly demanding biomechanical situation in clear aligner therapy [1, 5]. Because forces transmitted through the aligner are primarily delivered through the clinical crown and may act away from the tooth's center of resistance, the initial force–moment relationship may generate distal crown tipping, rotation, vertical displacement, and comparatively limited root displacement rather than pure translation [2, 4]. During subsequent clinical tooth movement, this mechanical environment is further modified by time-dependent material behavior, force decay, changes in tooth position, and continuously evolving aligner–tooth and aligner–attachment contact relationships [1, 3, 6, 7]. Thus, the biomechanical response observed at the onset of aligner

activation represents only the initial stage of a dynamic treatment process. Nevertheless, characterization of this initial response provides mechanistic information regarding how a given appliance configuration distributes forces and moments before biological tooth movement and progressive changes in appliance engagement occur.

Composite attachments are commonly incorporated into clear aligner systems to modify mechanical coupling between the aligner and the tooth and thereby alter the transmission of orthodontic forces and moments [2, 8,9]. Attachment geometry, dimensions, and position can influence aligner deformation, contact mechanics, stress distribution, and the resulting initial tooth displacement pattern [2, 4, 10]. Accordingly, finite element and experimental studies have demonstrated configuration-dependent differences in the mechanical response generated during aligner activation. However, these initial biomechanical differences should be distinguished from cumulative attachment performance over successive aligner stages, during which progressive tooth displacement, tipping, rotation, and changes in aligner–attachment engagement may substantially modify the force system. Therefore, comparison of attachment configurations under a standardized initial activation provides information about their immediate mechanical behavior rather than their longitudinal effectiveness throughout canine distalization.

In addition to attachments, Class II intermaxillary elastics may be incorporated into clear aligner treatment to modify the force system during extraction-based mechanics. When applied through an orthodontic button and a button-cut aligner design, the elastic introduces an additional force vector that interacts with the force system generated by the activated aligner. This interaction may modify the magnitude and direction of the initial forces transmitted to the canine as well as stress distribution within the periodontal ligament and the resulting displacement pattern. Previous finite element studies have suggested that elastic force magnitude, direction, and point of application can alter the biomechanical response of clear aligner systems [11]. However,

evidence regarding the initial biomechanical interaction between attachment configuration and button-cut Class II intermaxillary elastic mechanics during a programmed canine distalization step remains limited.

Three-dimensional finite element analysis (FEA) provides a computational framework for isolating and comparing the mechanical responses generated by different appliance configurations under standardized loading conditions. In clear aligner research, FEA enables detailed evaluation of aligner and periodontal ligament stress distributions, force transmission, and initial three-dimensional tooth displacement patterns that are difficult to characterize comprehensively under clinical conditions [12]. Importantly, however, a single-activation FEA represents the mechanical state at the onset of aligner engagement and does not reproduce the cumulative changes in tooth position, attachment engagement, contact relationships, or force–moment systems that develop over successive aligner stages. Consequently, single-step models are most appropriately interpreted as analyses of the initial biomechanical response rather than simulations of longitudinal tooth movement or predictors of attachment effectiveness throughout treatment.

Although attachment designs and intermaxillary elastic mechanics have been investigated in previous biomechanical studies, limited evidence is available regarding their combined influence on the initial mechanical response generated during clear aligner–mediated canine distalization following first premolar extraction. Therefore, the aim of this study was to compare the initial biomechanical responses generated by different attachment configurations and button-cut Class II intermaxillary elastic mechanics during a single 0.25-mm programmed activation for maxillary canine distalization. Initial three-dimensional crown and root displacement patterns and stress distributions within the clear aligner and periodontal ligament were evaluated under standardized loading conditions. The null hypothesis was that attachment configuration and the incorporation of button-cut Class II intermaxillary elastic mechanics

would not produce differences in the initial stress distributions or canine displacement patterns generated during the simulated activation step.

Methods

Study design

This comparative three-dimensional finite element analysis (FEA) study was conducted to investigate the initial biomechanical responses generated by different attachment configurations and Class II intermaxillary elastic mechanics using a button-cut aligner design during a single programmed activation for maxillary canine distalization following first premolar extraction.

Ethics approval and consent to participate

The study protocol was approved by the Clinical Research Ethics Committee of the Faculty of Dentistry, Ankara University, Ankara, Turkey (Approval No. 36290600/26/2021; March 17, 2021), and the study was conducted in accordance with the Declaration of Helsinki. The CBCT data used for finite element model construction were retrospectively retrieved from the institutional archive and had been acquired previously for routine diagnostic purposes; therefore, no additional radiographic exposure was performed for this study. Written informed consent had been obtained from the patient before radiographic examination, including consent for the anonymized use of clinical and radiographic data for scientific research.

Three-dimensional model construction

Cone-beam computed tomography (CBCT) data from an adult patient with complete permanent dentition, no craniofacial anomalies, no previous orthodontic treatment, and no radiographic evidence of periodontal bone loss or root pathology were retrieved from the institutional archive and used to construct the three-dimensional finite element model. The CBCT scan had been previously acquired for diagnostic purposes; therefore, no additional radiographic exposure was

performed for this study. The images were acquired with a voxel size of 0.10 mm, exported in Digital Imaging and Communications in Medicine (DICOM) format, and imported into 3D Slicer (version 4.11.20210226; Surgical Planning Laboratory, Harvard Medical School, Boston, MA, USA) for image segmentation and three-dimensional reconstruction. The maxillary dentition together with the cortical and trabecular bone structures were segmented to generate three-dimensional surface models, which were subsequently exported as stereolithography (STL) files.

The STL models were imported into Altair Evolve (Altair Engineering Inc., Troy, MI, USA) for reverse engineering and geometric refinement. A uniform 0.20-mm-thick periodontal ligament (PDL) layer was generated around the root surfaces of all teeth, and the anatomical structures were assembled to create the maxillary finite element model. Digital models of the clear aligner, composite attachments, and orthodontic button were subsequently designed according to the planned experimental configurations and integrated into the final assembly. The attachment geometries incorporated into the finite element models are illustrated in Figure 1. Finite element preprocessing and mesh generation were performed using Altair HyperMesh (Altair Engineering Inc., Troy, MI, USA), and all numerical analyses were carried out using the implicit Nastran-based solver Altair OptiStruct (Altair Engineering Inc., Troy, MI, USA).

Experimental models

Six finite element models representing different attachment configurations and auxiliary mechanics were constructed to compare their initial biomechanical responses during a single programmed activation for maxillary canine distalization. The experimental models differed only in attachment design and the presence of Class II intermaxillary elastic mechanics, whereas all other anatomical structures, material properties, boundary conditions, contact definitions, and aligner activation parameters were kept identical to allow direct comparison of the resulting initial mechanical responses. The six experimental models are illustrated in Figure 2.

200 The experimental configurations were defined as follows:

201 Model 1: No attachment.

202 Model 2: Vertical rectangular attachment (2 mm × 5 mm × 1 mm).

203 Model 3: Inclined vertical rectangular attachment (2 mm × 5 mm; mesial thickness 0 mm, distal
204 thickness 1 mm).

205 Model 4: Angulated rectangular attachment (2 mm × 5 mm × 1 mm).

206 Model 5: Angulated rectangular attachment combined with Class II intermaxillary elastic
207 mechanics using a button-cut aligner design.

208 Model 6: Optimized attachment (1.5 mm × 1.5 mm × 1 mm).

209 **Material properties**

210 All components of the finite element model were assumed to be homogeneous, isotropic, and
211 linearly elastic, consistent with the assumptions adopted in previous finite element studies of
212 clear aligner biomechanics. The mechanical properties assigned to the cortical bone, trabecular
213 bone, enamel, periodontal ligament (PDL), clear aligner, composite attachment, and orthodontic
214 button were obtained from previously published studies and are summarized in Table 1.

215 The PDL was modeled as a uniform 0.20-mm-thick linear elastic layer. Although the PDL
216 exhibits nonlinear and viscoelastic behavior under physiological conditions, a linear elastic
217 constitutive model was adopted because it remains a commonly used approach in comparative
218 finite element analyses of orthodontic tooth movement and facilitates standardized comparison
219 among different experimental configurations. The elastic modulus and Poisson's ratio assigned
220 to the PDL were selected according to contemporary finite element studies investigating clear
221 aligner biomechanics.

222 **Contact definitions**

223 The contact interactions between the clear aligner and the dentition were defined to simulate
224 the mechanical behavior of the thermoplastic appliance during initial aligner engagement.
225 Nonlinear surface-to-surface frictional contact was assigned to both the aligner–tooth and
226 aligner–attachment interfaces, allowing sliding between the contacting surfaces during force
227 transmission. A coefficient of friction of 0.20 was assigned to both interfaces according to
228 previously published finite element studies of clear aligner biomechanics.

229 Bonded contact was assigned to the tooth–periodontal ligament (PDL), PDL–alveolar bone,
230 tooth–attachment, tooth–button, and cortical bone–trabecular bone interfaces, assuming
231 complete adhesion without relative displacement or separation between the connected
232 structures throughout the simulation. Geometric nonlinearity resulting from the contact
233 interactions was considered in all finite element analyses.

234 **Mesh generation**

235 The finite element meshes were generated using second-order tetrahedral solid elements in
236 Altair HyperMesh (Altair Engineering Inc., Troy, MI, USA). In accordance with previously
237 validated finite element modeling strategies, local mesh refinement was applied to regions
238 expected to experience high stress gradients, including the periodontal ligament, attachment
239 surfaces, orthodontic button, and aligner–tooth contact interfaces, to improve numerical
240 accuracy while maintaining computational efficiency [13, 14]. The total numbers of nodes and
241 elements for each experimental model are summarized in Table 2.

242 **Boundary conditions**

243 To prevent rigid-body motion during finite element analysis, the superior surface of the
244 maxillary bone was fully constrained in all translational and rotational degrees of freedom.

These boundary constraints simulated the anatomical stability of the maxilla during orthodontic loading. The applied boundary conditions are illustrated in Figure 3.

Loading protocol

The clear aligner was digitally designed on a target dentition incorporating a programmed 0.25-mm distal displacement of the maxillary canine, representing a single aligner activation step. This produced an initial geometric mismatch of 0.25 mm between the activated aligner geometry and the pretreatment dentition. During virtual insertion of the activated aligner onto the pretreatment dentition, elastic deformation of the thermoplastic appliance generated the initial orthodontic force system through its elastic recovery. Accordingly, orthodontic forces were not directly prescribed to the canine; rather, they arose from the interaction between the activated aligner and the initial dentition.

The simulation was limited to this initial activation state and was designed to characterize the immediate mechanical response at the onset of aligner engagement. No sequential aligner stages, progressive tooth repositioning, or cumulative changes in aligner–tooth or aligner–attachment engagement were simulated. Accordingly, the resulting stress and displacement fields were interpreted as initial biomechanical responses to the programmed activation rather than as predictions of cumulative tooth movement over the course of treatment.

In Model 5, auxiliary mechanics were incorporated using a button-cut aligner design, in which a Class II intermaxillary elastic was applied between the orthodontic button bonded to the maxillary canine and the corresponding mandibular anchorage unit. A constant elastic force of 1.50 N was applied in accordance with the manufacturer's recommendations. The composite attachment remained bonded to the canine while the orthodontic button was positioned adjacent to the attachment, allowing simultaneous engagement of the aligner and Class II elastic, as illustrated in Figure 2. The Class II elastic was activated concurrently with the initial aligner

engagement and remained active throughout the simulated loading step. Apart from attachment configuration and the presence of Class II elastic mechanics, all loading conditions were identical among the experimental models.

Outcome variables

The following variables were evaluated to characterize the initial biomechanical response generated by each experimental configuration:

- Initial three-dimensional displacement of the maxillary canine crown and root along the predefined x-, y-, and z-axes.

- Minimum principal (P_{min}), maximum principal (P_{max}), and equivalent (von Mises) stress distributions within the clear aligner during the initial activation step.

- Minimum principal (P_{min}), maximum principal (P_{max}), and equivalent (von Mises) stress distributions within the periodontal ligament (PDL) during the initial activation step.

These variables were interpreted as indicators of the immediate mechanical response to aligner activation and were not used to predict cumulative tooth movement across successive treatment stages.

Results

Initial Stress Distribution in the Clear Aligner

A generally similar initial stress distribution pattern was observed within the clear aligners across all experimental models following the single programmed activation. As illustrated in Figure 4, stress concentrations were consistently localized around the activated canine region and the attachment-aligner interfaces, although stress magnitudes varied among the experimental configurations.

Model 1 (no-attachment model) exhibited the highest maximum principal tensile stress, whereas Model 6 (optimized attachment model) demonstrated the greatest compressive stress and equivalent (von Mises) stress values. Models 2 and 3 (vertical rectangular and inclined vertical rectangular attachment models) showed comparatively lower overall stress magnitudes than the remaining attachment configurations (Table 3).

In the attachment-containing models, compressive and equivalent (von Mises) stress concentrations were primarily distributed along the active mesial surfaces of the attachments. Model 6 exhibited pronounced stress accumulation around the gingivally positioned attachment–aligner interface (Figure 4).

Initial Stress Distribution in the Periodontal Ligament

A comparable initial principal stress distribution pattern was observed within the periodontal ligament across all experimental models. Tensile and compressive stresses were consistently concentrated in the cervical region, although the localization of peak stresses varied according to attachment configuration (Figure 5).

Model 1 demonstrated the highest tensile, compressive, and equivalent (von Mises) stress values within the PDL, whereas the remaining attachment configurations exhibited lower overall stress magnitudes (Table 4).

Regarding equivalent (von Mises) stress localization, similar concentration patterns were observed in Models 1, 2, 4, and 5, predominantly within the distopalatal cervical region of the canine. In contrast, Model 3 demonstrated stress concentration near the mid-distogingival cervical region, whereas Model 6 exhibited stress accumulation predominantly in the mid-buccal cervical region (Figure 5).

Initial Canine Displacement Patterns

Following the single 0.25-mm programmed activation, the greatest initial total displacement in all experimental models was observed at the distobuccal cusp tip of the maxillary canine, whereas the lowest displacement values occurred in the distobuccal root region.

Model 1 generated the greatest initial total canine displacement, followed by Model 4, whereas the lowest initial total displacement values were observed in Models 3 and 5 (Tables 5 and 6).

Directional displacement analysis demonstrated a generally consistent initial pattern across the experimental configurations, characterized by distal and palatal crown displacement accompanied by slight extrusion and displacement of the root in the opposite direction. This crown–root displacement relationship was consistent with an initial tipping-dominant mechanical response rather than translational displacement (Tables 5 and 6).

Model 1 demonstrated the greatest overall initial displacement and the largest extrusive displacement component. In contrast, Model 6 exhibited a smaller extrusive displacement component and a more balanced initial crown–root displacement pattern.

Compared with the corresponding angulated rectangular attachment configuration without elastic mechanics (Model 4), incorporation of Class II intermaxillary elastic mechanics in Model 5 was associated with lower initial total canine displacement and slightly lower PDL stress values. Model 5 also demonstrated lower initial distal and palatal crown displacement than Model 4, whereas the vertical displacement component remained largely unchanged (Tables 4–6).

Discussion

In this three-dimensional finite element analysis, the initial biomechanical responses generated by different attachment configurations, with and without button-cut Class II intermaxillary elastic mechanics, were evaluated during a single 0.25-mm programmed activation for maxillary canine distalization following first premolar extraction. Attachment configuration

influenced the initial stress distributions within the clear aligner and periodontal ligament (PDL), as well as the three-dimensional crown–root displacement pattern of the maxillary canine. Among the evaluated configurations, the optimized attachment produced a more balanced initial crown–root displacement pattern and a smaller extrusive displacement component; however, a tipping-dominant initial displacement pattern was observed across all configurations. Furthermore, incorporation of button-cut Class II intermaxillary elastic mechanics into the angulated rectangular attachment configuration reduced the initial overall canine displacement while slightly modifying force transmission and PDL stress distribution. These findings represent the immediate mechanical response at the onset of aligner engagement and should not be interpreted as cumulative tooth movement or attachment performance over successive aligner stages.

The tipping-dominant displacement pattern observed across all experimental configurations reflects the initial force–moment relationship generated at the onset of aligner engagement. Although modifications in attachment geometry altered this initial mechanical response and produced configuration-dependent differences in the crown–root displacement pattern, greater displacement of the canine crown relative to the root remained evident across the models. This finding may be explained by the transmission of aligner-generated forces predominantly through the clinical crown and away from the tooth's center of resistance, resulting in a force–moment relationship that favors crown tipping during the initial activation rather than pure translation. Chen et al. demonstrated that attachment configuration significantly influenced the displacement pattern of the maxillary canine in finite element simulations; however, none of the evaluated attachment designs completely eliminated the initial tendency for tipping [15]. Similarly, Li et al. reported a tipping-dominant displacement pattern during simulated canine distalization even when optimized root-control attachments were incorporated [16]. Consistent with these finite element findings, the optimized attachment in the present study generated a

more balanced initial crown–root displacement pattern than the other configurations, while a tipping-dominant response remained evident during the simulated activation. From a clinical perspective, Wang et al. demonstrated in a three-dimensional study of premolar extraction cases treated with clear aligners that distal root movement of the maxillary canine was considerably smaller than crown movement [17]. Although this longitudinal clinical observation cannot be directly equated with the initial displacement predicted by the present single-activation model, it provides complementary evidence that crown–root displacement discrepancies remain relevant during clinical canine distalization. Collectively, these findings indicate that attachment geometry can modify the initial force–moment relationship and crown–root displacement pattern generated during aligner engagement; however, the present single-step analysis does not determine whether these initial differences translate into superior root control or bodily movement over successive aligner stages.

One of the notable findings of the present study was that the incorporation of button-cut Class II intermaxillary elastic mechanics into the angulated rectangular attachment configuration modified the initial biomechanical response of the maxillary canine. Compared with Model 4, the addition of the Class II elastic in Model 5 was associated with reduced initial distal and palatal crown displacement, accompanied by slightly lower maximum principal and equivalent (von Mises) stress values within the periodontal ligament, whereas the vertical displacement component remained largely unchanged. These findings indicate that, during the simulated activation step, the biomechanical contribution of the intermaxillary elastic was not limited to the additional traction force itself. Rather, the interaction among the Class II elastic, clear aligner, and attachment modified the initial force–moment system generated at aligner engagement, resulting in configuration-specific differences in canine displacement and PDL stress distribution. Accordingly, the observed response should be interpreted as an immediate

mechanical effect of incorporating the elastic into the activated aligner system rather than as evidence of its cumulative influence on canine distalization over successive treatment stages.

Similarly, Li et al. demonstrated that variations in the point of force application and the direction of Class II elastic traction could alter both stress distribution within the periodontal ligament and the resulting tooth movement pattern [18]. More recently, Song et al. reported that the use of orthodontic buttons may improve the efficiency of elastic force transmission [19]. These findings support the concept that the biomechanical response to intermaxillary elastics depends not only on force magnitude but also on the direction and point of force application and its interaction with the clear aligner system. Consistent with these observations, incorporation of button-cut Class II intermaxillary elastic mechanics in the present study modified the initial canine displacement pattern and PDL stress distribution rather than increasing the initial distal displacement of the canine. This finding suggests that, within the conditions of the present single-activation model, the Class II elastic acted primarily by modifying the initial force system generated by the aligner–attachment complex rather than simply augmenting the distalizing component of force. Because this analysis represents only the immediate mechanical response at the onset of aligner engagement, however, these initial effects cannot be extrapolated to the cumulative influence of Class II elastics on canine movement over successive aligner stages.

In the present study, the optimized attachment model produced a more balanced initial crown–root displacement pattern and a smaller extrusive displacement component than the other attachment configurations, although a tipping-dominant response remained evident during the simulated activation. Interestingly, despite exhibiting the highest compressive and equivalent (von Mises) stresses within the aligner, the optimized attachment model generated a distinct initial displacement pattern characterized by a smaller extrusive component and reduced root displacement. This apparent discrepancy between stress magnitude and displacement suggests

that the initial mechanical response may depend not only on the magnitude of stress generated within the aligner but also on how forces and moments are transmitted and distributed through the attachment–aligner interface. The pronounced stress concentration observed around the optimized attachment may therefore reflect configuration-specific engagement between the attachment and aligner, resulting in a different initial force–moment relationship and crown–root displacement pattern. However, these findings characterize the immediate mechanical behavior of the optimized attachment during the simulated activation and do not establish its effectiveness in controlling canine movement over successive aligner stages.

These findings are consistent with previous finite element studies demonstrating that attachment configuration can modify the biomechanical response of the canine during clear aligner activation. Gomez et al. reported that composite attachments improved the control of canine movement compared with an attachment-free configuration, although tipping could not be completely eliminated [20]. Chen et al. further demonstrated that even the most favorable attachment configuration improved bodily movement efficiency without completely preventing tipping, which was attributed to the predominant transmission of orthodontic forces through the clinical crown [15]. Likewise, Li et al. reported that a tipping tendency persisted even when optimized root-control attachments were used and that attachment wear further altered biomechanical control [16]. Consistent with these observations, the optimized attachment configuration in the present study produced a more balanced initial crown–root displacement pattern than the other configurations, although the initial response remained tipping-dominant. Taken together, these findings indicate that attachment geometry can modify the manner in which forces and moments are transmitted through the aligner–attachment–tooth interface, thereby producing configuration-dependent differences in the initial crown–root displacement pattern. Within the scope of the present single-activation model, these differences should be

interpreted as variations in initial force transmission rather than as evidence of cumulative movement control or attachment effectiveness throughout treatment.

The stress distributions observed in the present study indicate that different attachment configurations influenced not only the magnitude of initial canine displacement but also the manner in which orthodontic forces were transmitted from the aligner to the tooth during the simulated activation. Stress concentrations within the aligner were predominantly localized around the activated canine and the attachment–aligner interfaces, suggesting that these regions represented principal sites of initial force transmission. Within the periodontal ligament, maximum tensile and compressive stresses were concentrated primarily in the cervical region, consistent with the tipping-dominant initial crown–root displacement pattern observed across the experimental configurations. These findings indicate that stress distribution should be interpreted not only in terms of peak stress magnitude but also in relation to its spatial localization, as this provides complementary biomechanical information regarding the pathways of force transmission and the resulting initial displacement response.

These findings are consistent with previous finite element studies demonstrating that attachment design influences both tooth displacement and stress distribution within the clear aligner and periodontal ligament [11, 15, 16, 20]. Similarly, although the different attachment configurations evaluated in the present study altered the magnitude and spatial localization of initial stress concentrations, the overall displacement response remained tipping-dominant during the simulated activation. This suggests that attachment geometry modified the initial mechanical environment and force transmission without fundamentally changing the predominant displacement pattern generated by the single programmed activation. Accordingly, interpretation of finite element results should consider the spatial distribution and localization of stresses in addition to peak stress values, as these parameters provide complementary

information regarding the initial biomechanical response associated with different attachment configurations.

The findings of the present study suggest that the initial biomechanical response generated during a programmed canine distalization step is determined not only by the presence of an attachment but also by the combined force system arising from attachment geometry and auxiliary elastic mechanics. The configuration-dependent differences observed in crown–root displacement and stress distribution indicate that these components interact with the activated aligner to modify the initial transmission and distribution of forces and moments. In particular, the more balanced initial crown–root displacement pattern observed with the optimized attachment configuration and the modified displacement and PDL stress patterns associated with button-cut Class II intermaxillary elastic mechanics illustrate two distinct ways in which appliance configuration can alter the immediate mechanical response. These findings provide mechanistic insight into the initial force systems generated by different clear aligner configurations; however, they do not establish whether the observed differences persist, diminish, or change as tooth position and aligner–attachment engagement evolve over successive activation stages. Accordingly, the present findings should be interpreted as initial biomechanical evidence rather than as a basis for ranking attachment configurations or recommending specific auxiliary mechanics for clinical canine distalization.

This study has several limitations. First, the present finite element model was designed to characterize the initial biomechanical response generated during a single 0.25-mm programmed aligner activation. Although this approach enables standardized comparison of stress distributions and initial displacement patterns among different attachment and auxiliary configurations, it does not reproduce the cumulative biomechanical changes that occur over successive aligner stages. In particular, progressive tooth displacement, tipping, and rotation may alter aligner–tooth and aligner–attachment engagement and, consequently, the force–

moment system generated during subsequent activations. Therefore, the configuration-dependent differences observed in the present study should not be interpreted as predictors of attachment effectiveness, root control, or cumulative tooth movement throughout treatment. This limitation is consistent with the broader clear-aligner FEA literature, as a recent systematic review reported that most computational studies have focused primarily on initial instantaneous biomechanical effects, with limited evidence regarding long-term or sequential biomechanical responses [12]. In addition, the model does not account for time-dependent biological processes associated with periodontal ligament and alveolar bone remodeling. The simulations were based on a single patient-specific geometry and assumed idealized material properties, while clinical factors such as aligner force decay, attachment wear, and individual biological variability were not incorporated. Furthermore, model-specific mesh convergence and sensitivity analyses were not performed; therefore, although the finite element model was developed using established modeling strategies, the influence of mesh density and selected material parameters on the numerical outcomes cannot be completely excluded. Future studies incorporating staged or sequential activation models, together with experimental and clinical validation, are warranted to determine whether the initial biomechanical differences identified here persist or change as treatment progresses.

Conclusion

This finite element analysis demonstrated that attachment configuration and button-cut Class II intermaxillary elastic mechanics produced configuration-dependent differences in the initial biomechanical response generated during a single 0.25-mm programmed activation for maxillary canine distalization. The optimized attachment produced a more balanced initial crown–root displacement pattern, whereas the incorporation of Class II elastic mechanics modified initial canine displacement and periodontal ligament stress distribution without increasing distal displacement. These findings characterize the immediate mechanical behavior

of the evaluated configurations at the onset of aligner engagement and should not be interpreted as evidence of cumulative attachment effectiveness or tooth-movement control over successive aligner stages. Further studies incorporating staged or sequential activation models, together with experimental and clinical validation, are needed to determine whether these initial biomechanical differences persist during treatment.

List of Abbreviations

Abbreviation	Definition
3D	Three-Dimensional
CBCT	Cone-Beam Computed Tomography
DICOM	Digital Imaging and Communications in Medicine
FEA	Finite Element Analysis
PDL	Periodontal Ligament
P_{min}	Minimum Principal Stress
P_{max}	Maximum Principal Stress
STL	Standard Tessellation Language (<i>or Stereolithography File Format</i>)
MPa	Megapascal
mm	Millimeter
N	Newton

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589 **Declarations**

590 **Ethics approval and consent to participate**

591 The study protocol was approved by the Clinical Research Ethics Committee of the Faculty of
592 Dentistry, Ankara University, Ankara, Türkiye (Approval No. 36290600/26/2021; March 17,
593 2021), and the study was conducted in accordance with the Declaration of Helsinki. The CBCT
594 data used for finite element model construction were retrospectively retrieved from the
595 institutional archive and had been acquired previously for routine diagnostic purposes;
596 therefore, no additional radiographic exposure was performed for this study. Written informed
597 consent had been obtained from the patient before radiographic examination, including consent
598 for the anonymized use of clinical and radiographic data for scientific research.

599 **Consent for publication**

600 Not applicable.

601 **Availability of data and materials**

602 The datasets generated and/or analyzed during the current study are available from the
603 corresponding author on reasonable request.

604 **Competing interests**

605 The authors declare that they have no competing interests.

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608 **Technologies Ltd.** were financially supported by **Orthero Clear Aligner Company (Şeffaf**
609 **Aparey Ortodonti ve Elektronik San. Tic. A.Ş., Istanbul, Türkiye).** The funding body had

no role in the study design, data analysis, interpretation of the results, preparation of the manuscript, or decision to submit the manuscript for publication.

Authors' contributions

B.S.: Conceptualization, Methodology, Investigation, Data Curation, Writing – Original Draft.

H.A.: Conceptualization, Methodology, Formal Analysis, Writing – Original Draft, Writing – Review & Editing, Supervision, Corresponding Author.

R.E.: Investigation, Validation, Writing – Review & Editing.

N.Y.: Finite Element Model Development, Software, Visualization, Formal Analysis.

M.B.K.: Conceptualization, Methodology

A.T.A: Conceptualization, Supervision, Writing – Review & Editing.

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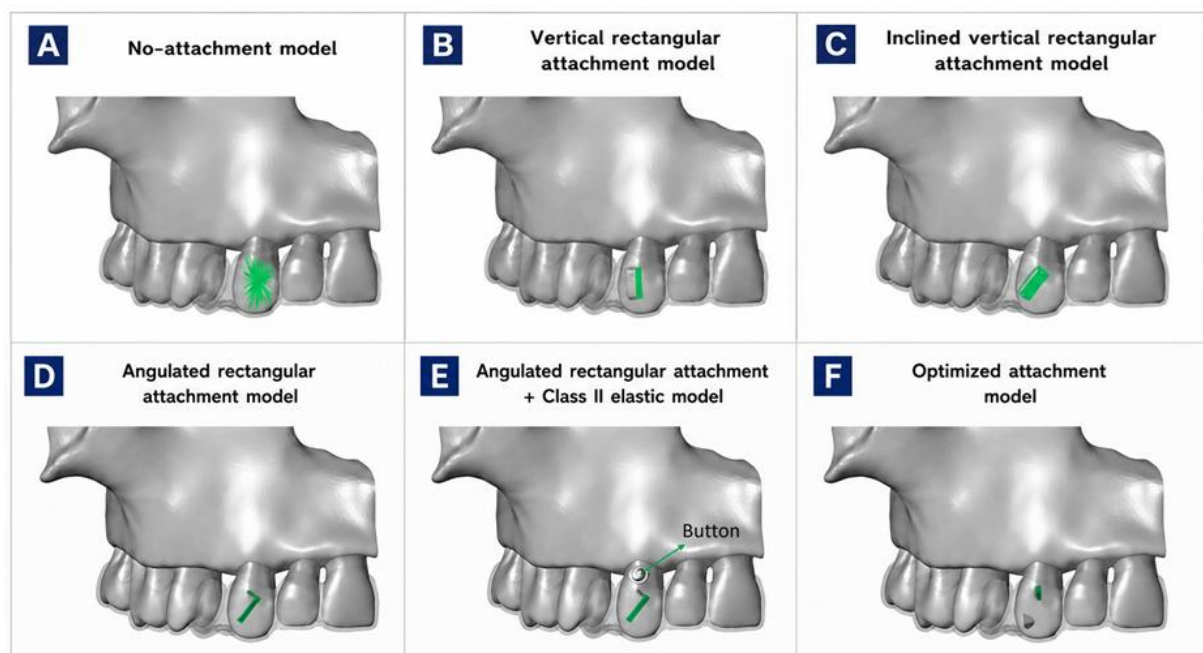


Figure 1. Experimental attachment configurations used for finite element analysis of clear aligner-mediated maxillary canine distalization following first premolar extraction. (A) *No-attachment model*. (B) *Vertical rectangular attachment model*. (C) *Inclined vertical rectangular attachment model*. (D) *Angulated rectangular attachment model*. (E) *Angulated rectangular attachment combined with Class II intermaxillary elastic force applied via an orthodontic button*. (F) *Optimized attachment model*.

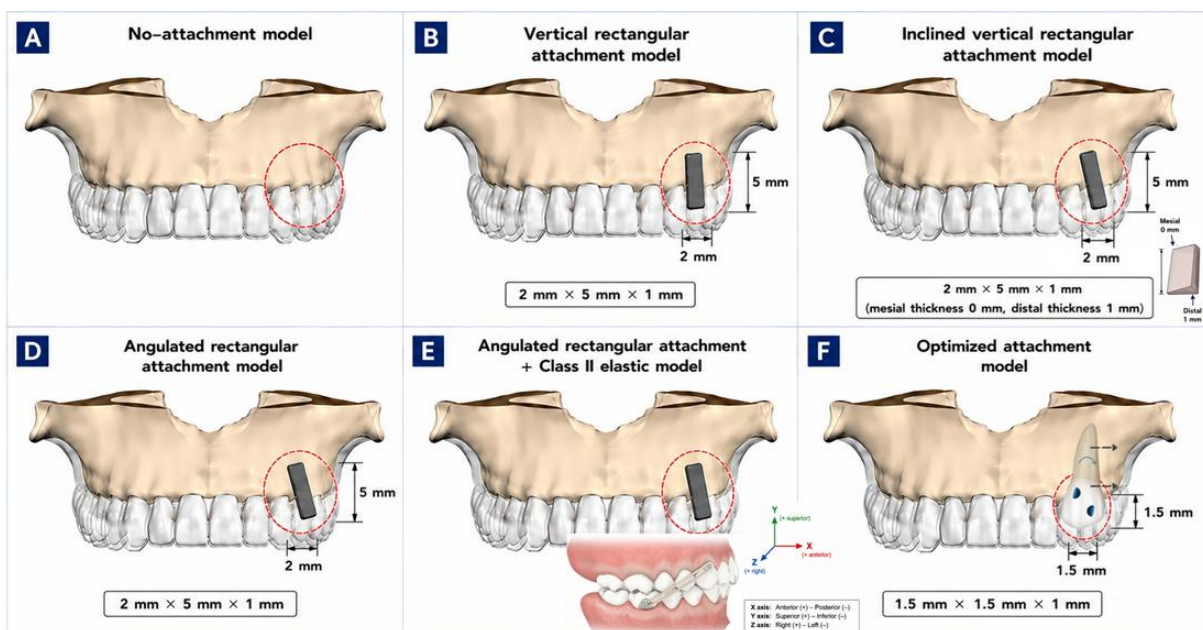


Figure 2. Loading configurations used in the finite element simulations. (A) *No-attachment model*. (B) *Vertical rectangular attachment model*. (C) *Inclined vertical rectangular attachment model*. (D) *Angulated rectangular attachment model*. (E) *Angulated rectangular attachment combined with Class II elastic loading applied via an orthodontic button*. (F) *Optimized attachment model*. Green regions and arrows illustrate the location and direction of the 0.25-

mm programmed canine distalization incorporated into the activated aligner geometry. The initial orthodontic force system was generated through geometric mismatch and elastic recovery of the aligner during virtual insertion onto the pretreatment dentition.

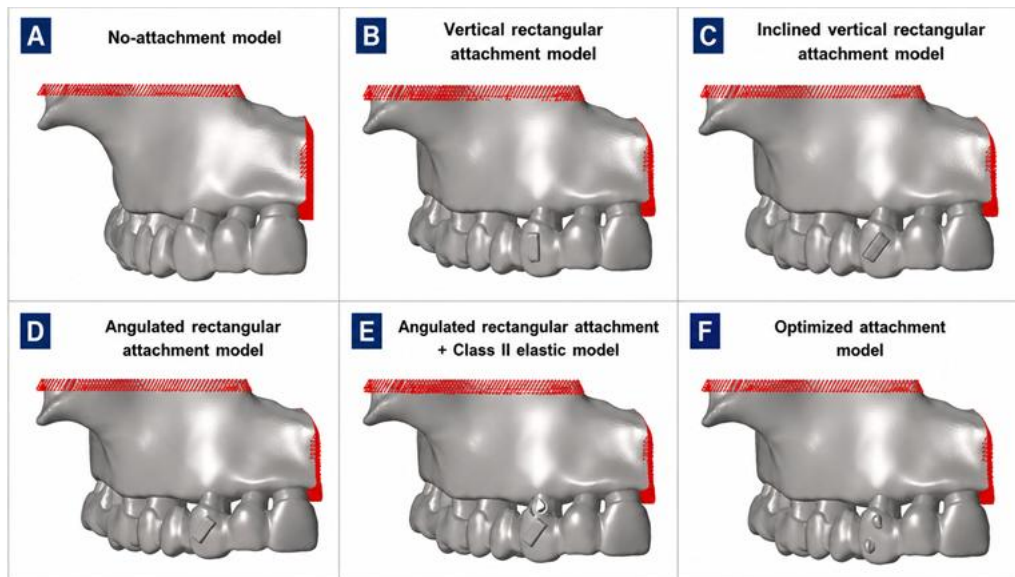


Figure 3. Boundary conditions and constraint configurations used in the finite element simulations. (A) *No-attachment model.* (B) *Vertical rectangular attachment model.* (C) *Inclined vertical rectangular attachment model.* (D) *Angulated rectangular attachment model.* (E) *Angulated rectangular attachment combined with Class II elastic loading.* (F) *Optimized attachment model.* Red regions indicate fixed boundary constraints applied to the maxillary structure in each finite element model to ensure numerical stability during simulation.

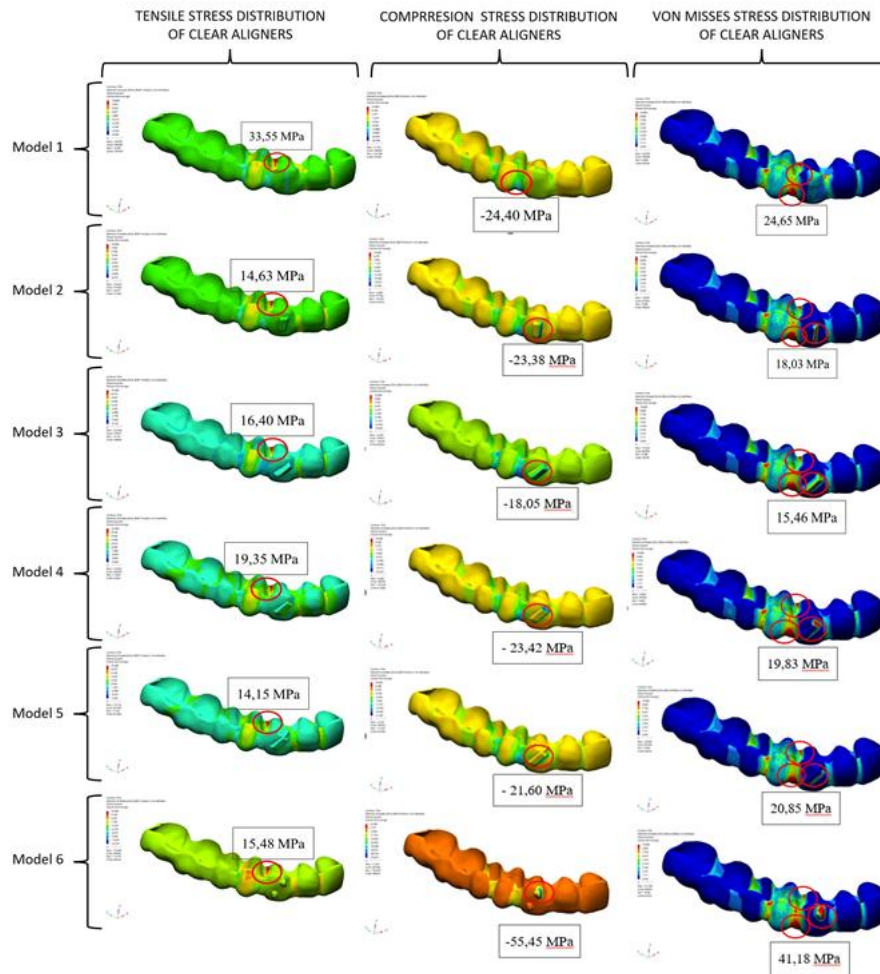


Figure 4. Stress distribution patterns within the clear aligner under different attachment configurations. Representative distributions of maximum principal (P_{max}), minimum principal (P_{min}), and von Mises stresses within the clear aligner across six experimental finite element models. Stress concentrations were predominantly localized around the activated canine and attachment-aligner interfaces.

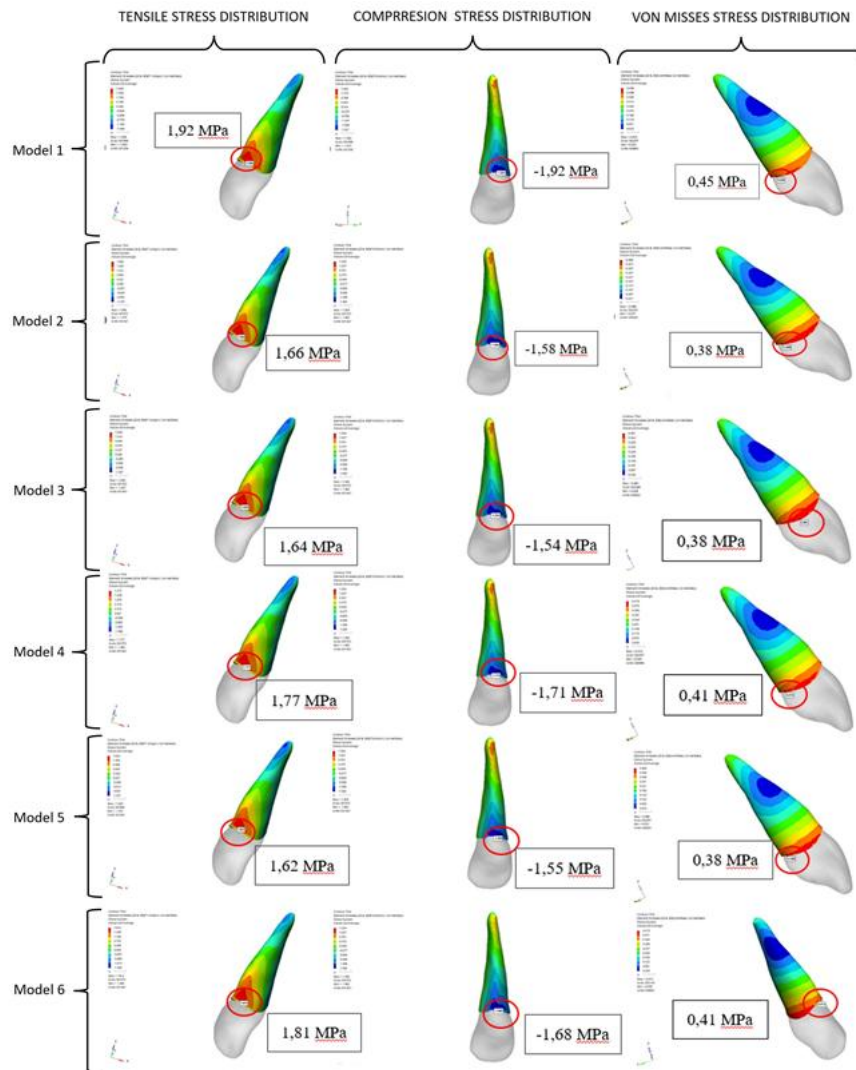


Figure 5. Periodontal ligament stress distribution patterns during the initial activation step under different attachment configurations. Representative distributions of maximum principal (P_{max}), minimum principal (P_{min}), and equivalent (von Mises) stresses within the periodontal ligament across the six experimental finite element models. Stress concentrations were predominantly localized within the cervical region of the maxillary canine, with configuration-dependent differences in their spatial distribution.