ORIGINAL ARTICLE

Finite Element Analysis of Stress Distribution in Clear Aligner Attachments Versus Conventional Brackets During Space Closure: An In Vitro Study

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ABSTRACT

Background

Controlled space closure is a biomechanically demanding phase of orthodontic treatment. Clear aligner attachments are increasingly used for esthetic extraction or diastema management, but their stress-transfer pattern relative to conventional brackets requires structured evaluation.

Methods

A three-dimensional finite element in vitro simulation was performed using a maxillary dentoalveolar model with first premolar extraction spaces. Two appliance systems were compared: clear aligner therapy with optimized vertical-rectangular attachments and conventional pre-adjusted edgewise brackets with stainless-steel archwire. A distalizing/retraction load equivalent to 150 g per side was applied for space closure. Von Mises stress, maximum principal stress, periodontal ligament stress, tooth displacement, rotation tendency, and appliance deformation were recorded.

Results

The bracket model produced higher mean periodontal ligament von Mises stress at the canine cervical region than the aligner-attachment model (0.184 ± 0.021 MPa vs 0.132 ± 0.018 MPa, $p<0.001$). The aligner model showed lower peak alveolar cortical stress (4.31 ± 0.44 MPa) compared with brackets (5.76 ± 0.61 MPa, $p<0.001$), but exhibited greater crown tipping tendency (0.118 ± 0.014 mm vs 0.086 ± 0.011 mm, $p=0.002$). Brackets demonstrated more efficient bodily translation, with a root/crown displacement ratio of 0.79 ± 0.06 compared with 0.61 ± 0.07 for aligner attachments ($p<0.001$).

Conclusion

Clear aligner attachments distributed stress more diffusely and reduced peak periodontal and cortical bone stresses, whereas conventional brackets provided superior root control during space closure. Attachment geometry and staging compensation remain essential when aligners are used for extraction-space closure.

Keywords

clear aligner; orthodontic brackets; finite element analysis; space closure; periodontal ligament; stress distribution; attachment; biomechanics

INTRODUCTION

Orthodontic space closure requires the coordinated control of force magnitude, point of force application, center of resistance, anchorage, and frictional response. In conventional fixed appliances, brackets and archwires provide a relatively stable mechanical framework for sliding or loop mechanics; however, this system may concentrate forces around the periodontal ligament and alveolar crest when force vectors are not aligned with the center of resistance. Clear aligners were introduced as a more esthetic and removable alternative, and their clinical adoption has expanded because of patient comfort, hygiene advantages, and improved digital planning workflows [1].

Despite their popularity, clear aligners do not deliver tooth movement in the same way as fixed appliances. The appliance is a thin thermoplastic shell that contacts multiple crowns simultaneously, and its ability to generate controlled movement depends on aligner material, fit, thickness, trimline, activation, staging, and the shape and position of composite attachments. Systematic reviews have shown

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that clear aligners can be effective for mild to moderate tooth movements but remain less predictable for complex movements such as torque expression, root control, rotations of rounded teeth, and extraction-space closure [2,3]. Comparative clinical evidence also suggests that fixed appliances may still provide more consistent control in complex orthodontic movements, although aligner systems continue to improve with auxiliary designs and digital refinements [4].

Finite element analysis (FEA) has become an important method for studying orthodontic biomechanics because it permits controlled estimation of stress, strain, displacement, and deformation in the tooth-periodontal ligament-bone complex under predefined loading conditions. The method is particularly useful where direct in vivo measurement is difficult or ethically impractical [5]. Recent reviews emphasize that FEA can clarify the initial mechanical response of orthodontic systems, although results are influenced by assumptions regarding periodontal ligament thickness, material linearity, mesh density, boundary conditions, and load application [6].

In aligner biomechanics, attachments are not merely retention features. They modify the contact surface between the aligner and the tooth, improve force coupling, and may increase the moment-to-force ratio needed for bodily movement. Previous FEA studies have reported that canine translation, inclination, and rotation produce different periodontal stress maps and that stress is often concentrated around the cervical periodontal ligament during aligner-driven movements [7]. Composite attachments can improve the force system generated by plastic aligners and reduce uncontrolled tipping during attempted bodily movement [8]. Similarly, attachment-assisted plastic aligners have been shown to improve diastema closure by changing the direction and magnitude of tooth displacement [9].

During maxillary anterior retraction and extraction-space closure, clear aligner protocols frequently require staged distalization, optimized attachments, power ridges, elastics, or overcorrection to improve root control. Three-dimensional FEA studies of aligner-based en-masse retraction have shown that force application and staging can alter displacement patterns of both anterior and posterior teeth [10]. Attachment design is therefore clinically relevant because it influences the distribution of contact stress and the ability of aligners to approximate bodily movement [11].

Conversely, conventional brackets deliver force through a slot-archwire interface. This approach may offer greater control of torque and bodily movement, but bracket systems may produce localized stress peaks at the periodontal ligament and alveolar bone, especially during sliding mechanics or when frictional resistance is present. FEA studies of fixed appliance en-masse retraction have shown that lever arm length, mini-implant position, and force direction can substantially alter stress and displacement patterns [12]. Therefore, a direct comparison between aligner attachments and conventional brackets under the same simulated space-closure condition may provide useful biomechanical guidance.

The research gap lies in the limited direct comparison of stress distribution between optimized clear aligner attachments and conventional labial brackets during the same space-closure scenario using identical dentoalveolar geometry and comparable retraction loads. Most prior studies have evaluated either aligner variables or fixed-appliance mechanics separately. The present in vitro finite element study aimed to compare stress distribution, tooth displacement, rotation tendency, and appliance deformation between clear aligner attachments and conventional brackets during maxillary canine space closure. The null hypothesis was that there would be no significant difference in periodontal ligament stress, alveolar bone stress, or tooth movement pattern between the two appliance systems.

MATERIALS AND METHODS

Study design: This was an in vitro computational finite element study designed to compare two orthodontic space-closure systems under standardized loading conditions. The study model represented an adult maxillary arch with bilateral first premolar extraction spaces. A digital workflow was used to generate tooth, periodontal ligament, cortical bone, cancellous bone, appliance, attachment, bracket, and archwire components. No human intervention was performed, and the model was anonymized and reconstructed from a representative cone-beam computed tomography and intraoral scan dataset used for simulation purposes.

Model construction: The maxillary dentition from right second premolar to left second premolar was segmented. Teeth were modeled as individual solid bodies. A uniform periodontal ligament layer of 0.25

mm was generated around each root. Cortical bone thickness was modeled as 1.5 mm overlying cancellous bone. The first premolars were removed digitally to create extraction spaces. The canine, lateral incisor, and second premolar were the primary units assessed because these teeth are commonly affected during space closure mechanics.

Appliance groups: Two principal models were created. Group A represented clear aligner therapy with optimized vertical-rectangular composite attachments on the canine and second premolar. The aligner was modeled as a 0.75-mm thermoplastic shell with a scalloped gingival margin ending 1 mm above the gingival zenith. Attachments were 4.0 mm in height, 2.0 mm in width, and 1.0 mm in prominence with rounded edges to approximate a clinically polishable composite attachment. Group B represented conventional labial fixed appliances with 0.022-inch pre-adjusted brackets, a 0.019 × 0.025-inch stainless-steel archwire, and sliding mechanics. Brackets were bonded at the facial-axis point of each clinical crown.

Material properties: All structures were assigned homogeneous, isotropic, and linearly elastic properties for initial response analysis. Enamel/dentin was assigned an elastic modulus of 20,000 MPa and Poisson ratio of 0.30; periodontal ligament 0.0689 MPa and 0.45; cortical bone 13,700 MPa and 0.30; cancellous bone 1,370 MPa and 0.30; composite attachment 12,500 MPa and 0.30; thermoplastic aligner 1,500 MPa and 0.35; stainless-steel bracket/archwire 200,000 MPa and 0.30. Contact between aligner and tooth/attachment surfaces was defined as frictional surface-to-surface contact. Bracket-archwire contact was modeled with a coefficient of friction of 0.20.

Meshing and convergence: Tetrahedral elements were used for all complex structures. Mesh refinement was performed around the periodontal ligament, cervical root region, bracket slot, attachment edges, and alveolar crest. Convergence was accepted when additional mesh refinement changed peak von Mises stress by less than 5%. The final models contained approximately 1.25 million elements in the aligner-attachment model and 1.08 million elements in the bracket model. Five repeated computational runs were performed after minor load-node perturbations to evaluate numerical stability.

Loading and boundary conditions: The superior and posterior surfaces of the maxillary bone block were fixed in all degrees of freedom. In both groups, a distalizing/retraction load equivalent to 150 g per side was applied to simulate space closure. In the aligner group, activation was simulated by prescribing distal movement of the canine within the aligner shell, corresponding to a 0.25-mm staging step, and by allowing aligner deformation against attachments. In the bracket group, retraction force was applied from canine hook to molar anchorage through the archwire system. The direction of force was parallel to the occlusal plane and directed posteriorly.

Outcome variables: Primary outcomes were maximum von Mises stress in the periodontal ligament and alveolar bone around the canine. Secondary outcomes included maximum principal tensile stress, compressive stress, crown displacement, root apex displacement, root/crown displacement ratio, rotational tendency, appliance deformation, and location of stress concentration. Stress values were recorded in MPa, displacement in millimeters, and rotation tendency in degrees. Regional stress maps were inspected qualitatively and quantitative values were extracted from predefined cervical, middle, and apical root zones.

Statistical analysis: The mean and standard deviation were calculated from repeated simulation outputs. Intergroup comparison was performed using independent-samples t-test for normally distributed variables and Mann-Whitney U test for non-normal variables. A p-value <0.05 was considered statistically significant. Because FEA produces deterministic values, repeated runs were interpreted as numerical sensitivity estimates rather than biological replicates. Analysis was performed using standard statistical software.

RESULTS

The models achieved stable convergence, and mesh refinement did not change peak stress by more than 4.2%. Stress concentration was observed primarily at the cervical periodontal ligament of the canine in both appliance systems. However, the distribution pattern differed between groups. The clear aligner attachment model showed a broader, more diffuse stress pattern over the buccal and distal cervical periodontal ligament, whereas the bracket model demonstrated sharper stress concentration near the bracket level and cervical root surface. Quantitative comparison of stress outcomes is shown in Table 1.

Table 1. Comparison of stress distribution between clear aligner attachments and conventional brackets during space closure

Parameter	Clear aligner attachment model (mean ± SD)	Conventional bracket model (mean ± SD)	p-value
Canine PDL von Mises stress (MPa)	0.132 ± 0.018	0.184 ± 0.021	<0.001
Canine PDL maximum principal tensile stress (MPa)	0.091 ± 0.012	0.126 ± 0.016	<0.001
Canine PDL compressive stress (MPa)	0.104 ± 0.014	0.147 ± 0.019	<0.001
Peak cortical bone von Mises stress (MPa)	4.31 ± 0.44	5.76 ± 0.61	<0.001
Peak cancellous bone stress (MPa)	0.83 ± 0.10	1.05 ± 0.13	0.006
Stress concentration zone	Buccodistal cervical PDL	Distal cervical PDL and alveolar crest	--

Table 2. Tooth displacement and movement control during simulated space closure

Parameter	Clear aligner attachment model	Conventional bracket model	p-value
Canine crown distal displacement (mm)	0.118 ± 0.014	0.086 ± 0.011	0.002
Canine root apex distal displacement (mm)	0.072 ± 0.009	0.068 ± 0.008	0.421
Root/crown displacement ratio	0.61 ± 0.07	0.79 ± 0.06	<0.001
Canine distal tipping tendency (degrees)	2.46 ± 0.31	1.42 ± 0.22	<0.001
Mesiodistal rotation tendency (degrees)	1.18 ± 0.19	0.84 ± 0.16	0.011
Incisor anchorage displacement (mm)	0.036 ± 0.006	0.029 ± 0.005	0.038

Table 3. Appliance deformation and biomechanical efficiency indicators

Parameter	Clear aligner attachment model	Conventional bracket model	p-value
Maximum appliance deformation (mm)	0.274 ± 0.031	0.091 ± 0.012	<0.001
Maximum appliance von Mises stress (MPa)	18.62 ± 2.24	64.18 ± 5.72	<0.001
Predicted bodily movement efficiency (%)	61.4 ± 5.8	78.6 ± 6.1	<0.001
Stress distribution pattern	Diffuse and attachment-mediated	Localized at bracket-wire-root complex	--
Primary biomechanical limitation	Residual crown tipping	Localized PDL stress peak	--
Clinical compensation suggested	Overcorrection/ staged root control	Force-vector and anchorage control	--

Displacement analysis demonstrated that conventional brackets produced a more controlled bodily movement pattern. The root/crown displacement ratio was significantly higher in the bracket model (0.79 ± 0.06) than in the aligner attachment model (0.61 ± 0.07, $p<0.001$). The aligner group showed a greater crown displacement than root apex displacement, indicating residual distal tipping despite attachment assistance. Detailed displacement values are presented in Table 2.

Appliance deformation differed substantially between groups. The aligner shell demonstrated visible deformation around the canine attachment and extraction space, with maximum appliance displacement of 0.274 ± 0.031 mm. The bracket-archwire assembly demonstrated lower appliance deformation but higher stress transfer through the bracket-wire interface. The aligner model showed lower stress peaks within supporting tissues, whereas brackets maintained a more linear force vector and better torque control. Appliance-related outcomes are shown in Table 3.

Overall, the null hypothesis was rejected. Clear aligner attachments and conventional brackets differed significantly in stress distribution, displacement pattern, and appliance deformation during simulated space closure. The aligner attachment model reduced peak periodontal and alveolar stress but demonstrated greater crown tipping. The bracket model improved bodily translation and root control but generated higher localized stress values in the periodontal ligament and cortical bone.

DISCUSSION

The present finite element study compared clear aligner attachments and conventional brackets during orthodontic space closure using identical dentoalveolar geometry and comparable force magnitude. The major finding was that clear aligner attachments produced a more diffuse and lower peak stress pattern in the periodontal ligament and cortical bone, whereas conventional brackets generated more controlled bodily movement with a higher root/crown displacement ratio. This indicates that the apparent biological gentleness of aligner stress distribution may be counterbalanced by reduced root-control efficiency during complex space closure.

The lower periodontal ligament von Mises stress observed in the aligner model is consistent with the biomechanical behavior of removable thermoplastic appliances. Clear aligners contact a broad surface area and distribute load across multiple teeth and attachment surfaces. This differs from fixed appliances, where force is transmitted through a discrete bracket slot and archwire system. The role of aligner thickness, material stiffness, and contact surface geometry has been emphasized in previous biomechanical studies and reviews [13,14]. The present findings support the concept that aligners may reduce localized tissue stress peaks when properly adapted, but the direction and predictability of movement remain dependent on attachment configuration.

The bracket model demonstrated higher peak periodontal and cortical bone stresses, particularly at the distal cervical periodontal ligament of the canine. This pattern is clinically understandable because sliding mechanics concentrate force through the bracket-wire interface and the force vector may pass occlusal to the center of resistance. Fixed appliances nevertheless produced superior bodily movement efficiency in the present model. The root/crown displacement ratio was significantly greater in the bracket group, indicating better torque control and less uncontrolled crown tipping. Fixed appliance FEA studies have similarly shown that root control depends strongly on lever arm length, anchorage unit position, and force vector orientation [12].

The residual tipping tendency in the aligner group agrees with earlier FEA observations that clear aligners may generate incomplete moment control during bodily movement unless attachment design and staging are optimized. Gomez et al. demonstrated that composite attachments improved the force system generated by plastic aligners during bodily movement [8]. Yokoi et al. also reported that attachments could improve diastema closure mechanics by influencing tooth movement direction [9]. However, attachments cannot fully eliminate the inherent limitations of a flexible shell appliance. The aligner deforms under activation, and a portion of activation energy is lost as shell deformation rather than converted into root movement.

The clinical implication is that aligner-based space closure should not be planned as a simple digital translation of teeth. Root-control staging, optimized attachments, power ridges, elastics, overcorrection, and possibly auxiliary anchorage may be needed in extraction cases. Jiang et al. reported that different clear aligner retraction protocols altered anterior and posterior tooth behaviors in extraction models [10]. Hong et al. further demonstrated that attachment geometry can be modified to improve bodily movement efficiency [11]. More recent FEA literature has also highlighted the potential of overhanging attachments and gingival trimline extensions to bring the line of action closer to the center of resistance and improve root-controlled movement [15]. The present model did not test overhanging or power-arm-like attachments, but its results support the rationale for such designs.

From a biological standpoint, the lower peak stresses in the aligner group may be favorable for minimizing concentrated periodontal overload, especially in patients with thin cortical plates or reduced periodontal support. However, lower stress peaks should not be interpreted as automatically superior treatment efficiency. Orthodontic tooth movement depends on biologically effective stress and strain distributions, not simply minimal stress. If stress is too diffuse or poorly directed, the clinical result may be tipping, incomplete root movement, longer treatment duration, or need for refinements. Cattaneo and Cornelis emphasized that FEA provides insight into initial mechanical behavior but should be interpreted with clinical limitations in mind [6].

The bracket group had the advantage of lower appliance deformation and better force-vector stability. The archwire provides a continuous mechanical reference that resists rotation and tipping. This explains the higher predicted bodily movement efficiency in the bracket group. Nevertheless, the higher localized stress values around the periodontal ligament and alveolar crest highlight the importance of using physiologic force levels and appropriate anchorage planning in fixed appliance space closure. Excessive localized stress may theoretically increase the risk of hyalinization, discomfort, root resorption, or anchorage loss, although these biological outcomes cannot be inferred directly from an initial FEA model.

The present findings align with broader reviews indicating that clear aligner therapy is effective for selected movements but less predictable for complex translational and torque movements [2,3]. Contemporary FEA reviews also note the lack of standardization in aligner models, material assumptions, and reporting formats [14]. Therefore, while the present study provides a structured comparison, values should be interpreted as model-specific. The relative differences between groups are more meaningful than absolute stress magnitudes.

This study has limitations. First, the periodontal ligament was modeled as homogeneous, isotropic, and linearly elastic, whereas the real periodontal ligament is viscoelastic and anisotropic. Second, only the initial mechanical response was studied; long-term bone remodeling, biological adaptation, and aligner wear were not simulated. Third, one attachment design and one bracket prescription were compared. Different attachment sizes, aligner thicknesses, trimline designs, archwire dimensions, bracket slot play, and anchorage systems may alter the results. Fourth, statistical analysis was performed on repeated numerical sensitivity outputs, not biological specimens. Despite these limitations, the study offers a clinically relevant comparison under standardized conditions.

FEA studies of diastema closure have also confirmed that stress and strain distributions change markedly when the point of force application or appliance support is modified [16-20]. Therefore, future studies should include patient-specific models, nonlinear periodontal ligament behavior, staged multi-step simulations, different attachment morphologies, power-arm or overhanging attachments, and validation using experimental tooth-movement setups. Integration of FEA with digital treatment planning may allow clinicians to anticipate tipping risk and customize attachment designs before treatment begins.

CONCLUSION

Within the limitations of this finite element in vitro study, clear aligner attachments produced lower and more diffuse periodontal ligament and alveolar bone stress during simulated space closure, while conventional brackets provided superior bodily movement and root-control efficiency. The aligner model showed greater appliance deformation and residual crown tipping, indicating that attachment design, staging, overcorrection, and auxiliary biomechanics are critical for extraction or space-closure cases. Conventional brackets remain biomechanically advantageous for controlled space closure, but careful force-vector and anchorage management is necessary to avoid localized periodontal stress concentration.

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