Does the trimline extension and attachment size affect maxillary arch expansion in clear aligner therapy ? A finite element study

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Objective: Using finite element analysis (FEA), the aim of the present study was to evaluate the effects of different aligner trimline extensions and attachment sizes on maxillary first and second molars under expansive forces delivered by clear aligner therapy
Methods: The study utilised 3 mm and 4 mm horizontal rectangular attachments on the maxillary first and second molars. Two main models were created: a High and Flat Trimline Aligner (HTLA), and a Low and Flat Trimline Aligner (LTLA). Six distinct model variations were created for the analysis: (1) LTLA and no attachment (NA), (2) LTLA and 3 mm horizontal rectangular attachment (3HA), (3) LTLA and 4 mm horizontal rectangular attachment (4HA), (4) HTLA and NA, (5) HTLA and 3HA, (6) HTLA and 4HA.
Results: In all models, the crowns of the maxillary molars exhibited buccal displacement, whereas the root displayed palatal displacement. The LTLA-NA model had the greatest displacement of all models, whereas the HTLA-4HA model had the lowest displacement. The greatest PDL stress value was identified in the coronal third region of the palatal root of the molars.
Conclusion: Buccal tipping of the molars was observed during aligner expansion in all models. By increasing the attachment size and heightening the aligner trimline extension, the occurrence of buccal tipping was significantly reduced.
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Introduction

The impact of numerous conventional orthodontic treatment methods on arch width has been effectively examined.[1–6] Nevertheless, the ongoing search for progress in orthodontics has heralded the advancement of clear aligners (CA), with the objective of providing patients with enhanced comfort, reduced treatment duration, improved oral hygiene, and increased compliance throughout treatment.[7]

CA therapy has proven to be successful in achieving maxillary dental arch expansion.[8–14] This method involves precise digital planning of tooth movements and allows the posterior teeth to be moved buccally through a combination of tipping and bodily movement.[12] Additional studies asserted that adding attachments enhances the efficacy of tooth movement, and increasing the number of attachments applied to the posterior teeth provides greater control.[15,16]

Aligner providers have developed an array of attachment shapes, sizes and material features to enhance the accuracy of tooth movement.[15–19] According to prominent researchers, a high trimline extension of an aligner results in a greater surface

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area over which force may be applied to the teeth, leading to improved efficiency and control.[17] As a result, ClearCorrect's aligner material has been specifically designed with a high and flat trimline that extends approximately 1.5 mm ± 0.5 mm above the gingival margin. The objective of this change is to simultaneously enhance the accuracy of tooth movement and improve root control.[17]

The configuration of the attachment has a significant mechanical influence as it is capable of altering the force value and torque generated by the aligner.[20,21] The effectiveness of aligner treatment has been improved by attachments which can be related to and modify the force system required to move the teeth. The force arises from the geometric disparity between the teeth and the aligner material which is subsequently transferred to a larger tooth contact region that is often less well delineated.[22] Attachments therefore, facilitate the application of complex and diverse forces to achieve tooth movement.[23,24] Gaining knowledge of the suitable attachment configuration for a certain clinical situations can aid orthodontists in achieving the most effective force and moment to avoid any adverse effects. To make an informed decision and digital plan, the orthodontist must have knowledge of aligner materials and attachment characteristics.

A study conducted by Ahmad et al.[19] examined the impact of attachment size on force delivery. It was reported that both the force and moment increased as the attachment size became larger. Additionally, it was observed that a larger attachment size resulted in better alignment of the teeth in the intended direction of movement.[19] Therefore, was concluded that a suitable force magnitude can be achieved by selecting the appropriate attachment size.

Finite element analysis (FEA) is a computational simulation method employed for intricate biomechanical study. The benefits of this technique encompass the capacity to produce several simulations with precise control over variables and exceptional consistency. This enables the creation of a comprehensive database for future clinical trials by eliminating redundant repetition.[25–28]

There are few studies which focus on enhancing the control of maxillary posterior teeth during arch extension using CAs.[26] The literature has not directed sufficient attention to the impact of connection geometry on the bucco-lingual/expansion movement of the posterior teeth which therefore justifies experimental investigation. Hence, the aim of the present study was to evaluate the effects of different attachment sizes and aligner trimline extensions on the expansion of maxillary molars using FEA. A further objective was to analyse the displacement and stress distributions of the teeth, aligner, and periodontal ligament (PDL), and to guide clinical practice by establishing an optimal attachment protocol.

Materials and methods

Model creation

Three-dimensional (3D) finite element models were generated using cone beam computed tomography (CBCT) data, and finite element stress analysis was conducted using HP workstations equipped with INTEL Xeon E-2286 processors running at 2.40 GHz clock speed and 64 GB ECC memory. From the CBCT data, 3DSlicer software was utilised to generate a 3D model in .stl format. Reverse engineering and 3D CAD tasks were performed using ANSYS Spaceclaim software. The solid models were prepared for analysis and an optimal mesh was generated using ANSYS Workbench software. LS-DYNA solver was utilised for the solution of the finite element models.

Material properties

Analyses utilised linear material properties predicated on the Elastic Modulus and Poisson Ratio. The

Table I. Material properties

Material	Elastic modulus [MPa]	Poisson ratio [v]
Trabecular bone[28–30]	1.37×10^3	0.30
Cortical bone[28–30]	1.37×10^4	0.26
Teeth[28–30]	1.96×10^4	0.30
PDL[28–30]	6.9×10^{-1}	0.45
Attachments[28–30]	1.25×10^4	0.36
CA[28,29]	5.28×10^2	0.36

CA, clear aligner; PDL, periodontal ligament.

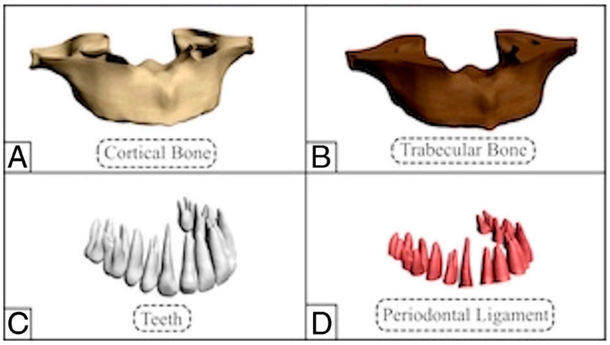

Figure 1. Different components of the finite element model.

material properties of the model under analysis are specified using numerical values in Table I.

Cortical bone, trabecular bone, teeth, and periodontal ligament

The study utilised the existing CBCT data of an adult subject to generate the maxillary bone model. The CBCT data was reconstructed with a slice thickness of 0.1 mm and subsequently transferred to 3DSlicer software in DICOM (.dcm) format. The DICOM 3D data was segmented based on specific Hounsfield values using the 3DSlicer software and transformed into 3D models through the segmentation procedure. The 3D Models as .stl files were imported into ANSYS Spaceclaim program to simulate maxillary cortical bone and tooth geometry. The trabecular bone was designed based on the inner surface of the 3D cortical bone, whereas the 0.25 mm thick periodontal ligament was designed based on the outside surface of the teeth. The prepared models were positioned accurately in 3D space using ANSYS Spaceclaim software, which completed the modelling process (Figure 1).

Obtaining mathematical models

Upon completion of the modelling process, 3D models were generated using ANSYS Workbench software and prepared for analysis. The created mathematical models were transferred to the LS-DYNA solver for analysis (Figure 2). The basic attachment size was within the range of the ClearCorrect® attachment (length, 3.0 and 4.0 mm; width, 1.5 mm; thickness, 1 mm).

Model categorisation

The study utilised 3 mm and 4 mm horizontal rectangular attachments on the maxillary first and second molars. All model adjustments were created using ANSYS SpaceClaim software. Two main models were created: High and Flat Trimline Aligner (HTLA) positioned 2 mm above the gingival margin, and Low and Flat Trimline Aligner (LTLA) positioned 0.5 mm above the gingival margin. Six distinct model variations were created for analysis and are listed below:

- Model 1 (LTLA-NA): LTLA and no attachment (NA)
- Model 2 (LTLA-3HA): LTLA and 3 mm horizontal rectangular attachment (3HA)
- Model 3 (LTLA-4HA): LTLA and 4 mm horizontal rectangular attachment (4HA)
- Model 4 (HTLA-NA): HTLA and no attachment (NA)
- Model 5 (HTLA-3HA): HTLA and 3 mm horizontal rectangular attachment (3HA)

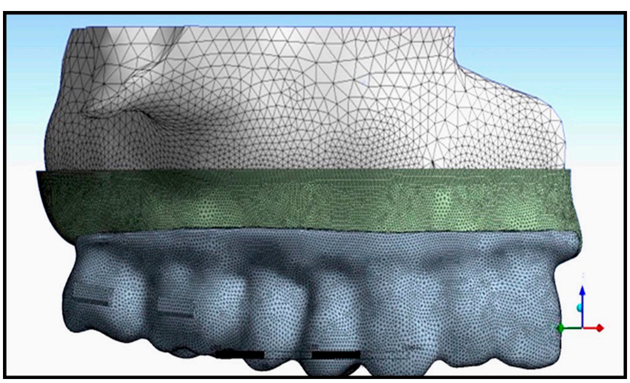

Figure 2. Mesh structure.

- Model 6 (HTLA-4HA): HTLA and 4 mm horizontal rectangular attachment (4HA)

Quantitative model details

Table II displays the quantity of nodes and elements within each group.

Loading and boundary conditions

An activation deflection of 0.3 mm was delivered to the maxillary first and second molars in all models. The aligner's forces on the teeth were estimated based on the activation force and applied to the model in the buccal direction. A boundary condition perpendicular to the *X*-axis and symmetrical relative to the *Y–Z* plane was imposed on all components in the model,. Six non-linear static analyses were conducted on six analysis models according to the prescribed force and boundary conditions. The *X*-axis in the 3D co-ordinate system indicated the buccopalatal direction. A positive *X*-axis value signified movement towards the palatal direction, whereas a negative value showed movement towards the buccal direction. The *Y*-axis denoted a mesiodistal direction. A positive value signified movement towards the distal direction, whereas a negative value implied movement towards the mesial direction. The *Z*-axis indicated the direction of occlusogingival movement. A positive value along the axis signified gingival movement, whereas a negative value indicated occlusal movement.

System integration and interconnection of components

Non-linear frictional contact with a coefficient of μ = 0.2 was specified at the aligner-tooth and aligner-attachment interfaces for all models. A bonded contact type was established among the tooth-PDL, tooth-attachment, cortical bone-PDL, and trabecular bone-PDL components. This technique assumed that the components moved in full correlation throughout movement.

Results

Aligner deformation

The greatest aligner deformation was consistently found on the occlusal surface of the second molar in all models. The aligner exhibited the highest deformation in the LTLA-NA model (0.4209 mm), followed by LTLA-3HA (0.4207 mm) and LTLA-4HA (0.4204 mm) models. The maximum aligner deformation in LTLA models was higher than in HTLA models. Furthermore, for both types of main aligner trimline models, the maximum aligner deformation was greater in the NA groups (0.4121 mm), followed by the 3HA (0.4119 mm) and 4HA (0.4116 mm) models (Table III and Figure 3).

Three-dimensional displacements of the molar teeth

Four cusp points were chosen at the crown level to measure the 3D displacement of the first and second molars: distopalatal (DPC), distobuccal (DBC), mesiopalatal (MPC), and mesiobuccal (MBC). Additionally, three apex points were selected at the root level: palatal (PA), distobuccal (DBA), and mesiobuccal (MBA).

The results of the total tooth displacements in the global co-ordinate system are illustrated in Figure 4. The NA model showed the greatest total movement at all points on the crown and root level for the first and second molars in the HTLA and LTLA models, followed by 3HA and 4HA models. Furthermore, the total displacement recorded in LTLA models exceeded that of HTLA models.

Table II. Quantity of nodes and elements within each group

Models	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
Nodes	477893	481455	482530	476430	477132	478566
Elements	1800007	1811720	1815508	1796580	1798170	1803712

Tooth movements of the first and second molars in the LTLA and HTLA models are depicted in Figures 5 and 6, respectively, along with the relevant results presented in Table IV. In all models, the crown measurement points of maxillary molars exhibited buccal displacement along the *X*-axis, whereas the root measurement points displayed palatal displacement. The LTLA-NA model had the greatest displacement among all models, whereas the HTLA-4HA model had the lowest displacement. Moreover, in all models, distal measurement points (DBC + DPC) at crown level showed greater buccal displacement compared to mesial measurement points (MBC + MPC). All crown points, except for the mesiobuccal crown point (MBC) of the first molars, exhibited more buccal displacement when compared to the second molars.

For all models, crown measurement points moved towards the mesial along the Y-axis, whereas molar root measurement points moved towards the distal. The LTLA-3HA model had the most displacement, whilst the HTLA-NA model showed the least displacement. In all of the models, the mesial tipping of the first molars exceeded that of the second molars.

Along the Z-axis, all palatal crown and molar root measurement points relocated occlusally, and buccal crown and root measurement points were displaced gingivally in all models. The LTLA-NA (MBC + DBC) model exhibited the greatest displacement, and the HTLA-4A (MBC + DBC) model showed the lowest displacement. The vertical movement of the second molars was greater than that of the first molars in all models.

Stress distribution in the PDL

The stress distribution values and regions in the PDL are provided in Figure 7. The greatest PDL stress value was identified in the coronal third region of the palatal roots of the first and second molars in all models. The LTLA-NA model had the highest PDL stress distribution, whereas the HTLA-4A model displayed the lowest stress. Furthermore, the stress distribution in the PDL was greater in the first molars compared to the second molars.

Discussion

Aligners are frequently utilised in orthodontic therapy to treat malocclusions. The control and predictability of tooth movement during CA therapy is affected by factors related to the trimline extension of the aligner material, the position, geometric design, and dimension of applied attachments.[15–17] Recently, computer technological advancements have led to the utilisation of FEA as a valuable tool in researching orthodontic biomechanics.[6,25,26,28–32] The present study aimed to thoroughly assess maxillary molar expansion and the subsequent movement pattern of the molars using CAs by applying FEA. Furthermore, the FEA approach was utilised to research the impact of the trimline extension of the aligners and the size of attachments on tooth movement.

Aligners may successfully treat minor to moderate discrepancies in dental alignment by buccal crown tipping of the posterior teeth with a reasonably predictable outcome.[13,33] The various attachment configurations used with CA are crucial in determining the efficiency of different movements produced by the applied forces.[19,30,34] Horizontal rectangular attachments are generally preferred for controlling torque in the posterior teeth during maxillary expansion.[26] Ahmad et al.[19] contended that the size of the attachment utilised in aligner therapy impacted the force and moment distribution, consequently affecting the control of tooth movement. Therefore, in the present investigation, the use of horizontal rectangular attachments on the maxillary first and second molars was favoured as a

Table III. Maximum aligner deformation and location

Models	Maximum deformation (mm)	Maximum deformation location
LTLA-NA	0.4209	Occlusal surface of the second molar
LTLA-3HA	0.4207	Occlusal surface of the second molar
LTLA-4HA	0.4204	Occlusal surface of the second molar
HTLA-NA	0.4121	Occlusal surface of the second molar
HTLA-3HA	0.4119	Occlusal surface of the second molar
HTLA-4HA	0.4116	Occlusal surface of the second molar

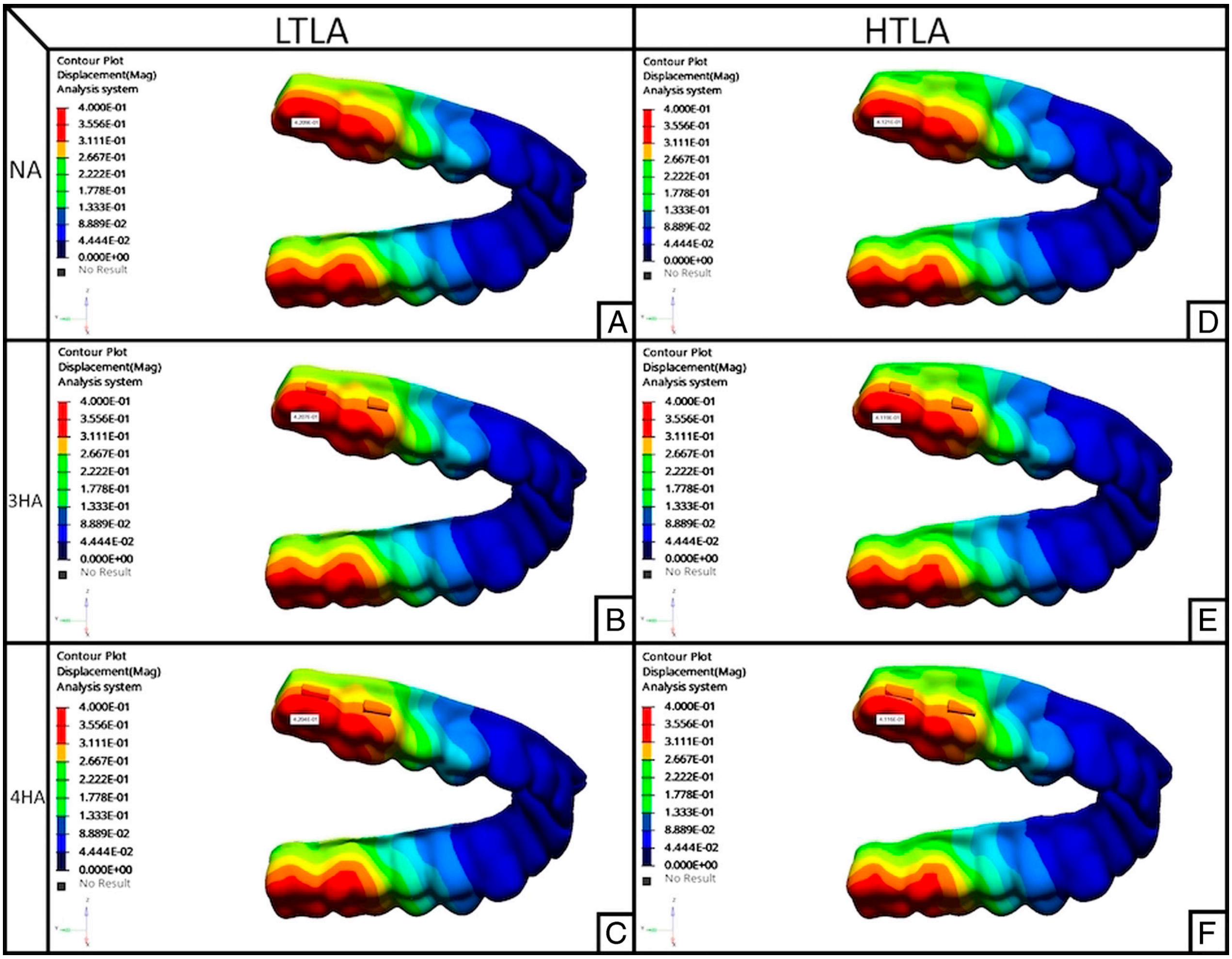

Figure 3. Clear aligner deformation. (A) Low and flat trimline aligner, and no attachment; (B) Low and flat trimline aligner, and 3 mm horizontal rectangular attachment; (C) Low and flat trimline aligner, and 4 mm horizontal rectangular attachment; (D) High and flat trimline aligner, and no attachment; (E) High and flat trimline aligner, and 3 mm horizontal rectangular attachment; (F) High and flat trimline aligner, and 4 mm horizontal rectangular attachment.

benefical method of regulating root movement during buccal tooth movement. Furthermore, Elshazly et al.[17] conducted a study on trimline design and the edge extension of aligners, to determine the impact of the trimline modification on tooth movement. In support, different aligner trimline models were used to ascertain the impact of the aligner extension on the molars during maxillary arch expansion in the present study.

Aligner deformation greatly impacts the outcomes of clear aligner therapy,[35] and significant deformation of the aligner in the occlusal area of the second molar is due to its correlation with the material's shape and mechanical characteristics. This could explain the decrease in sensitivity as aligners transition from the anterior to the posterior region, as reported in prior research.[9,34] The FEA results of Fan et al. showed that the aligner deformation decreased as the number of attachments increased.[36] In the current investigation and compared to the no attachment model, it was found that deformation decreased as the attachment size increased. However, the difference in deformation within these values was insignificant. Therefore, it may be concluded that the presence or absence of attachments on the models does not result in any noticeable variation in aligner deformation. In addition, the maximum aligner deformation in HTLA models was lower than in LTLA models, indicating that aligners with a high trimline extension may have better retention performance. As is well known, FEA studies are performed on ideal

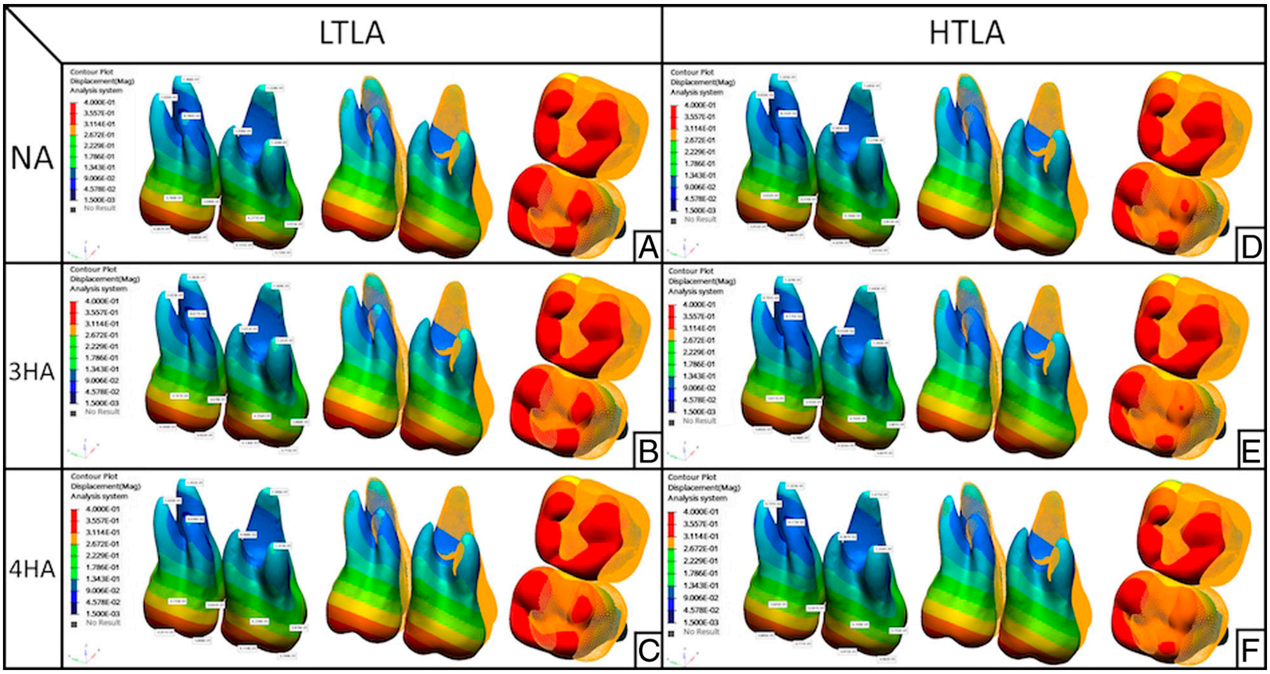

Figure 4. Total tooth displacement. (A) Low and flat trimline aligner, and no attachment; (B) Low and flat trimline aligner, and 3 mm horizontal rectangular attachment; (C) Low and flat trimline aligner, and 4 mm horizontal rectangular attachment; (D) High and flat trimline aligner, and no attachment; (E) High and flat trimline aligner, and 3 mm horizontal rectangular attachment; (F) High and flat trimline aligner, and 4 mm horizontal rectangular attachment.

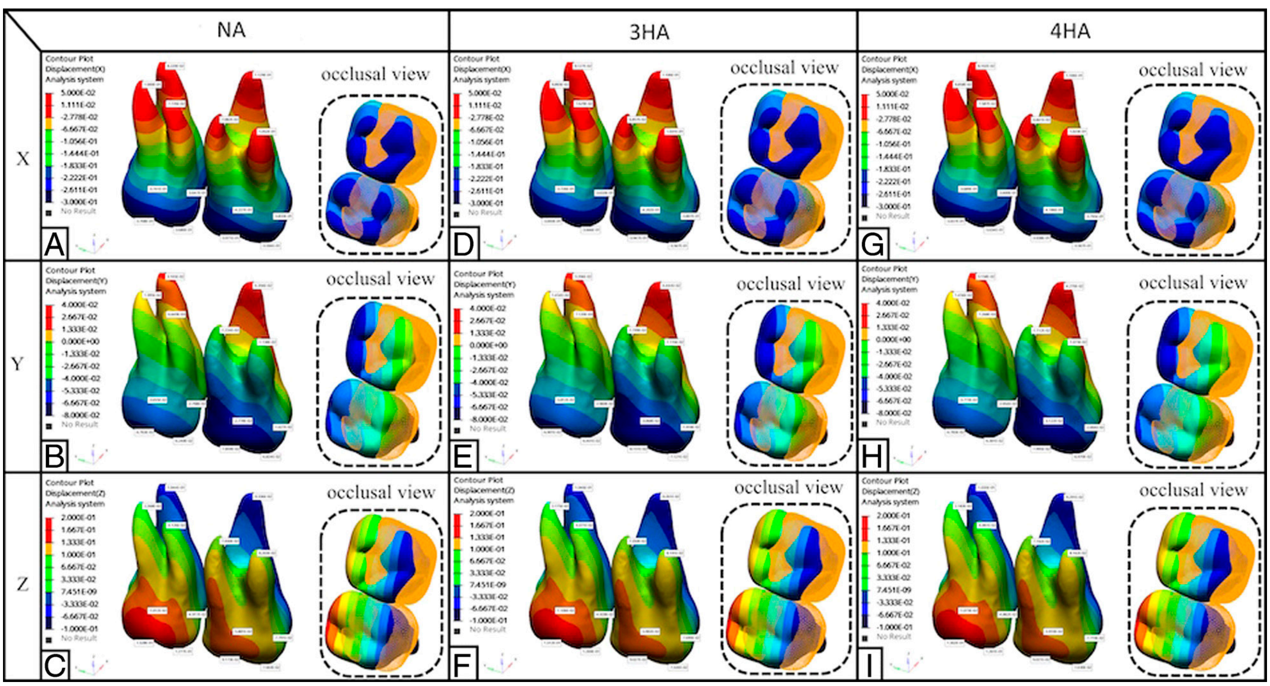

Figure 5. Three-dimensional displacement tendency of the maxillary first and second molars in low and flat trimline aligner (LTLA) models. No attachment: (A) Displacement along the x-axis; (B) Displacement along the y-axis; (C) Displacement along the z-axis; 3 mm horizontal rectangular attachment: (D) Displacement along the x-axis; (E) Displacement along the y-axis; (F) Displacement along the z-axis; 3 mm horizontal rectangular attachment: (G) Displacement along the x-axis; (H) Displacement along the y-axis; (I) Displacement along the z-axis.

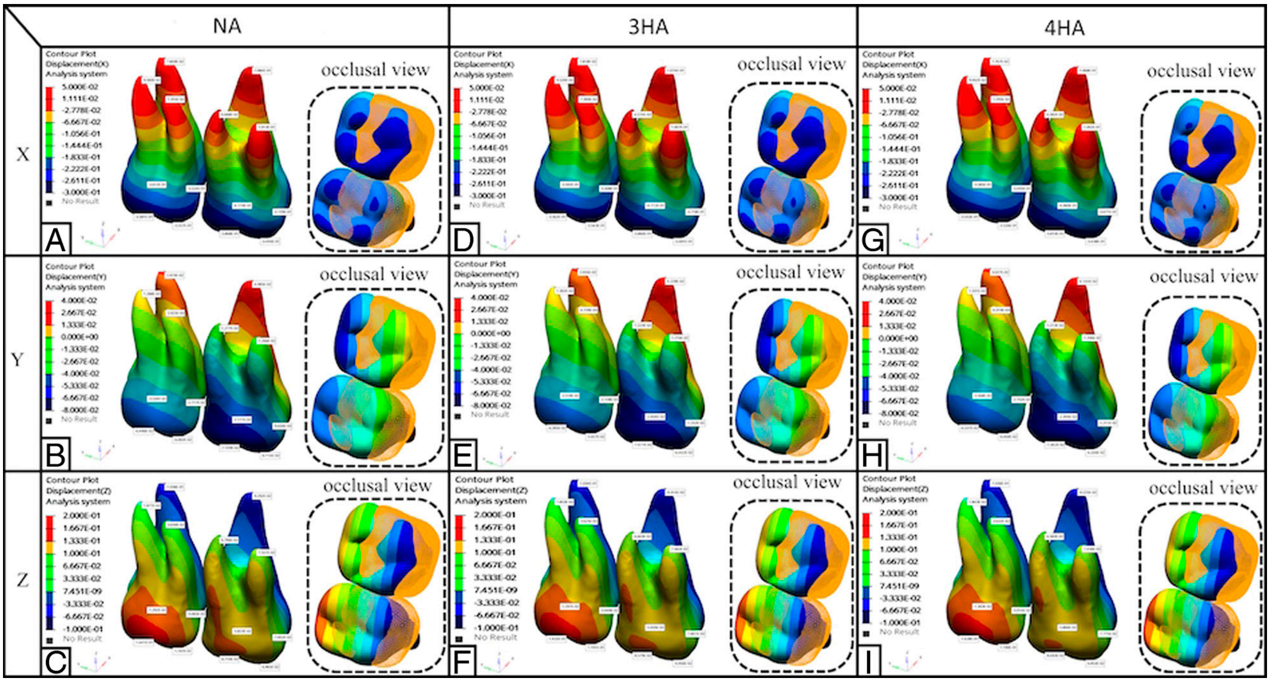

Figure 6. Three-dimensional displacement tendency of the maxillary first and second molars in high and flat trimline aligner (HTLA) models. No attachment: (A) Displacement along the x-axis; (B) Displacement along the y-axis; (C) Displacement along the z-axis; 3 mm horizontal rectangular attachment: (D) Displacement along the x-axis; (E) Displacement along the y-axis; (F) Displacement along the z-axis; 3 mm horizontal rectangular attachment: (G) Displacement along the x-axis; (H) Displacement along the y-axis; (I) Displacement along the z-axis.

model formations to demonstrate potential result trends. In clinical studies, it is common for factors such as aligner fit to deviate from a perfect design.[37] It is expected that FEA studies will produce result trends that are as similar as possible to clinical results.

Several studies have demonstrated the constraints of aligner treatment, particularly in arch expansion through bodily tooth movement.[13,14,33] Many authors have indicated the significance of attachments and aligner trimline extension to reduce constraints, enhance the efficiency of tooth movement, and improve predictability by improving aligner retention.[16,17,19,26,30,33] In the assessment of tooth movement in the transverse direction following expansion, buccal crown tipping of maxillary molars was observed in all models. The low trimline and no attachment model exhibited the highest level of buccal tipping, consistent with prior studies.[17,30] A slight buccal tipping of the molars was observed due to the increased extension of the aligner trimline and the larger size of the attachment. This outcome corresponds with the findings of Ahmad et al.[20], who demonstrated that a larger attachment size led to increased force, moment, and improved movement control. Furthermore, the results of the present research corroborated the conclusions obtained by Elhazy et al.[17] that using higher trimline aligners decreased tooth tipping by enhancing the effective force transferred to the cervical region.

The results of the present research supported the conclusions obtained by Mao et al.[38] regarding the displacement of molar crowns in a mesiodistal direction. This could be attributed to the occlusal flattening tendency of CAs, affecting the curve of Spee, and the mesial displacement of the crowns of the molar teeth caused by the shortening and expanding of the aligners.[37] Aligners with a high trimline extension showed reduced mesial tipping compared to aligners with a low trimline extension, regardless of the attachment. This could be due to improved control of tooth movements facilitated by the increased aligner surface area, as noted by Elhazy et al.[17]

In the occlusogingival direction, gingival displacement was found at the buccal cusps and occlusal displacement at the palatal cusps of the molars due to buccal tipping noted in all models after expansion. The higher aligner trimline extension and greater attachment size helped reduce the tipping

Table IV Directional movements of maxillary first and second molar teeth in the X, Y, Z axes

			Measurement points	LTLA			HTLA		
				X	Y	Z	X	Y	Z
Maxillary First Molar									
	NA	Crown	DPC	-0.42270	-0.02778	-0.05881	-0.41190	-0.02110	-0.05823
			DBC	-0.39710	-0.07859	0.09173	-0.38680	-0.07149	0.08710
			MPC	-0.38330	-0.01627	-0.07791	-0.37290	-0.00965	-0.07852
			MBC	-0.35940	-0.06824	0.07563	-0.34930	-0.06114	0.06965
		Root	PA	0.11290	0.04356	-0.09336	0.10840	0.04085	-0.09292
			DBA	0.07082	-0.01224	0.07460	0.06668	-0.01277	0.06766
			MBA	0.10520	-0.01138	0.08203	0.10130	-0.01266	0.07557
	3HA	Crown	DPC	-0.42020	-0.03068	-0.05902	-0.41120	-0.02404	-0.05926
			DBC	-0.39470	-0.08151	0.09027	-0,386	-0.07477	0.08579
			MPC	-0.38070	-0.01918	-0.07690	-0.37180	-0.01252	-0.07841
			MBC	-0.35670	-0.07121	0.07534	-0.34810	-0.06442	0.06950
		Root	PA	0.11060	0.04444	-0.09261	0.10740	0.04228	-0.09314
			DBA	0.06857	-0.01199	0.07350	0.06574	-0.01223	0.06663
			MBA	0.10310	-0.01116	0.08191	0.10070	-0.01216	0.07562
	4HA	Crown	DPC	-0.41860	-0.03122	-0.05910	-0.40600	-0.02346	-0.05866
			DBC	-0.39380	-0.07995	0.09021	-0.38100	-0.07342	0.08483
			MPC	-0.37950	-0.02004	-0.07719	-0.36710	-0.01211	-0.07775
			MBC	-0.35670	-0.06970	0.07430	-0.34380	-0.06302	0.06853
		Root	PA	0.11060	0.04270	-0.09291	0.10680	0.04144	-0.09225
			DBA	0.06841	-0.01112	0.07192	0.06582	-0.01213	0.06583
			MBA	0.10230	-0.01073	0.08162	0.10020	-0.01206	0.07456

Table IV Continued

			Measurement points	LTLA			HTLA		
				X	Y	Z	X	Y	Z
Maxillary Second Molar									
	NA	Crown	DPC	-0.37410	-0.03655	-0.01012	-0.36120	-0.03534	-0.01292
			DBC	-0.37080	-0.06763	0.15280	-0.35810	-0.06490	0.14410
			MPC	-0.36470	-0.02798	-0.04917	-0.35240	-0.02717	-0.05065
			MBC	-0.36800	-0.06248	0.12770	-0.35570	-0.06002	0.11970
		Root	PA	0.08220	0.03165	-0.10440	0.07848	0.02973	-0.10380
			DBA	0.10000	0.01395	0.02268	0.09560	0.01288	0.01871
			MBA	0.07726	0.00664	0.04126	0.07355	0.00592	0.03650
	3HA	Crown	DPC	-0.37260	-0.03812	-0.01106	-0.35920	-0.03518	-0.01297
			DBC	-0.36930	-0.06901	0.15120	-0.35620	-0.06395	0.14320
			MPC	-0.36330	-0.02969	-0.04928	-0.35080	-0.02728	-0.05048
			MBC	-0.36660	-0.06401	0.12690	-0.35430	-0.05927	0.11910
		Root	PA	0.08127	0.03206	-0.10460	0.07818	0.02935	-0.10340
			DBA	0.09893	0.01454	0.02175	0.09526	0.01302	0.01853
			MBA	0.07629	0.00712	0.04071	0.07300	0.00615	0.03625
	4HA	Crown	DPC	-0.36890	-0.03773	-0.01073	-0.35850	-0.03568	-0.01303
			DBC	-0.36570	-0.06783	0.15020	-0.35530	-0.06537	0.14280
			MPC	-0.36000	-0.02954	-0.04862	-0.34950	-0.02752	-0.05014
			MBC	-0.36340	-0.06301	0.12610	-0.35260	-0.06050	0.11900
		Root	PA	0.08102	0.03158	-0.10350	0.07767	0.03027	-0.10300
			DBA	0.09858	0.01456	0.02183	0.09462	0.01331	0.01843
			MBA	0.07587	0.00726	0.04061	0.07295	0.006310	0.03632

3HA, 3 mm Horizontal Attachment; 4HA, 4mm Horizontal Attachment; DBA, Distobuccal Apex; DPC, Distopalatal Cusp; DBC, Distobuccal Cusp; HTLA, High and Flat Trimline Aligner; LTLA, Low and Flat Trimline Aligner; MPC, Mesiopalatal Cusp; MBA, Mesiobuccal Apex; MBC, Mesiobuccal Cusp; NA, No-Attachment; PA, Palatal Apex. X-axis, (+) for palatal and (-) for buccal; Y-axis, (+) for distal and (-) for mesial; Z-axis, (+) for intrusion and (-) for extrusion.

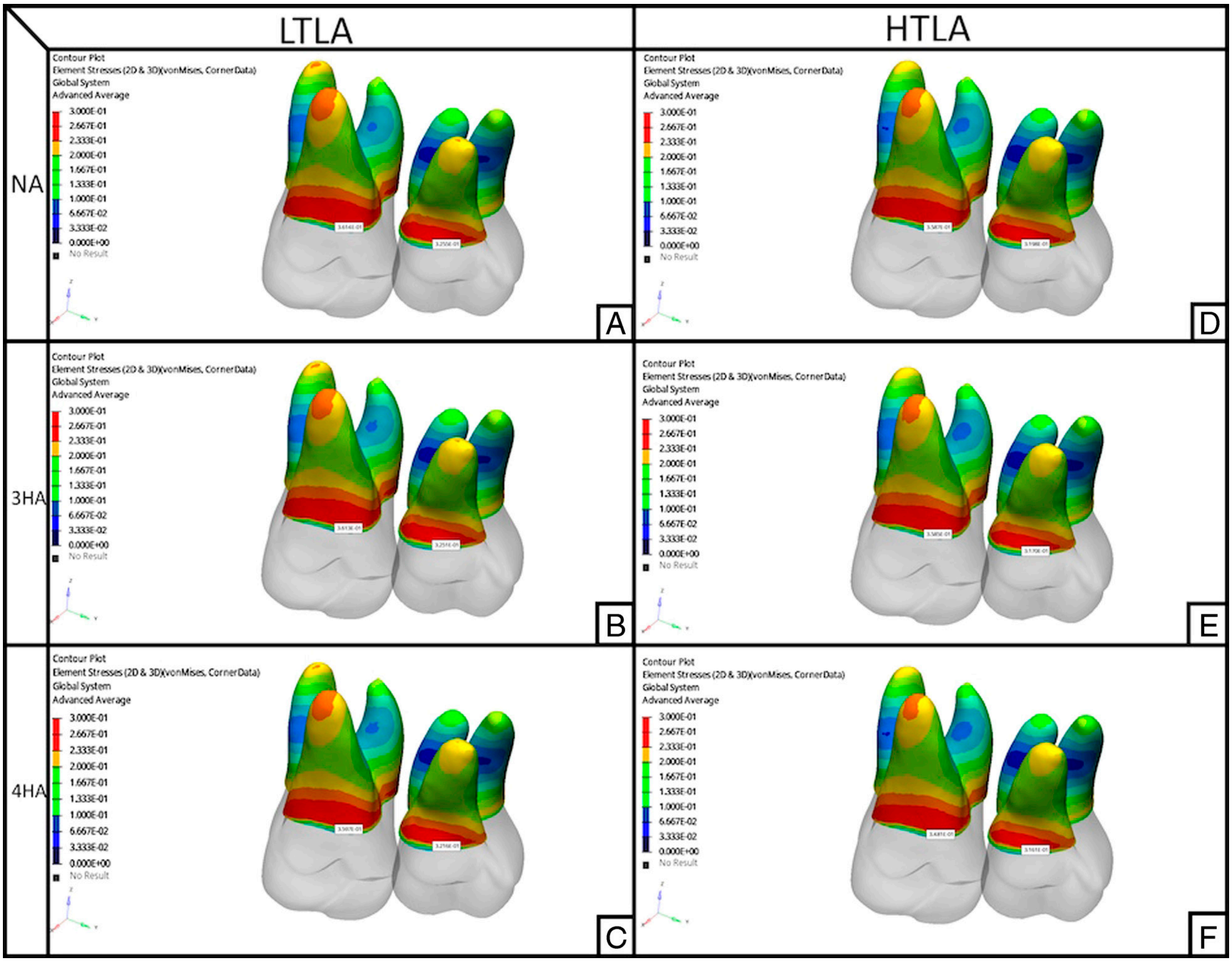

Figure 7. Stress distribution in periodontal ligament. (A) Low and flat trimline aligner, and no attachment; (B) Low and flat trimline aligner, and 3 mm horizontal rectangular attachment; (C) Low and flat trimline aligner, and 4 mm horizontal rectangular attachment; (D) High and flat trimline aligner, and no attachment; (E) High and flat trimline aligner, and 3 mm horizontal rectangular attachment; (F) High and flat trimline aligner, and 4 mm horizontal rectangular attachment.

movements in the vertical direction. The rationale behind this phenomenon is that the high trimline extension of the aligner and larger attachment size (4 mm) enhanced the surface area across which force was applied to the tooth, thereby efficiently controlling tooth movement.[17,19] Furthermore, consistent with numerous studies, the increase in movement differences from the first molar to the second molar, particularly in the vertical direction, could be caused by a decrease in aligner retention from anterior to posterior and the increasing width and flexibility of the aligner-tooth gap.[37–39]

It is widely acknowledged that the width of the aligner edge plays a crucial role in the transmission of force. Forces produced by the aligners are transferred to the teeth, which are then conveyed to the surrounding periodontium.[20] Considering both the surface area and buccal tipping, the present study identified that the greatest stress on the PDL was focused at the coronal area of the palatal root of the first and second molars. Additionally, the aligner model without attachments and with a low trimline extension exhibited the largest distribution of PDL stress, further supporting the tooth movement findings.[30]

The present study solely investigated the movement of the maxillary first and second molars with appliance extension using FEA, which limited the ability to accurately represent actual orthodontic treatment conditions. The main limitation of the study was the exclusion of associated factors related to the aligner's presence in the mouth, aligner wear protocol, and chewing function. The study solely focused on analysing the impact of force transmission from the aligner on the teeth through biomechanical analysis. Hence, there is a requirement for clinical trials to assess the efficacy of moving multiple teeth simultaneously under in vivo orthodontic therapy situations. An additional restriction is that the aligner force applied to the tooth is anticipated to decrease in clinical situations as the aligner deformation occurs more from anterior to posterior.[39,40] However, this could not be replicated precisely in the study due to the exclusive use of the FEA method.

Conclusions

The present FEM study demonstrated that arch expansion using aligners caused buccal tipping of the maxillary molars, whereas buccal tipping movement decreased when the attachment sizes were increased and aligners with a high trimline extension, were utilised.

Conflict of interest

The authors declare that there is no conflict of interest.

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Data availability

All data generated or analysed during this study are included in this published article.

Authors' contributions

NK designed the study and analysed the dataset, and contributed greatly to the writing of the manuscript. FY and AD interpreted the research data. ÖPO contributed to the development of the research and supervised the research. All authors read and approved the final manuscript

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