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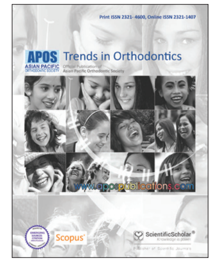

Original Article

Biomechanical impact of attachment design on canine retraction and stress patterns following first premolar extraction: An *in silico* study

Prakash C[1], Praveen Kumar Varma[1], Padma Priya C.V[1], Pradeep Kandikatla[1], Nagisetti Haribabu[1], Nachu Lakshmi Manojna[1]

[1]Department of Orthodontics, Vishnu Dental College, Bhimavaram, Andhra Pradesh, India.

***Corresponding author:**
Pradeep Kandikatla, MDS, MOrth RCSEd, FOrth RCSEd, Associate Professor, Department of Orthodontics, Vishnu Dental College, Bhimavaram, Andhra Pradesh, India.

kpradeep@vdc.edu.in

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ABSTRACT

Objectives: The objective of the study is to evaluate the characteristics of tooth movement during canine retraction in a first premolar extraction case using clear aligners with vertical rectangular attachment and semi-elliptical attachment.

Material and Methods: The canine retraction using a clear aligner is simulated using finite element analysis. A geometric model of the maxillary arch was constructed using CBCT data, which includes teeth, alveolar bone, and periodontal ligament, using SolidWorks 2021. The two types of attachments used in this study are vertical rectangular attachment and semi-elliptical attachment, while a model without attachment is used as a control. The first premolar was extracted, and an aligner thickness of 0.5 mm was used in this study. A mesh model was created using Hypermesh 14.0, which is incorporated into Abaqus 6.14 for finite element analysis. A force of 2N is applied on the canine in the distal direction and evaluated for stress distribution and initial displacement of the canine.

Results: The model with vertical rectangular attachment (0.0315 mm) showed more crown movement than the model without attachment (0.0308 mm) and semi-elliptical attachment (0.0309). The model with vertical rectangular attachment (0.00970 mm) showed more root movement than the model without attachment (0.00947 mm) and semi-elliptical attachment (0.00951 mm). The least von Mises stress is seen in the model with vertical rectangular attachment (0.496 MPa) when compared with semi-elliptical (0.759 MPa) and without attachment (0.835 MPa).

Conclusion: Within the limitations of an initial displacement of Finite Element (FE) analysis, the vertical rectangular attachment demonstrated slightly more efficient force transmission during canine retraction. Thus, the vertical rectangular attachment can be preferred for canine retraction in first premolar extraction cases rather than the semi-elliptical attachment. However, the magnitude of differences was minimal; therefore, clinical extrapolation should be made with caution.

Keywords: Canine retraction, Clear aligners, Composite attachment, Finite element analysis, Premolar extraction

INTRODUCTION

The clear aligners are a removable appliance made up of biocompatible thermoplastic substance that are engineered to deliver gentle, constant forces which gradually guide teeth into their desired positions.[1] The clear aligner therapy (CAT) has several advantages, such as being visually appealing, oral hygiene maintenance, and removable, but patient compliance is needed because the minimal wear time of the aligner is 20–22 h per day.[2] However, aligners are initially employed only for the correction of minor to moderate crowding, spacing, and relapse cases. A study by Djeu *et al.*,[3] compared the efficacy of clear aligners and fixed orthodontics using the American Board of Orthodontics objective grading system and concluded that aligners are not as effective as conventional braces, particularly in achieving anteroposterior movement. This clearly shows that the aligner could not achieve canine retraction in extraction cases in the early days.

In CAT, the tooth movement will be planned by staging, where each individual tooth will be moved in each stage, thereby enhancing anchorage.[4] Although the biomechanics of canine retraction have been well documented for fixed orthodontic appliances, it is still unpredictable in CAT.[5] The major shortcoming of an aligner is the generation of moment necessary to achieve bodily movement, and this can be resorted by the use of supplemental elements like attachments and power ridges.[6]

Attachments are tiny units made of tooth colored composite material that are adhered to the tooth surface, thereby promoting aligner retention and altering the line of force required for intricate tooth movements. Several case reports showed that vertical rectangular and semi-elliptical attachments are used effectively in closing the extraction space in CAT.[7,8] The biomechanical effectiveness varies with different sizes, shapes, and orientations of attachments.

A study by Song *et al.*,[9] showed that clear aligners with attachments showed more palatal tipping of incisors, distal tipping of canine, and mesial tipping of molars when compared to fixed appliances, indicating the need for further studies to improve the control over the tooth movement. However, using animals and humans in research to directly test various mechanical aspects of orthodontic tooth movement is unethical, which can be analyzed by employing finite element analysis (FEA).[10] In the field of orthodontics, its primary use has been to analyze factors such as stress distribution and tooth displacement patterns, and also been applied to study and validate the structural and developmental characteristics of craniofacial components.[11]

A FEM study by Xiang *et al.*[12] retracted canine using aligners without attachment in an extraction case and noticed distal tipping and extrusion of anterior teeth with simultaneous mesial tipping and intrusion of posterior teeth. In orthodontic literature, there is a scarcity of evidence for understanding the biomechanics of tooth movement utilizing auxiliary elements in CAT during individual canine retraction. This finite element study aims to assess the effectiveness of various attachment types in canine retraction after first premolar extraction.

MATERIAL AND METHODS

This study received approval from the Institutional Ethics Committee with IEC Ref No: IECVDC/23/PG01/ODFO/IVT/13.

Preparation of geometric model

A geometric model is constructed using retrospective CBCT data of an adult patient with clinically and radiographically acceptable periodontium taken from the department of oral medicine and radiology. The obtained CBCT data are exported in Digital Imaging and Communications in Medicine (DICOM) format and transferred into SolidWorks 2021 (Dassault Systèmes SolidWorks Corp., Waltham, USA) for refinement of the model. The teeth and alveolar bone were derived from CBCT of the patient and the periodontal ligament (PDL) was created by giving a 0.25 mm offset between teeth and alveolar bone.[13] The first premolar is removed from the model, and the alveolar socket is filled with bone to simulate canine retraction. The three types of models used in this study were: without attachment, vertical rectangular attachment, and semi-elliptical attachment**.** The vertical rectangular attachment of (3 mm × 2 mm × 1 mm) and two semi-elliptical attachments of 2 mm diameter and 0.8 mm thickness are placed on the labial surface of the canine after confirming the position of attachment for canine retraction using Maestro 3-D Dental studio (AGE Solutions S.r.l., Pisa, Italy).[14,15] The aligner thickness of 0.5 mm is constructed using Boolean merging, subtraction and offset functions of SolidWorks software.[16]

Conversion of geometric model into finite element model

The completed geometric model is imported as a DICOM file into Hypermesh 14.0 (Altair Engineering, Michigan, USA) software for meshing. The mesh convergence test is performed, and the mesh sizes of maxilla (0.5 mm), teeth (0.25 mm), PDL (0.2 mm), aligner (0.2 mm), and attachment (0.2 mm) were used in this study. Tetrahedral-shaped elements were used in this study. A total of 1,49,991 nodes and 4,81,201 elements were used in the model without attachment, and 1,50,364 nodes and 4,82,315 elements were used in the model with vertical rectangular attachment, and 1,51,164 nodes and 4,85,095 elements were used in the model with semi-elliptical attachment. The finite element model is illustrated in [Figure 1].

Material properties

This finite element model is transferred as an STL file to Abaqus 6.14 (Dassault Systèmes, France) for iteration. As the teeth, bone, attachments, and aligners are a rigid body, all these were considered as linear elastic, isotropic, homogenous materials. The PDL has a viscoelastic nature, so it was considered as a non-linear elastic, isotropic, homogenous material.[17] The Young's modulus and Poisson's ratio of the materials used in this study are mentioned in [Table 1].[18]

Boundary conditions and contact interactions

A fixed support was applied to the upper part of the maxilla.[19] The contact between teeth and the PDL, teeth and attachment, and bone to the PDL is stitched together; meanwhile, teeth to the aligner and aligner to attachment is kept as a sliding contact with a co-efficient of friction of 0.2.[20,21]

Loading configuration

The retraction force of 2N is applied on both the right and left canine, and the amount of force is decided based on a study done by Choi *et al*. [Figure 2].[22] The force is applied on the mesial crown surface of the center of the canine in the distal direction. After force application, all three models were assessed for factors such as stress distribution pattern and initial displacement of the right canine. The X-axis represents the direction of the coronal plane, with the positive direction being toward the labial surface of the tooth. The Y-axis represents the sagittal plane, with the positive direction being toward the distal surface of the tooth. The Z-axis represents the vertical plane, with the positive direction being toward the gingival tissue.

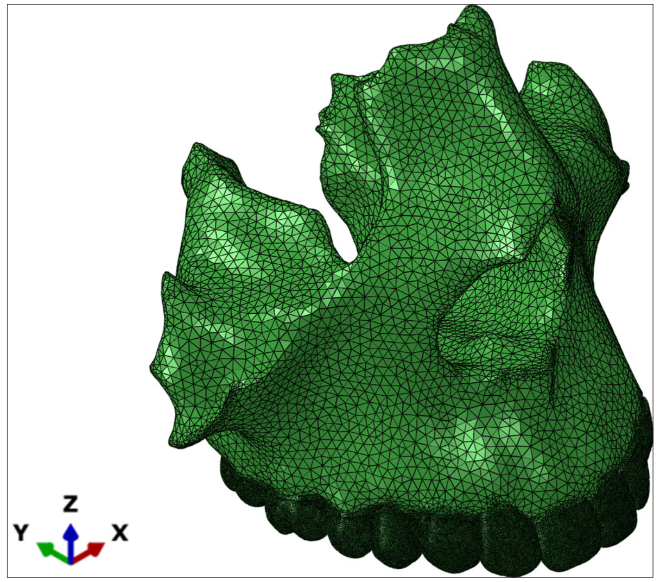

Figure 1: Finite element model of maxilla. X-axis (Red): Transverse plane, Y-axis (Green): Sagittal plane, Z-axis (Blue): Vertical plane

Table 1: Material properties.

Name	Young's Modulus (Mpa)	Poisson's ratio
Teeth	1.96×10^4	0.30
Maxilla	1.37×10^3	0.30
Attachment	1.25×10^3	0.36
Aligners	528	0.36
Periodontal ligament	0.69	0.45

Table 2: Amount of movement observed in canine after retraction.

Cases	Displacement of canine (mm)		
	X-Axis	Y-Axis	Z-Axis
Without attachment			
Crown tip	0.000	0.030	−0.013
Root tip	0.000	0.009	−0.002
Vertical rectangular attachment			
Crown tip	0.000	0.031	−0.013
Root tip	0.000	0.009	−0.002
Semi elliptical attachment			
Crown tip	0.000	0.030	−0.013
Root tip	0.000	0.009	−0.002

RESULTS

Initial displacement

The amount of canine movement achieved in all three planes is illustrated in [Table 2]. The maximum distal displacement is seen in a canine with vertical rectangular attachment (crown – 0.0315 mm; root – 0.00970 mm), followed by canine with semi-elliptical attachment (crown – 0.0309 mm; root – 0.00951 mm), and the least displacement is seen in canine without an attachment (crown – 0.0308 mm; root – 0.00947 mm) [Figure 2]. In all three models, extrusion and palatal movement of the canine is seen, with the highest movement observed in the vertical rectangular attachment. The tipping, rotation, and inclination changes are mentioned in [Table 3]. The distal tipping and distolingual rotation of the canine is more in vertical rectangular attachment than semi-elliptical attachment and without attachment.

Stress distribution

The highest von Mises stress generated in various components is mentioned in [Table 4]. Comparing the overall von Mises stress of the canine in all three models, the least stress is seen in the vertical rectangular attachment when compared with the semi-elliptical and the one without attachment [Figure 3a]. In the PDL of the canine, the model with vertical rectangular attachment produced the least stress, and the model with semi-elliptical attachment produced the highest stress [Figure 3b]. The least amount of stress is produced on the aligner with semi-elliptical attachment

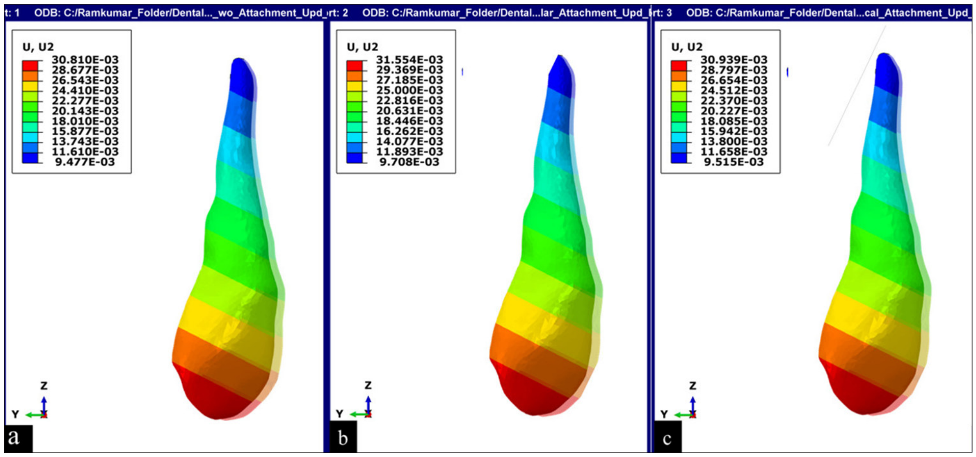

Figure 2: Sagittal displacement of canine after retraction force application. (a) Model without attachment (b) Vertical Rectangular attachment (c) Semi-elliptical attachment. Y-axis: (+) indicates distal and (-) indicates mesial movement, Z-axis: (+) indicates intrusion and (-) indicates extrusion movement

Table 3: Angular changes seen in canine after retraction.

Cases	Teeth angulation - canine (degree)		
	Distal tipping	Distolingual rotation	Buccolingual inclination
Without attachment	0.044	0.038	0.002
Vertical rectangular attachment	0.045	0.039	0.003
Semi elliptical attachment	0.044	0.038	0.003

Table 4: Highest von Mises stress of various components.

Cases	Von Mises stress (Mpa)		
	Without attachment	With vertical rectangular attachment	With semi-elliptical attachment
Maxilla	1.462	1.221	1.471
Teeth	0.835	0.860	0.885
Canine	0.835	0.493	0.759
PDL	0.002	0.002	0.002
Aligner	1.087	0.906	0.834
Attachment	-	0.035	0.045

Mpa: Mega pascal, PDL: Periodontal ligament

compared to vertical rectangular and without attachment [Figure 4a]. Among attachments, more stress is generated in the semi-elliptical attachment than in the vertical rectangular attachment [Figure 4b]. In all three models, the highest tensile stress is seen in the mesiocervical, distal middle third, and apex of the root [Figure 5a]. In all three models, the highest compressive stress is seen in the distocervical and mesial middle third of the root [Figure 5b].

DISCUSSION

The field of dentistry has seen digital evolution in the past few decades, whereas in orthodontics, it leads to the invention of clear aligners. Clear aligners effectively move the teeth by push force, unlike fixed appliances, which tend to work by producing pull force. To date, three generations of aligners have been witnessed. The first generation lacked attachments entirely, the second generation allows orthodontists to place the attachments according to their preferred position, and the third generation involves auto-generation of attachments by aligner software based on the specific clinical scenario.[23]

When the concept of attachments and auxiliary elements is introduced in CAT, the efficiency of managing an extraction case has improved. Attachment increases the contact area between teeth and the aligner, thereby successfully achieving root movement. Various systematic reviews[24,25] explored the biomechanics of attachments as well as their shape, location, and found that attachments help to retain aligners and enable complicated tooth movements, but their effectiveness varies based on their placement and design.

The most suitable way to assess stress patterns and displacements in orthodontics is finite element analysis (FEM) because it facilitates accurate simulation of the orofacial framework in an *in silico* environment. The present study is intended to analyze the stress distribution pattern and initial displacement of canine after retracting the canine using two attachments of different configurations while treating with clear aligners.

Comparison of model without attachment, vertical rectangular, and semi-elliptical attachment

The maximum amount of retraction is seen in canine with vertical rectangular attachment, when compared to canine

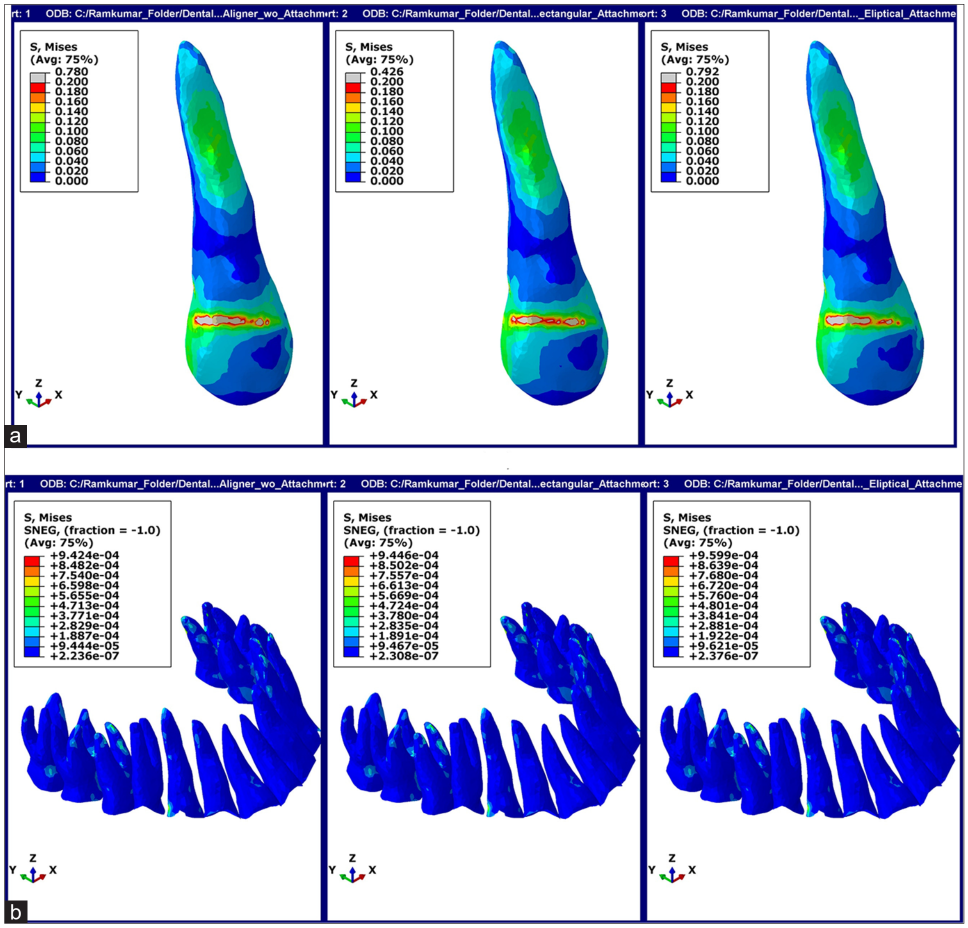

Figure 3: Von Mises stress generated after canine retraction. (a) Canine tooth, (b) Periodontal ligament. X-axis (Red): Transverse plane, Y-axis (Green): Sagittal plane, Z-axis (Blue): Vertical plane.

with semi-elliptical attachment and without attachment. Meanwhile, the vertical rectangular attachment showed more extrusion and less palatal movement of the canine than the remaining two models. The other effects, such as extrusion and palatal movement of anterior teeth with simultaneous intrusion and buccal movement of posterior teeth, are also seen in all three simulations, with the maximum limit being observed in vertical rectangular attachment. This clearly shows that the reciprocal movement of anterior teeth is clearly seen in the posterior region, which might be due to the bowing effect of the aligners. The angular changes, such as distal tipping, distolingual rotation, extrusion of the canine, and intrusion of the molar, are also seen more in models with vertical rectangular attachments. Kawamura *et al.*[26] conducted a dynamic finite element analysis, when the movement is repeated (n = 500), and found that initially there was tipping and rotation of the canine in all models, which is similar to that of our study. On repeated tooth movement, the canine got uprighted and derotated in all models with attachment when compared to the model without attachment. This study evaluated only the initial movement of the canine, and the results obtained are consistent with the expected clinical situation. The overall von Mises stress on canine teeth is less in the model with vertical rectangular attachment when compared to the model with semi-elliptical attachment and without attachment. The highest tensile stress is seen in the mesiocervical, distoapical, and mesioapical region of the canine root, and the highest compressive stress is seen in the distocervical region of the canine root. The compressive stress is more in the distocervical region, which might me because of the distal tipping of the crown without bodily movement. The apical region showed more tensile stress due to the extrusion of teeth. In a study by Gomez *et al.*[15], the canine exhibited uncontrolled tipping and a poor stress pattern when retracted without any attachment. While using semi-elliptical attachment, uniform compression is seen in the distal surface of the canine, which is not consistent with the present study. Melo Andrade *et al.*[27] conducted a finite element analysis and observed that retraction of the canine without attachment and vertical rectangular attachment resulted in uncontrolled tipping, and the tipping decreases with beveled

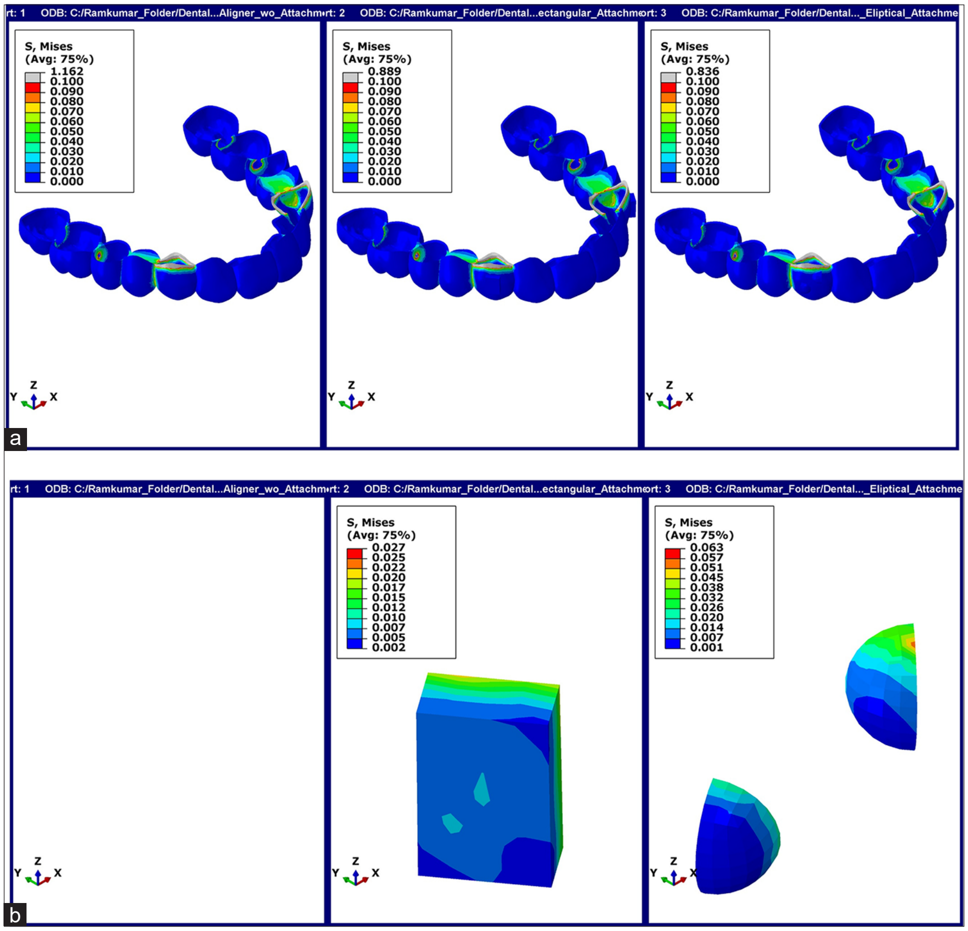

Figure 4: Von Mises stress generated after canine retraction. (a) Aligners, (b) Attachments. X-axis (Red): Transverse plane, Y-axis (Green): Sagittal plane, Z-axis (Blue): Vertical plane

vertical rectangular attachment, but bodily movement is seen only with the application of optimized attachment. Another similar study by Comba *et al.*[28] showed that canines without attachment and with vertical rectangular attachment underwent uncontrolled distal tipping and labial crown movement, but optimized attachment showed bodily movement of the canine, which does not match our study. Moreover, canines showed intrusion in all models in contrast to the present study, where an extrusion effect is seen. They also reported that the optimized attachment model exhibited superior stress distribution compared to the vertical rectangular attachment, which is in contrast to the outcomes observed in our study. Meanwhile, extrusion of the anterior teeth and intrusion of the posterior teeth were observed in a finite element study by Xiang *et al.*[12], which is confluent with our findings, as they also tested using a full maxillary model in their analysis. In their study, the highest compressive stress is seen in the distocervical and mesioapical region of the root, and the highest tensile stress is seen in the mesiocervical and distoapical region of root, which is confluent with our findings, except mesioapical area, which showed tensile stress in our study, which might be due to the distal movement of the canine root along with slight extrusion.

The rate of tooth movement is seen more in vertical rectangular attachment with less stress distribution, which is ideal for bone remodeling, suggesting that better force transmission is achieved by vertical rectangular attachment than semi-elliptical attachment. The results of this study suggest that using attachment is beneficial for treating complex cases like extraction in CAT.

The limitation of this study is that the study does not evaluate any biological response, because finite element analysis determines only the mechanical aspect of tooth movement and so we cannot derive a final conclusion without clinical trials. Further studies can be planned with different dimensions and position of attachments. Dynamic finite element analysis can be used to obtain a better understanding. A finite element study can be planned with directly printed aligners.

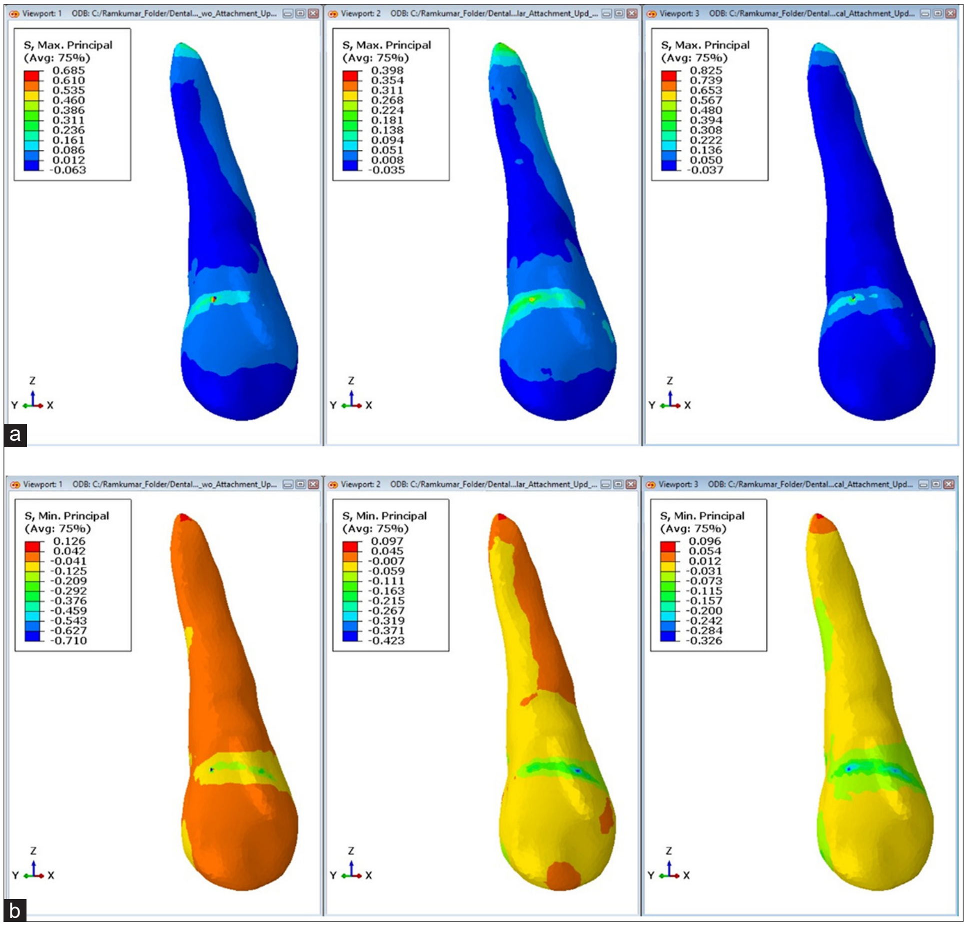

Figure 5: Tension-compression pattern of canine. (a) Highest tensile stress developed in canine, (b) Highest compressive stress developed in canine. X-axis: (+) indicates buccal and (-) indicates palatal movement, Y-axis: (+) indicates distal and (-) indicates mesial movement, Z-axis: (+) indicates intrusion and (-) indicates extrusion movement

CONCLUSION

The following are the conclusions of the present study: To conclude, the vertical rectangular attachment can be preferred for canine retraction in CAT the semi-elliptical attachment. The model with vertical rectangular attachment showed more distal crown and root movement of canine followed by model with semi-elliptical attachment, and least by model without attachment. The von Mises stress of canine is less in the vertical rectangular attachment when compared to model without attachment and the semi-elliptical.

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Ethical approval: The research/study was approved by the Institutional Review Board at Vishnu Dental College, approval number IECVDC/23/PG01/ODFO/IVT/13, dated 28th March, 2023.

Declaration of patient consent: Patient's consent not required as there are no patients in this study.

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Conflicts of interest: There are no conflicts of interest.

Use of artificial intelligence (AI)-assisted technology for manuscript preparation: The authors confirm that there was no use of artificial intelligence (AI)-assisted technology for assisting in the writing or editing of the manuscript and no images were manipulated using AI.

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