Biomechanical Assessment of Maxillary Second Molar Mesialization Using Clear Aligners with Different Attachments: A Finite Element Analysis

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Abstract:

Background : Clear aligners are having an upsurge for providing esthetic treatment option, but achieving complex tooth movement like molar mesialization still remains challenging.This study uses finite element analysis to compare different attachments and auxiliaries in facilitating molar mesialization and analyzing displacement patterns**.**

Aim: The aim of the study was to analyse biomechanical effects of different attachments patterns on second molar mesialization with clear aligners.

Materials and Methods: A 3D finite element maxillary model was created with both first molars extracted. Four models were tested with different attachment patterns on second molar: 1. no attachment, 2. vertical rectangular attachment, 3. optimised attachment, 4. Optimised attachment with class III elastic engagement. Stress and strain distribution pattern and 3D tooth displacement patterns were verified via finite element analysis using ANSYS software.

Results: The optimised attachment and class III elastic engagement provided the maximum amount of mesial displacement of second molar in comparison to other but also resulted in excessive buccal tipping and extrusion at the same time. Although displacement pattern was similar in all groups, the amount of displacement increased with combination of auxiliaries and change in attachment shape.

Conclusion: This finite element study demonstrated that varying attachment shape and addition of auxiliaries such as class III elastics, optimised the effects on mesial displacement of maxillary second molar. The study advocates the need for optimizing attachment designs to achieve bodily movement of molar during mesialization biomechanics owing to the mesial tipping movements of second molar in all our study models.

Keywords - Aligners, Molar mesialization, Finite element analysis, Aligner attachments, Biomechanics.

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INTRODUCTION

The tooth that is considered highly susceptible to caries is the first molar and thus its absence in the dentition is the most commonly experienced entity in the clinical practice.[1,2] When this loss of permanent molars is left untreated, it might result in future problems such as- supraeruption of the opposing tooth, loss of the alveolar ridge height, periodontal health issue involving pocket formation leading to plaque retention and deranged occlusion.[3,4].

Conventionally the early loss of permanent 1st molars has been treated either with prosthetic bridge, removable partial dentures, auto transplantations or the latest option being dental implants. But these options do not pose a sufficient survival rate ranging from 60-65% for fixed partial dentures and 80-82% for dental implants. [5,6]

Another treatment option in such cases involves closing the edentulous space by space closure orthodontically, which majorly involves mesialization of the 2nd molars into the edentulous space. This treatment option significantly prevents damage to vital adjacent teeth, the need for FPD's and dental implant but also helps regain the reduced alveolar bone height. [7,8]

Also, in orthodontic cases like class III malocclusion with reverse overjet, class II malocclusion where premolar extraction has been attempted, mesialization of molars is attempted.

The increasing number of adult orthodontic population prompts an upsurge in the demand for esthetic and comfortable alternatives to traditional fixed orthodontic therapy. In mild to moderate malocclusion cases, aligner treatment has proved to be advantageous in factors such as good oral hygiene, less chairside time, predictable treatment outcomes and many more.[9]

In conventional fixed orthodontic therapy, many auxiliaries have been used to assist the molar mesialization. But with respect to clear aligner therapy, such combinations with auxiliaries and customising attachments have not been seen. Thus, the biomechanical effects of molar mesialization with auxiliaries and optimised attachments remains underground.[10]

Finite element studies have been successfully applied to study the distribution patterns of mechanical stress and strain in engineering. It is an in-vitro highly sophisticated and a non-invasive study, applied to the human skeleton to elucidate the biomechanics and measure stresses for orthodontic tooth movement especially in clear aligner studies. This digital approach is ideal to be incorporated in CAD and to extract the results virtually in a similar patient model.[11]

Therefore, the purpose of this study was to simulate the biomechanical effects of maxillary 2nd molar mesialization in clear aligner therapy with different attachment design and auxiliaries using a finite element analysis.

MATERIALS & METHODS:

The invitro study employed 3-dimensional finite element analysis for the investigation of stress and strain distribution around the maxillary dentition during mesialization of second molar using clear aligners.

Softwares used-

The modelling process utilizes tools such as for visualization and segmentation of CT images and conversion into the DICOM data into a geometric model we have used MIMICS 8.11.

A 3D finite element model of maxilla with full dentition from second molar to second molar was constructed except the first molars, representing all the biological properties of the teeth, PDL and alveolar bone. The CT scan of a skull was procured and processed using MIMICS 8.11 and then the dicom data was converted into geometric model processing via STL format model to Rapidfrom. Further from Rapid form the data was exported in IGES format and refined using Hyper Mesh 13.0. **(fig.1)**

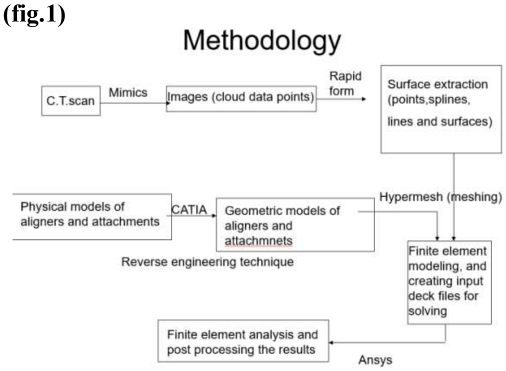


Fig.1. Methodology for FEM model processing

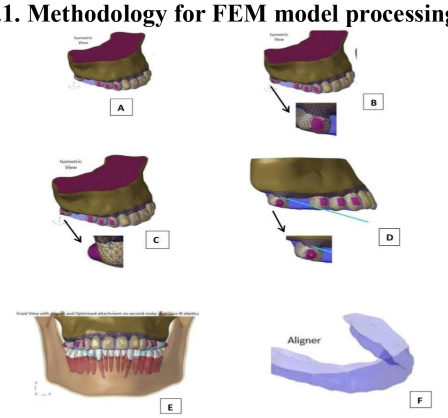


Fig.2. Finite element study models

(A)Model 1: 2nd molar without attachment, (B) Model 2: 2nd molar with vertical rectangular attachment, (C) Model 3: 2nd molar with optimised attachment, (D) Model 4: 2nd molar with optimised attachment and class 3 elastic, (E) Model illustrating bilateral class 3 elastic engagement, (F) Aligner geometric model

To establish natural anatomy of dentition, periodontal ligament around the roots of all teeth was fabricated as a linear elastic film with an average thickness of 0.25mm. As the study was on clear aligners, aligner set were developed via simulation having 0.38 mm of thickness, external offsets for all crowns and attachments. Vertical rectangular attachments were incorporated on teeth from canine to second premolar bilaterally.

The irregular geometries of teeth, PDL and bone were meshed by tetrahedron elements, that optimized the computational efficiency of dental applications.

Four models were created, first model with no attachment on 2nd molar, second model with vertical rectangular attachment on 2nd molar, third model with optimized attachment on 2nd molar and fourth model with optimized attachment on 2nd molar and class III elastic attachment on 2nd molar to be mesialized. **(fig.2)**

The finite element mesh was divided by discretization process and nodes and linear elements were generated for all models.

Material properties:

Different structures involved in this study include cancellous bone, cortical bone, bone, PDL, tooth, plastic aligners, and composite attachments. Each structure possessed a specific material property. **(Table 1)**

Material	**Young's Modulus(Mpa)**	**Poisson's Ratio**
Tooth	19890	0.31
PDL	501	0.49
Cancellous bone	13700	0.30
Cortical bone	13700	0.30
Plastic aligners	528	0.36
Composite attachments	12500	0.36

Table.no.1 Material properties for study

(Mpa: Megapascal, PDl- Periodontal ligament)

In this study, the materials used were homogenous, isotropic, and linearly elastic.

Boundary conditions

The boundary conditions were defined to simulate how the model was constrained and to prevent it from free body motion. The nodes attached to the area of the outer surface of the bone is fixed in all directions to avoid free body movement of teeth. The base of maxilla was the fixed boundary condition for all the four models. Between the aligner and tooth crown surface along with attachment a friction-based condition was established in contact interface with the friction coefficient of 0.2.

Loading

The simulation for finite element analysis was done based on static loading.

The step activation for second molar mesialization was set as 0.5mm displacement along the y (-) axis. For the first set, the second molar was moved 0.5mm mesially to generate a clear aligner under a loading condition. The loading force thus is applied over the teeth due to discrepancy between the initial dentition and the aligner set. The force is simulated in three axes- X(buccal-lingual), Y(mesial-distal) and Z(vertical), using ANSYS 12.1.

Result interpretation-

Finite element analysis was carried out and movement of bones and stresses were extracted in which stress and displacement were presented as different colour bands, representing different magnitude. The simulations were made for bodily mesial movement of second molar.

We established three coordinate system for reference. Force direction was simulated using FEM in three axes- X axis (buccal-lingual) where (-X) denoted buccal movement and (+X) denoted lingual movement, Y axis (mesial-distal) where (-Y) denotes mesial movement and (+Y) denotes distal movement, Z axis (intrusion -extrusion) where (-Z) denotes extrusion and (+Z) denotes intrusion of teeth. The stresses (Mpa) were calculated and presented in colourful contour bands, where different colours represent different stress levels. For all the maxillary dentition models, this coordinate framework was used to interprete the stress and displacement pattern.

RESULTS

The result of an FEA is called as post processing. The analysis was done to evaluate stress and strain distribution around maxillary dentition during mesialization of the second molar using clear aligners with different attachments. Stresses were calculated and presented in colourful bands; different colours represented different stress levels in deformed state. The results were obtained as distribution of Von-Mises stresses on maxillary teeth, cortical bone, cancellous bone, periodontal ligament **(Table.2).**

Displacement of teeth was calculated in three planes i.e. transverse, sagittal and vertical plane using X, Y, Z axis respectively.

ELEMENT	MODEL 1	MODEL 2	MODEL 3	MODEL 4
Cancellous Bone	1.907	1.907	2.86	7.627
Cortical Bone	7.17	14.35	19.12	28.68
PDL	0.005	0.01	0.012	0.019

Table 2 : Von-Mises stress comparison (Mpa) in all models for different structures of maxillary dentition. (Mpa: Megapascal)

Displacement was expressed in millimetres(mm) and stress was expressed in megapascal (Mpa).

Our results showed that the stress was highly absorbed in the cortical bone, and very little stress was transmitted to the cancellous bone.

The von-mises stress in the cortical bone was observed to increase progressively with the change in attachments at 2nd molar. This progressive increase depicts that the amplified stress concentrations at the cervical region with the change in attachments alter the biomechanical load distribution for second molar mesialization. **(fig.3)**

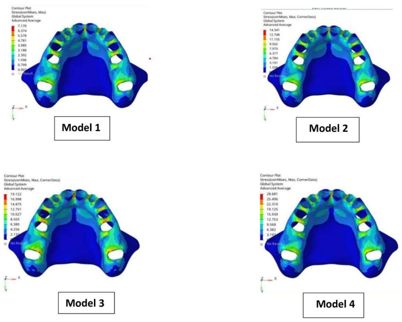


Fig.3. Von mises stresses in cortical bone

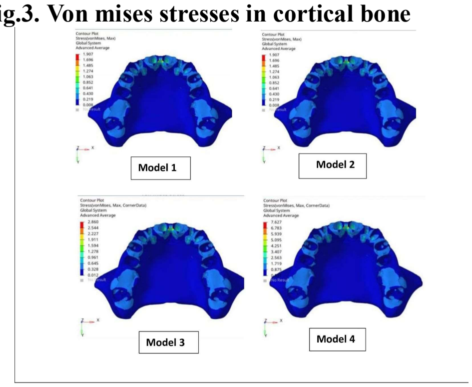


Fig.4.Von mises stresses in cancellous bone

In the cancellous bone, the maximum Von-Mises stress was again observed at the cervical margins and followed same progressive increase pattern as in cortical bone but at a lower magnitude.

In the cancellous bone, the maximum Von-Mises stress was again observed at the cervical margins and followed same progressive increase pattern as in cortical bone but at a lower magnitude. **(fig.4)**

The Von-Mises stresses, in the PDL were observed to be maximum in the cervical region of canine PDL possessing value of 0.019 Mpa in the 4th model with an optimised attachment and class 3 elastic engagement. The significantly lower values of stresses in PDL spotlights its role in stress dissipation, with higher PDL stress at canine in optimised attachment and class 3 elastic group possibly owing to enhanced extrusion forces. **(fig.5) (table 2)**

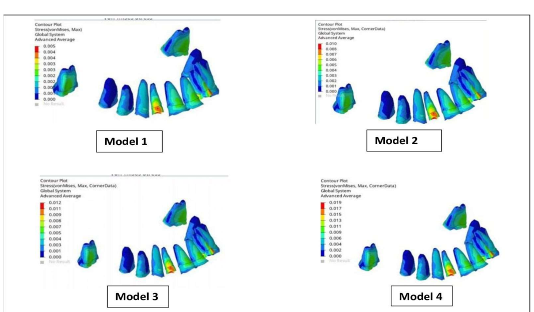


Fig.5.Von mises stresses in PDL

Three-dimensional displacement of teeth

TOOTH	AXIS	MODEL 1	MODEL 2	MODEL 3	MODEL 4
CENTRAL INCISOR	X	0.001	0.002	0.003	0.005
	Y	0.009	0.012	0.019	0.037
	Z	-0.007	-0.01	-0.014	-0.029
LATERAL INCISOR	X	0.005	0.012	0.009	0.0018
	Y	0.009	0.014	0.018	0.036
	Z	-0.007	0.002	-0.014	-0.027
CANINE	X	0.003	0.012	-0.006	-0.012
	Y	0.007	0.011	0.013	0.026
	Z	-0.004	-0.011	-0.009	-0.018
1ST PREMOLAR	X	0.003	-0.007	-0.009	-0.019
	Y	0.005	0.004	0.007	0.065
	Z	0.001	0.003	-0.005	-0.046
2ND PREMOALR	X	0.002	-0.011	-0.019	-0.033
	Y	0.002	-0.004	-0.006	-0.061
	Z	0.001	0.007	-0.012	-0.118
2ND MOLAR	X	-0.001	-0.003	-0.005	-0.045
	Y	-0.004	-0.010	-0.017	-0.171
	Z	0.001	-0.011	-0.014	-0.144

Table.3.Three dimensional displacememt of teeth(mm)

While evaluating second molar mesial displacement via FEA, with different attachments, a varied displacement pattern was observed across the maxillary dentition in the buccolingual(X), mesial-distal(Y) and vertical(Z) directions. **(table 3)**

The central incisor in all four models followed a similar displacement pattern, with lateral movement in x-axis, lingual tipping in y-axis and extrusion in z-axis with increasing amount of displacement from 1st model with no attachment to 4th model with optimised attachment and class 3 elastics engagement.

The lateral incisor followed a same trend as central incisor except that in the 2nd model with vertical attachment on 2nd molar, the lateral incisor underwent intrusion 0.002mm.

The canine predominantly expressed distal movement in Y-axis and extrusive movement in Z-axis with increasing values of displacement in all the four groups, whereas in X-axis, the canine followed a lingual tipping movement in models with no attachment and a vertical rectangular attachment on 2nd molar, and buccal tipping movement in models with only optimised attachment and optimised attachment with class 3 elastic group.

The first bicuspid exhibited distal tipping movement in all the four models along the Y-axis with increasing values of distal movement. But along the X-axis, the 1st bicuspid expressed buccal tipping movement in all the three models expect in the 1st model with no attachment on molar with a lingual tipping movement of 0.003mm. Also, along the Z-axis, in the first two models (no attachment & vertical rectangular attachment) intrusion was seen while in the 3rd and 4th model (optimised attachment & class 3 elastic with optimised attachment) extrusion movement of 0.005mm and 0.046mm respectively was noted.

The second premolar followed the same trend of vertical movement along the Z-axis as first premolar but with increased values of displacement in all the four groups. Along the X-axis, the second premolar exhibited buccal tipping movement in all the three groups except the first model with no attachment on 2nd molar. Comparing the mesial-distal movement on the Y-axis, mesial displacement was predominant in the other three groups expect that the distal tipping movement was found in first model.

While comparing the three dimensional movement tendency at the maxillary 2nd molar, the tooth that is to be mesialized, the 2nd molar followed a similar trend in all the four models with buccal tipping movement along the X-axis and mesial tipping movement along the Y-axis with highest values of displacement being 0.045mm and 0.171mm respectively in the model with optimised attachment and class 3 elastic engagement(fig.6&7)(table.4). Along the Z-axis extrusion displacement pattern was similar in the other three models expect that in the first model (no attachment on 2nd molar), where intrusion movement of a negligible amount was expressed. **(Fig.6)**

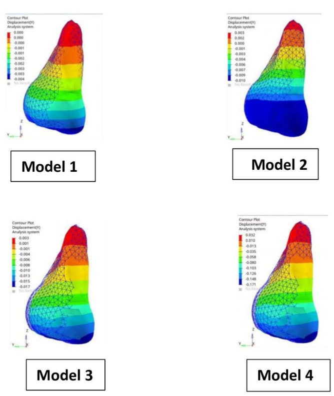


Fig.6. Mesial movement of second molar in four different models

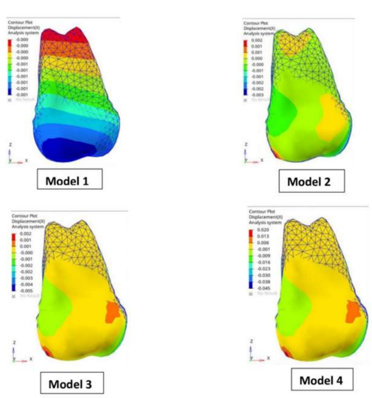


Fig.7.Bucco-lingual displacement of second molar in four different models

MODEL 1	MODEL 2	MODEL 3	MODEL 4
-0.004	-0.01	-0.017	-0.171

Table.4 : Mesial movement of second molar (mm)

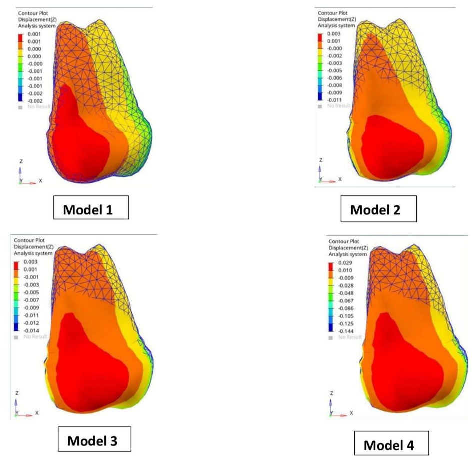
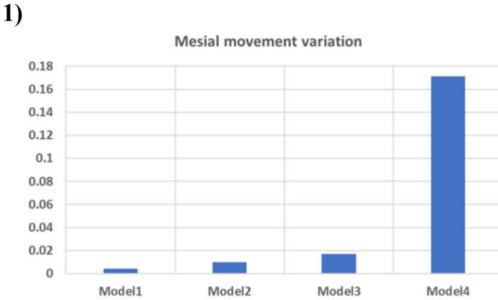


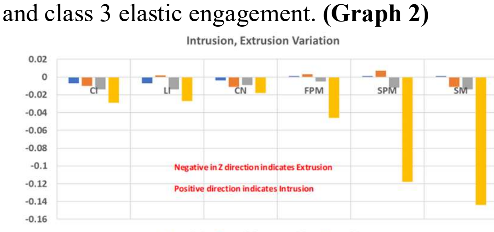
Fig.8.Intrusion-Extrusion displacement of second molar in four different models

All the above results showed that the efficiency of the mesialization is more in 4th model with optimised attachment along with class 3 engagement. **(Graph 1)**



Graph.1.Comparison of second molar mesial movement

When analysing the intrusion-extrusion variations among all the models, the maxillary dentition almost in every model underwent extrusion displacement pattern with highest extrusive movement of second molar in the fourth model with optimised attachment and class 3 elastic engagement. **(Graph 2)**



Graph.2.Intrusion extrusion variations in four models

Angular changes due to movement

While evaluating the tipping angular changes in all the four models, it was found that the central incisor exhibited lingual tipping while buccal tipping was exhibited by the canine, 1st and 2nd premolar and the 2nd molar. The largest angular change in the buccal direction was exhibited by the second molar (5.6) in the fourth model with optimised attachment and class 3 elastic engagement. While, the least angular change (0.4) was depicted in the first model with no attachment on second molar. **(Table.5)**

TIPPING	TEETH	MODEL 1	MODEL 2	MODEL 3	MODEL 4
LINGUAL TIPPING	CI	2.3	2.1	2.2	3.5
	LI	2.1	1.8	2.2	3.4
BUCCAL TIPPING	CN	1.8	2.3	1.9	3.2
	1ST PM	1.1	1.4	1.8	4.1
	2ND PM	0.8	1.3	1.5	4.1
	2ND M	0.4	0.9	1.2	5.6

Table.5: Tipping angle comparison(degrees) in four models during clear aligner movement
(CI-Central incisor, LI-Lateral incisor, CN-Canine, PM-Premolar, M-Molar)

DISCUSSION:

Since a decade, clear aligner technology has evolved unexpectedly. The property of aligner material deformation under pressure, the controlled orthodontic forces are created due to the rebound forces that helps in orthodontic tooth movement. Over the past few years, the aligners were limited to the correction of minor crowding and spacing in class I malocclusions. Currently, the integration and judicious use of various attachment designs and auxiliaries have significantly aided to use aligners in complex orthodontic cases. [12,13]

Clear aligner therapy, uses computational three-dimensional software for the treatment planning and required orthodontic tooth movements. But mostly it has been observed that the software generated plans do not successfully work out owing to the complex biomechanical responses of the teeth and material properties of aligners applied.[14]

The aim of our study was to evaluate the comparative effectiveness of different attachments for second molar mesialization and stress and strain distribution around maxillary dentition.

Many studies in the past have proposed that the aligners fundamentally produce intrusive and tipping forces, and the translational tooth movements are limited, but the emerging studies suggest something different. A study conducted by Simon et al [15], is demonstrative of approximately 1.5-3mm maxillary molar distalization along with bodily movements such as premolar derotation, incisor torquing etc. According to a systemic review conducted by Rossini et al, molar mesialization with clear aligners has been proved to require higher level of forces, is often challenging and has low predictability of planned movement.[16]

Four models (no attachment, vertical rectangular attachment, optimised attachment, optimised attachment with class III elastic) were tested to evaluate the magnitude and nature of tooth movement and also the stress over maxillary dentition. All the four designs had no rotational effect on tooth but the final position of second molar in all the models indicated mesial tipping with varying magnitude.

In many orthodontic cases treated with aligner, vertical rectangular attachment is preferred over other attachments for challenging tooth movement. But our study reported mesial tipping of second molar with vertical rectangular attachment, this may be due to the inability of attachment to generate counter balancing moment for root uprighting. In many extraction cases treated with aligners, molars have found to be mesially tipped instead of translation.[17]

In the model with optimised attachment over second molar, the tooth exhibited buccal tipping, extrusion and mesial tipping and same was the case with optimised attachment and class III elastic group with varied magnitude of displacement.

In our study, the step advancement of 0.5mm was set for mesial displacement of maxillary second molar. In all of the four models tested, we found that the final position of 2nd molar indicated much of mesial tipping and not bodily translation. These findings of our study were similar to those of Baldwin et al and Drake et al [18,19], who reported that despite the initial programmed translatory movement of teeth, the resultant movements were frequently uncontrolled tipping movement. In our study highest mesial displacement was found in the optimised attachment with class III elastic group, but the group also exhibited the highest level of buccal tipping and extrusion of 2nd molar which are not desirable. The reason for the much of buccal tipping and extrusion can be granted to the point of force application being buccal to the centre of resistance.

In a study on mandibular molar mesialization with clear aligners, Lyu et al [20] found mesiolingual tilting of the molar, which was counteracted with the use of auxiliaries such as lever arms, which exerted further distal tipping and extrusive forces. These results with use of lever arms spotlights the limitations of clear aligner use alone and calls our attention to integrating auxiliaries with aligners for enhanced biomechanical results with control over tooth movements.

Co-ordinating with the above observations from Lyu et al study, the use of auxiliary, i.e., class III elastics in our 4th study model rapidly increased the amount of mesial displacement of maxillary 2nd molar from being 0.004mm (no attachment group) to 0.171mm. (optimised attachment with class III elastic group).

So, our study exemplifies the successful mesialization of maxillary 2nd molar in all the groups, no matter where the position and shape of attachment was. Although the movement in all the groups was an uncontrolled tipping movement and not translation. The results of our study, has exemplified the need of necessary forces for root uprighting in order to achieve bodily movement. A recent study conducted by Resul Vatansever [21], shows the use of Yin-Yang attachment design, which replicates the arch wire-bracket effect to straighten the roots by controlling wires and confirms the mesio-distal control.

Additionally, the study also illustrated use of optimized double semi-ellipsoidal attachments, which depicted initial tilting and rotation, which was followed by uprighting and rotational correction and the design produced least amount of tipping during mesiodistal movement.

Concluding, our study demonstrated surge in the mesial displacement of maxillary 2nd molar in no attachment group with 0.004mm, vertical rectangular attachment with 0.010mm, optimised attachment with 0.017mm, and optimised attachment and class III elastic with 0.171 mm. Additionally, with increasing mesial displacement, the second molar also exhibited increasing buccal tipping and extrusive movement which was undesirable. This study had several limitations, the invitro nature of the study assumes the homogenous and isotropic material properties for PDL and bone, which might have an effect on accuracy of stress and displacement.

CONCLUSIONS:

This finite element study, on maxillary second molar mesialization with aligners using different attachments demonstrated that varying attachment shape and addition of auxiliaries such as class III elastics, optimised the effects on mesial displacement of maxillary second molar. The study proved that the aligner biomechanics needs addition of auxiliaries especially in case of mesialization biomechanics owing to the results of 4th model with optimised attachment and class III elastics with showed the highest amount of mesial displacement being 0.171mm. Also, the study demonstrates the need of different attachment designs to achieve bodily/translatory movement of molar during mesialization biomechanics owing to the mesial tipping movements of second molar in all our study models. The results of our study will guide the orthodontist in planning molar mesialization with clear aligners, about precise use of attachments on molar and combining the auxiliaries in order to enhance the treatment outcome and achieve precision.

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