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Comparative Analysis Of Intrusion Force Vectors With Different Temporary Anchorage Device Placements And Heights In Orthodontic Treatment: A Three Dimensional Finite Element Analysis

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ABSTRACT
Aim and Background: This study aims to analyze the intrusion force vectors by utilizing two combinations of temporary anchorage device placements. Combination I involves two mini-screw implants placed bilaterally between the roots of maxillary first molars and second premolars. Combination II includes an additional midline mini-screw implant placed between the roots of maxillary central incisors at a height of 12 mm from the archwire. The objectives are to assess the maximum principal stress in the bone, implant, and periodontal ligament (PDL) and to determine the initial displacement patterns in vertical and antero-posterior directions under varying conditions.
Methods: Finite element analysis (FEA) was employed to simulate and evaluate the stress distribution and displacement patterns. The study considered different heights of implants (13 mm, 10 mm, and 7 mm from the archwire) and variations in the orientation of anterior retraction hooks. Two groups were analyzed: Group I with bilateral implants and Group II with an additional midline implant at 10 mm height. Each group was subdivided based on the pull direction and height of the implants and hooks.
Results: The analysis revealed that Group II implant placement generally resulted in lower stress levels in the PDL and bone compared to Group I. The 3 mm occlusal anterior retraction hook produced the highest stress in most regions. High-pull implants in Group II were most effective in causing anterior segment intrusion. Initial displacements were influenced by the implant placement combination, height, and hook orientation, with significant variations observed across different setups.
Conclusion: Combination II implant placement with a high-pull orientation and specific anterior retraction hook height can optimize stress distribution and displacement patterns, enhancing the effectiveness of orthodontic treatment. Clinical Significance: This study provides valuable insights into the optimal placement and configuration of mini- screw implants and retraction hooks. For efficient intrusion the use of a mini-screw in the midline along with posterior implant that is combination II was better than only placing 2 mini-screws in the posterior region as in combination I.
Keywords: Finite element analysis, fixed orthodontics, intrusion, mini-implants, temporary anchorage devices

INTRODUCTION

Intrusion in orthodontics can be classified into absolute intrusion and relative intrusion. In absolute intrusion, incisors are intruded but the molars are in place. In relative intrusion, incisors are prevented from erupting further, while growth provides vertical space into which the posteriors are erupted.[1,2]Anchorage control, especially in the vertical dimension, is paramount if bite opening needs to be achieved by genuine intrusion of the anterior teeth. The selection
of the point of application of the intrusive force with respect to the Cres of the anterior segment is also important in the placement of the implants, so that the tooth movement can be predicted more accurately.[3]One should not be mistaken that placing an implant anywhere in the posterior region and applying a retractive force will bring about bodily movement since pre-adjusted brackets are being used.[4]
It is interesting to note that by adjusting the position of the Temporary Skeletal Anchorage Device (TAD) in relation to the occlusal plane and by altering the hook length from where the force originates, individual segments of the arch as well as the final tooth movements can be manipulated.[5]
Analysis of force is very crucial in understanding biomechanics. With the advent of temporary skeletal anchorage devices in the form of mini-screws placed between premolars and molars are being used in cases needing intrusion and retraction. Low, medium and high pull vectors have been identified based on the location of the screw from the occlusal plane.[6] However, some authors have also used just one miniscrew in midline or two (one between central and lateral incisor on either side). Hence, the question would arise as to which combination to be used based on the stress patterns produced in the bone.[7]
In deep-bite cases, implants should be placed as apically as possible whether in the maxilla or mandible between the roots of second premolars and first molars. However, due to anatomic restrictions, this may not always be possible. Hence an additional mini-implant, placed in the area between the roots of the central incisors can be used for bite opening. This accomplishes some anterior retraction along with intrusion.[8]
The finite element analysis makes it possible to analytically apply various force systems at any point and in any direction. In this this FEA study was planned employing combination of 2 (one on either side i.e. between the roots of maxillary second premolars and maxillary first molar) and 3 miniscrews (one on either side and one in the midline between the roots of maxillary central incisors) to analyse the stress distribution in the periodontal ligament and bone with different forces applied from a simulated archwire to miniscrews placed at different levels in the bone. Additionally, the levels of wire attachment as would affect the force vectors were studied.

Objectives

Therefore the aim of this study was to analyse the maximum principal stress with implants at height of 13mm, 10mm and 7mm from the archwire and with added mini-implant in midline at 10mm in second group with at a height of 12mm with variations in anterior hooks. The other aim was to determine the initial displacement in vertical and antero- posterior direction with changes in the number of implants, height of implant placement, height and orientation of anterior retraction hook.

Methods

The study was done using a three dimensional finite element analysis for which the MIMICS 8.11(Materialise's Interactive Medical Imahe Control System) , ANSYS 2.1 , Rapid FORM 2004 and Hypermesh 11.0 was used.In this study, the geometric model was converted into Finite element model by using software called HYPERMESH, which is a general purpose processor and supports many problem solvers like Nastran, Ansys and LS-Dyna. (Figure 1) Nastran was the solver used to do the analysis of the present study.

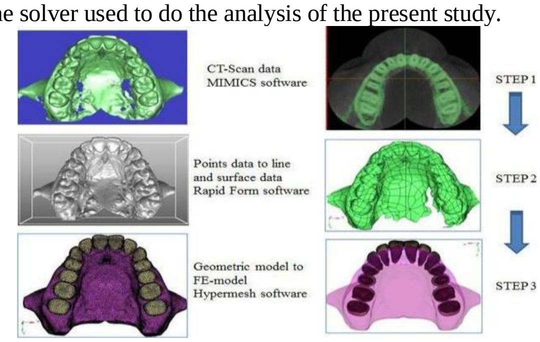

Figure 1: Summary of sequence of conversion process from the stage of CBCT scan

The assignment of proper material problems to a Finite element model is a necessary step to ensure predictive accuracy. Stress-strain relationship in a structure is based on the material properties. These are the Young's Modulus (or modulus of elasticity or elastic modulus) and Poisson's Ratio. (Table 1)

Table 1: Material Properties

Material	Modulus of elasticity (MPa)	Poisson's Ratio
Tooth	80000	0.3
PDL	0.1	0.45
Staineless Steel Wire and Brackets	210 X 10^3	0.3
Cortical / Hard Bone	13800	0.26
Trabecular/Soft bone	345	0.31
Titanium implants	110 x 10^3	0.3

The boundary conditions was determined such that all the six degrees of freedom were restricted at the cut face of the maxilla. Between the arch wire and bracket slots contacts were modeled and all the degrees of freedom were free. Sliding is permitted between 0.019”×0.025” stainless steel arch wire and 0.022 slot used in the study. Linear isotropic properties were used and non-linear static analysis was carried out.

The force application was applied from the bilateral mini-implants to the anterior retraction hook. The anterior retraction hooks are placed between the maxillary lateral incisor and canine one on either side. The loads from the mid-implant are applied directly to the portion of the archwire between the two brackets of maxillary central incisors. The loads applied from both the bilateral implants and the mid-line implants are equal in magnitude for each case.

In this study based on the positioning of implant at various heights in relation to the archwire and number of implants, they can be classified in different groups and sub-groups. (Table 2)

Group	Sub-group	Number and Position of implants
Group I	Group - IA	2 Bilateral low-pull implants one on each side at a height of 7mm from the arch wire
	Group - IB	2 Bilateral Medium-pull implants one on each side at a height of 10mm from the arch wire
	Group - IC	2 Bilateral High-pull implants one on each side at a height of 13mm from the arch wire
Group II	Group - IIA	2 Bilateral low-pull implants one on each side at a height of 7mm from the arch wire and a midline implant at a height of 12 mm the arch wire
	Group - IIB	2 Bilateral Medium-pull implants one on each side at a height of 10mm from the arch wire and a midline implant at a height of 12 mm the arch wire
	Group – IIC	2 Bilateral High-pull implants one on each side at a height of 13mm from the arch wire and a midline implant at a height of 12 mm the arch wire

Table 2: Number and positioning of implants

A space of 2mm distal to canine is created to facilitate for intrusion in the model. (Figure 2) In addition to the bilateral implants an additional

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single implant is placed between the roots of Maxillary central incisors at a height of 10 mm from archwire. Each Bilateral implant was placed between the roots of maxillary second premolar and maxillary first molar. The effect of single mid-line implant along with bilateral implants on intrusion force vectors will be studied in each case i.e. along with High pull; medium pull and low pull implants.

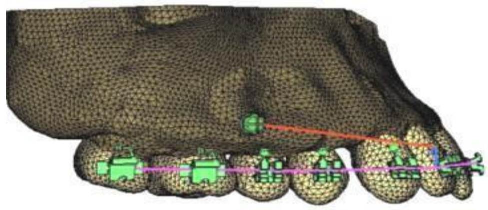


FIGURE 2 : FEM Models with low pull implants at a height of 7mm from arch wire and space of 2mm created distal to canine to facilitate intrusion

The height and orientation of the hooks are also varied as 3mm hook gingivally, 6mm hook gingivally , 9mm hook gingivally and 3mm hook occlusally. The different combinations of implants and hook heights are subjected to loads of magnitude of 90gms, 120 gms , 150 gms , 180 gms and 210 gms. (need to add figure/table) . In this study 24 FEA models and the details of FEM Models. (Table 3 and Figure 3)

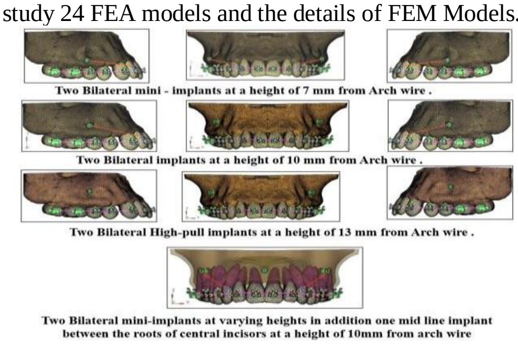


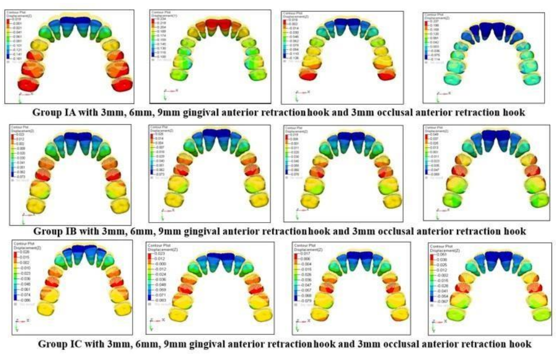
FIGURE 3 : EXAMPLE DEPICTING THE FEA MODELS

Table 3: Details of FEM models

Sl. No MODEL	POSITION OF IMPLANT IN GROUPS	PLACEMENT OF HOOK
Model 1	Low pull implants 2 only	3 mm hook gingivally
Model 2	Low pull implants 2 only	6 mm hook gingivally
Model 3	Low pull implants 2 only	9 mm hook gingivally
Model 4	Low pull implants 2 only	3 mm hook occlusally
Model 5	Medium pull implants 2 only	3 mm hook gingivally
Model 6	Medium pull implants 2 only	6 mm hook gingivally
Model 7	Medium pull implants 2 only	9 mm hook gingivally
Model 8	Medium pull implants 2 only	3 mm hook occlusally
Model 9	High pull implants 2 only	3 mm hook gingivally
Model 10	High pull implants 2 only	6 mm hook gingivally
Model 11	High pull implants 2 only	9 mm hook gingivally
Model 12	High pull implants 2 only	3 mm hook occlusally
Model 13	Low pull implants 2 & 1 mid implant	3 mm hook gingivally
Model 14	Low pull implants 2 & 1 mid implant	6 mm hook gingivally
Model 15	Low pull implants 2 & 1 mid implant	9 mm hook gingivally
Model 16	Low pull implants 2 & 1 mid implant	3 mm hook occlusally
Model 17	Medium pull implants 2 & 1 mid implant	3 mm hook gingivally
Model 18	Medium pull implants 2 & 1 mid implant	6 mm hook gingivally
Model 19	Medium pull implants 2 & 1 mid implant	9 mm hook gingivally
Model 20	Medium pull implants 2 & 1 mid implant	3 mm hook occlusally
Model 21	High pull implants 2 only & 1 mid implant	3 mm hook gingivally
Model 22	High pull implants 2 only & 1 mid implant	6 mm hook gingivally
Model 23	High pull implants 2 only & 1 mid implant	9 mm hook gingivally
Model 24	High pull implants 2 only & 1 mid implant	3 mm hook occlusally

Results

The results indicate varied effects of different retraction hooks on anterior and posterior segments in orthodontic intrusion. In Group IA (2 low-pull implants), extrusion of the entire anterior segment was observed with 3mm and 6mm gingival hooks and a 3mm occlusal hook, while the 9mm gingival hook caused intrusion in lateral incisors and canines. (Figure 4) The posterior segment showed intrusion with 3mm and 6mm gingival hooks, except for the first premolar, and extrusion with a 9mm gingival hook. Group IIA (2 low-pull implants and 1 mid-line implant) exhibited anterior segment extrusion with a 3mm gingival hook, while other hooks caused intrusion in central incisors and extrusion in lateral incisors and canines. The posterior segment intruded with a 3mm occlusal hook but extruded with 6mm and 9mm gingival hooks (Figure 5) Group IB (2 medium-pull implants) showed anterior extrusion with all hooks, and posterior intrusion with 3mm and 6mm gingival hooks and a 3mm occlusal hook, while the 9mm gingival hook caused molar extrusion. Group IIB (2 medium-pull implants and 1 mid-line implant) showed central incisor intrusion with all hooks, with the posterior segment intruding with 3mm gingival and occlusal hooks, but extruding with 9mm gingival hooks. In Group IC (2 high-pull implants), all hooks caused anterior extrusion, while 3mm gingival and occlusal hooks caused posterior intrusion, with varying effects from 6mm and 9mm gingival hooks. Finally, in Group IIC (2 high-pull implants and 1 mid-line implant), 3mm hooks caused overall intrusion, while 6mm and 9mm gingival hooks caused anterior intrusion and extrusion of canines and molars.



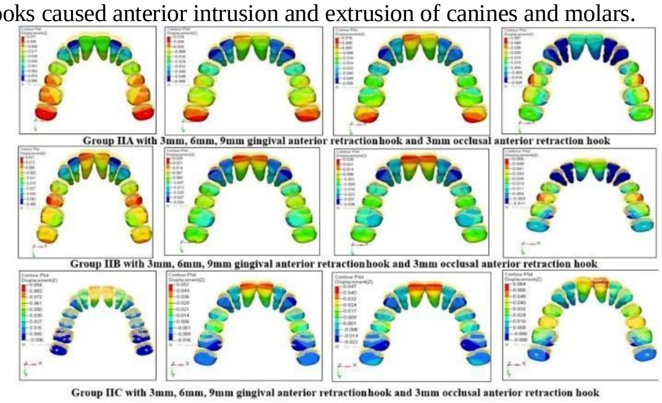


Figure 4: Displacement contours of teeth in vertical direction in group I | Figure 5: Displacement contours of teeth in vertical direction in group II

The results show that the antero-posterior movement of anterior teeth varies with different groups and retraction hooks. (Figure 6 and 7) In Group IA (2 low-pull implants), a combination of bodily movement and palatal tipping occurred, with maximum retraction using a 3mm gingival hook. Group IIA (2 low-pull implants and 1 mid-line implant) showed similar movement but with a tendency for labial tipping, and less overall posterior movement compared to Group IA. Group IB (2 medium-pull implants) also experienced palatal tipping and posterior movement, but less than Group IA due to a greater vertical force component. Group IIB (2 medium-pull implants and 1 mid-line implant) showed more labial tipping with the root moving more posteriorly, and reduced posterior movement compared to Group IB. In Group IC (2 high-pull implants), the movement was characterized by palatal tipping and increased posterior displacement compared to Group IB. Group IIC (2 high-pull implants and 1 mid-line implant) exhibited labial tipping with less posterior movement compared to Group IC. Across all groups, some degree of posterior segment movement was consistently observed. The 3mm gingival anterior retraction hook generally caused the most retraction in all configurations.

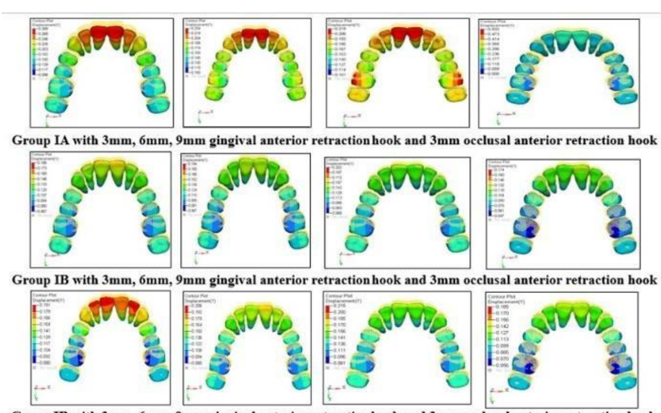


Figure 6: Displacement contours of teeth in antero-posterior direction in Group I on application of force of 90 gms

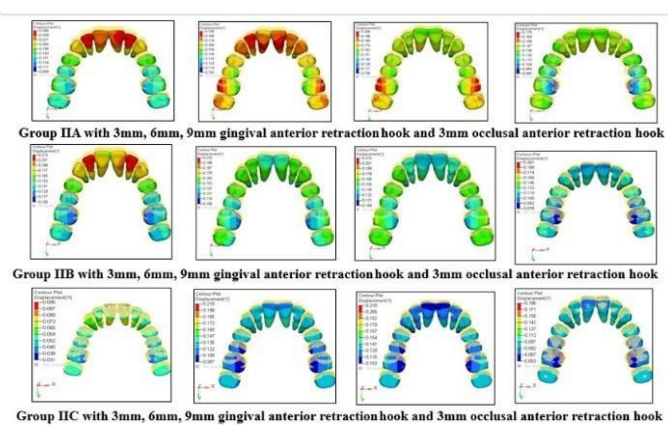


Figure 7 : Displacement contours of teeth in antero-posterior direction in Group II on application of force 90 gms

Discussion

In this study, the maximal principal stress occurring in the bone around the implant region and within the implant was examined across various groups and orientations of retraction hooks. It was found that the stresses produced in the bone around the implant were generally higher with occlusal orientation of the 3mm anterior retraction hook, except in Group IB (2 medium pull implants with 3mm retraction height). In several groups (IA, IB, IIB, and IIC), stresses were lower with a 3mm gingival retraction hook. In Group IIA, the 6mm and 9mm gingival anterior retraction hooks produced similar, lower stress values. For Group IC, the 9mm gingival anterior retraction hook resulted in the least stress. As the magnitude of force increased, the stress levels in both the bone and implants rose accordingly.

The results of the initial displacements of teeth in the vertical direction revealed that Group IA exhibited extrusion of the entire anterior segment with 3mm and 6mm gingival hooks and a 3mm occlusal hook, while the 9mm gingival hook caused intrusion in lateral incisors and canines. The posterior segment showed intrusion with 3mm and 6mm gingival hooks, except for the first premolar, and extrusion with the 9mm gingival hook. Group IIA showed anterior segment extrusion with a 3mm gingival hook, while other hooks caused intrusion in central incisors and extrusion in lateral incisors and canines. The posterior segment intruded with a 3mm occlusal hook but extruded with 6mm and 9mm gingival hooks.

Mini- screws or Temporary Anchorage Device (TAD) assisted intrusion have consistently shown that TADs provide reliable anchorage for vertical tooth movements, significantly improving treatment outcomes in cases requiring intrusion of posterior teeth to correct anterior open bites or excessive overjet. Similar studies in literature Alqerban et al. (2018) and Kuroda et al. (2020), has focused on optimizing mini-implant placement and the biomechanics of different retraction hook orientations. These studies highlight that the orientation and height of the retraction hook can significantly affect stress distribution and tooth movement patterns, similar to our findings where the 3mm gingival retraction hook generally resulted in lower stress levels in both bone and implants across several groups[9,10]

The findings of our study showed that medium pull and high pull groups where there was an increased vertical force component resulted in higher stress levels this was in accordance to the study by Park et al.(2011) when the investigated the biomechanical effects of different force directions and point of application on mini-implants finding that higher forces and certian retraction hook heights can lead to increased stress on surrounding bone.[11] Yao et al. (2014) demonstrated that mini-implants placed in the posterior maxilla could significantly reduce molar intrusion and assist in effective anterior tooth retraction, similar to our findings where strategic placement of mini-implants influenced both posterior and anterior tooth movements.[12] A systematic review by Cornelis et al. (2015) concluded that mini-implants are versatile and effective in managing complex orthodontic movements, including intrusion and retraction. They emphasized the importance of precise biomechanical control, which is consistent with our results indicating that careful selection of implant position and retraction hook orientation can optimize treatment outcomes.

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Zhu et al. (2016) focused on the stress distribution in the periodontal ligament and bone with different mini-implant positions and force vectors. Their findings support the notion that varied implant positions can significantly impact stress distribution and tooth movement patterns, underscoring the importance of individualizing treatment plans based on biomechanical principles, as demonstrated in our study.[14]

Moreover, Motoyoshi et al. (2019) explored the longevity and stability of mini-implants under different force conditions, finding that well-placed implants could sustain significant forces without failure. This reinforces our findings that strategic placement and appropriate force application can lead to successful and stable orthodontic outcomes.[15]

The findings of this study align with and expand upon the existing literature regarding orthodontic biomechanics, particularly in managing stress distribution and tooth movement with mini-implants and retraction hooks. Previous studies have consistently demonstrated the efficacy of mini-implants in providing stable anchorage for orthodontic treatments. The variation in stress levels and tooth movement patterns observed in this study underscores the importance of precise biomechanical control and strategic placement of implants and hooks.

Motivational and reminder therapy could significantly improve patient compliance with fixed appliances, which is crucial for achieving optimal treatment outcomes in orthodontics.[16] Enhanced compliance ensures the effectiveness of biomechanical systems, including the strategic use of temporary anchorage devices (TADs). This supports the notion that patient cooperation is vital for the success of the configurations studied.

Fractal analysis to evaluate alveolar bone microstructure has shown that bone quality significantly impacts the outcomes of orthodontic treatments.[17] This complements our findings on stress distribution, as variations in bone density and structure can influence the stability and performance of mini-implants.

The correlation between craniofacial morphology and orthodontic parameters highlights the role of anatomical factors in determining treatment strategies.[18] Similarly, this study demonstrated how implant placement and hook height could be adjusted to account for individual anatomical variations, optimizing stress distribution and displacement patterns.

The effects of local bisphosphonate administration on orthodontic anchorage concluded that such treatments could enhance bone density and implant stability.[19] While this study focused on mechanical configurations, future research could explore integrating pharmacological adjuncts to further improve outcomes.

The use of chlorhexidine oral rinses in preventing plaque accumulation and gingivitis during orthodontic treatment has been systematically reviewed.[20] Maintaining oral hygiene is critical for the success of mini-implant-assisted systems, as inflammation or infection around the implant sites could compromise their stability.

The role of materials and coatings in reducing friction and enhancing orthodontic mechanics was highlighted by studies on nanoparticle coatings.[21] These findings align with our study's emphasis on minimizing adverse effects through careful selection of mechanical components, such as hook orientation and implant height.

The prevalence of white spot lesions in patients treated with fixed orthodontic appliances emphasizes the importance of preventive measures.[22] While this study focused on biomechanical aspects, the integration of preventive strategies could further enhance patient outcomes.

The comparative evaluation of different mini-implant configurations and their biomechanical effects reinforces the findings of this study.[23-25] Strategic placement and appropriate force application can optimize stress distribution and tooth movement, minimizing unwanted side effects such as root resorption or implant failure.

In summary, this study's findings contribute to the growing body of evidence supporting the use of TADs for effective anchorage and controlled tooth movements. By integrating insights from the cited literature, this study underscores the importance of individualized treatment planning and the potential for combining mechanical and pharmacological strategies to enhance orthodontic outcomes.

The limitation of this study is that it is a Finite element Analysis (FEA), the results may vary in clinical set up. The finite element method (FEM) simulations, while highly informative, are based on idealized models that may not account for individual anatomical variations and biological responses. Additionally, the study's focus on specific retraction hook orientations may limit the generalizability of the findings to other clinical scenarios where different configurations might be used. Future research should aim to include clinical trials that validate these FEM findings and explore a broader range of hook orientations and force magnitudes.Additionally, the study's focus on specific retraction hook orientations may limit the generalizability of the findings to other clinical scenarios where different configurations might be used. Future research should aim to include clinical trials that validate these FEM findings and explore a broader range of hook orientations and force magnitudes.

conclusion

This study concludes that the 13 mm height for posterior implants provides the most effective anchorage for anterior retraction and posterior intrusion. The addition of an extra midline implant between the maxillary central incisors enhances control over stress distribution and overall tooth movement, making Group II (two low-pull implants and one midline implant) superior to Group I (two low-pull implants only). Group II consistently demonstrated better

results in terms of reducing unwanted tipping and achieving more controlled bodily movement. The 3mm gingival anterior retraction hook emerged as the most effective in producing significant intrusion with minimal adverse effects. Additionally, medium retraction forces were found to be optimal for achieving the desired tooth movements without overloading the implants or causing excessive stress on the periodontal ligament. These findings suggest that a combination of strategically placed mini-implants and appropriate retraction hook height and force can significantly enhance orthodontic treatment outcomes.

Understanding the effects of different retraction hook orientations and force magnitudes on stress distribution and tooth movement can aid in designing more effective and individualized treatment plans. This is particularly important for patients requiring significant tooth intrusion or retraction, where precise control over biomechanics is essential to prevent unwanted side effects such as root resorption or loss of anchorage.

LIST OF ABBREVIATIONS

FEA – Finite element analysis FEM-
Finite element method PDL-
Periodontal ligament
TAD – Temporary anchorage devices
MIMICS- Materialise's Interactive medical Imahe Control System

FIGURE LEGENDS :

Figure 1:Summary of sequence of conversion process from the stage of CBCT scan data to the generation of Finite Element (FE) Model
FIGURE 2 : FEM Models with low pull implants at a height of 7mm from arch wire and space of 2mm created distal to canine to facilitate intrusion

FIGURE 3 : EXAMPLE DEPICTING THE FEA MODELS

Figure 4: Displacement contours of teeth in vertical direction in group I Figure 5:
Displacement contours of teeth in vertical direction in group II
Figure 6: Displacement contours of teeth in antero-posterior direction in Group I on application of a force of 90 gms Figure 7 : Displacement contours of teeth in antero-posterior direction in Group II on application of a force of 90 gms

TABLE LEGENDS:

Table 1: Material properties
Table 2: Number and positioning of implants Table 3: Details
of FEM models

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