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Original Article

Finite Element Method (FEM) Analysis of Dentoskeletal Changes on Temporary Anchorage Device (TAD)-Assisted Mandibular Advancement

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Main Points

- Finite element analysis revealed that Class II elastics combined with interconnected implants produce significant skeletal stress in the posterior ramus of the mandible and the lateral nasal aperture of the maxilla, with minimal dental stress
- The observed stress patterns indicate a tendency toward maxillary distalization and mandibular advancement, which reflects a greater contribution of skeletal displacement compared to dental movement.
- The findings support the potential of this approach in achieving skeletal correction, but further clinical validation under dynamic loading conditions is necessary.

ABSTRACT

Objective: Temporary anchorage devices (TADs) enhance the efficiency of fixed functional appliances (FFAs) by providing stable anchorage, improving skeletal and dental corrections, optimizing vertical control, and enhancing treatment outcomes for Class II and III malocclusions. TADs also help prevent the proclination of the lower incisors and the distalization of the molars, which are commonly observed with FFAs lacking skeletal anchorage. This study aims to analyze the displacement and stress distribution patterns generated in craniofacial structures and dentition using conjoined implants and intermaxillary elastics for growth modification in growing Class II patients.

Methods: Finite element analysis was conducted using cone-beam computed tomography data from an 11-year-old patient with Class II Division 1 malocclusion. Mini-implants and miniplates were designed and assembled in SolidWorks, meshed using HyperMesh, and analyzed in Abaqus 6.14 to evaluate stress and displacement patterns under a 450 g orthopedic force applied via Class II elastics.

Results: In the mandible, the highest principal and von Mises stresses were observed on the posterior surface of the ramus, whereas in the maxilla, stress concentrations were noted lateral to the nasal aperture. Additional stress concentrations were identified in the region posterior to the glenoid fossa. The mandible was displaced anteroinferiorly as a whole, while the maxilla exhibited posterosuperior displacement. Dental movements included maxillary expansion with intrusion of the anterior teeth, and anterior displacement of the mandibular dentition, primarily resulting from bodily movement.

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Conclusion: The use of Class II elastics in combination with Temporary Anchorage Devices (TADs) produces greater stress and displacement in skeletal structures compared to the dentition. As a result, this treatment approach is more likely to produce substantial skeletal changes than dental alterations.

Keywords: Anchorage devices, biomechanics, bone remodeling, Class II, displacements, retrognathic mandible, temporary anchorage devices

INTRODUCTION

Growth plays a significant role in modulating treatment plans for skeletal and dental corrections. Fixed functional therapy with fixed functional appliances (FFAs) is a primary method for correcting Class II skeletal discrepancies due to a retrognathic mandible in growing patients. Class II malocclusion is often characterized by mandibular retrusion, and a variety of functional appliance modalities have been developed to optimize mandibular positioning in both the sagittal and vertical dimensions.[1]

FFAs are considered "non-compliant Class II inter-arch correctors" and achieve significant growth modification. These appliances promote mandibular advancement by mitigating dental interference and consolidating the dental arches, leading to craniofacial orthopedic, soft tissue, and orthodontic changes.[2-7] However, research has shown undesirable dental effects, including forward tipping of the lower incisors, backward tipping of the upper incisors, and a decrease in the interincisal angle, which can prolong treatment time.[8] Increased lower incisor inclination reduces the amount of skeletal correction achievable and increases the risk of relapse. Additionally, external root resorption has been reported as statistically significant in cases treated with the Forsus Fatigue Resistant Device (FFRD) and the Herbst appliance, with resorption of up to 0.81 mm and 1.55 mm, respectively.[9-11]

Skeletal anchorage is the most effective method for reinforcing anchorage, regardless of the type of planned tooth movement in orthodontics. To this end, many appliances have been modified to include Temporary Anchorage Devices (TADs) to improve anchorage.[12] The use of TADs in conjunction with FFAs has been shown to augment anchorage and prevent the adverse effects associated with FFAs alone.[13] For instance, Ince-Bingol et al.[14] found that the relapse rate one year post-treatment was not significantly different between cases managed with a combination of FFAs and TADs compared to those treated with FFAs alone. Bakdach and Hadad[15] reported that the Forsus appliance combined with bilateral miniplates enhanced skeletal and dental corrections in Class II growing patients, with treatment effects being largely dentoalveolar and a reduction in proclination of the lower incisors.

The miniplate-supported Forsus FRD appliance has been found to significantly retract both the maxillary and mandibular incisors compared to the effects observed with the activator appliance and untreated control groups. The authors suggested that the results might differ if the force were applied through skeletal anchorage in both jaws.[16] In 2016, Al-Dumaini et al.[17] described a treatment approach for Class II skeletal correction in growing patients using miniplate-based skeletal anchorage in conjunction with Class II elastics delivering up to 450 g of force bilaterally. However, a disadvantage of miniplates is that they provide indirect anchorage from the bone surface, and their placement in children is invasive. While miniscrews engage the bone directly, their stability is compromised when high forces are applied.[18] Connecting two miniscrews with a miniplate can enhance the stability of the anchorage system.[19-21]

Protraction of the mandible generates forces that produce stress and strain in various parts of the orofacial complex and the temporomandibular joint, thereby influencing biological changes. The application of elastics introduces an additional layer of complexity to the patterns of stress distribution and bone remodeling. The finite element method provides a unique analytical framework for examining stress patterns, deformations, and displacements in systems with irregular geometries and non-homogeneous material properties. Finite element analysis (FEA) can quantify stress levels at specific points within the teeth, periodontal ligaments, alveolar bone, and craniofacial structures. It also facilitates in vitro simulation of the oral environment and graphical representation of displacements caused by applied forces.[22]

The authors of the present study developed a model to correct Class II skeletal malocclusions in growing patients. In this model, extraoral elastics delivering a force of 450 g are applied from a hook on a miniplate—supporting a pair of mini-implants placed in the attached gingiva of the mandibular molar region—to a miniplate hook located in the maxillary canine region. Finite element analysis (FEA) was used to evaluate the displacement and stress patterns induced in the maxilla, mandible, condyle, and maxillary-mandibular dentition by the application of 450 g orthopedic forces through elastics connected between implants in the maxillary canine and mandibular molar regions.

METHODS

This research was designed and conducted at Saveetha Dental College the Institution in Chennai, India Ethics Committee approved the study protocol SRB/SDC/ORTHO-2102/23/231. Prior to enrollment, informed consent was obtained from the participant. An 11-year-old female patient with protrusive maxillary incisors, exhibiting Angle's Class II Division 1 malocclusion—characterized by a normal upper jaw, a retrognathic lower jaw, average growth pattern, favorable facial esthetics, well-aligned lower dentition, and no signs of temporomandibular joint disorder—was selected for this investigation. Comprehensive pre-treatment records, including study models, photographs, and cone-beam computed tomography (CBCT) scans, were collected for this patient.

For clarity, the methodology may be divided into the following steps:

1. File Conversion and Design

The CBCT acquired in Digital Imaging and Communications in Medicine (DICOM) format was converted to Standard Tessellation Language (STL) format using Geomagic Freeform software (3D Systems). SolidWorks Software (Dassault Systèmes) was used to design the miniplate and mini-implants. The dimensions of the mini-implants were 8 × 1.5 mm. Mini-implants were placed in the interradicular areas - between upper lateral incisor and the upper canine and, between upper canine and upper first premolar - their positioned 10 mm apical to the cementoenamel junction. The miniscrews were connected to each other with a miniplate bearing a hook to serve as the point of force application. A similar arrangement was designed in the lower arch, with the mini-implants were placed mesial and distal to the mesiobuccal root of the first molar.

2. Computer-Aided Design Modelling

The CBCT data, along with the designed miniplate and miniscrews, were imported in Standard Tessellation Language (STL) format into SolidWorks software (Dassault Systèmes) for computer-aided design (CAD) modeling. The STL model underwent geometric corrections and fine-tuning. The finalized CAD model is shown in Figure 1.

3. Pre-processing

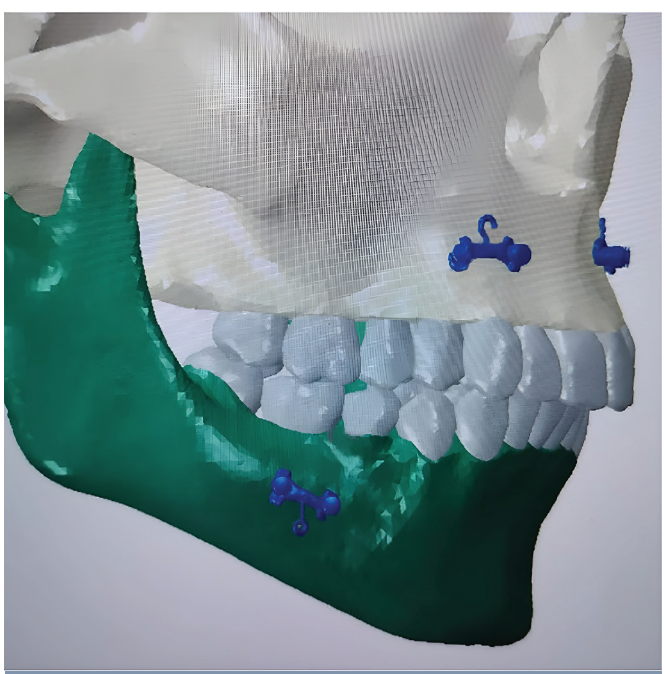

Figure 1. The CAD model with designed conjoined miniscrews
CAD, computer-aided design

Finite element meshing was performed using Altair HyperMesh 14.0.120, as illustrated in Figure 2, to generate a finite element model (FEM). Cortical and trabecular bone, along with the teeth, were modeled as homogeneous linear elastic materials. A thickness of 1 mm covering the surface areas of the jawbones where the teeth were located was defined as cortical bone, with the underlying region modeled as trabecular bone. The miniplate and miniscrews were then assembled onto the finite element model. Table 1 lists the material properties assigned to each component, and Table 2 provides the number of nodes and elements in the FEM.[23-28]

Boundary conditions were applied to constrain the maxilla, and contact interactions were defined. To simulate the intermaxillary elastics hooked between the maxillary and mandibular anchors, a pulling force of 450 g was applied.

4. Solving

Once the FEM was completed, the model was data-checked and prepared for analysis. Linear static analysis was performed for the applied load using Abaqus 6.14 software. Once the analysis is completed, the results were post-processed using the Abaqus Viewer. Stress values were expressed in megapascals (MPa). The color scale on the left side of each figure indicates the corresponding stress levels. Statistical analysis was not performed, as the study did not include multiple patient groups. The assessed outcomes included principal stresses, von Mises stresses, and displacements.

RESULTS

Principal Stresses and Von Mises Stresses

For the applied load on the FE model, the calculated stresses are reported in Table 3 and illustrated in Figure 2. The maximum stress recorded in the FE model was observed in the maxilla and mandible, with values of approximately 7 MPa. While the maxilla and mandible exhibited similar von Mises stress values, principal stresses in the maxilla (10.2 MPa) were higher than those in the mandible (7.1 MPa). In the maxilla, the highest stress concentration was observed around the miniscrew insertion site, in the region latero-inferior to the nasal aperture and posterior to the glenoid fossa. In the mandible, however, the greatest stress concentration was located on the posterior surface of the ramus. The miniplate exhibited significantly

Table 1. Material properties used in the study

Name	Young's Modulus (Mpa)	Poisson's Ratio
Maxilla	2,000	0.3
Mandible	7,000	0.3
Teeth	20,000	0.3
PDL	5	0.3
Implant	2,00,000	0.3
Miniplate	200000	0.3

PDL, periodontal ligament

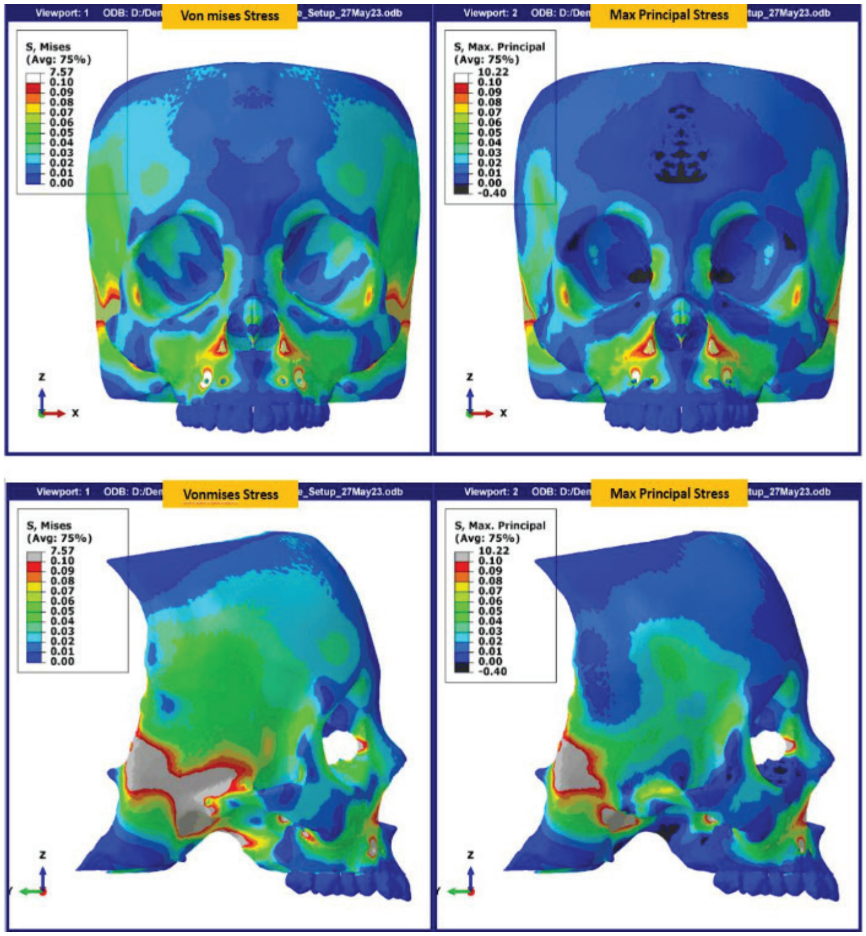

Figure 2. Stress distribution in the maxilla in frontal and lateral view

Table 2. The number of nodes and elements in the FE model		
	Model	
Name	No. of Nodes	No. of Elements
Maxilla	115113	526770
Mandible	23036	98969
Maxillary teeth	25020	107293
Mandibular teeth	23265	99164
Maxillary PDL	2194	4146
Mandibular PDL	3136	5991
Implant	14500	55940
Miniplate	27216	113932
Total	233480	1012205

PDL, periodontal ligament; FE, finite element

greater stress than the miniscrew.

Displacements in the Finite Element Model

Displacements were recorded in all three spatial dimensions and are displayed in Figure 3. The X-axis represents displacements in the transverse plane, the Y-axis corresponds to the sagittal plane, and the Z-axis to the vertical plane. In the maxilla, the observed displacement occurred primarily along the X-axis, indicating transverse expansion. In the mandible, a forward displacement of the coronoid process followed by the condyle was observed, along with posterior displacement of the mental region. A superior displacement of the anterior portion of the mandible was also observed, with its magnitude decreasing in the anteroposterior direction.

Table 3. Summary of stresses generated in the model		
Maximum Stress Result Summary (MPa)		
Name	Von Mises	Max Principal
Maxilla	7.57	10.218
Mandible	7.379	7.191
Maxillary teeth	0.81	0.776
Mandibular teeth	1.827	2.067
Maxillary PDL	0.006419	0.003725
Mandibular PDL	0.013126	0.014975
Implant	105.696	88.529
Miniplate	334.294	271.893

PDL, periodontal ligament

Displacements in the dentition were observed both en masse and in relation to the alveolar bone. As depicted in Figure 4, in the maxillary dentition, the highest displacements in the transverse plane were recorded for the first molars, followed by the second molars and premolars. In the sagittal plane, a mesial displacement was noted for the anterior teeth up till the premolars. In the vertical plane, intrusion of the anterior teeth and extrusion of the second molars were recorded. In the mandibular arch, the greatest expansion was observed in

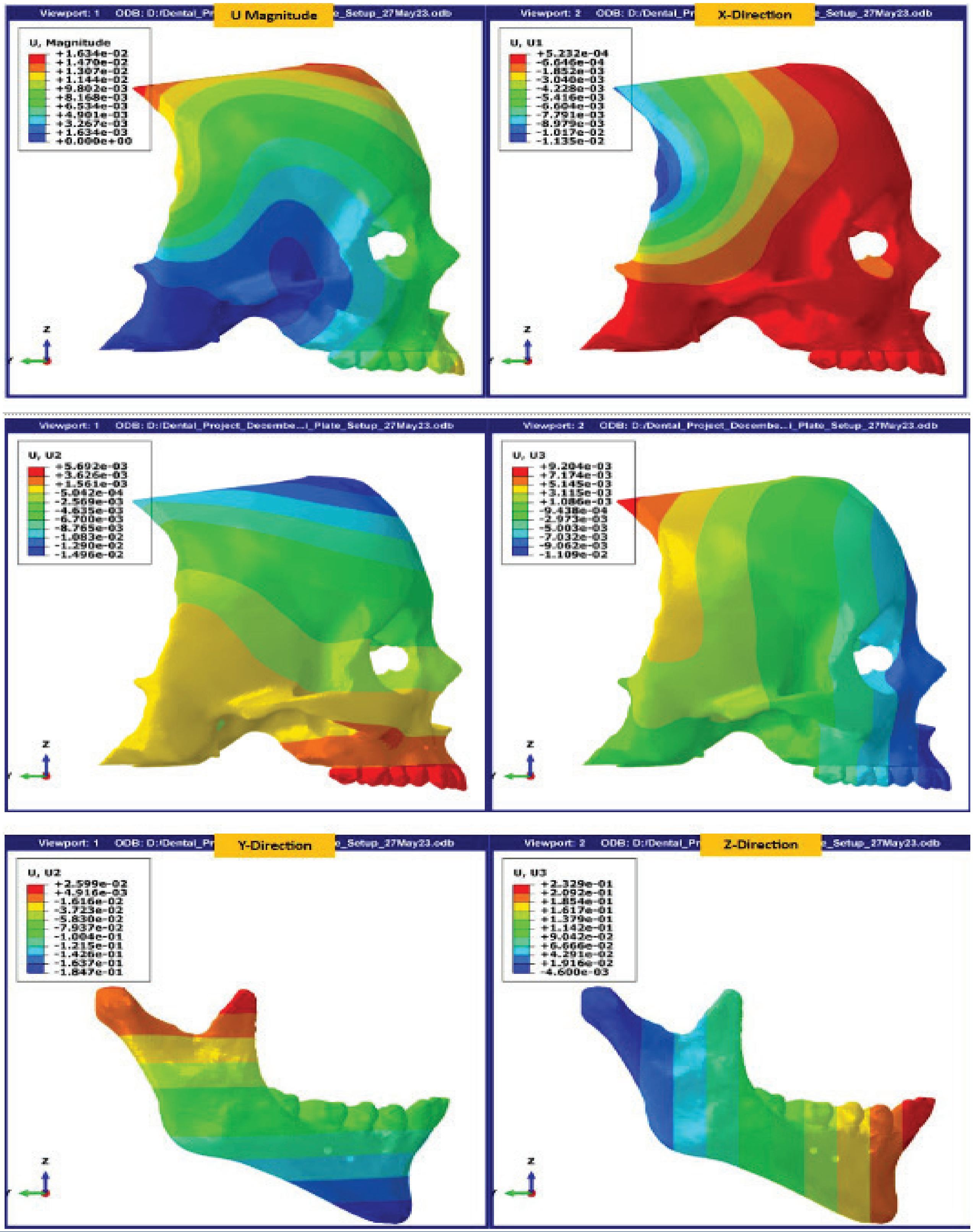

Figure 3. Displacements of the maxilla and mandible

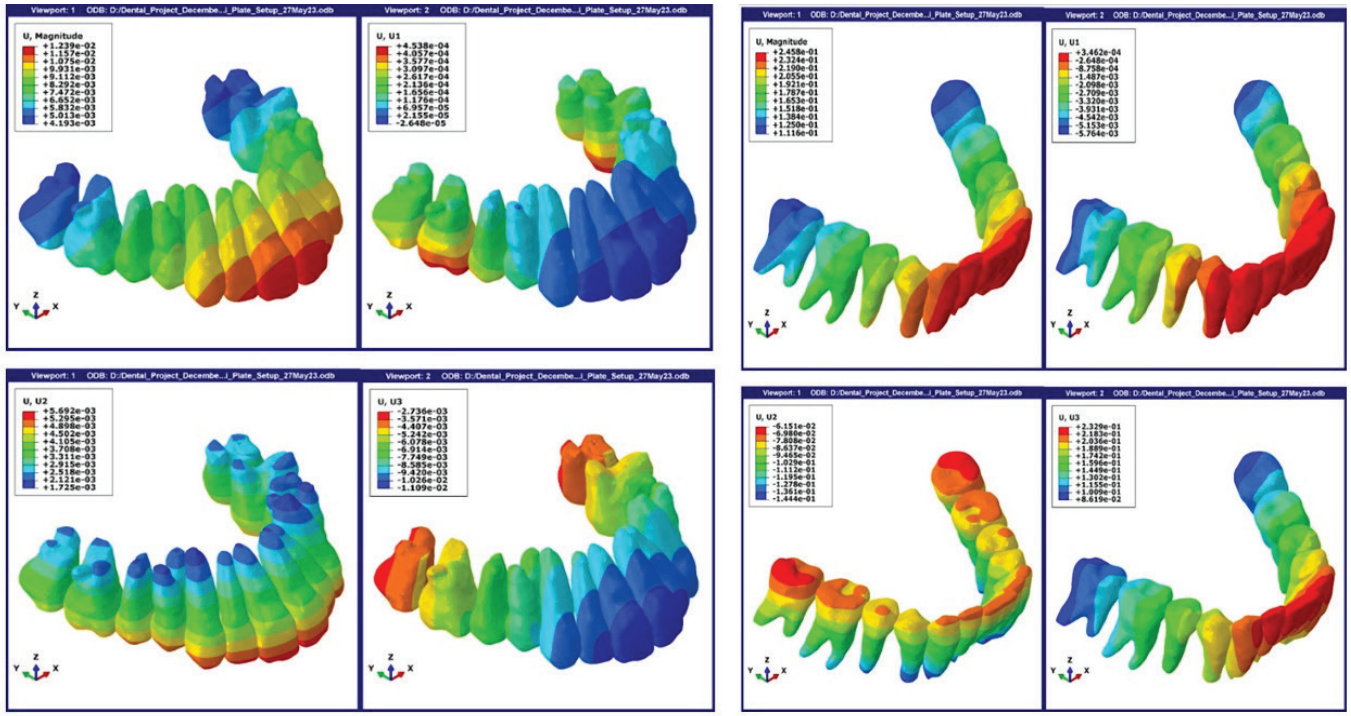

Figure 4. Maxillary and mandibular dentition displacement

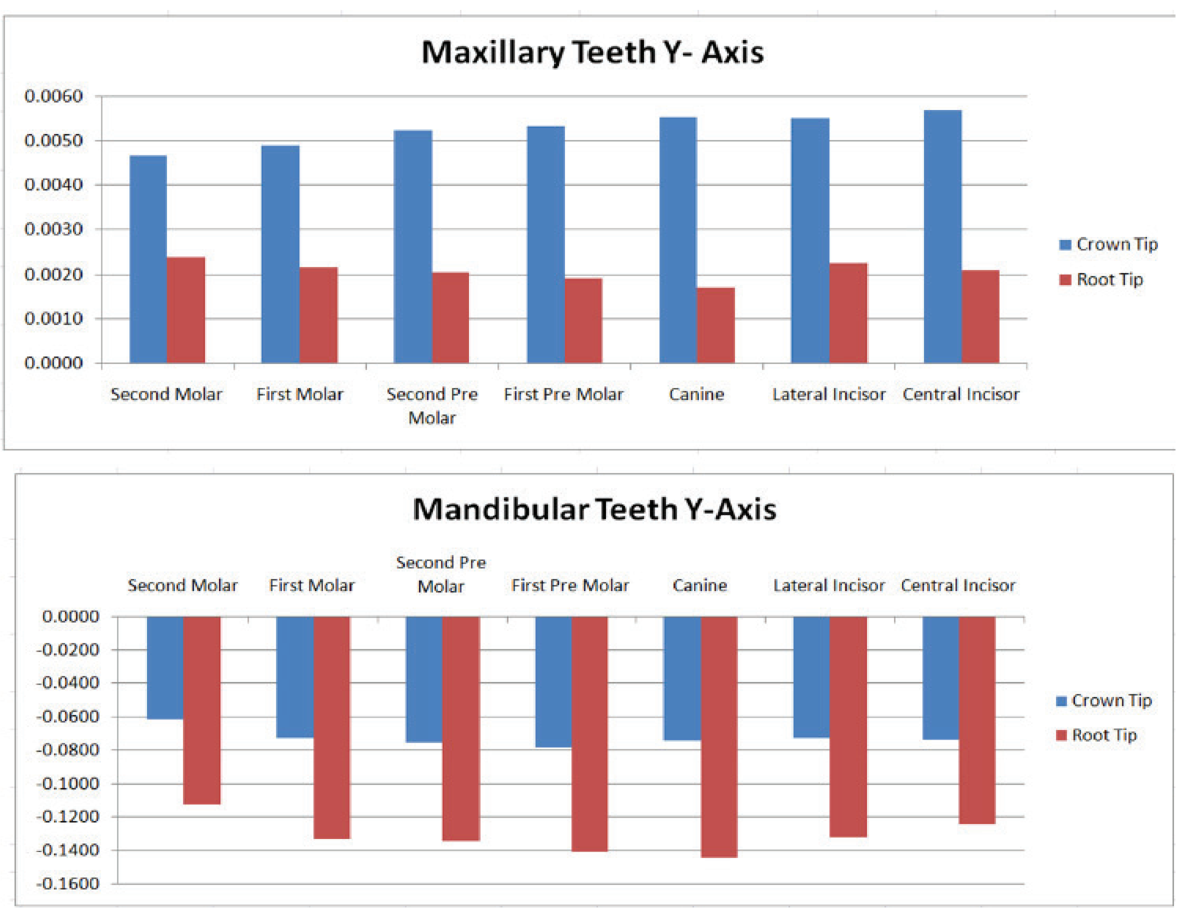

Figure 5. Distalization of the maxillary dentition and mesialisation of the mandibular dentition as seen in the sagittal plane

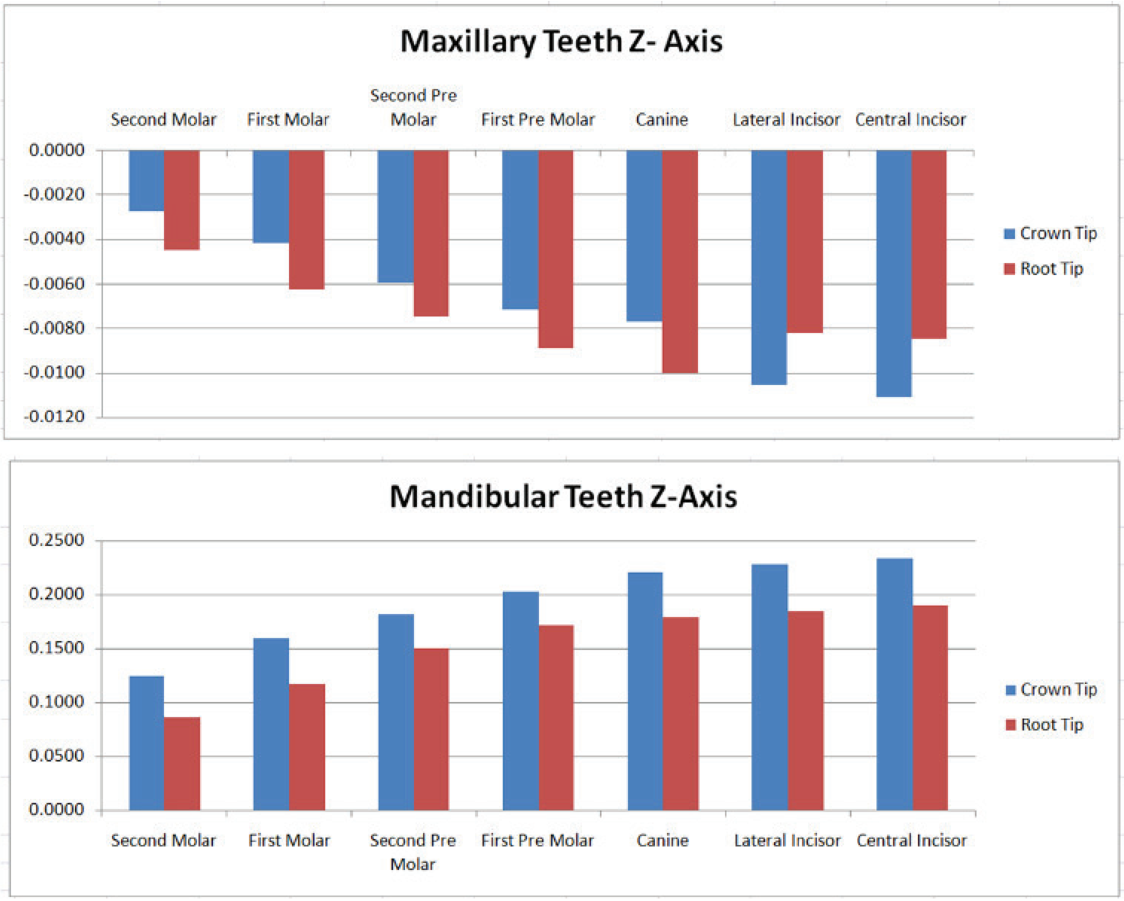

Figure 6. Extrusion of the maxillary crown and Intrusion of the mandibular of the crown and roots as seen in the vertical plane

the anterior dentition. Anterior displacement was observed in both the molars and incisors, with the greatest extrusive displacement occurring in the incisors. These displacements are illustrated in Figure 4.

Figures 5 and 6 provide a graphical representation of crown and root displacements along the Y-axis and Z-axis, respectively. In the Y-axis, displacement values are greater for the crown than the root in the maxillary dentition, while the opposite is observed in the mandibular dentition. This suggests that the retroclination (posterior displacement) of the maxillary teeth is primarily due to tipping, whereas in the mandible, the teeth exhibit anteriorly directed bodily displacement.

Similarly, extrusion of the maxillary posterior teeth is primarily caused by bodily movement, whereas in the anterior segment it is due to tipping. In the lower arch, extrusion of the mandibular teeth appears to result from tipping movements rather than translational displacement.

The finite element analysis investigating the effects of Class II elastics used in conjunction with conjoined implants yielded several significant findings. Notably, in the mandible, the maximum principal and von Mises stresses were concentrated in the cortical bone region of the posterior ramus, whereas the mandibular dentition experienced comparatively lower stress levels. In the maxilla, the highest stresses were observed in the region lateral to the nasal aperture. Additionally, mild expansion was noted in the maxillary dental segments.

Moreover, the condylar process and sigmoid notch exhibited the highest concentrations of principal and von Mises stresses. The analysis also indicated a distalizing effect on the maxilla and a protractive effect on the mandible. Interestingly, dental movements along the mandibular arch in the sagittal plane were primarily attributed to bodily displacement.

However, it is important to note that FEA considers only static loading of the maxilla and mandible. Therefore, a clinical study is necessary to assess the dynamic forces exerted by this therapy. Such a study would provide a more comprehensive understanding of the treatment effects and help validate the findings derived from FEA.

DISCUSSION

The finite element method (FEM) is a computational approach used to approximate solutions for boundary-value problems in engineering applications. It facilitates the simulation of biomechanical parameters, including stress, strain, and displacement, which occur within living systems due to the application of external forces. Bone remodeling occurs in response to compressive and tensile stresses induced by functional orthopedic forces. Understanding displacements and stresses can aid in predicting treatment outcomes.[22-35] Applying FEM analysis to TAD-assisted mandibular advancement enables the study of forces and deformations on the mandible and associated soft tissues.

FEM analysis enables the assessment of force and deformation distribution across the mandible and adjacent soft tissues during TAD-assisted mandibular advancement. This analysis provides valuable insights into the biomechanical response of the dentoskeletal system to TAD-assisted mandibular advancement, supporting treatment planning. FEM analysis also allows for the evaluation of mechanical stresses induced by TADs during mandibular advancement and their impact on dental and craniofacial structures. In this study, the finite element model was constructed to evaluate stress and displacement in the dentition and craniofacial skeleton under a 450 g force applied via intraoral elastics to miniplates connecting two miniscrews placed in the upper canine and lower molar regions. The use of a skeletally anchored appliance prevents unnecessary loading of the dentition, particularly since bone bears mechanical loads more effectively and has a higher modulus of elasticity than the periodontal ligament (PDL).

The study findings revealed that the highest stress concentrations occurred around the miniscrew insertion sites. Furthermore, elevated stress concentrations were observed in the vicinity of the nasal aperture and posterior to the glenoid fossa in the maxilla. In the mandible, notable stress concentrations were found both at the miniscrew insertion sites and on the posterior surface of the ramus, inferior to the condylar neck. These findings suggest that TAD-assisted mandibular advancement can induce significant stress in the mandible and adjacent structures.

The net resultant displacement caused by the application of a pulling force between the maxillary and mandibular miniplates was a restraining force, leading to posterior displacement and expansion of the maxilla, and a tipping force that induced retroclination of the maxillary teeth. The maxillary skeletal base exhibited a posterior directional shift, as evidenced by corresponding nodal displacement. This shift can be attributed to the posterosuperior force applied to the maxilla by the appliance. The maxillary anterior teeth demonstrated a distal and intrusive displacement pattern, whereas the maxillary molars exhibited a distal and extrusive displacement.

In the mandible, forward displacement of the coronoid process and condyle was observed, which opened the bite and caused posteriorly directed displacement of the mental region. Anterior displacement of the lower incisors occurred as a result of the forward movement of the mandible en masse, rather than from loss of anchorage and tipping, as typically seen at the end of treatment with FFAs.

Von Mises stress is a theoretical measure used to estimate material strength, whereas principal stress represents a directly observable mechanical load. Principal stress appears to play a pivotal role in the remodeling processes of craniofacial and alveolar bone. These observations suggest more pronounced remodeling activity on the posterior aspect of the mandibular ramus, with relatively limited dental effects, as documented in clinical research.[35]

Previous FEM studies involving FFA applications have reported findings similar to those of the present study, including distal and extrusive displacement of the maxillary anterior teeth, as well as distal and intrusive displacement of the maxillary molars. The highest von Mises stresses were observed in the mandibular cortical bone—spanning from the canine to premolar regions—and in the sigmoid notch, corresponding to the area where the FFRD engaged in the lower arch.[36] The difference between these results and those of the present study is attributed to the direct attachment of the FFA to the mandibular dentition, which resulted in force application to the teeth—an effect that was circumvented in the current study. Prior studies employing treatment protocols analogous to that of the present investigation have reportedly yielded enhanced skeletal outcomes and reduced mandibular incisor protrusion—findings consistent with the results of the current study.

These findings suggest that TAD-assisted mandibular advancement using Class II elastics is a viable alternative to FFAs and potentially to skeletally anchored FFAs. Since FEM accounts only for static loading and records instantaneous stress patterns, the results may not be clinically reproducible. Therefore, a clinical trial applying this treatment model is necessary to confirm its efficacy. In the current model, the hooks were placed apically. This setup can be replicated in clinical scenarios only when there is sufficient sulcus depth. In cases of insufficient sulcus depth, the hook must either be made very short or positioned mesially on the maxillary plate and distally on the mandibular plate. Alternatively, the hooks may also be placed occlusally. In both scenarios, variations from the current model's results would be expected due to changes in force vectors resulting from altered hook positioning.

A limitation of this study is that mesh structure details were not included due to constraints in the scope and focus of the research, which prioritized overall outcomes and comparative analysis over specific meshing parameters. Additionally, mesh generation was conducted using automated algorithms within the FEM software, with default settings employed to ensure efficiency and consistency across simulations.

CONCLUSION

Finite element analysis demonstrated that Class II elastics combined with interconnected implants generate significant stress concentrations in the posterior ramus of the mandible and the lateral nasal aperture region of the maxilla, with minimal stress on the dentition. This treatment approach produced a distalizing effect on the maxilla and a protractive effect on the mandible, primarily through skeletal displacement. These findings suggest that this approach may be more effective in producing skeletal changes than dental movements. Further clinical studies are required to validate these results under dynamic loading conditions.

Ethics

Ethics Committee Approval: Saveetha Dental College the Institution in Chennai, India Ethics Committee approved the study protocol SRB/SDC/ORTHO-2102/23/231.

Informed Consent: Prior to enrollment, informed consent was obtained from the participant.

Footnotes

Author Contributions: Surgical and Medical Practices - N.V.V.; Concept - N.V.V.; Design - N.R., M.C.; Data Collection and/or Processing - S.H.; Analysis and/or Interpretation - N.R., K.R., G.M.; Literature Search - M.D.B., H.U.; Writing - M.D.B., H.U., G.M.

Conflict of Interest: The authors have no conflicts of interest to declare.

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