Evaluation of displacements and stress changes in the maxillo-mandibular complex with fixed functional appliance skeletally anchored on mandible using miniplates: A finite element study

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Abstract:
OBJECTIVES: Fixed functional appliances (FFA) have been used for correction class II malocclusion but cause proclination of teeth. Recently, few studies have advocated the use of skeletal anchorage along with FFAs to prevent this side effect. The purpose of the study was to evaluate the stress distribution and displacements produced by miniplate anchored Forsus-fatigue resistant device on the maxilla, mandible, and the dentition in a Class II malocclusion patient by finite element analysis.

MATERIALS AND METHODS: Cone beam computed tomography of a class II division 1 patient indicated for FFA was used to construct a 3D finite element model using MIMICS 8.11 and Hypermesh 13.0 software. Various material properties, boundary, and loading conditions were then applied. The model was analyzed for principal stress and von Mises stress in maxilla, mandible, and their dentition using ANSYS 12.1 software.

RESULTS: In the mandible, maximum principal and von Mises stresses were seen in the cortical bone area in the symphyseal region, whereas mandibular teeth showed comparatively lesser stresses. In the maxilla, higher principal and von Mises stresses were seen in the maxillary molar region compared to the maxillary cortical bone. The entire mandible was displaced antero-inferiorly, whereas the maxilla showed a postero-superior displacement.

CONCLUSION: Using skeletally anchored FFA results in more stresses and displacements in the skeletal structures compared to the dentition.

Keywords: Displacements, fixed functional appliance, skeletally anchored, stresses

Introduction
Functional appliance treatment is a well-accepted treatment modality to optimize the development of facial skeleton in Class II malocclusions in the growing age. With mandibular retrusion being the most common characteristic of Class II malocclusion, different types of functional appliances to alter the mandibular position sagittally and vertically have been developed.\(^1\) The pressure created by stretching of the muscles and soft tissues because of the mandibular relocation is transmitted to the teeth and skeletal structures in craniofacial region resulting in orthodontic and orthopedic changes.\(^2\)
Both removable and fixed functional appliances (FFA) have been used to bring about this mandibular repositioning.\cite{3} Removable functional appliances are large, uncomfortable, unaesthetic, and their success depends on patient compliance. FFA are on the other hand are less dependent on patient cooperation and can be used along with fixed orthodontic treatment.\cite{4} Various studies have proved the efficiency of FFA and their effects, such as forward and downward displacement of the mandible, postero-superior displacement of the maxillary dentition and pterygoid plates.\cite{3} However, mandibular incisor proclination is the most pronounced disadvantage reported with FFA.\cite{5,6} This not only limits the skeletal correction but also increases the relapse tendency. Recently, the use of skeletal anchorage (miniscrew and miniplates) with FFA has shown to minimize mandibular incisor protrusion and increase the skeletal contribution.\cite{3,9}

The changes produced by functional appliances have been studied for enhancing the understanding of the mode of action of the functional appliances.\cite{10,14} Force generated when the mandible is protracted produces a pattern of stresses and strains in the temporomandibular joint (TMJ) and oro-facial complex. These stresses are considered responsible for the resulting biological changes. It is important to explicate the relationship of these stresses to bone remodelling. The finite element method (FEM) that has been successfully applied to the study of stresses and strains in engineering\cite{13} has been introduced in orthodontics as a potent research tool for analysis of growth, remodeling, and biomechanical effects of various force systems on craniofacial structures.\cite{16} The FEM analyses both the deformation and stress distribution in bodies that are exposed to external force especially in systems with irregular geometry and non-homogeneous physical properties making it especially suitable for the oral structures.\cite{15}

Functional appliances produce stresses on teeth, periodontium, and adjacent oro-facial structures. Studies have been conducted to analyze these stresses using FFA Forsus-fatigue resistant device on a patient using the FEM.\cite{14} Effects of this appliance reinforced with miniscrews in maxillary arch have also been studied.\cite{17} These studies have shown an increase in stress generation at condylar and mandibular structures. In a recent clinical study, skeletally anchored FFA using miniplates at the mandibular symphysis region has shown to minimize mandibular incisor proclination.\cite{3} However, to the best of our knowledge, no FEM study has been conducted on skeletally anchored FFA to evaluate the stresses and displacements on maxilla, mandible, condyle, dentition, periodontal ligament (PDL), and area of miniplate application. Thus, the purpose of this study was to analyze the displacements and biomechanical effects of the forces applied by miniplate anchored FFA (Forsus) on maxilla, mandible, condyle, and maxillary–mandibular dentition using finite element analysis.

**Materials and Methods**

The study was designed to evaluate stress patterns and displacements in different regions of mandible with miniplate anchored Forsus appliance using FEM and was carried out after ethical approval from institutional ethical committee (PGIDS/IEC/2018/13, dated 30/11/2018). A 14-year-old female patient with forwardly placed upper front teeth, having Class II division 1 malocclusion with retruded mandible, ANB >4, average growth pattern, minimum crowding in lower arch, positive visual treatment objective indicated for treatment with FFA, and no symptoms of TMJ disorder was selected for the study.

All the pretreatment records were taken for the patient, including study models, photographs, and Cone Beam Computed Tomography (CBCT) scan. The computer with following configurations – Intel core 2 duo with 2.1 GHz, 2 GB of RAM, 2GB Graphics card and 320 GB Hard Disc was used. CBCT using CS 9300 CBCT machine with 17 × 13.5 cm field of view with patient in upright posture was used to prepare an FE model. The CBCT scan data were fed into MIMICS software (version 8.11 Materialise HQ, Leuven, Belgium) and processed further to extract only the region of interest for the study, such as maxilla, upper teeth, PDL, mandible, and lower teeth. After obtaining “region of interest,” scatters on the image were removed using “Lasso tool.” This was followed by constructing a 3D model using the various regions of interest obtained [Figure 1]. Finally, smoothing of the model was done. The extracted Digital Imaging and Communications in Medicine data were then imported to Hypermesh software version 13; Altair engineering, Huntsville, Ala) for making geometric model. For creating geometric model 1.4-mm thick cortical bone and cancellous bone were separated. Teeth were modeled with 0.25-mm thick PDL. Sutures were also created. The physical models of the MBT brackets with 0.022 × 0.028 slot, stainless steel miniplates with three holes and a hook, stainless steel screws with 2-mm diameter and 8-mm length, and Forsus appliance were converted to geometric models by reverse engineering method. Finite element model was created from all the geometric models using hypermesh software (version 13; Altair engineering, Huntsville, Ala). Brackets were placed on maxillary teeth and wire was modeled. Miniplates were fixed in the mandibular symphses area using three screws on each side such that hook reached the center of portion of the mandibular canine on each side. Forsus appliance was attached to upper first molar tube.
Kumar, et al.: Stress distribution of skeletally anchored fixed functional appliance.

The finite element model was divided into a number of small units called elements. The model in this study had 625529 3D tetrahedral elements and 113731 nodes. The material properties were assigned for each part, such as PDL, teeth, bones, sutures, brackets, etc., [Table 1]. After assigning boundary conditions and material properties to the model, a load of 200 gm as per the Forsus appliance (spring action) was applied to the model and it was exported to ANSYS software (version 12.1 Canonsburg Pa). The model was run using ANSYS software and various parameters such as stresses and displacements in bone and teeth area were recorded.

Results

Results were recorded in the form of stresses and displacements in the cortical bone, cancellous bone, PDL, teeth, and condyle [Tables 2–4]. Both principal and von Mises stresses were recorded. The displacements [Table 5] were measured in X, Y, and Z direction. Color scale in each figure indicates the stresses and displacements.

Stress distribution

On applying skeletally anchored FFA, the entire mandible experienced tensile stress except a small area near the upper miniscrew that shows a compressive stress of ~17.41 MPa. The maximum principal stress (27 MPa) was recorded in mandibular cortical bone followed by mandibular dentition (8.26 MPa), condyle (3.13 MPa), and mandibular PDL (0.021 MPa). The maximum value of von Mises stresses (48.89 MPa) was also recorded in mandibular cortical bone area followed by mandibular dentition (7.52 MPa), condyle (3 MPa), and mandibular PDL (0.019 MPa) [Figures 3-6].

In the naso-maxillary complex, most nodes experienced compressive stresses except a few areas near zygomatico-maxillary suture and maxillary molar where tensile principal stresses of 5.38 MPa and 17.48 MPa, respectively were observed. Another important difference (when compared to mandible) was that the maximum value of von Mises stresses was observed in the dentition (29.89 MPa) followed by maxillary cortical bone (10 MPa) and PDL (0.011 MPa).

Displacements

In the sagittal direction, maxillary structures (nodes corresponding to point A, ANS, and all maxillary teeth) showed a backward displacement, whereas the
mandible (Point B and entire mandibular dentition) was displaced in a forward direction. In the vertical direction, the anterior portion of maxilla and anterior teeth were displaced inferiorly, whereas posterior structures and dentition were displaced superiorly. All the mandibular structures (Point B, pogonion, and mandibular teeth) were displaced inferiorly [Figures 7 and 8].

**Discussion**

This study was conducted to assess the stress pattern distribution using the FEM in different parts of the mandible, maxilla, and dentition because of Forsus FFA skeletally anchored on the mandible. This modification of combining skeletal anchorage with FFA was recently reported in few case reports and clinical studies and has shown to increase the skeletal effects and decrease the mandibular incisor proclination.\(^{[24-26]}\) This study attempts to check for validation of the clinical studies on miniplate anchored FFA.

In this study, the maximum value of von Mises and principal stresses were seen in the cortical bone of the mandible at the bone–miniplate interface followed by dentition, condyle, and PDL. As the modulus of elasticity of cortical bone is far higher than the PDL and bone is in a better condition to bear mechanical stresses compared to teeth, using a skeletally anchored FFA can prevent unnecessary loading of teeth. With various

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**Table 1: Material properties of various components**

| Model                        | Elastic Modulus (MPa) | Poisson’s Ratio (MPa) |
|------------------------------|-----------------------|-----------------------|
| Cortical bone                | 13700\(^{[18,19]}\)   | 0.3                   |
| Cancellous bone              | 1370\(^{[18,19]}\)    | 0.3                   |
| PDL                          | 0.068\(^{[20]}\)      | 0.49                  |
| Suture                       | 7\(^{[21]}\)          | 0.4                   |
| Cementum                     | 18700                 | 0.3                   |
| Dentin                       | 18600\(^{[22]}\)      | 0.31                  |
| Enamel                       | 84000\(^{[22]}\)      | 0.3                   |
| Stainless steel (wires, brackets, appliance, miniplates) | 200000\(^{[21]}\) | 0.3                   |

MPa=Megapascals, PDL=Periodontal ligament
biomechanical studies showing that principal stress is crucial in remodeling of alveolar and craniofacial bone, these findings indicate more remodeling of bone in mandible (where FFA is skeletally anchored) and lesser dental effects in concordance with findings of clinical studies. The findings are similar to the only other FEM study on skeletally anchored FFA by Patil et al.\[27\] who also have reported maximum stresses in the mandibular cortical bone followed by mandibular dentition and condyle. However, in other FEM studies on FFA, maximum stresses have been reported at teeth followed by cortical bone and condyle.\[14,23\] Panigrahi et al.\[23\] also evaluated stresses and displacements on craniofacial structures because of FFA and reported tensile stresses on entire dentition (except maxillary molars). The difference is because of the direct attachment of the FFA on the mandibular dentition in all these studies thus resulting in the force application on the dentition that has been circumvented in this study.

Being the only FEM study analyzing the displacements produced by skeletally anchored FFA, the findings regarding displacement of mandible, maxilla, and dentition in this study could be correlated only with clinical studies. On evaluating the mandibular base, an anterior direction of movement of point B was seen that has also been reported in the clinical studies on skeletally anchored FFA.\[3,24-26\] Correction of class II molar relationship in response to FFA because of mesial displacement of mandibular molars just like other studies was also observed in this study.\[8,28\] However, instead of eruptive movements seen in previous studies, mandibular molars in this study showed a slight movement in intrusive direction.\[25,29\] This may be because of the fact that there was absence of any reactive forces to the inferiorly directed forces of skeletally anchored Forsus. Hence, the entire mandibular dentition showed an inferior displacement. Mandibular anteriors in this study showed a displacement in forward direction, whereas in the clinical studies on skeletally anchored FFA, a backward displacement of mandibular incisors has been reported.\[25,24-26\] However, it is worth mentioning that nodes in mandibular anterior dentition areas were less stressed than all other areas [Figure 6] showing that though the direction of displacement is forward but its magnitude was relatively lower than of skeletal areas. Thus, skeletally anchored FFA produces less proclination of mandibular incisors even though retroclination reported in clinical studies has not been found in this study.

The maxillary skeletal base moved in a posterior direction as indicated by the corresponding nodes. This is because of the postero-superiorly exerted force on the maxilla because of the appliance. Point A and ANS also moved posteriorly similar to previous clinical studies.\[3,8,24\] The changes in position of point A can be attributed to the retrusive movements of maxillary anteriors. The maxillary anterior teeth showed a distal and extrusive movement, whereas maxillary molars showed distal and intrusive displacements in this study supporting the clinical findings in previous studies.\[25,26\]

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**Table 2: Maximum principal and von Mises stresses**

| Structure                   | Max. Principal Stresses (MPa) | Max. von Mises Stresses (MPa) |
|-----------------------------|-----------------------------|-------------------------------|
| 1. Maxillary cortical bone  | 5.38                        | 10                            |
| 2. Mandibular cortical bone | 27                          | 48.89                         |
| 3. Maxillary cancellous bone| 1.6                         | 3.5                           |
| 4. Mandibular cancellous bone| 0.698                      | 2.27                          |
| 5. Maxillary Dentition      | 17.48                       | 29.89                         |
| 6. Mandibular Dentition     | 8.26                        | 7.52                          |
| 7. Condyle                  | 0.007                       | 0.011                         |
| 8. Mandibular PDL           | 0.021                       | 0.019                         |
| 9. Maxillary PDL            | 3.13                        | 3                             |
| 10. Mandibular PDL          | 132.86                      | 145.72                        |

MPa=Megapascals, PDL=Periodontal ligament
This study has thus shown that in the mandible where the FFA is skeletally anchored the maximum von Mises stresses and more displacement is seen in the cortical bone and less stress was found in PDL and teeth thus maximizing the skeletal and reducing the dental effects.

However, in the maxilla where the Forsus is attached in the conventional manner on the maxillary first molar, the maximum stress is seen in the dentition. These findings thus clearly indicate that using a skeletally anchored FFA prevents unnecessary loading of teeth and also reduces the dentoalveolar effects produced by the conventional FFA.

**Conclusions**

This FEM study done to evaluate the stresses and displacements induced by miniplate anchored Forsus appliance has shown that –

1. The maximum principal and von Mises stresses in the mandible occurred in the cortical bone area in the symphyseal region, with mandibular dentition showing lower stresses.
2. In the maxilla, maximum principal, and von Mises stresses were seen in the maxillary molar region and were higher than stresses at the maxillary cortical bone.
3. Condylar process and sigmoid notch show some principal and von Mises stresses.
4. The direction of displacement of maxilla, mandible, and dentition were similar to previous clinical studies except for mandibular molars that showed a slight intrusive movement with skeletally anchored Forsus in contrast to the eruptive movement seen with conventional FFA.

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Conflicts of interest
There are no conflicts of interest.

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