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Evaluation of stress changes in the maxilla with fixed functional appliances—A 3D FEM study

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Abstract:

AIM: To evaluate the stress changes in the maxilla during fixed functional appliance use using three-dimensional finite element method (FEM) stress analysis.

SETTINGS AND SAMPLE POPULATION: A three-dimensional finite element model of the maxilla was constructed using the images generated from the cone-beam computed tomography of a patient treated for Class II malocclusion with a fixed functional orthodontic appliance. The FEM was used to study the stress changes seen in the maxilla, which were evaluated in the form of highest von Mises stress and maximum principal stress before and after the application of fixed functional appliance.

RESULTS: Higher areas of stress were seen in the model of the maxilla with the fixed functional appliance (140 MPa) compared to that in the resting stage (58.99 MPa).

CONCLUSIONS: An increase in the maximum principal stress and von Mises stress in the posterior regions of the maxilla and maxillary teeth was seen. The stresses seen were double than that without the appliance. A high distalization force on the maxilla was seen with the fixed functional appliance.

Keywords:

Finite element analysis, fixed functional appliance, maxilla

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Introduction

There are many ways to correct a Class II Division 1 malocclusion. Some fixed functional appliances have also been used along with many removable functional appliances which include activators, bionators, Frankel, and Twin-block. The Class II correctors which were used for sagittal advancement of the mandible have certain advantages over removable functional appliances. Less dependence on patient compliance is needed and they can be used along with fixed mechanotherapy. This reduces the overall treatment duration. When compared with removable appliances, enhanced mandibular growth and more horizontal condylar growth were produced upon the use of these Class II Correctors.[1,2]

Fixed functional appliances achieved significant growth and were more appropriately termed "noncompliant Class II inter-arch correctors". A fixed appliance aims to concentrate on the dentition and provides the required dental corrections which include facilitating mandibular advancement by eliminating dental interferences and consolidating the arches to minimize the dental side-effects which are seen. In recent years, several fixed functional appliances have gained popularity to help achieve better results in noncompliant patients which include the Herbst appliance, Forsus Fatigue Resistant Device (3M Unitek, Monrovia, California

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USA), and Powerscope class II corrector (American Orthodontics).

Along with the effects on the mandible, some effects on the maxilla were also caused by the Class II correctors. They exert force on the maxilla which causes distalization and intrusion of the upper molars.[3] Another effect of fixed functional appliances included steeping of the maxillary occlusal plane. No changes in the sagittal maxillary jaw base position were seen with fixed functional appliance therapy.[3] Downward tipping of the palatal plane is also seen in some cases which relapsed without proper retention. With the use of the fixed functional appliance, a pronounced high-pull headgear effect is seen on the maxillary complex. The effect is temporary, without proper retention. This effect seen can be case sensitive for every case and can be retained if it is desirable in that particular case.

The precision and understanding of the regions in the maxilla and mandible have increased with the recent use of cone-beam computed tomography (CBCT) in creating the 3-dimensional (3D) model of the dentofacial skeleton.[4-6] The biomechanical response of bone seen to orthopedic forces is usually quite complex. With the use of the finite element method (FEM), a precise analysis of the biomechanical effects of various treatment modalities was achieved initially in medical orthopedics and later in dentistry, especially orthodontics. To study stresses and strains in engineering, the FEM is successfully applied.[5] This makes it possible for evaluating the biomechanical components such as displacements, strains, and stresses induced in living structures from various external forces.[7-10] FEM has many advantages in orthodontics.[11] FEM measures the actual amount of stress experienced at any point on teeth, alveolar bones, periodontal ligaments, and craniofacial bones and it is a noninvasive technique. In vitro, the oral environment can be simulated along with graphical visualization of the displacement of the tooth. By varying the point of application, magnitude, and direction of a force, the clinical situation can be easily simulated. The physical properties of the material used are not affected by the reproducibility. Another advantage included the repetition of the study as many times as the operator wishes. The FEM is therefore introduced as a powerful research tool in orthodontics, which is used for solving various structural biomechanical problems. The relationship between stresses have been analyzed by the FEM and the biological changes of the bony structures have been reported by many other studies.[12-15] The limitation of an FEM study is that it can only record instantaneous stress patterns.

Many studies have evaluated the dental and skeletal changes seen in the mandible during fixed functional appliance therapy. However, the evaluation of stress patterns in the maxilla during rest and during the action of the fixed functional appliance has not been studied extensively. Hence, the purpose of this study was to evaluate the stress pattern distribution with a Class II Corrector (Powerscope American Orthodontics) in different parts of the maxilla on a patient using FEM with a CBCT-generated 3D image.

Material and Methods

This study was designed to evaluate stress pattern distributions in different regions of the maxilla with a Powerscope appliance using the FEM. A 15-year-old boy diagnosed with a typical Class II Division 1 malocclusion with an overjet of 8 mm was selected. Ethical approval of this study was given by the Institutional Review Board, Ethical Committee AJ College of Dental Sciences (AJCDS/2018/xxxx). The patient complained of an unpleasant appearance along with backwardly positioned mandibular front teeth. After a thorough clinical examination, it was planned to treat the patient with a fixed functional appliance, a Powerscope. The patient presented a skeletal Class II relationship with a normal maxilla, a retrognathic mandible, a positive visual treatment objective, an abnormal musculature, and a favorable growth pattern.

Pre-treatment records including study models, photographs, CBCT scans, and interocclusal biting force recordings were recorded for the patient. A Powerscope was planned to be given to the patient. Informed consent was obtained from the patient's parents to participate in the study. The DICOM (Digital Imaging and Communication in Medicine) images of the maxilla, dentition, and associated structures were generated using CBCT scans which were used to construct the mesh diagram for the finite element analysis with the Mimics software (version 8.11; Materialise HQ, Leuven, Belgium) and the HyperWorks software (version 9.0; Altair Engineering, Huntsville, Ala).

A 0.022-in MBT (Mclaughlin Bennett Trevisi) prescription was used for full bonding and banding of the maxillary, as well as mandibular arches. After leveling and aligning, the arches were U-shaped but in a Class II relationship. A single-step mandibular advancement was used with the Powerscope appliance when the rectangular wire stage reached 0.019 × 0.025-in stainless steel. The appliance was attached at the mandibular canine and premolar interface to the maxillary first molars. A Correx gauge and Dontrix gauge (approximately 2.5-3 newton) were used to calculate the oblique force values. CBCT scans of the tooth and the entire maxilla were analyzed with the Mimics software for constructing the finite element model.

The Solid Edge 2004 software (Siemens, Plano, Tex) was used to generate the surface data of the metal casting and the maxilla. From the 3D image of the CBCT, a mesh diagram was generated with the help of the HyperWorks software. Finite element models were constructed from the DICOM images of slices 1 mm thick which was generated by the DICOM software. The assembled finite element model of the maxilla was imported into the Ansys software (version 12.1; Canonsburg, Pa) for analysis. This finite element model consisted of 38,250 elements and 52,400 nodes. A vertical biting force of 116 gms was applied in the molar region and a horizontal force of 111 gms was seen distal to the canine in the horizontal direction. Young's modulus (13,700 MPa) and the Poisson's ratio (0.3) were the material properties assigned to the compact bone while for cancellous bone it was 7930 MPA and 0.3, respectively. The model was modified at the outer part of the skull and its most posterosuperior edges. This modification allowed the visualization of deformation and stress generation in the maxilla. The distribution of stresses was calculated at two stages, the resting stage of the maxilla with the Powerscope and after the fixation of the Powerscope appliance at the stage of its maximum activation. The occlusal forces were not taken into consideration. The maximum principal stress region was seen as red, which is mainly tensile stress, and the minimum principal stress region was seen as blue, which is compressive stress. The results were calculated using von Mises and principal stresses in the following regions: cortical bone, teeth, and periodontal ligament.

Results

The results of this FEM analysis showed the areas of tension and compression in the maxillary posterior region and associated structures. The highest von Mises stresses of 46 MPa was in the cortical bone and 29 MPa was in the teeth were seen in the resting stage of the maxilla. The maximum principal stresses were 58.99 MPa in the cortical bone and 18.53 MPa in the teeth in the resting stage [Figure 1 and Table 1]. The highest von Mises stresses were 118 MPa in the cortical bone and 82 MPa in the teeth [Figure 2]. The maximum principal stresses were 140 MPa in the cortical bone and 60 MPa in the teeth with the use of Powerscope [Figure 3 and Table 2].

Discussion

FEM is a computer-based technique used to obtain solutions to boundary–value problems in engineering. It is practical to explain the biomechanical components such as displacements, strain, and stresses generated in living structures from various external forces with the help of FEM. The biomechanical studies reported that the compressive and tensile stresses from functional orthopedic forces are the key factors that affect the remodeling of the bones.[13] In this study for evaluating the stress patterns seen in different parts of the maxilla, a finite element model was constructed. A pronounced high-pull headgear effect on the maxillary complex along with positioning the mandible forward is seen with fixed functional appliances. The remodeling of the bone by mechanical forces might be correlated with the location of the tensile and compressive stress patterns which was suggested by our findings. The maxilla, maxillary first molar teeth, and the alveolar bone surrounding the maxillary first molar are also affected during clenching of the teeth.[3]

Table 1: Distributions of von Mises and stress distribution in the resting stage

Part	von Mises Stress (MPa)	Principal Stress (MPa)
Cortical Bone	46	58.99
Teeth	29	18.53

Table 2: Distributions of von Mises and principal stresses in the cortical bone and in the teeth with the Powerscope

Part	von Mises Stress (MPa)	Principal Stress (MPa)
Cortical Bone	118	140
Teeth	82	60

Very few of the previous FEM studies evaluate the effects of the Class II correctors on the maxilla. Other studies evaluated the forces acting on the nasomaxillary complex with different types of headgears that have been discussed along with FEM. The maxilla is a static structure, which is attached to the cranial base through circummaxillary sutures. The forces acting on the maxilla can be transferred to the other bones (cranial base and cranium) through the sutures and may shift towards the muscles and soft tissues attached to it.

In our study, at the resting stage of the maxilla, the von Mises stress in the cortical bone was maximum at the surrounding region of the first molar teeth bilaterally and may be at the distal aspect of the maxillary lateral incisor because of the occlusal forces shifting from the mandible to maxilla. A minimal amount of stress was found at the zygomatic process of the maxilla which can be due to the shifting of occlusal forces from the mandible to the maxilla. In the resting stage, the maximum principal stresses in the cortical bone were seen in the region surrounding the roots of the first molars. This was due to the occlusal forces being transferred from the mandible to the maxilla. With a fixed functional appliance, the highest von Mises stresses in the cortical bone were from the bone surrounding the roots of the first molars and second premolars and in the medial aspect of the zygomatic process of the maxilla. In the resting stage, it was maximum at the bone surrounding the roots of

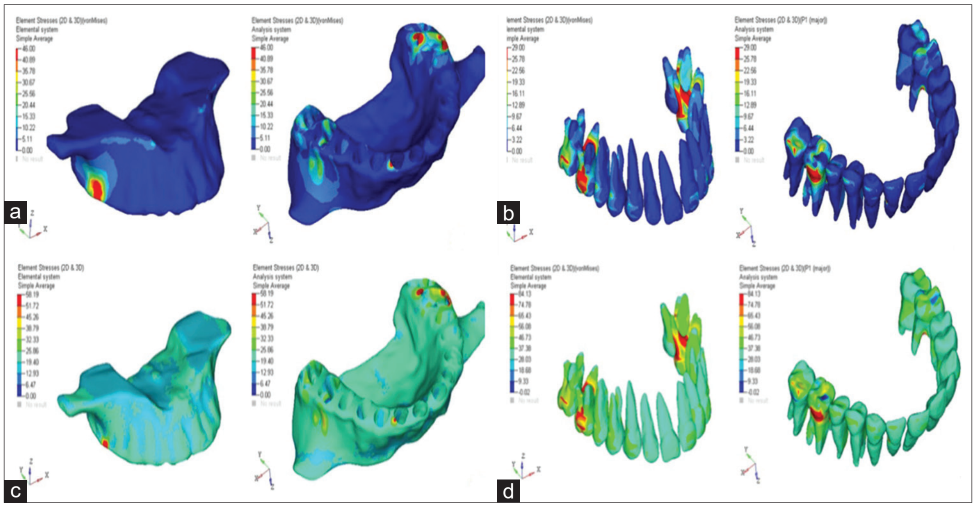

Figure 1: (a) von Mises stresses in the cortical bone at the resting stage, (b) von Mises stresses in the teeth at the resting stage, (c) Principal stresses in the cortical bone at the resting stage, (d) Principal stresses in the teeth at the resting stage

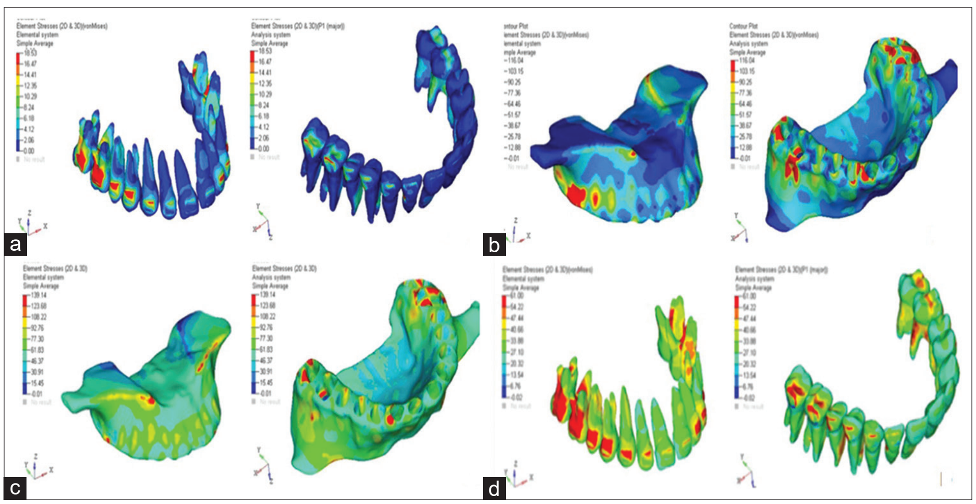

Figure 2: (a) von Mises stresses in the teeth with Powerscope, (b) von Mises stresses in the cortical bone with Powerscope, (c) Principal stresses in the cortical bone with Powerscope, (d) and Principal stresses in the cortical bone with Powerscope

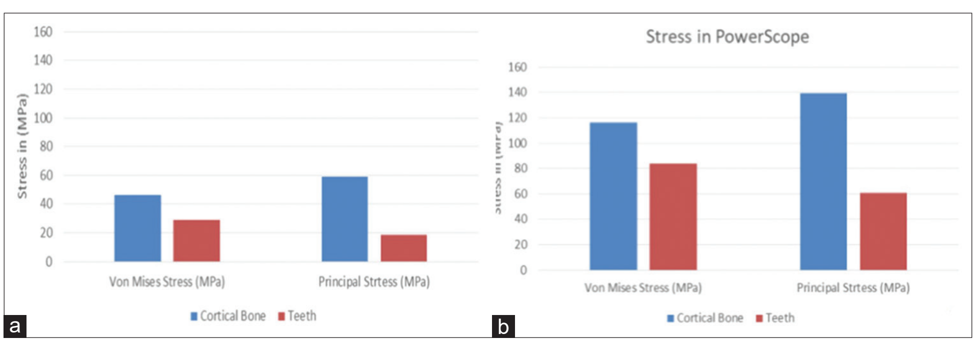

Figure 3: (a) Stress levels in the cortical bone and teeth at the resting stage, (b) von Mises stresses and Principal stresses in the cortical bone and teeth with Powerscope

the first molar area and at the distal aspect of the roots of the lateral incisor. Whereas minimum stresses were seen in the second premolar area and the rest of the areas of the maxilla. When the patient was wearing the Powerscope, an increase of more than 2 times in the stress was seen in the cortical bone area. The teeth showed an almost 3 times increase in stress with the Powerscope because it is a tooth-borne appliance, whereas during the zygomatic process, there was no increase in stress levels while wearing the appliance.

Panigrahi *et al*.[16] studied the stress region with the FEM in a dry human skull with fixed functional therapy. An anteroinferior movement of the mandible was seen along with posterosuperior displacement of maxillary dentition. The entire dentition experienced tensile stress except for the maxillary posterior teeth. The maximum principal stresses seen in the cortical bone in our study were from the first molar and second molar area, distal aspect of the lateral incisor, and the anteromedial border of the zygomatic process. In the resting stage, the maximum principal stresses were seen in the first molar area in the cortical bone and at the roots of the first molar in the dentition. In the teeth, these were seen at the first and second molars which were followed by all the maxillary teeth at their bracket level. In the resting stage, the maximum stress was seen at the cervical area and the roots of the first molar teeth. In the cortical bone, the principal stress increased by more than 2 times, and the teeth showed a 3 times increase in stress compared to the resting stage. There was a 3 times increase in stress in the anteromedial aspect during the zygomatic process.

In the study done by Pancherz,[3] the short- and long-term effects of the Herbst appliance were evaluated on the maxillary complex. The upper molars were distalized in 96% of the subjects (maximum 4.5 mm) and the upper molars were intruded in 69% of the subjects (maximum 3.5 mm) during the Herbst treatment. The opening of the maxillary occlusal plane was seen in 82% of the subjects (maximum 7.5^0) whereas the sagittal maxillary jaw base position was unaffected by therapy. The palatal plane was tipped downwards in 47% of the subjects (maximum 2^0). Most of the treatment changes seen were reverted during the first 6 months after therapy. The normal developmental changes prevailed during the following 5.9 years after treatment: the upper molars moved mesially and the teeth extruded, the occlusal plane was closed, the maxilla grew anteriorly, and the palatal plane showed downward tipping. In conclusion, a pronounced high-pull headgear effect was seen on the maxillary complex by the Herbst appliance. Without the help of proper retention, the effect seen was temporary.[14,16] In our study, the Powerscope appliance exerted forces on the maxilla which are enough to cause the pronounced high-pull headgear effect.

An analytical model was developed by Gautam *et al*.[17] from the sequential computed tomography scan images taken at 2.5-mm intervals of a dry skull of a 7-year-old. To simulate cervical-pull, straight-pull, and high-pull headgear, different headgear forces were simulated by applying 1 kg of posteriorly directed force in the first molar region. The most effective headgear in restricting the anteroinferior maxillary growth vector was the high-pull headgear.[18] With all the three headgear types, a mid palatal suture opening was seen similar to rapid maxillary expansion. For both the maxilla and the zygomatic complex, the center of rotation varied with the direction of headgear forces.[19] With the headgear loading, the potential was seen for chondrogenic and osteogenic modeling of the articular fossa and articular eminence.[20] In our study, the stresses distributed in the maxilla are similar in location to this study and are responsible for the high-pull headgear effect mentioned in the above study.

Conclusions

An increase in the maximum principal stress and von Mises stress in the posterior regions of the maxilla and maxillary teeth was seen. There was a 2 times increase in the von Mises stress in the cortical bone. The maximum principal stress was increased by more than 2 times in the cortical bone and by more than 3 times in the teeth. The stresses seen were double than that seen without the appliance. A high distalization force was seen on the maxilla with the fixed functional appliance.

Declaration of patient consent

The authors certify that they have obtained all appropriate patient consent forms. In the form, the patient has given his consent for his images and other clinical information to be reported in the journal. The patient understands that his name and initial will not be published and due efforts will be made to conceal their identity, but anonymity cannot be guaranteed.

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Conflicts of interest

There are no conflicts of interest.

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