Original Article

Evaluation of stress distribution in maxilla, mandible, and glenoid fossa after Class III intermaxillary traction: A three-dimensional finite element analysis study

ABSTRACT

Aim: In this study, we aimed to evaluate the stress distribution on maxilla, mandible, and glenoid fossa after application of Class III intermaxillary anteroposterior orthopedic forces of 150, 250, and 400 gas applied to a three-dimensional (3D) model of the young human dry skull.

Methods: A 3D finite element model was developed from the computed tomography images of a growing boy (age, 13 years). ANSYS (version 16.0) software used to simulate Class III force of progressively increasing intensity over maxilla, mandible, and glenoid fossa to quantify the biomechanical reaction with two components, direction and stress.

Results: We quantified detailed changes in the maxillofacial sutures, dentition, mandible, and glenoid fossa with bone-anchored maxillary protraction (BAMP) to analyze their effects.

Conclusions: As the force increases from 150, 250 to 400 g, stresses are increased on all structures associated except maxillary central incisor which show a decrease in the stresses. Although forces were for maxillary protraction, stress generated at the circummaxillary sutures was minimal. As with any other Class III force, stresses were distributed on whole of condyle, capsular ligament, and minimal at glenoid fossa. This suggests that BAMP has more of mandibular restraining effect.

Keywords: Bone anchored maxillary protraction, finite element analysis, stress distribution

INTRODUCTION

Class III malocclusion is most commonly associated with retrognathic maxilla, however, prognathic mandible or combination of both can also be present. Despite its low prevalence, clinicians generally agree that Class III malocclusion is one of the most difficult malocclusions to treat. Different treatment approaches such as growth modification, camouflage, or surgery to address Class III malocclusion have been used.

Facemask therapy combined with rapid maxillary expansion as growth modification therapy has been proved to be effective in the treatment of Class III malocclusions with maxillary deficiency.[1] However, as seen with all tooth-borne appliances, dentoalveolar effects are inevitable. In contrast to facemask therapy, bone-anchored maxillary protraction (BAMP) applies continuous anteriorly directed force to the maxilla and continuous retraction force to the mandible.[2,3] It has the advantage of minimal dentoalveolar and greater skeletal changes created with a continuous force of lower magnitude.

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Moreover, better compliance can be expected from patients for intraoral elastic traction rather than an extraoral device.

Previous studies have evaluated the effects of BAMP on maxillary displacement, mandibular, and glenoid fossa changes by using of cone-beam computed tomography (CBCT) images.[4,5] CBCT studies have shown that BAMP stimulates forward displacement of the zygomaticomaxillary complex, and also, mandibular shape rather than mandibular size is affected by continuous intermaxillary traction.[4,5] CBCT studies showed high correlation between modeling of the anterior and posterior eminences of the glenoid fossae and displacement of the opposing condylar surfaces.[5] Liu *et al*. in a three-dimensional (3D) finite element method (FEM) study found effects of BAMP on the growth of the maxillofacial bones. The reactions of the glenoid fossa and the mandible were not reported.[6]

Finite element analysis (FEA) is a numerical method that is able to calculate under specific loads and boundary conditions, displacements, stresses, and strains of an arbitrary geometry. Its application to study the produced stresses and displacements in the craniofacial complex to anteroposterior orthopedic forces requires an amalgamated effort of the engineering and orthodontic disciplines.

The aim of this study was to evaluate the stress distribution on maxilla, mandible, and glenoid fossa after application of Class III intermaxillary anteroposterior orthopedic forces of 150, 250, and 400 gas applied to a 3D model of the young human dry skull.

METHODS

This study was approved by the Institutional Ethics Committee. The study was carried out in collaboration with a sophisticated computer workstation at Milestone PLM Solutions Pvt. Ltd.

The analytical model was developed from the computed tomography (CT) images of a young patient, a boy aged 13 years with underlying skeletal Class III base due to retrognathic maxilla and prognathic mandible with good periodontal health, and no temporomandibular joint (TMJ) disease. CT scan images of the skull including the mandible were taken in the axial direction, parallel to the Frankfort horizontal plane. Sequential CT images were taken at 1-mm intervals to reproduce finer and detailed aspects of the geometry. This spacing of CT images enabled a higher geometric accuracy than that used by Jafari *et al*.,[7] Iseri *et al*.,[8] and Tanne *et al*.[9] To make the sutures distinguishable in the CT scans, a method as described by Jafari *et al*.[7] was used. In this method, traces were placed in the form of barium sulfate pellets in 0.25-mm circular pits, made at 3 points along each of the craniofacial sutures. We used cotton pellets dipped in nonionic contrast medium (Ultravist 300, SCHERING) instead of barium sulfate pellets to avoid distortion of the CT images. This procedure made it possible to transfer the precise location of the various sutures onto the finite element model.

The CT data output was transferred to Mimics software, a medical visualization software, and a rectangular coordinate system [Figure 1]. In Mimics, segmentation masks were used to highlight regions of interest. It provided a flexible interface for quickly calculating a 3D model of the region of interest. Information about height, width, volume, surface, etc., is available for every 3D model. ANSYS (version 16.0 Milestone PLM Solutions Pvt Ltd. Mumbai, Maharashtra, India) software allowed us to achieve simulation with Class III (anteroposterior) force of progressively increasing intensity, i.e., 150, 250, and 400 g over maxilla, mandible, and glenoid fossa to quantify the biomechanical reaction with two components, direction and stress. This model consisted of 258190 nodes and 148143 Tet 10 elements. Values are assigned to the material properties according to the final geometric structure [Table 1].

After creation of the 3D-FEM model, boundary conditions were defined. These conditions restrict unwanted displacements of the model when subjected to force. Top part of skull bone was assumed to be fixed, so that TMJ joint moves freely in lateral directions with respect to the vertical place of symmetry. This was done to investigate the stress distribution and deformation of the TMJ. All other points of the skull on the model were constrained to have no motion perpendicular to this plane. An exception for these boundary conditions was the points at the TMJ and glenoid fossa bone that was left completely unrestrained. In addition, a zero-displacement and zero-rotation boundary condition was imposed on the

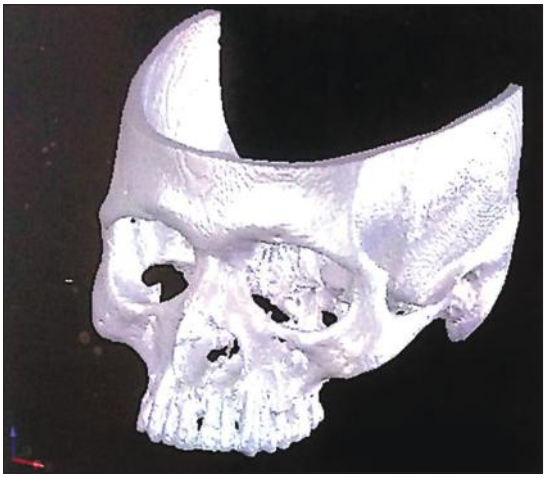


Figure 1: Preliminary three-dimensional model of the skull built by the Mimics software after the computed tomography scan

nodes along the superior and posterior surface of the skull and along the foramen magnum.

Class III forces of 150, 250, and 400 g were applied on the left and right infrazygomatic crests of the maxillary buttress and between the lower left and right lateral incisors and canines [Figure 2]. The displacements and von-Mises stresses in continuous anteriorly directed forces to the maxilla, and continuous retraction forces to the mandible were studied on different nodes located at various structures of the craniofacial complex and the stress distribution patterns were analyzed.

RESULTS

The results of the FEM analysis showed the stress distribution in maxilla, mandible, and glenoid fossa by application of progressively increased Class III intermaxillary anteroposterior orthopedic forces of 150, 250, and 400 g.

The nodes that were selected on maxillary structures corresponded to the incisal edge of maxillary central incisor, lateral incisor, and first molar, and also, mid palatal suture anterior, mid palatal suture posterior, temporozygomatic suture, frontozygomatic suture, frontonasal suture, base of nose, and zygomaticomaxillary suture. As the magnitude of orthopedic force (stress) increased from 150, 250 to 400 g in a anteroposterior Class III direction stresses on maxillary incisors decreased from 30.88, 30.33 to 28.68 MPa, respectively, stresses on maxillary molar highly increased from 109.88, 190.75 to 306.52 MPa, stresses on the base of nose increase from 10.61, 11.73 to 12.98 MPa. Midpalatal suture anterior and maxillary lateral incisor showed less stresses as compared to maxillary central incisor, maxillary first molar, and base of nose but showed more than mid palatal suture posterior, first molar, temporozygomatic suture, frontozygomatic suture, frontonasal suture, zygomaticomaxillary suture [Figures 3-5 and Table 2].

The nodes that were selected on mandibular structures corresponded to the incisal edge of mandibular central incisor, mandibular lateral incisor, and condyle showed noticeable increase in stresses as the magnitude of orthopedic force increased from 150, 250 to 400 g in anteroposterior Class III direction; increased from 37.11, 65.29, 84.43 MPa with mandibular central incisor; 26.96, 32.96, 54.22 MPa with mandibular lateral incisor; and 22.765, 42.5, 59.33 MPa with condyle. First molar, ramus, gonial angle, chin showed little stresses compared to above structures in the mandibular region [Figures 6-11 and Table 3].

Table 1: Material properties

Materials	Young's modulus (MPa)	Poisson's ratio
Teeth	2.07×10^4	0.30
Bone	1.37×10^4	0.30
Sutures	38.6	0.45
Disc	0.036	0.5

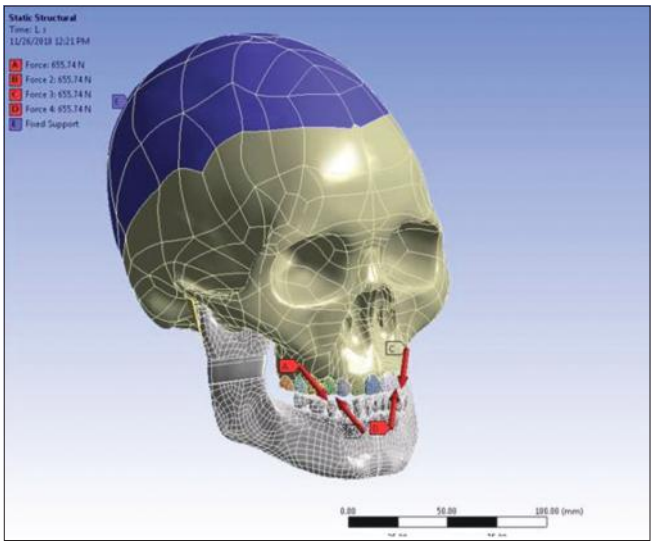


Figure 2: Different nodes located at various structures of the craniofacial complex and showing Class III force

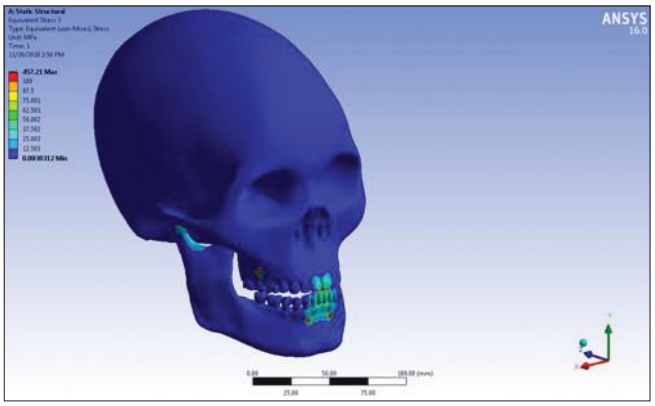


Figure 3: Static structural equivalent stress on maxilla: Class III with 150 g of force

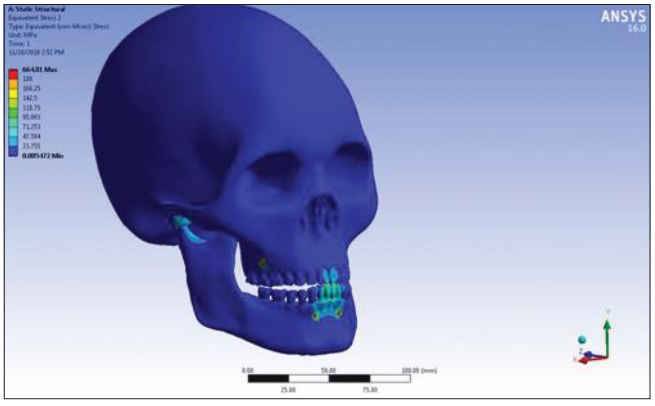


Figure 4: Static structural equivalent stress on maxilla: Class III with 250 g of force

The nodes that were selected on glenoid fossa structures corresponded to the capsular ligament showed noticeable increase in stresses as the magnitude of orthopedic force increases from 150, 250 to 400 g in anteroposterior Class III direction, from 42.6, 67.9, 93.5 MPa as glenoid fossa showed minimum stresses on the region 1.32, 3.05, 3.57 MPa [Figures 12-14 and Table 4].

Comparison of von-Mises stress at maxilla, mandible, and glenoid fossa with varying amounts of Class III stress, i.e., 150, 250, 400 g [Table 5].

DISCUSSION

Many authors have investigated the effects of BAMP on the craniofacial structures using methods ranging from conventional radiography, histological methods use of strain gauge, photoelastic, and laser holographic or finite element techniques. However, according to Geramy,[10] each method of study had certain short comings.

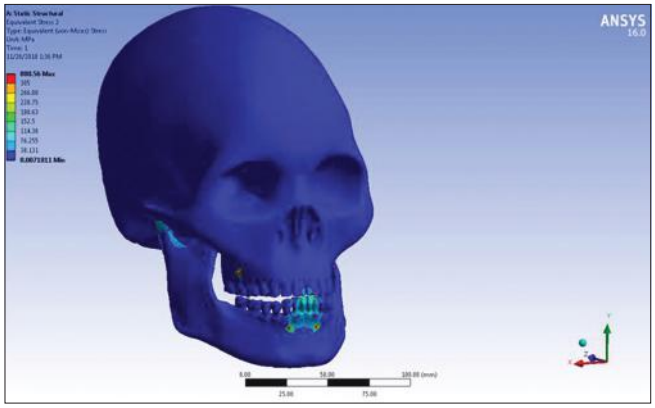


Figure 5: Static structural equivalent stress on maxilla: Class III with 400 g of force

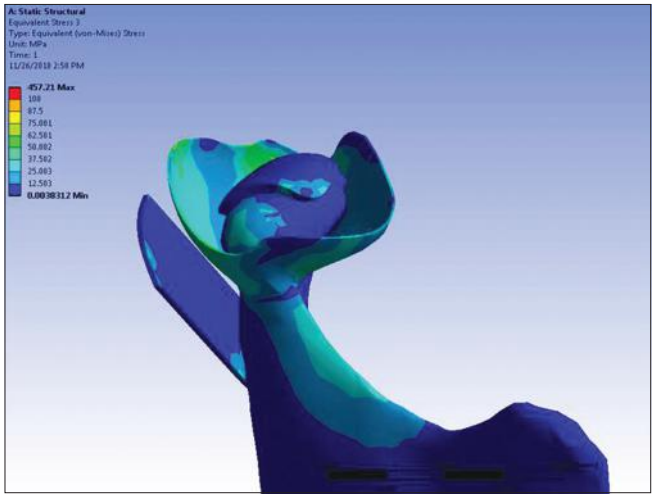


Figure 7: Static structural equivalent stress on condyle: Class III with 150 g of force

The FEA was the only feasible method that could help in achieving the objectives and also overcome the shortcomings of the above methods. Moreover, it is an appropriate method that can represent the irregular geometry and lack of homogeneity of bone. The most important advantage of this model was the ability to test an unlimited number of force application systems once an adequate FEM is created. The 3D-FEM used in the present study provides the freedom to simulate orthodontic force systems applied clinically and allows analysis of response of the craniofacial skeleton including mandible to the orthodontic loads in 3D space.

In this study, an attempt was made to build a FEM of young human skull to simulate the anatomical feature as closely as possible. Such a model would enable to study the effects of Class III anteroposterior orthopedic forces. Since the skull is a complex structure in which sutures and defects affect the mechanical resistance to force application, therefore, the

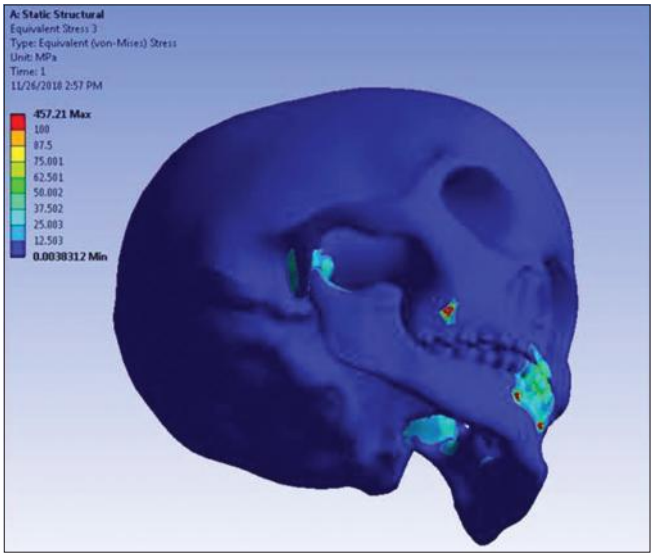


Figure 6: Static structural equivalent stress on mandible: Class III with 150 g of force

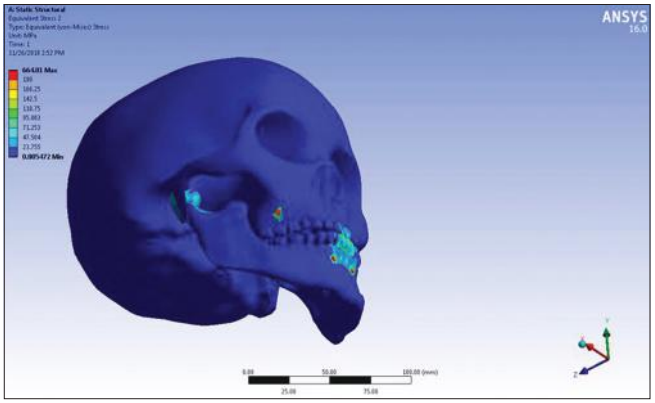


Figure 8: Static structural equivalent stress on mandible: Class III with 250 g of force

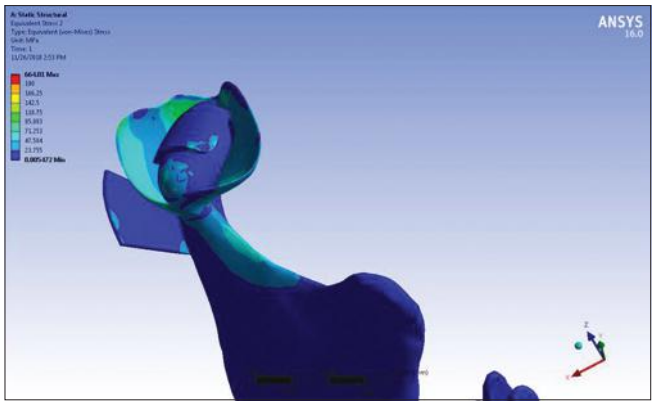


Figure 9: Static structural equivalent stress on condyle: Class III with 250 g of force

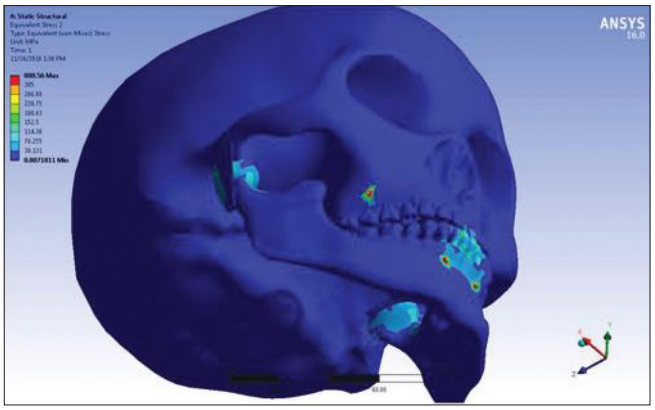


Figure 10: Static structural equivalent stress on mandible: Class III with 400 g of force

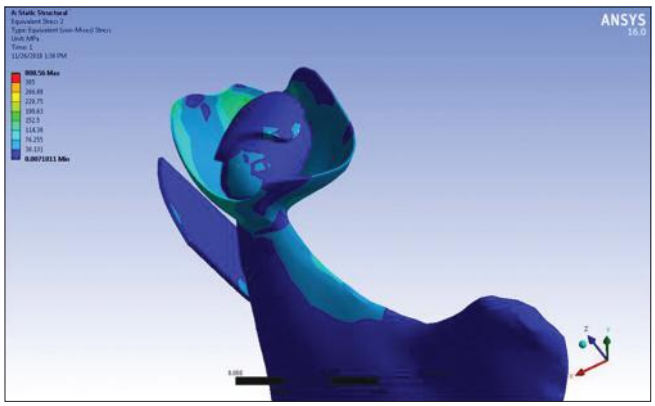


Figure 11: Static structural equivalent stress on condyle: Class III with 400 g of force

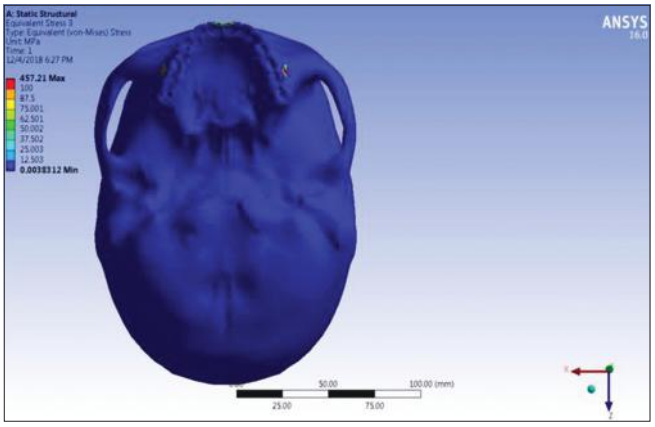
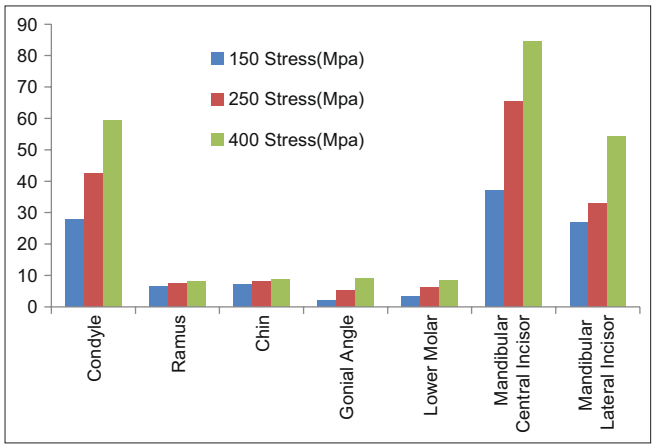


Figure 12: Static structural equivalent stress on glenoid fossa: Class III with 150 g of force

Table 2: Stresses in the mandibular region



creation of an accurate FE model was of utmost importance. Hence, during model development, accuracy of the geometry and assigning material properties were considered.

Several studies have been conducted to investigate histologically, morphologically, and radiographically, the response of the craniofacial complex to BAMP. In previous studies on human or animal skulls, it was possible only to determine the response of surrounding bones to high-level forces and the experiment could not be repeated. The experimental method employed in this study permitted the visualization of bone reactions, even with the lowest loading degree. One should be aware that the structural and spatial relationships of various craniofacial components vary among individuals. It is important to realize that these factors may contribute to the varied responses of the craniofacial components on loading *in vivo*. Thus, the results of this study are valid only for a single specific human skull. This can be seen as a problem in generalizing the findings obtained in this study. On the other hand, studies done by Iseri *et al*.[8] and Jafari *et al*.[7] yielded the same results in spite of the differences in method used and the variation in skull geometry. Iseri *et al*.[8] used CT images of a 12-year-old patient while Jafari *et al*.[7] constructed the model from CT images of dry human skull with an approximate age of 12 years. They showed that although there were differences in the craniofacial structures between subjects, the responses to the same mechanical forces were same in the FEM. Hence, although there were quantitative differences, qualitatively, the mechanical response was

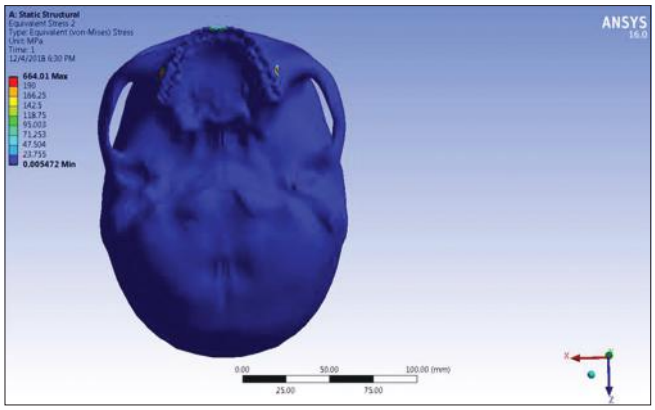


Figure 13: Static structural equivalent stress on glenoid fossa: Class III with 250 g of force

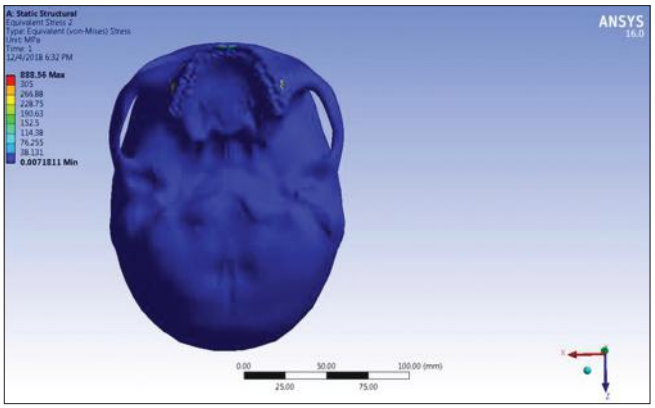
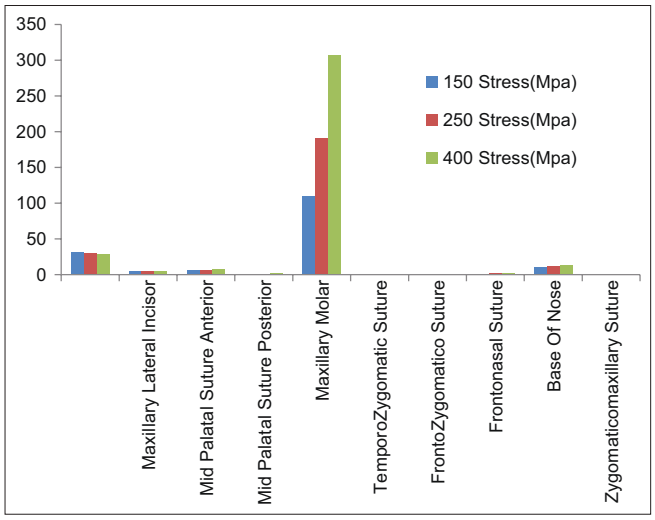


Figure 14: Static structural equivalent stress on glenoid fossa: Class III with 400 g of force

Table 3: Stresses in the maxillary region



predicted in the same manner, which is a positive indication for the validity of the qualitative conclusions.

In the present study, the Class III force was given in stages simulating the BAMP by magnitude of 150, 250, and 400 g on each side. This was done so as to assess the stresses at the various structures of the craniofacial complex including the mandible that occurs as the amount of stress increased in anteroposterior direction.

The findings of the present study show that there is a downward trend in the maxillary region as the Class III force increases from 150, 250 to 400 g. The stresses on maxillary central incisor decreased with increase in force magnitude while that on maxillary molar increased with increase in force magnitude. This can be explained on the bases of "optimum force concept" given by Storey.[11] Forces above and below the optimum bring about delayed tooth movement. The unexpected finding of this study was maxillary protraction force showed minimal stresses on circummaxillary sutures. Clinical studies by Nguyen *et al*.[4] and De Clerck *et al*.[5] showed a forward displacement of maxilla over a period of 1 year. However, this forward maxillary displacement is due to Class III force or growth remains unanswered. Our FEM study does not show any effect of Class III force on maxillary sutures but also cannot evaluate the effect of growth or displacement over a period of time.

It was observed that there was counter clockwise trend in mandibular region with whole of mandible under the deformation with Class III force and stresses increased uniformly all over with increase in magnitude of force. Similar findings were reported by De Clerck *et al*.[3] in their clinical study with BAMP. They concluded that BAMP treatment approach offers an alternative to restrain mandibular growth for Class III with component of mandibular prognathism so as to compensate for maxillary deficiency in patients with hypoplasia of the mid-face. Nguyen *et al*.[12] also commented that BAMP induces favorable control of the mandibular growth pattern and can be used to treat patients of mandibular prognathism.

It was observed that there was an upward trend with maximum stresses on capsular ligament and very minimal on glenoid fossa. However, a clinical study by De Clerck *et al*.[5] with BAMP found a remodeling of the glenoid fossa at the anterior eminence 1.38 ± 1.03 mm and bone resorption at the posterior wall −1.34 ± 0.6 mm in most patients.

CONCLUSIONS

The findings from the present FEM study showed that with BAMP Class III skeletal force, stresses developed on maxilla, mandible, and glenoid fossa and structures associated with them. As the force increases from 150, 250 to 400 g, stresses are increased on all structures associated except maxillary central incisor which show a decrease in the stresses.

Table 4: Comparison of von- Mises stress at maxilla, mandible and glenoid fossa with varying amount of class III stress i. e., 150, 250 and 400 g

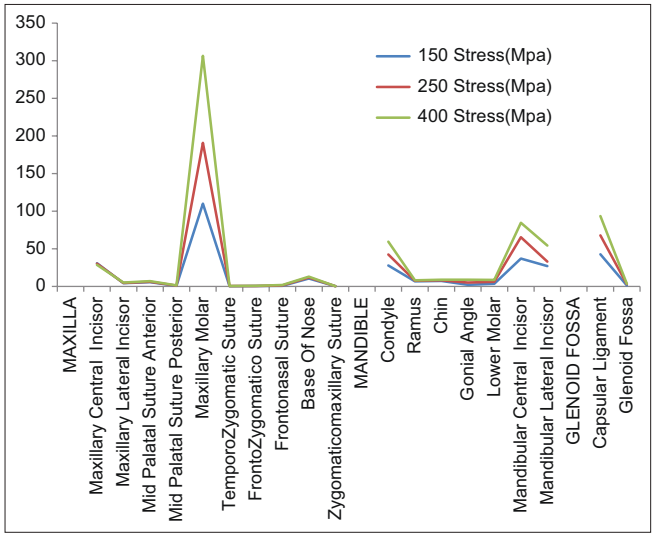
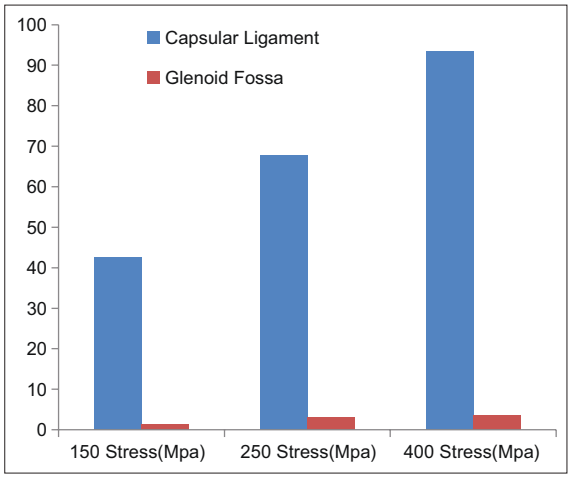


Table 5: Stresses in glenoid fossa region



Maximum stresses are developed in maxillary molar, mandibular incisor, maxillary incisor, condyle, and capsular ligament region. Although forces were for maxillary protraction, stress generated at the circummaxillary sutures was minimal except at anterior midpalatal sutures and base of nose. As with any other Class III force, stresses were distributed on the whole of condyle, capsular ligament, and minimal at glenoid fossa. This suggests that BAMP has more of mandibular restraining effect.

Limitation of the study

The limitation of our study was that displacement over a period of treatment time could not be evaluated as FE studies can record only instantaneous stress pattern.

Scope for future research

A need of advanced finite element software is needed so that stresses over a period of time with orthodontic force, growth, and other forces acting on the craniofacial complex can be simulated and studied.

Financial support and sponsorship

Nil.

Conflicts of interest

There are no conflicts of interest.

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