Evaluation of masticatory stress distribution in mandible of class I, II, III malocclusion cases: a CBCT developed finite element method study.

Dr. Kratika Mishra[a], Dr. P.G. Makhija [b]

Abstract

Objective: Evaluation of distribution of stresses in human mandible generated during clenching in various malocclusion groups like class I, II, III malocclusion for better diagnosis and treatment and rearrangement of teeth to distribute forces.

Materials and methods: 3D anatomical models were generated using DICOM images from CBCT scans. These jaw models were exported using STL format. Such models were developed from class I, II, III malocclusion Cone Beam Computed Tomography (CBCT) data. Complete model was saved as .stl file which were imported in HyperMesh software to generate volume mesh from surface volume by refining the mesh volume of each part of all cases.

Result: In **CLASS I MALOCCLUSION** the stress trajectories were observed from **beneath the teeth in the alveolar process, lower border of mandible.** The stress was **homogeneously distributed throughout the mandibular body, symphysis region, ramus, gonial angle**. In **CLASS II MALOCCLUSION,** the high concentration of stress is seen on symphysis region and beneath the posterior crest of alveolar bone. In case of **CLASS III malocclusion**, the force is not homogeneously distributed throughout entire mandibular body and was observed more in the ramus of the mandible and posterior part even the coronoid process.The low amount of stress was observed in anterior part of mandible and on condylar head.

Conclusion: Various Von Mises stress distributions trajectories and stress patterns were observed in different classes of malocclusion i.e. in class I, II, III malocclusion in cases with normal maxilla and skeletal class I, II, III malocclusion

Key words :CBCT, DICOM, Finite element analysis,Regional thresholding,Von Mises stress,Trajectories.

INTRODUCTION

The biomechanical functions of teeth generally result in stresses, which are transferred from the teeth through the periodontal ligaments, mandible, maxilla and temporomandibular joints and produce strains and stresses in all of them. Understanding the nature of strain and stress distribution in orthodontics is essential for better arrangement of teeth, diagnosis and treatment of stomatognathic diseases and reconstruction of masticatory function. [1]

Antero-posterior disproportions have been categorized into class I (nor-mal), class II (retrusion of the mandible/ Protraction of Maxilla), and class III (protrusion of the mandible/ retrusion of maxilla). These disproportions can affect facial morphology, soft tissue outlines, and occlusal patterns and force dissipation. [3] Several methodologies and study models have been developed to evaluate the masticatory system dynamics. These methods include photoelastic analysis, finite element analysis. [2] The form and function of human mandible report that the region of the mandibular body reshapes itself forward of the stresses generated in the teeth and muscle action. Functionally, teeth and masticatory muscle stimulate and activate the formation and organization of the mandibular bone tissue. The knowledge of stress distribution in mandible contributes to understand the effect of surgical approaches (e.g., orthognathic surgery). The literature reports that structures such as the oblique line, body, and base of the mandible concentrate stress from masticatory loads.[5]

In a study conducted by D.Parle et al [6] (2013) for estimation of individual bite force during normal occlusion using FEA, the effect of jaw alignment on bite force within the framework of FEA using impact analysis were investigated. It was observed that in case of receding lower jaw maximum stress with value of 84.10 MPa was induced whereas protruding lower jaw has minimum stress with value 65.18 MPa. They also concluded that stress distribution is more uniform in lower jaw than the upper jaw. They concluded that the stress distribution varies in different alignments of lower jaw. Results of their study were not similar because of dissimilar parameters were used in that study.

The use of finite element method allows studying a single tooth, a set of teeth, or even the relationship between maxillary and mandibular dental arches on a more solid and precise biomechanical basis than other methods such as photoelastic models and strain gauges. Therefore, with

a- Post graduate Student, Department of Orthodontics and Dentofacial Orthopaedics, Modern dental college and research centre.
b- Professor & Head, Department of Orthodontics and Dentofacial Orthopaedics, Director Academics, Modern Dental College and Research Centre.

this methodology it is possible to have quantitative and qualitative representations of dental and mandibular biomechanics to evaluate displacements, strains and stresses, which may occur in biomechanical structures. [1]

MATERIAL AND METHODS

The CBCT data of adult patients undergoing orthodontic treatment and having CBCT records with skeletal class I, II, III with normal maxilla were collected from our department

The inclusion criterion includes Age above 18 years. X-ray showing erupted second molars and erupted or unerrupted third molars and patients undergoing routine orthodontic treatment have CBCT records with skeletal Class I, II, and III malocclusion.

The exclusion criteria includes

Records of Patients with short maxilla, long maxilla, and syndrome cleft palate., History of Bruxism in patient's records, Age < 18 years, Patients with previous orthodontic treatment, Patients with periodontal , temporomandibular joint disease, transverse discrepancies, Patients with signs of condylar lesions.

Method:

1.Acquisition /selection Acquisition / selection of data

(All the data for FEM models were selected as per inclusion criteria for class I, II, III from records with Orthodontic FOV, CBCT scans of patients were taken by the [Kodak CS 9300] CBCT machine.

- Anatomical data obtained from Cone-Beam Computated Tomography in the form of Dicom files format, was imported in the 3D- Slicer Software.

- After importing in 3D-Slicer software, [Slicer 3D 4.5.0-10, *http://www.slicer.org*] 3D model of individual teeth, maxilla, mandible of each case was generated by applying different threshold values i.e. bone threshold values to CBCT data.

- Regional thresholding was done to develop areas of condylar region.

2. Volume visualization and segmentation. Saving 3D stl

The complete model was saved as .stl file. Also the skull, maxilla, individual teeth of both arches, mandible were sculpted out and saved in .stl file format individually for class I, II, III cases.

3. Remeshing to volumetric mesh and generating FEM model

Saved .stl files are imported in the HyperMesh software (version 8.0; Altair Engineering, Troy, MI, USA) to generate volume mesh from surface volume by refining the mesh volume of each part of all cases.

4. FEM analysis -After refining and volume mesh is created, combined model was ready for the Finite Element Analysis exported in ANSYS software (version 8.0, Canonsburg, Pa) in .cdb file format for class I, II, III independently. Predetermined loads in different areas were applied and results documented appropriately.

METHODOLOGY:-

1. The anatomical model consisted of 6 basics parts: Maxillary Teeth, Mandibular teeth, Mandible, Maxilla, TM Joint, and Skull

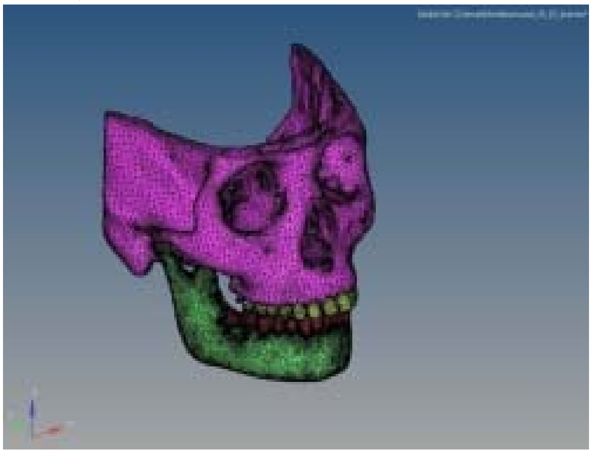


Fig.1 Three dimensional Finite Element Model of the skull for performing FEM analysis

2. Conversion of anatomical model to a finite element model-

The .STL files were imported to HyperMesh software (version 8.0; Altair Engineering, Troy, MI, USA), meshes were cleaned and models were made solid with tetrahedral nodes.

MESHING-These steps involved subdivision of geometric model in discrete elements. The resulting set is called Mesh. Hyper mesh provides various options to produce 3D mesh.

This process is called discretisation. The main idea behind discretisation is to improve the accuracy of the results. Structurally articular discs are fibro cartilaginous tissue so their geometric shape could not be scanned by means of computed tomography. Therefore we generated the geometry of articular discs mathematically by using a mathematical "material forming" procedure. The obtained geometrical shape of the articular disc is assumed to be as initial one for subsequent calculations.

Material	Elastic modulus	Poisson ratio
Articular disc	30.9	0.4

Table.1 Material properties of Articular Disc. Data from Tanaka et al [1]

Biological form of the articular disc's perimeter is not relevant to the experimental analysis of stresses because in the physiological clenching conditions articular discs are "fixated" onto mandibular condyles. This STL model was converted into finite element model, the finite element modeling is the representative of complex geometry of anatomical forms in terms of finite number of elements and nodes.

Number of nodes and elements will vary according to model, software and operator.

No. Of Nodes	271441
No. Of Elements	1230025

Table.2 Showing number of nodes and elements for three dimensional finite element model in class I Malocclusion

No. Of Nodes	270941
No. Of Elements	1229525

Table.3 Showing number of nodes and elements for three dimensional finite element model in class II Malocclusion

No. Of Nodes	271941
No. Of Elements	1230525

Table.4 Showing number of nodes and elements for three dimensional finite element model in class III Malocclusion

3. Materials and LBC'S (Loads and boundary conditions)

For the material characteristics of bone, assumptions were made, as in other FE studies,[1] that cortical bone is isotropic, homogeneous and linearly elastic.

Material properties	Values
THICKNESS	5 MM
YOUNG'S MODULUS	± 10^{10}N M^{-2}
DENSITY	1.5 G CM^{-3}
POISSON'S RATIO	—0.21

Table.5 The physical parameters attributed to the FEM model.

The model of maxillary dental arch was fixed in space. The model of mandibular dental arch with mandible was able to move in space synchronically with the mandibular condyles under action of applied forces, which were considered as prescribed and known at points of attachment of masticatory muscles. Clenching was simulated by the action of resultant force vectors of four bilateral masticatory muscles, responsible for the elevation of the mandible (masseter, temporalis, lateral and medial pterygoid muscles), which was assumed as static occlusal load [9]

Maximum muscle forces, related with their physiological cross-sectional areas, were defined as shown in Table:-6[8].

Masticatory Muscle	Physiological Cross-Section, Cm^2	Maximum Muscle Force, N
Masseter Muscle	8.0	376.0
Temporalis Muscle	9.1	427.7
Lateral Pterygoid Muscle	0.8	37.3
Medial Pterygoid Muscle	4.4	207.6

Table.6 Physiological Cross-Sections and Maximum Forces of the Masticatory Muscles

Clenching movements were simulated by a simultaneous activation of the masticatory muscles, with a load of 1000N applied to whole jaws through 5 areas i.e. through incisors, canine, premolars and molars to distribute the load uniformly. Five areas were selected bilaterally for full arch loading.

4. Loading and FEM Analysis Loading

Vertical forces were directed to the mandible by keeping maxilla constant in the space with the help of the masticatory system, mandible is kept movable and full dental arch loading was applied. Different tests were performed to check varying single point vertical loading force that showed different types of stress and strain pattern in mandible that spread through the trajectories in class I, II, III malocclusion. Values taken for comparison of loading points and full dental arch loading 1000N of force was applied to the nodes. On full dental arch loading, force is distributed bilaterally between first molar, second molar, canine and central incisor. The values were 260N, 280N, 200N, 148N, 112 N respectively. Vonn Mises (VM) criteria were selected to describe the stress strain pattern of the mandible during simulated occlusal loading, analysis of VM pattern.

5. Visualization of results and evaluation of stress distributions

The step involves visualization of various results such as VM Stresses and contact forces. The stresses generated were observed in CLASS I, CLASS II, CLASS III malocclusions. Colored histograms depicting various stress values were displayed for different trajectories.

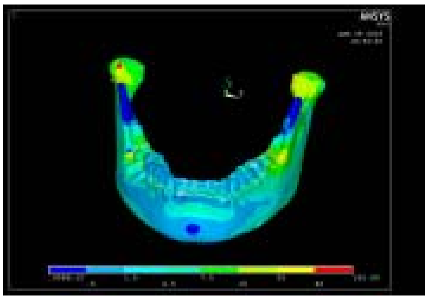


Fig.2 Showing the Von Mises Stress Distribution after simulation in Class I malocclusion.

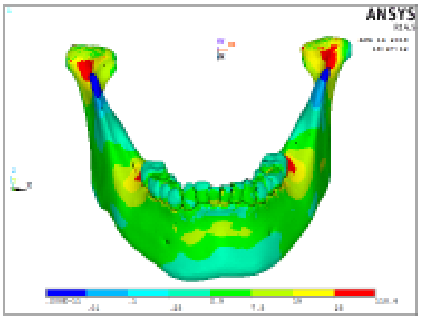


Fig.3 Showing the Von Mises Stress Distribution after simulation in Class II malocclusion.

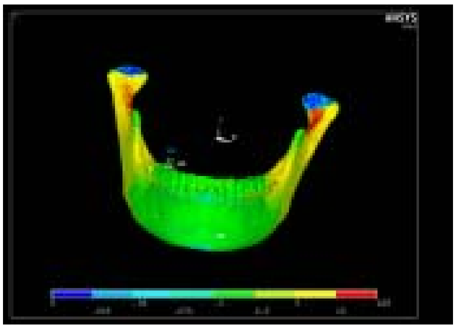


Fig.4 Showing the Von Mises Stress Distribution after simulation in Class III malocclusion.

RESULT:

CLASS I MALOCCLUSION **:-** When the occlusal forces were applied on the mandibular teeth, the stresses were observed from beneath the teeth in the alveolar process, lower border of mandible. The stresses were homogeneously distributed throughout the mandibular body, symphysis region, ramus, gonial angle. No stress was observed in the region of coronoid process.

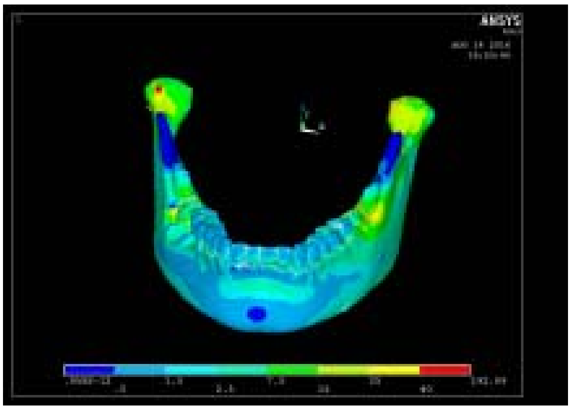


Fig.5 showing Von Mises Stress distribution in mandible in class I malocclusion (front view)

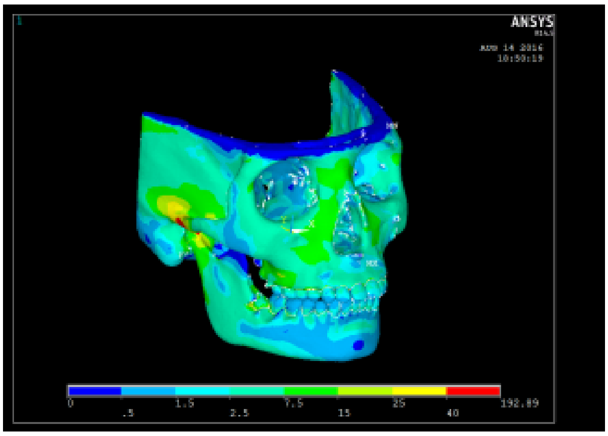


Fig.6 showing Von Mises Stress distribution in entire skull in class I malocclusion

CLASS II MALOCCLUSION

When the occlusal forces were applied on full dental arch loading, the stresses are distributed from beneath the teeth in the alveolar process, lower border of mandible. The stresses were homogeneously distributed throughout the mandibular body, symphysis region, ramus, gonial angle. No stress was observed in the region of coronoid process. In class II pattern stresses are generally distributed throughout the mandibular body, the stress distribution is slightly asymmetric. The high concentration of stress is seen on symphysis region and beneath the posterior crest of alveolar bone. On vertical loading of the first molar loading point, the stresses were also located on the central part of articular discs, directly contacting with mandibular condyles. During this vertical loading articular discs were in central position, typical of maximum intercuspation.

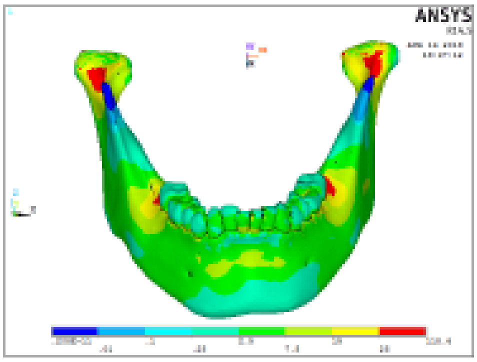


Fig.7 showing Von Mises Stress distribution in mandible in class II malocclusion (front view)

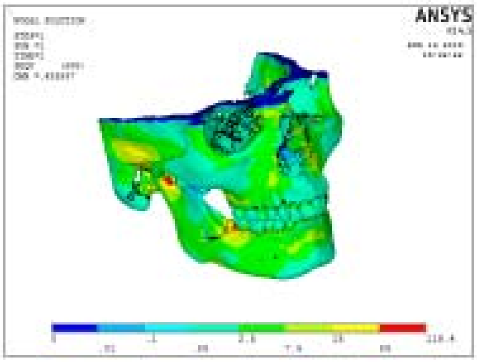


Fig.8 showing Von Mises Stress distribution in skull in class II malocclusion (oblique view)

CLASS III MALOCCLUSION

In case of class III malocclusion, the force is not homogeneously distributed through entire mandibular body, The stress concentration was also observed more in the ramus of the mandible and posterior part even the coronoid process.The low amount of stress was observed on condylar head which was different in situations in class I and class II malocclusion cases.

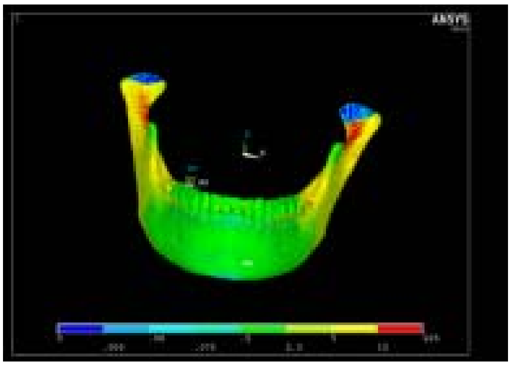
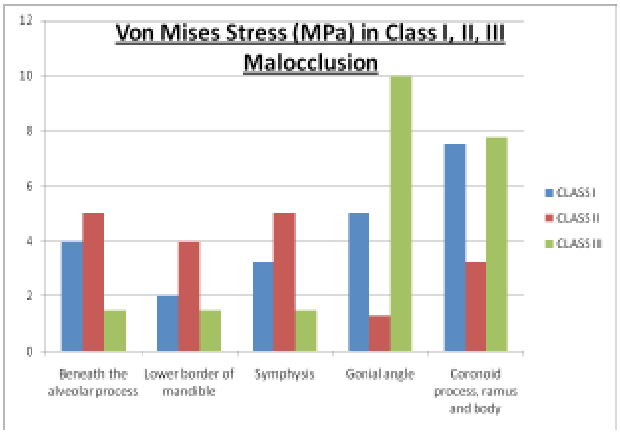


Fig.9 showing Von Mises Stress distribution in mandible in class III malocclusion (front view)

DIFFERENT REGIONS IN MANDIBLE	CLASS I	CLASS II	CLASS III
Beneath the alveolar process	4	5	1.5
Lower border of mandible	2	4	1.5
Symphysis	3.25	5	1.5
Gonial angle	5	1.3	10
Coronoid process, Ramus, Body	7.5	3.25	7.75

Table.7 showing Von Mises stress distribution comparison in Class I, II, III Malocclusion.



Graph 1 showing comparison of Von Mises Stress in different areas of mandible which represents various trajectories of forces. (X axis depicting Von Mises Stress and Y-Axis depicting trajectories of forces)

DISCUSSION:

In this study the evaluation of stress distribution in mandible of different skeletal Class I, II, III malocclusion with normal maxilla respectively is performed using finite element analysis. The full arch loading was done with a load of 1000 N, and the Von Mises stress distribution was observed in mandible. In this study, similar homogenous stress distribution pattern were observed in mandible following the normal trajectories of forces in class I malocclusion whereas the force in class II pattern stresses are generally distributed throughout the mandibular body, the stress distribution is slightly asymmetric. The high concentration of stress is seen on symphysis region and beneath the posterior crest of alveolar bone. In case of class III malocclusion, the force is not homogeneously distributed through entire mandibular body, instead it is more concentrated on the anterior region of mandible mostly in symphysis region shown by green colour.The stress concentration was also observed more in the ramus of the mandible and even the coronoid process. On comparing Class I with Class II **.** The low amount of stress was was observed on condylar head which was different in situations in class I and class II malocclusion cases. Benninghoff [4] did extensive study on dried craniofacial bones and concluded that the stress trajectories or lines of orientation of the bony trabeculae involve not only the cancellous bone but also the compact bone. These trajectories are formed not only in the direct response to functional influences, but also to epigenetic influences. The intrinsic genetic potential has no role in the formation of trajectories. The stress trajectories respond to the demands of functional forces collectively as a unit and not as a single bone. These trajectories or functional lines are called as Benninghoff lines. Such pattern of force lines is confirmed from our study.

The main goal of this study was to evaluate the final stress distributions in the mandible in class I, II, III malocclusion (with normal maxilla), for understanding the position of teeth, stress distribution. The stress distributions in our study were similar to the previous reports[1] and the stress levels from our model were within the range of reported stress magnitudes. Furthermore, previous reports were based on the partial models of temporomandibular joints, while our model included all the main elements of masticatory system. Wherein we have reconstructed higher accuracy three-dimensional geometry of all the parts, comprising teeth, alveolar bone, maxilla, mandible, TMJ, Skull, appropriate extensions of the model would enable to investigate distribution of stresses and strains in all parts and interaction between them in different simulated situations, such as disturbed occlusal equilibrium or alveolar bone loss due to the periodontal disease. Much research into the relationship between biomechanics and craniofacial morphology has focused on which loading regimes play the most important role in shaping craniofacial adaptation and how stresses are dissipated through the cranium. [7]

Earlier on anatomical models were used for FEM. Our method is superior in that the models are anatomical representation of actual class I class II class III malocclusion Study involving each tooth under different loading condition is not feasible at this stage of development and requires highest degree of expertise. Inspite of anatomical models these are given material properties which have to be decided by density of meshes. It does depend on the density of bone which is varied in regions with dense cortical bone and loose spongy bone. Despite its limitations, the current study shows that the simula-tion of CBCT images can be successfully integrated and the occlusal forces can be clearly simulated in different skeletal malocclusions.

CONCLUSION

1. In **CLASS I MALOCCLUSION**, when the occlusal forces were applied on the mandibular teeth, the stresses were observed from **beneath the teeth in the alveolar process, lower border of mandible.** The stresses were **homogeneously distributed throughout the mandibular body, symphysis region, ramus, gonial angle**. No stress was observed in the region of coronoid process. So this might be suggested as ideal arrangement of teeth.

2. In **CLASS II MALOCCLUSION,** the pattern stresses are generally distributed throughout the mandibular body, the stress distribution is slightly asymmetric. The high concentration of stress is seen on symphysis region and beneath the posterior crest of alveolar bone. It suggests that teeth might be under stress in anterior region. And they should be rearranged accordingly for better stability and health.

3. In case of **CLASS III malocclusion**, the force is not homogeneously distributed throughout entire mandibular body. The stress concentration was observed more in the ramus of the mandible and posterior part even the coronoid process.The low amount of stress was observed in anterior part of mandible and on condylar head which was different in situations in class I and class II malocclusion cases. In this case lower anterior teeth have least forces of occlusion.

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