Investigating the Biomechanics of the Human Mandible Through Three-Dimensional Modeling and Finite Element Analysis

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Abstract:- Finite Element Analysis (FEA) and 3D modeling are two powerful computational tools that have been widely used to study the human mandible. Both methods have been applied to understand the mechanical behavior of the jaw bone, and to support clinical decision making in areas such as surgical planning, orthodontic treatment, and implant placement. In a typical FEA study, a 3D model of the human mandible is first created from medical imaging data such as CT or MRI scans. The model is then divided into small elements, or finite elements, that are connected at nodes. These elements represent the underlying structure and properties of the bone, such as its material properties and geometric shape. The finite element model is then subjected to various loads and boundary conditions, such as chewing or biting forces, to study the behavior of the mandible under different conditions. In addition to FEA, 3D modeling of the human mandible can be used to create virtual representations of the bone that can be manipulated and visualized in different ways. This can be useful for a variety of applications, such as surgical planning, orthodontic treatment, and implant placement. For example, 3D models can be used to evaluate the fit of implant components, simulate the effects of orthodontic treatment on the jaw, or assess the outcomes of various surgical procedures. In conclusion, the combination of FEA and 3D modeling provides a powerful tool for studying the human mandible and supporting clinical decision making in various fields. The ability to create virtual representations of the jaw and simulate its behavior under different conditions offers valuable insights into the biomechanics and behavior of this complex structure.

Keywords: *Reverse Engineering, Computed Tomography, 3D Modeling, Finite Element Analysis, FEA, Human Mandible, Mechanical Behaviour, Jaw Bone, Clinical Decision Making, Surgical Planning, Orthodontic Treatment, Implant Placement, Medical Imaging Data, CT Scans, Biomechanics.*

I. INTRODUCTION

A. Human Mandible:

The human mandible, also known as the lower jaw, is a bone located in the facial region of the skull. It is the largest and strongest bone in the human face and is crucial for speech, chewing, and facial expression.

The mandible is a U-shaped bone that is connected to the skull by the temporomandibular joint, which allows for movement of the jaw. The mandible is composed of a body, which forms the front of the jaw, and two vertical branches, which extend upwards on either side of the face to form the jawline.

The body of the mandible is horizontal and has a prominent ridge called the mandibular symphysis that runs along its midline. The mandible also contains the alveolar process, which holds the teeth in place.

The mandible plays a critical role in the digestive process by providing a stable platform for the teeth to grind and break down food. Additionally, the mandible is responsible for the movements of the tongue and lips, which are important for speech.

In addition to its functional importance, the mandible also has aesthetic significance, contributing to the overall shape and contour of the face. Any malformation or injury to the mandible can have a significant impact on both function and appearance.

Fig 1 Human Mandible

B. Structure of Mandible:

➤ *Components:*

The mandible, or lower jawbone, is the largest and strongest bone in the human face. It is a complex bone that consists of several parts and features, including:

- *Body:* This is the main, horseshoe-shaped part of the mandible that forms the lower jawline and houses the lower teeth.
- *Ramus:* The ramus is the vertical portion of the mandible that extends upward from the body on each side of the jaw.
- *Coronoid process:* This is a bony projection on the anterior portion of the ramus that serves as an attachment point for the temporalis muscle, which is used in chewing.
- *Condyle:* The condyle is the rounded, knob-like portion of the posterior portion of the ramus that articulates with the skull's temporal bone to form the temporomandibular joint (TMJ), which allows for jaw movement.
- *Mandibular notch:* The mandibular notch is the concave depression between the coronoid process and the condyle.
- *Mental protuberance:* This is a bony prominence that forms the chin's lower surface.
- *Alveolar process:* The alveolar process is the thickened ridge of bone that contains the sockets for the lower teeth.
- These structures work together to provide support for the teeth and to allow for movements like chewing and speaking.

Fig 2 Mandible, Lateral Surface, Side View

➤ *Changes in Mandible with Age:*

The mandible, or lower jaw bone, undergoes several changes as a person ages. Some of these changes include:

- *Bone loss:* As people age, they naturally lose bone mass, including in the mandible. This can lead to a decrease in overall jaw size and a more pronounced chin.
- *Tooth loss:* Tooth loss is more common in older individuals and can affect the shape and size of the mandible. When teeth are lost, the jawbone can resorb or shrink, causing changes in the facial structure.

- *Wear and tear:* Over time, the mandible can experience wear and tear from chewing, grinding, and clenching. This can lead to changes in the shape and size of the jawbone.
- *Changes in muscle and fat distribution:* The distribution of muscle and fat in the face can change with age, which can affect the appearance of the mandible. For example, the loss of fat in the cheeks can make the jawline appear more prominent.

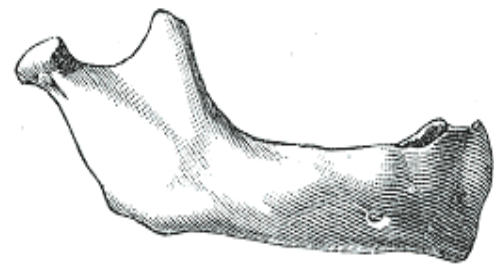Overall, these changes can lead to a less defined jawline and a more sunken appearance to the face in older individuals.
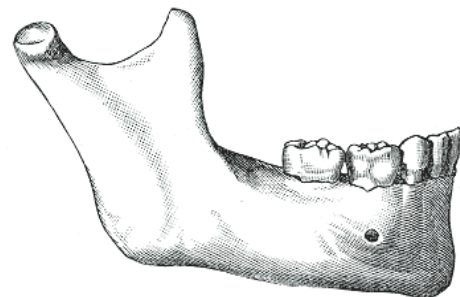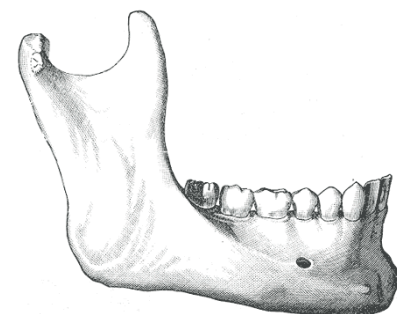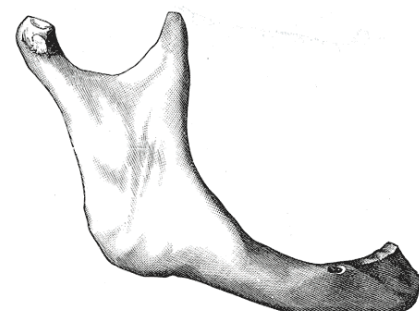

Fig 3 At Birth

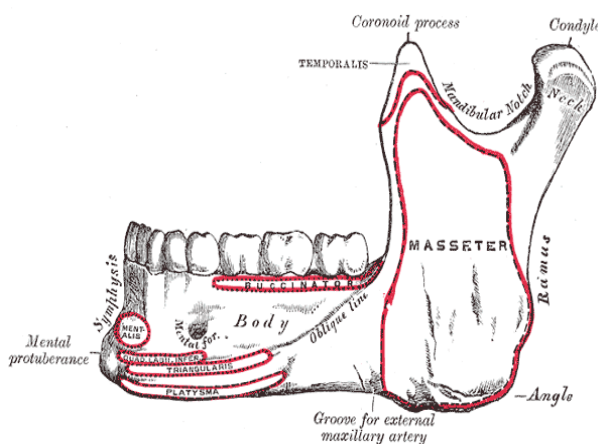Fig 4 In Childhood

Fig 5 In the Adult

Fig 6 In Old Age

➢ *Clinical Significance:*

• *Fracture:* Facial injuries often involve mandibular fractures, which account for one-fifth of all such injuries. [2] Twin fractures on the opposite side of the mandible are also common. However, there is no standard treatment protocol due to the absence of a consensus on the optimal techniques to be employed for a particular type of mandibular fracture. In most cases, metal plates are attached to the fracture to assist in the healing process. [3]

Table 1 Fracture Cause

Cause	Percentage
Motor Vehicle Accident	40%
Assault	10%
Fall	10%
Sport	5%
Other	5%

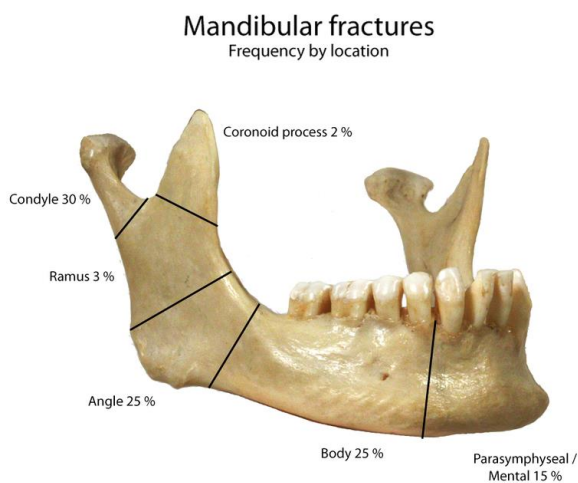Below figure shows the mandibular factures frequency by location:

Fig 7 Mandibular Fracture

• *Forensic medicine:* In the field of forensic medicine, the mandible is frequently discovered when human remains are found, and it may even be the only bone that is recovered. Trained professionals are capable of determining the age at which the individual passed away by analyzing the changes that occur in the mandible throughout a person's lifetime. [5]

C. Reverse Engineering:

Reverse engineering in the context of CAD (computer-aided design) refers to the process of creating a 3D CAD model of an existing physical object by analyzing its shape, dimensions, and other characteristics. This is typically done using specialized software and hardware tools that capture the object's geometry through scanning or measurement.

The goal of reverse engineering in CAD is to create a digital model that accurately represents the physical object, which can be used for various purposes such as redesign, modification, or replication. This process can be particularly useful in situations where the original design data is unavailable, incomplete, or outdated.

Reverse engineering in CAD typically involves several steps, including data acquisition, data processing, and model creation. During the data acquisition phase, the physical object is scanned or measured using tools such as laser scanners or coordinate measuring machines. The resulting data is then processed to remove any errors or noise and prepare it for modeling.

Finally, a CAD model is created based on the processed data, which may involve surface modeling, solid modeling, or other techniques depending on the complexity of the object and the desired level of detail. The resulting CAD model can then be used for further analysis, simulation, or manufacturing.

➢ *Reasons of RE:*
Reverse engineering is used for a variety of reasons, including:

• *Product redesign:* Reverse engineering can be used to create a 3D CAD model of an existing product, which can be modified or improved to create a new and improved product.
• *Legacy data:* In cases where the original design data is lost or unavailable, reverse engineering can be used to recreate the design data from the physical object.
• *Competitive analysis:* Reverse engineering can be used to analyze and understand a competitor's product, which can help inform the design and development of a competing product.
• *Quality control:* Reverse engineering can be used to verify the quality and accuracy of an existing product, which can help ensure that subsequent products meet the same standards.
• *Intellectual property:* Reverse engineering can be used to investigate and enforce intellectual property rights, such as patents, by identifying potential infringements.
• Overall, reverse engineering is a valuable tool for many industries, including manufacturing, engineering, and design, as it allows for the creation of accurate and detailed 3D CAD models of existing physical objects.

➢ *Reverse Engineering Differs from other Types of Engineering:*
Reverse engineering and forward engineering are two different approaches to designing and creating products or systems:

Reverse engineering is the process of taking an existing product or system and creating a 3D CAD model or digital representation of it. This approach is useful in situations where the original design data is unavailable or incomplete, or where an existing product needs to be modified or improved.

Forward engineering is the process of starting with a concept or idea and designing and creating a product or system from scratch. This approach involves defining requirements, creating designs, and then building and testing the final product.

In summary, the main difference between reverse engineering and forward engineering is the starting point. Reverse engineering starts with an existing product or system, while forward engineering starts with a concept or idea.

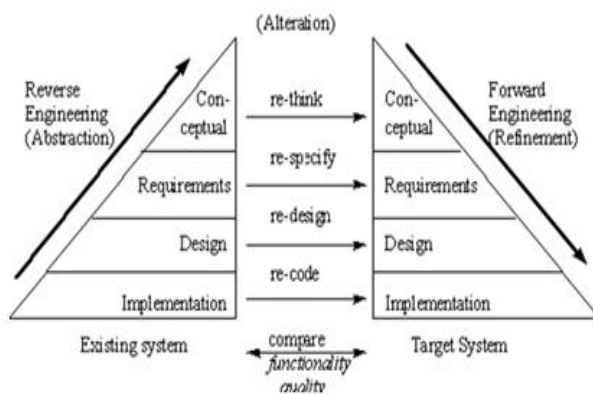Following figure clarifies the concept of forward and reverse engineering efficiently.

Fig 8 Reverse and Forward Engineering

➤ *Different Reverse Engineering Techniques:*
There are several techniques used in reverse engineering, including:

- *3D Scanning:* Using laser scanners, coordinate measuring machines (CMMs), or structured light scanners to capture the geometry and dimensions of a physical object.
- *X-ray imaging:* Using X-ray imaging techniques to capture internal features and structures of an object that cannot be seen from the surface.
- *CT scanning:* Using computed tomography (CT) scanning to capture a series of cross-sectional images of an object and then reconstructing them into a 3D model.
- *Photogrammetry:* Using photographs or images to extract 3D information and create a 3D model.
- *Disassembly:* Disassembling an object to examine its components and how they fit together, and then using this information to create a 3D model.
- *Reverse engineering software:* Using specialized software tools that can analyze data from various sources and generate a 3D CAD model.

Each of these techniques has its advantages and disadvantages, and the choice of technique will depend on factors such as the complexity of the object, the required level of detail, and the available resources. By using these techniques, reverse engineering can be used to create accurate and detailed 3D CAD models of existing physical objects.

D. CT Examination:
Computer Tomography (CT) is an imaging technique used in medical diagnostics that allows for non-invasive imaging of internal structures within the body. CT scanners use X-ray technology to produce detailed images of organs, bones, and other tissues within the body.

From an engineering perspective, CT scanners can be viewed as complex systems that involve the integration of multiple components, including X-ray generators, detectors, data acquisition systems, and image reconstruction algorithms.

X-ray generators are used to produce X-rays that pass through the body and are detected by the detectors. These detectors are typically made up of arrays of scintillators that convert the X-ray energy into visible light, which is then detected by photodiodes or other sensors.

The data acquisition system is responsible for collecting the signals from the detectors and converting them into digital signals that can be processed by a computer. The computer then uses image reconstruction algorithms to convert the digital signals into detailed 2D or 3D images of the internal structures within the body.

CT scanners also incorporate advanced software that allows for the optimization of image quality and the reduction of radiation exposure to the patient. This software may include algorithms for noise reduction, artifact correction, and dose optimization.

Overall, the design and implementation of CT scanners require a multidisciplinary approach, involving expertise in areas such as X-ray physics, detector technology, data acquisition, image processing, and software engineering.

➤ *Objective:*
The purpose of this research project is to achieve two main goals. Firstly, the project aims to create an accurate 3D model of the human mandible, which will be achieved by utilizing CT scan images and the specialized software MIMICS. This will allow for a highly detailed and precise representation of the mandible, which can be used for further analysis and simulations.

Secondly, the project seeks to conduct Finite Element Analysis (FEA) of the mandible during clenching. FEA is a method of analyzing the behavior of structures under various conditions by dividing them into smaller, more manageable parts. In this case, the mandible will be subjected to the stress and strain of clenching, and the FEA will enable researchers to understand the mechanical response of the mandible to this action. This information can be useful for a variety of applications, including the design of dental implants or the treatment of mandibular disorders. Overall, this research project aims to contribute to a better understanding of the human mandible's mechanical behavior and facilitate the development of new treatments and devices in this area.

II. METHODOLOGY

➢ *Modeling of Human Mandible using MIMICS:*

• *Importing CT Data:*
First step is to import the CT scan files to the Mimics software. With the Mimics software, the 150 slice images produced in the CT scan can be imported automatically.

Fig 9 Importing Data

• *Thresholding:*
Computed tomography (CT) images provide a pixel map representation of tissue's linear X-ray attenuation coefficient. The Hounsfield (HU) scale is applied to adjust the pixel values, setting the linear X-ray attenuation coefficient of air to -1024 and that of water to 0. Thresholding based on the HU scale can differentiate between the various parts of the mandible, including bones and encapsulated soft tissues. To isolate the human mandible structure and exclude the cartilage regions, a lower limit of 226 HU and an upper limit of 3071 HU are established. During the thresholding process, the bone structure is highlighted in green color. This technique allows for selective bone structure inclusion in 3D model generation, making thresholding an essential step in creating the mandible's 3D model.
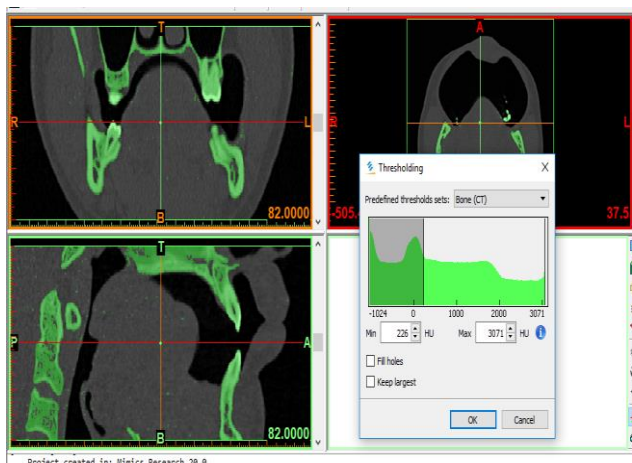

Fig 10 Thresholding

• *Cavity Filling:*
Thresholding and region growing techniques may not be sufficient to accurately select all bone structures in CT imaging due to density differences. This can result in only surface bones being included in the model, leading to inaccuracies. To address this issue, cavities in each layer of the mandible structure were filled to improve the accuracy of the 3D computer-aided design (CAD) model generated. By filling the cavities, a more complete representation of the mandible structure can be obtained, which can have important clinical and research applications.

• *3D Model Generation:*
The generated region masks were utilized to produce 3D models of both the bones and encapsulated soft tissues volume of the mandible. The 3D reconstruction process involved 3D interpolation techniques that transform the 2D images (slices) into a 3D model. To achieve a more accurate dimensional representation of the mandible structure, gray values interpolation was employed along with an accuracy algorithm. In order to eliminate small inclusions and reduce the number of mesh elements, shell and triangle reduction techniques were respectively applied. Afterward, each region was reconstructed to capture all the bones and encapsulated soft tissues volume that geometrically define the mandible structure.

Fig 11 3D Model Generation

• *Editing 3D Model in 3-Matic:*
The 3D model generated by the process described above may not be entirely accurate, and further refinement is needed. Additionally, the model's surface may be rough, requiring smoothing to create a more polished appearance. This is accomplished by selecting a smoothing factor between 0 and 1 and performing a number of iterations. With these refinements, an accurate and smooth 3D model can be generated.
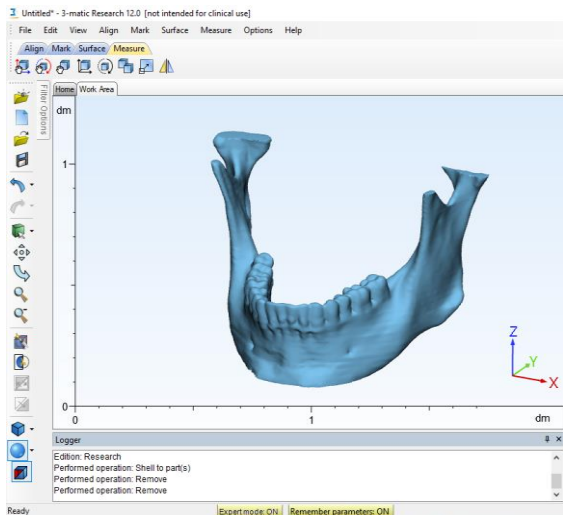
Fig 12 Smoothed 3D Model

- *Meshing of Model:*

Model is created, now next step is to mesh the whole part using adaptive mesh tool. This mesh will only performed on surfaces. So, for 3D model it is converted into the volumetric mesh.
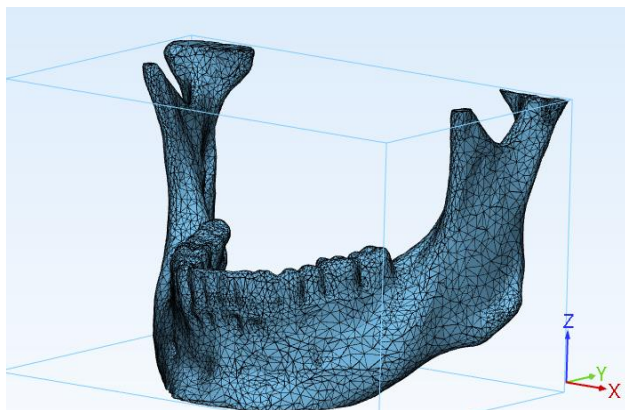

Fig 13 Volumetric Mesh

- *Exporting Files:*

After generating a 3D CAD model, it needs to be exported in an appropriate format for further analysis. In this study, the MIMICS software was used to export the file in .iges (Initial Graphics Exchange Specification) format.

III. FINITE ELEMENT ANALYSIS

Finite Element Analysis plays a crucial role in the research project as it helps to identify various stresses, strains, and displacements. In this analysis, the stress and displacement of the human mandible during clenching were calculated. ANSYS Workbench 19 software was used for static analysis project. The project was set up with static structural, as the objective was to conduct a static analysis. The geometry was imported in .iges format, and material properties were added. The model was generated, and the surface was converted to solid while adding material to it. Meshing was performed using tetrahedral triangles in medium mode. A fixed support was provided on a specific surface area, and the loading was applied at the location where it was required. After importing all necessary data, the solution for stress and deformation was selected and executed. This method enabled the researchers to obtain the required data on stress and deformation in their model.

- *Analysis Steps:*

- *Importing Geometry:*

To conduct finite element (FE) analysis of the human mandible, a 3D model of the mandible was developed. This study utilized an ideal human mandible model that was reconstructed from CT images in DICOM format. The model was then imported into ANSYS Workbench 19 in .iges format for further analysis.

- *Adding Material Properties:*

The necessary material properties, such as density, Young's modulus, yield strength, and Poisson's ratio, have been provided for the project. [7]

Table 2 Material Property

Material	Young's Modulus		Poison's Ratio	
Cortinal Bone	E_1	6.9	V_{12}	0.315
	E_2	8.2	V_{23}	0.325
	E_3	17.3	V_{13}	0.310

- *Model Generation:*

The model is created by importing the geometry and assigning appropriate material properties.

- *Meshing:*

In this particular model, a tetrahedral mesh was generated with a minimum element size of 1 mm and a maximum element size of 3 mm. After the meshing process was completed, a total of 36,065 nodes and 35,205 elements were created in the geometry.
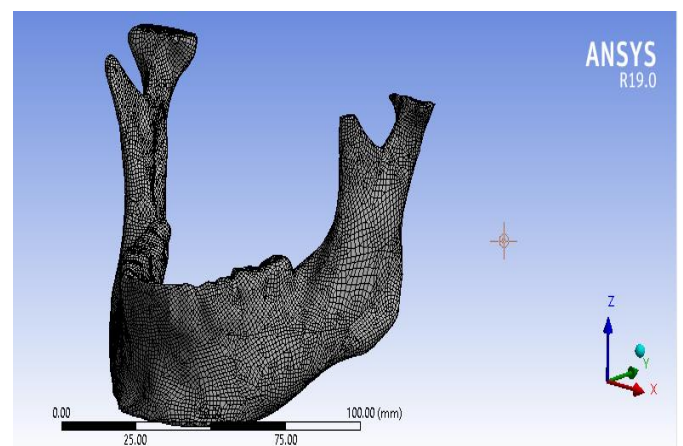

Fig 14 Meshing

- *Fixed Support & Loading Condition:*

To constrain the movement and displacement of the model during stress analysis, a fixed support is applied at the bottom of the mandible. The model is subjected to loads at different locations on the mandible for stress analysis purposes.

Fig 15 Loading Condition

IV. RESULT

After providing all the required input data, the stress and displacement are computed based on the assigned material and loading condition, which are as follows.

Fig 16 Total Deformation - Ansys Result

Maximum deformation is limited to 0.42214 mm, which is on condyle area of mandible. Average value of deformation is 9.3059e-002 mm. Maximum Stress induced in this analysis is 16.157 MPa. And Average value of Equivalent stress is 1.199 MPa.

Fig 17 Equivalent Stress - Ansys Result

V. CONCLUSION

In conclusion, this project has made a significant contribution to our understanding of mandibular biomechanics by showcasing the process of designing 3D mandibular models using reverse engineering.

This study has effectively demonstrated the potential of computer-aided modeling and finite element analysis in the biomechanical analysis of the mandible. These techniques have the potential to investigate many functional problems and could significantly reduce the time required for extensive experimentation.

The findings of this study suggest that the use of computer-aided modeling and finite element analysis has enormous potential for the study of mandibular biomechanics and could lead to significant advancements in the field of dental research.

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[8]. Eiji Tanaka, Kazuo Tanne and Mamoru Sakuda, "A three-dimensional finite element model of the mandible including the TMJ and its application 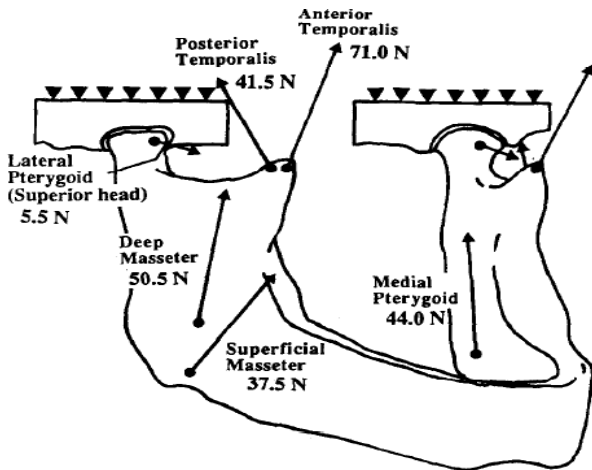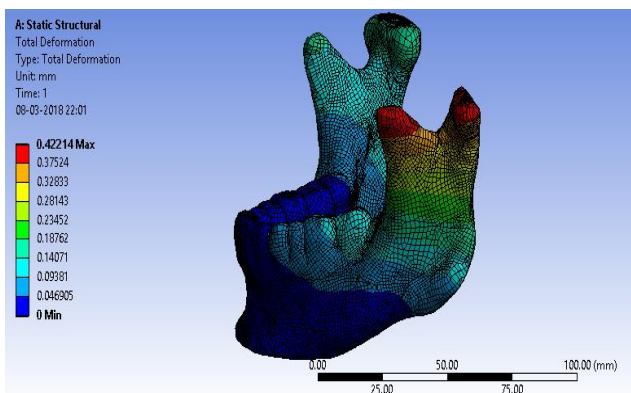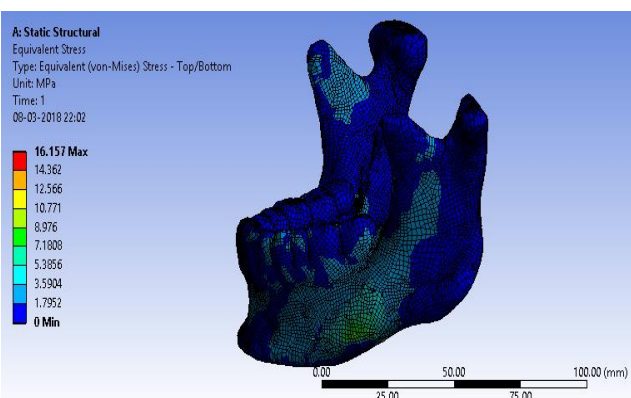to stress analysis in the TMJ during clenching", 1994.