Design and Finite Element Analysis of Mandibular Prosthesis

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***Abstract*: Many reconstructive surgeons are confronted with difficult issues when it comes to defect repair. It is not only necessary to repair the implant during the reconstruction, but it is also necessary to fix the complete mandible. Trauma, deformity, infection, exposure, and radiations can all lead to mandibular abnormalities. The goal of this research was to use finite element analysis to reconstruct a portion for a cancer-affected mandible and perform different stress-strain characteristics such as von-misses stress, vector sum displacement, and numerous features (FEA). Materialism's Interactive Medical Image Control System (MIMICS) software was used to produce computed tomography images of the mandible, which were then analyzed using ANSYS software. During chewing, swallowing, chatting, and laughing, the joint remained stable. Some of these motions entail joint rotation, while others involve sliding. When the loading conditions were applied, the values of displacement (mm), von-mises stress (Pa), and strain variations were measured as a result of the work. The modifications were represented using a graphical representation. The parameters of displacement (mm), von-mises stress (Pa), and strain variations were recorded and collated after the cancer was removed from the aberrant portion.**

***Index Terms*: Mandibular defect; mandible affected with cancer; Mandibular reconstruction; Finite element analysis (FEA); von Mises stress; vector sum of displacement.**

I. INTRODUCTION

The mandible, often known as the lower jaw or jaw bone, is the human face's biggest, strongest, and lowest bone. It is responsible for the formation of the lower jaw and the retention of the lower teeth. It is the skull's only moveable bone. The mandible's body is curved, and the front section gives the chin structure. The mandible is the most prominent feature of the face. The mandible protects the airway and supports the tongue and the muscles of the floor of the mouth, allowing for articulation and breathing. The coronoid process is a triangular protrusion from the bone that connects the skull, one of the chewing muscles. The moveable junction between the bone and a portion of the skull is known as the temper-mandibular joint called the temporal bone. The joint is in constant use during chewing, swallowing, talking and laughing.

Anatomy of Mandible

Flat bones make up the mandible. The mandible's corpus is thicker than the rami. On the level of the oblique line and the mandible-hyoid line, the thickest spots are found. When the mandible is forced against the jaw, here is where the most tension occurs [1]. The compact bone's structure is exceedingly dense, with particularly thick exterior and internal lamina at the mandible's base. The mandible's form and personality are also shaped by the muscles and ligaments that connect to it [7, 2, 5]. With the exception of the third molar, where the buccal side is the thickest, the internal sides (lingual) of the alveoli are substantially thicker than the external sides (buccal and labial) [7]. The mandibular foramen is the start of the mandibular canal.

When this canal is solitary, it runs arching ante-roily through the trabecular bone to the level of the medial incisor's alveolus. The canal is broad towards the mental foramen and narrows towards the medial side. The mylohyoid us sulcus originates near the mandibular foramen, or in the foramen itself [10, 41, 58]. The medial side of the mandibular ramus is uneven going posteriorly from this sulcus, forming the pterygoid tuberosity, where the medial pterygoid muscle connects [1, 7, 8]. The ectopterygoid fascia covers the medial aspect of this muscle [1]. The stylomandible ligament connects the medial pterygoid muscle and the masseter muscle to the angle of the mandible. After the clavicle, the mandible is the second bone to ossify [2]. On the lateral side of Meckel's cartilage, the bulk of the mandible originates as ossified connective tissue. An ossification center develops in each half of the mandible [8]. It emerges in the sixth to seventh week of intrauterine development and serves as the foundation for the formation of the mandibular corpus and rami. Following that, clusters of cartilage develop in the connective tissue, which slowly begins to ossify independently of Meckel's cartilage [2, 8]. On the top of the coronoid and condyloid processes, at the angle of the jaw, on the front ends of both sides of the mandible, and in the dental arch, such cartilage clusters develop [3]. All of them will come together in the next phase to create a single bone. 1 or 2 little mental bones grow in the connective tissue between both parts of the jaw shortly before birth (ossicula mentalis). The mental protuberance is formed when they join with the mandible shortly after birth [2]. The mandible is created from two parts in the neonatal period, which are joined by the mandibular symphysis, which ossifies in humans and primates in the first year after birth [5, 6].

Tooth loss is a very common problem and it can happen as a result of disease and trauma; therefore the use of dental implants to provide support for replacement of missing part has very long history. Although research on dental implants designs, materials and techniques has increased in the past few years and is expected to expand in the future, there is still a lot of work involved in the use of better biomaterials, implant design, surface modification and functionalization of surfaces to improve the long-term outcomes of the treatment.

In this project was to reconstruct the part for the mandible affected with cancer and perform various stress - strain characteristics including von-misses stress, vector sum displacement and various properties using the finite element analysis (FEA). The computed tomography images of mandible were obtained under standard conditions by Materialism's Interactive Medical Image Control System (MIMICS) software and ANSYS software the image was studied.

II. Literature Study

In [9] Computerized tomography scan images of a human mandible, fibula and iliac crest were collected to investigate the biomechanics of the mandible following reconstruction with autogenous bone grafts. Four finite-element analysis (FEA) models of mandibles reconstructed with autogenous bone were created. The principal stresses of marked points, the Von Mises stresses at anatomical index regions, and the force values of temporo-mandibular joints and masticatory muscles were calculated. And conclusion is Mandibles repaired with iliac crest grafts have more mechanical properties similar to normal than those repaired with fibula grafts. E. Armentani et al.,[10] the structural behavior of a mandible considering a unilateral occlusion is numerically analyzed by means of the Finite Element Method (FEM). The mandible, considered as completely edentulous, is modelled together with its articular disks, whose material behavior is assumed as elastic or hyper-elastic. The mandible model is obtained by computer tomography scans. The anisotropic and non-homogeneous bone material behavior is considered and the loads applied to the mandible are those related to the active muscle groups during unilateral occlusion.

From [11] Three-dimensional modeling and finite element analysis in treatment planning for orthodontic tooth movement was studied. Anatomically accurate 3-dimensional models reconstructed from cone-beam computed tomography scans were used to simulate the retraction of a single-rooted mandibular canine with a minis crew placed as skeletal anchorage. This model can be adapted as a patient-specific clinical orthodontic tool for planning movement of 1 tooth or several teeth. The study on Finite element analysis of dental implant loading on atrophic and non-atrophic cancellous and cortical mandibular bone [12]. Based on the results of the study, it can be concluded that the level of bone atrophy, implant geometries and thread patterns have an influence on strain distribution in the mandible. Furthermore, the BIC level plays a crucial role in implant stability and that strain distributions are foremost dependent on the bone shape and trabecular architecture of cancellous bone.

S. ROY et al., [13] to find out the optimum stiffness of a dental implant for a patient with a specific bone quality, which will generate osteointegration friendly mechanical situation at bone implant interface. The stiffness of the implants was varied by introducing porosity at implant stem. From weak to stronger, five different categories of bone, with different mandible sizes were considered for analyses aimed at finding out the optimum size and stiffness of implant for respective bone quality. Strain generated at bone implant interface was considered as index for ossiointegration at bone implant interface.

R. Shigemitsu et al., [14] made pilot study to investigate the purpose of this study was to investigate the mechanical stress distribution in a mandibular bone of the subject with an implant-supported over denture by a biological-data- based FEA and to evaluate the influence of the number of implants on the stress in peri-implant bone. Alessandro Lanza et al., [15] report a case of giant cell tumor (GCT) whose radiological features by computed tomography (CT) suggested the presence of bone malignancy, whereas the evaluation of a routine OPT scan comforted them about the benign nature of the lesion.

III. Software

MIMICS

Materialize Interactive Medical Image Control System (Mimics) is an abbreviation for Materialize Interactive Medical Image Control System. Materialize Mimics is a 3D design and modelling program that uses image processing. Mimics is a technique for creating 3D surface models from 2D picture data stacks. These 3D models may then be utilized for a wide range of technical purposes. Materialize 3 Matic, a design and meshing programmer for anatomical data, is included in Mimics [16]. Mimics include the following:

- Image segmentation is used by Process-mimics to create 3D surface models from stacked image data such as computed tomography (CT), magnetic resonance imaging (MRI), X-ray, and ultrasound.
- Data uploading—To initiate the segmentation process, CT or MRI scans may be uploaded into materialize mimics. Three alternative perspectives are available from this data: coronal, axial, and sagittal. A third window is available for viewing 3D items.
- Mask creation—the "new mask" tool may be used to draw attention to certain anatomy in the data.
- Models may be sent to 3D printers for printing.

ANSYS

Ansys software is used to produce simulations that evaluate the product's durability, temperature distribution, fluid motions, and electromagnetic characteristics, as well as to design goods and semiconductors. It has upgraded its fluid dynamics, electronics design, and other physical analysis technology. To simulate strength, toughness, elasticity, temperature distribution, electromagnetism, fluid movement, and other properties, the programmer builds simulated computer models of buildings, electronics, or machine components. Ansys is used to assess how a product will perform under various conditions without having to create test products or do crash testing [17].

IV. Methods

The step by step procedure of the work are as follows:

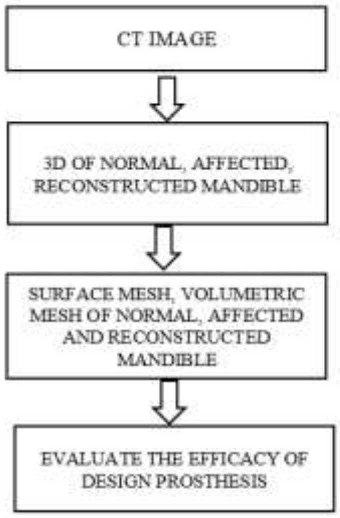


Figure 1. Work flow

1. CT image of the mandible was analyzed by mimic's evaluation software. It was used to convert the two dimensional image data sets into an outline if three dimensional model. The 3 dimensional model shows he level of infection after tumour infection. It is shown in Fig.2

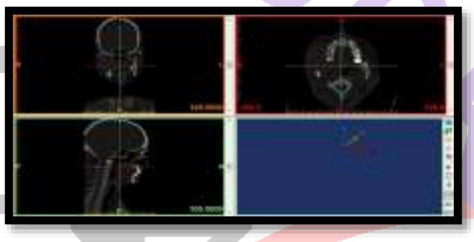


Figure 2. 2D image data is converted into 3D model

2. Bone segmentation was done through thresholding and three dimensional region growing technique procedure. The missing mandible has to be fitted with prosthesis design virtually through the surgical simulation module in mimics shown in Fig. 3

Figure 3. Bone segmentation using mimics software

3. A mirroring procedure is then carried out which creates a mirror image of the healthy portion (shown in Fig. 4). The mirrored portion is repositioned and trimmed appropriately so that it fits exactly the defective portion of the mandible in such a way that the prosthesis to be designed is in exact geometry of the mandible.

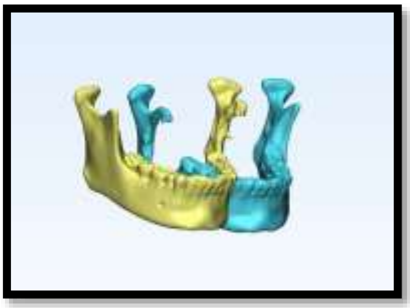


Figure 4. Mirror image of the healthy portion

4. The ANSYS workbench 10 was used for the FEA of the mandible. It used a preprocessor software engine to create its geometry. It used to convert the surface triangular mesh created by mimics into volumetric tetrahedral mesh shown in Fig. 5. The material property was defined.

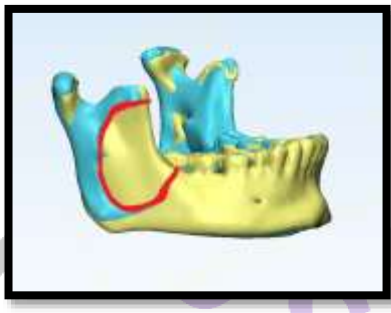


Figure 5. FEA of a Mandible

5. Then suitable loads were applied to the meshed geometry (shown in Fig. 6) . Finally, the resultant displacement, von-mises stress and strain were visualized in graphical form and the corresponding numerical value was obtained.

Figure 6. Mesh Geometry

6. This reconstructed mandible is then converted into 3 Matic option (shown in Fig. 7) in the FEA module.

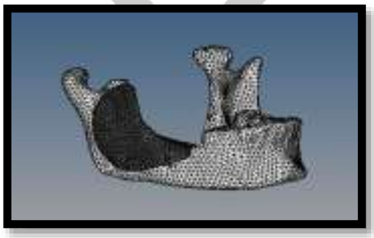


Figure 7. 3 Matic option

7. Re-meshing procedure is carried out so that smoothening of the 3D image can be done which is shown in Fig. 8.

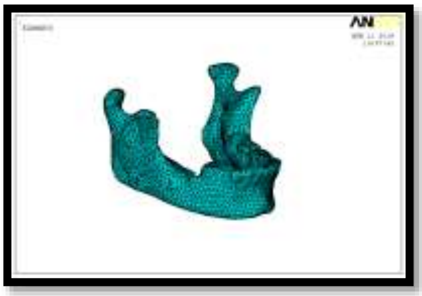


Figure 8. Smoothed 3D image

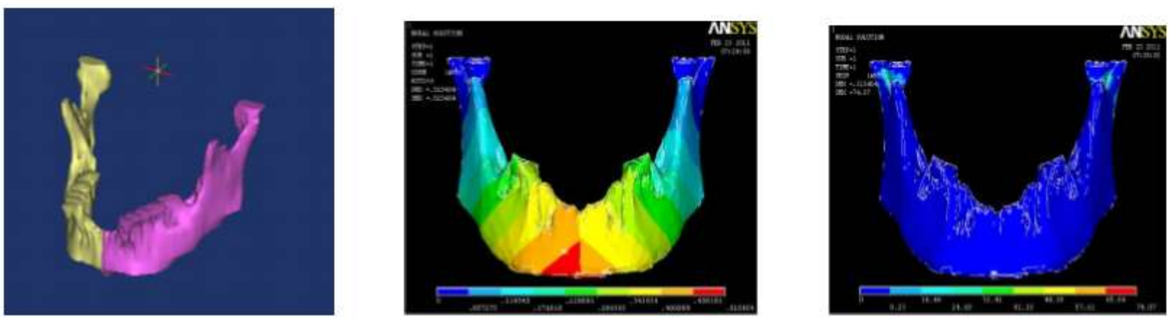
V. Results

The values of displacement (mm), von-mises stress (Pa) and strain changes were measured when the loading conditions were applied. The changes were visualized in the graphical form. The maximum stress (Pa) within the bone was found to be 258.28 and the maximum strain under this stress was found to be 0.241E-2. The vector sum of the displacement due to this stress was 1.648.

Table 1 Result from analyzing changes in graphical visualization

Case Study	Vector Sum Of Displacement (mm)	Maximum Value Of Von Misses Stress (Pa)	Maximum Value Of Total Strain
Normal Mandible (Chewing Force = 120N)	0.971	128.56	0.835E-2
Normal Mandible (Biting Force = 60N)	0.74899	102.44	0.11675E-01

When cancer was removed from the abnormal part, the values of displacement (mm), von-mises stress (Pa) and strain changes were measured and are tabulated. The maximum stress (Pa) within the bone was found to be 125.14 and the maximum strain under this stress was found to be 0.818E-2. The vector sum of the displacement due to this stress was 0.815. The analyzed graphical reading was tabulated in Table 1.



(a) Figure 9 (a) 3D view (b) Vector Sum of Displacement (c) Von-mises Stress Of the Reconstructed Mandible (right half) for chewing force of 120N

VI. Conclusion

The abnormal part with the cancer has maximum values of von Mises stress (Pa) and vector sum of the displacement. Thus by implementing the reconstruction technique using MIMICS the medical imaging software has added more advantages to the surgical procedure than any other methodologies. The properties of this software permits the surgeon to have a broader view of the surgical area and can plan for the surgery well in advance rather than risking the older methods which involved more hours of surgical planning and even more during the surgery while the patient is in the operating room. While with the advent of MIMICS minimizes the time of stay of the patient and cuts off the surgery time greatly. It also saves time by working directly on the scanned information , ensures a perfect fit by incorporating the anatomical geometry in the design, facilitates medical diagnostics, virtually simulates surgeries on patient data with the highest possible accuracy, optimizes surgical procedures and manufacture custom implants before entering the operating room.

VII. Future Prospects

The future work can be extended to perform rapid prototyping of the model as cited in reference 3 where the designed prosthesis can be made into a RP model, which is then subjected to a temperature of 300-600°C into a casting mold which is then post-processed for trimming and drilling and made into a custom titanium tray. This tray is then fitted with the bone graft taken from ileum or other autogenous site that is fixed through titanium screws. This idea shows that rapid prototyping and reverse engineering software are effective methods of fabricating custom trays for mandibular reconstruction after bone loss due to tumor. The method also permits implant fit testing before the surgery.

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