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Finite element modeling of human hard tissues using MRI Scan Data

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Abstract - Traumatic brain injury (TBI) is known as the most important reason for human fatalities in car accidents. Many studies have been performed to understand the structure and mechanisms of head and brain injuries. By the development of computer science in engineering, new numerical-based methods have been introduced to develop and analyze head and brain models and inquire a better explanation for head and brain traumas. The finite element method (FEM) opened a new gateway to perform easier and efficient numerical analysis. To obtain more realistic results, more sophisticated and comprehensive models have been also developed. Further development of three-dimensional techniques will improve the medical treatment due to a better understanding impact of damage, affected areas, and 3D visualization of the part. The main objective of this research is to develop a program to input data in the form of an array of images and perform the segmentation process, perform surface extraction process, create isosurfaces and export it in a neutral CAD format like .STL or stereolithography format. The generated .STL files can be imported in any finite element software for further simulation and detailed analysis procedures.

***Key Words*:** Biomechanics, MRI, MATLAB, Finite element, Trabecular Bone, Implant

1. INTRODUCTION

The introduction of new imaging techniques such as magnetic resonance imaging has increased the knowledge and treatment efficacy following traumatic brain injury. Further development of three-dimensional techniques will improve the medical treatment due to a better understanding impact of damage, affected areas, and 3D visualization of the part. The initial step in developing a 3D finite element model of the human head is to obtain some set of high-resolution MRI scanned images in a suitable format like DICOM format or in the form of an array of images. After the Preprocessing of the image data, the set of images are imported to MATLAB, and using a suitable algorithm developed the 3D finite element model can be obtained.

There are few commercial software provided by MRI or the CT manufacturing companies but there are certain challenges in producing a highly detailed head model, mainly because it is difficult to arrange and prepare a reliable image database of any skeletal part, The images should be in high resolution and with good contrast between all its parts and also it should have the capability to control the type of mesh and to produce an output file suitable for a commercial Finite element solver of our choice. Hence developing a custom program will overcome the difficulties listed above and also allows us to define the outputs as per our requirements.

The three-dimensional model creation, input, and processing of MRI data and export to a suitable neutral three-dimensional CAD format like stereolithography format is performed in MATLAB.

MATLAB (matrix laboratory) is a versatile and powerful numerical computing environment and fourth-generation programming language. A proprietary programming language developed by MathWorks, MATLAB allows matrix manipulations, plotting of functions and data, implementation of algorithms, creation of user interfaces, and interfacing with programs written in other languages, including C, C++, Java, Fortran and Python.

2. LITERATURE REVIEW

Chougule VN et al [1] proposed to extract point cloud data from the stack of CT scan images by using Image Processing techniques. The point cloud estimation is based on threshold techniques and edge detection methods. These measured point cloud data are visualized by using Image ware software. These point cloud data points are then transformed into a compact CAD model using fitting or interpolation techniques. A novel programming module is designed to get these point cloud data from input DICOM images. For verification of these data, Image ware software is used for visualization as well as for further processing of data viz. noise filtering, smoothening of data, B-spline curve fitting, etc.

Shaima Abd El-Kader et al [2] proposes Curvature Anisotropic Gaussian Filter (CADF) algorithm aimed to improve the estimation of the diffusion constant to facilitate better edge detection and preservation of details. They have demonstrated on how diffusion tensors are computed in an anatomically enhanced MRI brain image coordinate by (CADF). Also they have illustrated the efficiency of our generic curvature-preserving approach. Experimental results show that the new method can achieve better denoising results in a variety of MRI brain images, and the new approach shows superior performance on edge and curvature preserving edges and texture images.

Chawla et al [3] proposed a method to reduce the processing time and processing steps involved in finite element model creation from MRI Scan data. The conventional process for finite element meshing from MRI scan data requires two intermediate steps first interior and exterior contour point extraction of bones and second solid modeling from contour data extracted. Authors in their work presented an algorithm is developed and implemented to obtain a meshed model of bones directly from the contours.

Yong L. Chuan et al [4] 3D scaffold designs were made and investigation of the influence of design parameters on porous and mechanical properties via finite element analysis. Cubic porous scaffolds were designed with different architectures by varying design parameters by a commercial Finite element solver like ANSYS. Different types of models were generated by changing the layout properties like angles. The porosity and tensile properties were mathematically evaluated by MATLAB software. The scaffolds with feasible parameters were analyzed for compression properties via FEA. The porosity was calculated as the percentage of void voxels relative to the total number of voxels within the scaffold model. Based on the mathematical and finite element analysis it could be concluded that the design parameter have direct influences on the scaffold porosity and mechanical properties.

3. RESEARCH SIGNIFICANCE

Currently, there are a vast array of three-dimensional imaging techniques in the medical industry. Each imaging technique has there own advantages. But in the case of certain application requirements, it requires end-users to depend on multiple acquisition methods and image processing software. Coupling image acquisition, Image processing, Mesh generation, and Finite element solver will provide more benefits and also helps medical professionals in understanding the impact of damage, affected areas, 3D visualization of the part, and also develop patient-specific implants in a short time and cost-effective way.

The generation of a suitable finite element model of human body parts with an accurate anatomically specific geometry is a time consuming and laborious process, especially if a specific type of finite element model is required like Hexahedral meshed models [3]

Objectives of this research are:

- Develop a program to input data in the form of an array of images and perform the segmentation process.
- Using suitable algorithms and Gaussian filters in MATLAB perform the preprocessing steps.
- Using Delaunay Triangulation or a suitable method to triangulate the surface.
- Export of the model in suitable formats and import in Finite element preprocessor.
- Using open source Finite element preprocessors like Gmesh or Meshmixer to generate the mesh.
- Solve the problem with required loading conditions in a commercial finite element solver.

4. METHODOLOGY

The development of the three-dimensional models of any skeletal system part from an MRI or CT scan starts with a high-resolution array of images. The input images used in this research are taken from MRI, with a size of 256x256 pixels. It means a scan has 65536 intensity values. All intensity values are written in a binary file format of that binary file in 'ieee-be' (IEEE floating-point with big-endian byte ordering) machine format and precision of 'int16' i.e. an image intensity value is written as 16-bit Integer. The binary file contains two sections in the first section format information is written and in the last section all intensity values are written with a precision of. 'int16'.

Table 4.1: MRI Scan data Parameters

Acquisition timing	Acquisition area	Slice Thickness	Format
Seq, Slow	200 X 200	5	DICOM

The overall procedure of workflow carried out is shown in the flow chart in figure 4.1. An extensive range of image processing tools can be used to generate highly accurate models based on data from 3D imaging solutions, e.g. MRI, CT, Micro CT, and other methods.

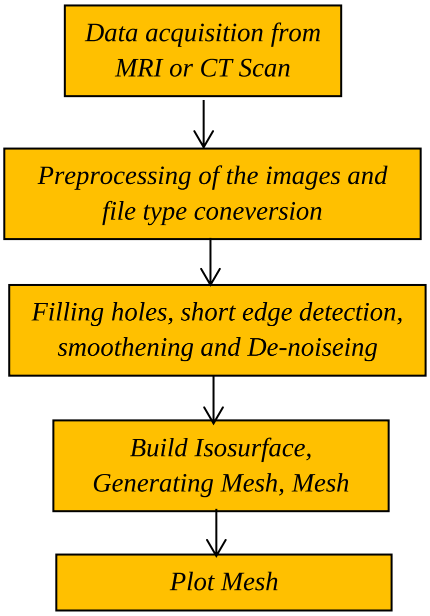

Fig 4.1: Flow chart of Mesh generation procedure

An example of the results of from MRI scan is shown in figure 4.1, where we can see that the image has a lot of voids, the unwanted irregular surface which has to be smoothened. The MRI images are captured basically at different heights in perpendicular to the scanning surface plan. The images captured are stored in a database. In figure 4.2 we can see few images of the human head captured in different sections.

Fig 4.2: MRI Scan images of the Human Head.

The second step in the process is the image clean-up process where the images are segmented, De-noised, and converted to suitable bit rates for easy automation of editing. The holes or voids which are not necessary are filled in. The voids are basically from the low-density soft tissues, the cerebrospinal fluid, etc. They can be removed or modified as per the requirement. To fill the binary holes of the image, an octave-based toolbox that is already installed in MATLAB software is being used. From the octave-based toolbox, we can carry out several operations on repairing binary images.

After the execution of the above program, the result obtained will be of the cleaned and hole-free binary image of the skull model. It is shown in figure 4.3. To create three-dimensional geometry from MRI scanned an images segmentation process carried out on images. Segmentation is nothing but grouping the image in parts having similar characteristics i.e. separating bone from other parts in scan image. This is based on the greyscale intensity value the segmentation process is performed. For the segmentation process, a MATLAB routine is created. The next step is to extract edges and stack the images and create isosurfaces. To perform this task image-processing toolbox in MATLAB is used.

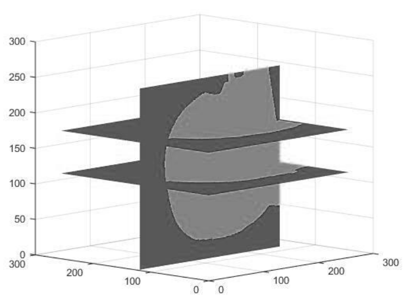

Fig 4.3: Images that are free from voids and free surfaces

Volumetric Mesh generation is the practice of generating a polygonal or polyhedral mesh that approximates a geometric domain. The concept of Delaunay Triangulation theory is used to generate tetrahedral meshes. Delaunay triangulation generates special triangles The concepts of Delaunay triangulation in 2D can be extended to 3D where the concept becomes the Delaunay tetrahedralization.

Using the built-in octave tools, and other suitable algorithms in MATLAB volume mesh is created. The mesh quality is controlled with a set of quality parameters which is intern controlled by the parameters of triangulation. The quality parameters are example facet angle, facet size, skewness, etc

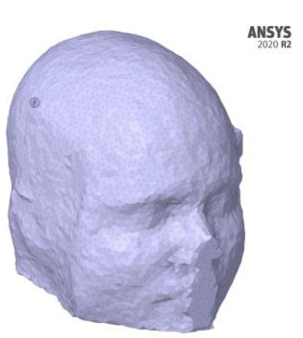

Fig: 4.4: Triangulated surface of Human Head

The generated surface can be dimensionally verified against the MRI scanned images and correct any errors if necessary. The triangulated surface can be exported in neutral CAD formats like.STL or the stereolithography format. STL files can be converted to a finite element model or a finite element mesh can be generated using any open source or commercial software.

The output of the finite element model in formats like .msh or .inp can be used to solve complex structural problems to analyze the behavior under mechanical loads.

The .stl file from MATLAB is imported into open-source volume mesh generation software. A suitable tetrahedral volume mesh was generated. The mesh file was imported in commercial finite element solver ANSYS 2020 R2. A static load simulating the impact on the forehead for performed. The results are shown in Figures 4.5 and 4.6.

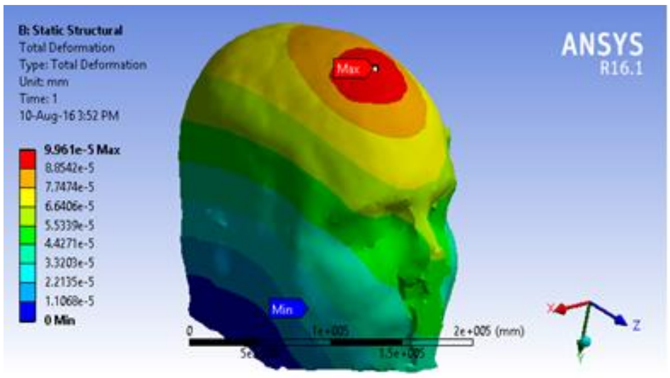

Figure 4.4: Displacement Contour

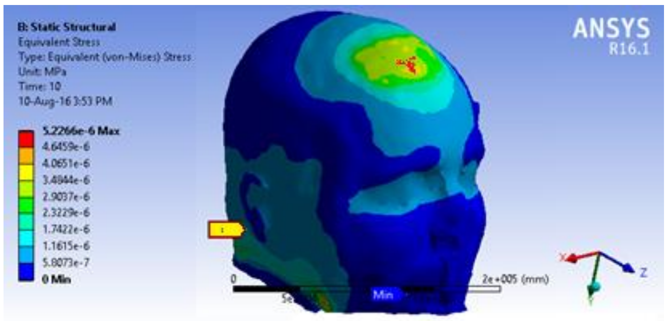

Figure 4.5: Equivalent von mises stress Contour

4. CONCLUSIONS

Using data from MRI or CT scans a three-dimensional finite element model was successfully prepared using MATLAB. The Finite element model can be used in many complex applications like patient-specific implant design, the study of bones under varying loading conditions, the behavior of implant and bone under structural loads, etc. The results from this code can be easily coupled with a FE solver or CAD software for endless applications.

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