DEVELOPMENT AND VALIDATION OF ROBUST 3D -SOLID MODEL OF HUMAN FEMUR USING CT DATA

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Abstract- An emerging focus on the investigation and analysis of the biomechanics of human bone is to generate a pre-clinical information which is helpful for the researcher and orthopedicians has been seen. For this, a geometric model that acts like a natural bone have increasingly been considered to better understand the mechanics of the bone. Hip joint is one of the most important joints in the human body. It is formed by the articulation of femur and acetabulum of the pelvis. It allows us to walk, run, and jump. It bears our body’s weight and the force of the strong muscles of the hip and leg. So, aim of this study is to reconstruct appropriate three-dimensional (3D) computer aided design (CAD) of femur for prediction of stress transfer after total hip replacement (THR). A 3D finite element model of femur was developed based on computed tomography (CT), DICOM images and finally a developed finite element (FE) model was analyzed under physiological load conditions. The results of the analysis are helpful for the orthopedic surgeon to understand the mechanical behavior of the femur bone and in hip replacement surgeries and implant fixation.

Keywords- Femur, Solid modelling, Image Segmentation, CAD.

I. INTRODUCTION

Bone joint is an area where two bones are attached for the purpose of permitting body parts to move by transmitting load. Therefore, joints are the important factor in qualitative life. Damage of bones cause deterioration in the functioning of joint to a greater extent. Nowadays, arthritis, bone ageing, osteoporosis and injuries are very common reasons to deteriorate any joint. Hip joint is one of the most important joint in the human body. It is formed by the articulation of femur and acetabulum of the pelvis. It allows us to walk, run, and jump. It bears our body’s weight and the force of the strong muscles of the hip and leg. Hip disorders are invariably associated with chronic pain, reduced mobility, disability and an increasing degree of dependence. It increases morbidity and mortality rate. So, the best solution to overcome this problem is the Total Hip Replacement (THR), i.e., the surgical approach to replace hip joint with a prosthetic implant. The longevity of the THR determine by the stress distribution on hip joint & prosthesis after THR. However, mechanical properties of bone are inhomogeneous which differentiate the bone geometrical structure as cortical and cancellous bone, in the same way as man-made engineering materials. Due to consideration of inhomogeneous to homogeneous material, helps make FE Analysis easier. This study is focused on generation of 3D solid model of femur by using Simpleware ScanIP software and this developed FE model was analyzed with a consistent set of forces extracted from research paper to validate our developed model which was simulated in ANSYS WORKBENCH R14.5, FE simulation software. Computational analysis can be performed for longevity estimation of fractured bone or bone damaged by orthopedic disorders (osteooporosis) and pre-clinical practice during hip arthroplasty and implant fittings. These results expected to be helpful for researcher & clinician as a pre-clinical information.

II. MATERIALS AND METHODS

A common approach to bone modeling for FE analysis was often taken, to demonstrate the work, i.e. solid model generation and FE analysis of femur a flow chart, as shown in Fig. 1, of the software used in this study were described.

Steps involved in complete analysis begins with acquisition of CT data that preserves the geometrical information of femur. A 3D model was developed using Trialed license copy of Simpleware ScanIP 6.0, a robust Image visualization and Processing Software and CREO 2.0 a CAD package for assembling of femur in which various steps involved, as shown in Fig. 1. and for the final case to investigate the mechanical behavior of developed model, FE analysis was done in ANSYS R14.5.

A. Image data Acquisition

In computational biomechanics exclusively for orthopedic applications, CT quantitative images are more suitable for bone remodeling since hard tissue (bone) has a high contrast relative to soft tissue (cartilage, ligaments etc.). CT scan data of a 56 years old healthy female patient whose body weight is 75 kg. The data acquired have an arterial phase and obtained in helical mode with a slice thickness of 1...
mm from a 64 slice CT scan, GE Medical System by aligning the lower extremity of the patient to the CT scanner rotating in clockwise direction, apparatus power condition were at 120 KV/350mA. The images obtained were in DICOM (Digital Imaging and Communication in Medicine) format. Number of slices obtained are 1286.

DICOM images for the lower limb to ScanIP 6.0 was imported, area of interest is cropped and resampled Figure 2. Histogram of the acquired data showing gray scale range which reduces number of slices from 1286 to 506 and memory requirement from 257.50 MB to 49.59 MB by making process fast & easier. Contrast enhancement can be carried out to improve the model by differentiating bone from other tissues and makes segmentation part easier. It is done by adjusting window width: 850.47 & level: 362.11 in histogram (Greyscale range -2000 to 2000), as shown in Fig. 2.

Multiple segmentation algorithm available for segmentation of images but in this study we have applied region growing method for automatic segmentation process. Further manual segmentation was done by using threshold technique. Region growing tool is a simple region-based segmentation. It is used to split the image into separate objects. It does not provide complete segmentation at one time but gives a clear view of parts near the complex regions of proximal and distal ends of femur by defining their boundaries. Due to this technique, the next step of manual segmentation becomes easier. Macroscopically, femur bone consist of cortical and cancellous bone. For FE analysis to differentiate between cortical and cancellous bone, we had used three different mask color, i.e., red mask for cortical bone, turquoise mask for cancellous bone at distal end & green mask at proximal end in femur, as shown in Fig. 3. and masks physical and imaging property were given in Table. I.

**B. Image Segmentation**

The second modelling phase is image segmentation, which can be defined as the process of partitioning a digital image into multiple segments (sets of pixels, also known as superpixels). The goal of segmentation is to simplify and/or change the representation of an image into something that is more meaningful and easier to analyze. It plays a vital role in many medical imaging applications by facilitating the description of anatomical structures and other regions of interest.
The region growing is applied with number of iterations to be 3, multiplier value of 2.0 and initial neighborhood radius (pixels) of 2 for cancellous bone while number of iterations decreased to 1 for cortical bone. Then manual segmentation is done by adjusting lower and upper threshold value in between 23 to 255 for red mask, 11 to 169 for turquoise mask and 19 to 100 for green mask.

After completing the segmentation part, smoothing of each mask was carried out using Recursive Gaussian filter. It reduces image noise and detail levels. Visually, it has the effect of blurring while mathematically, it has the effect of low pass filtering the image, as shown in Fig.4.

Due to the implication of data loss, morphological dilate filter of 1 (cubic values) was applied before performing smoothing operation so as to grow the mask of cortical region. Hence, Gaussian sigma of 2.5 (cubic values) was applied on cortical region mask and of 2.0 on the mask of cancellous region, as shown in Fig.5.

<table>
<thead>
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<th>Table I. Physical and imaging data extracted for each masks from SCAN IP.</th>
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<tr>
<td><strong>Mask</strong></td>
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<tr>
<td>Red Mask (Cortical)</td>
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<tr>
<td>Turquoise Mask (Cancellous at distal end)</td>
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<tr>
<td>Green Mask (Cancellous at proximal end)</td>
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<td>C. Generation of Solid Model and Construction of 3D Zones</td>
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Third and fourth phase of modeling is based on the polygonal model, NURBS (Non-Uniform Rational B-Splines) surfaces were created with its associated IGES format, as shown in Fig. 6(a), which represent the outer manifold (cortical) of femur and the border of inner medullary cavity. Then, the other surfaces were created, using advanced 3D CAD features, which divide the inside of femur into zones corresponding to regions with different inner structure i.e. proximal and distal region of femur which corresponds to cancellous bone as shown in Fig. 6(b). The construction of three-dimensional zones performed by the use of advanced modeling features in CREO 2.0. Then Solid feature, filling the whole outer manifold has then been created and divided into segments using the NURBS surfaces, as shown in Fig. 6(c) with ASM file format associativity.

Figure 5. 3D model of femur by applying Recursive Gaussian Filter after using morphological dilate.

Figure 4. Result of smoothing operation showing data loss in cortical regions at a) proximal portion of femur b) distal portion of femur.

Figure 6. Polygonal models (a) NURBS model showing outer cortical region, (b) Model showing outer(cortical) and inner(cancellous) at proximal & distal ends of femur, (c) Model showing solid outer(cortical) and inner(cancellous) at proximal & distal ends of femur.
D. FE Analysis of Femur
Final stage of modeling was to analyze the developed 3D solid model of femur. Static structural analysis was performed for single legged stance in ANSYS Workbench R14.5, an FE program for linear and nonlinear analysis.

E. Material Assignment
Bone material behavior was approximated by a homogeneous isotropic linear elastic material, distinguishing between cortical and cancellous bone. The average mechanical properties of each type of bone tissue are shown in Table II which were extracted from CES selector (Cambridge Engineering Selector, an engineering materials selection tool). The lower boundary of the bone properties was selected for these simulations as the subject age was more than 50 years.

Table II. Table of the material properties of bone used for the simulations (from CES selector).

<table>
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<tr>
<th>Structural Properties of Bone</th>
<th>Value</th>
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<tr>
<td>Young Modulus</td>
<td>1.76e10 Pa</td>
</tr>
<tr>
<td>Poisson's Ratio</td>
<td>0.31</td>
</tr>
<tr>
<td>Density</td>
<td>1.86e3 kg/m^3</td>
</tr>
<tr>
<td>Thermal Expansion</td>
<td>1.0e-5/°C</td>
</tr>
<tr>
<td>Tensile Yield Strength (elastic limit)</td>
<td>1.268 Pa</td>
</tr>
<tr>
<td>Compressive Yield Strength</td>
<td>1.14e8 Pa</td>
</tr>
<tr>
<td>Bulk Modulus <strong>a</strong></td>
<td>1.8e10 Pa</td>
</tr>
<tr>
<td>Values marked * are estimates</td>
<td></td>
</tr>
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F. Loading and Boundary Conditions
Most distal cross-section of the femur model i.e. area falling near femoral condyle were assumed to be fully fixed. Single load bearing case representing single-legged instance of a 750N human female was taken in this study. Magnitude and direction of forces on femoral head were X: -915N, Y: -1,492N, Z: -2,925N, and the resultant force on the femoral head was 4.54 body weight (BW). Magnitude and direction of forces by abductor muscles were X: 832N, Y: -1,342N, Z: -2,055N, and the resultant force was 3.54 body weight (BW).

III. RESULT AND DISCUSSIONS
At the end of simulation, generated solid model of intact femur was analyzed. Mechanical parameters were extracted from this simulation i.e. total deformation, equivalent stress and maximum principal stress. Equivalent von-Mises stress was obtained from stress analysis of femur with a maximum value of 27588Pa which occurred at the femoral shaft, as shown in Fig. 7.

Maximum deformation in femur was .004856m. Fig. 9, occurred at femoral head which indicates a critical location in a femur for the specified subject.

The comparison of these results was done with various literature reported. The behavior of our results was similar to behavior of results reported in literature. Slight variations associated with these mechanical behavior of femur was found due to high variation in material property and other physiological conditions.

Using this modeling approach, a next course of action, considering total hip replacement, implant fitting, fracture treatment may be undertaken.

Figure 7. Equivalent von-Mises stress in femur.
Figure 8. Maximum principal elastic strain in femur.
Figure 9. Maximum total deformation in femur.
CONCLUSION

In this paper, full model of generating solid model and static structural analysis of femur was done. This process includes generating of 3D model from quantitative CT scan images, NURBS meshing, assigning material properties and analyzing the model.

In this present work, the internal zones of 3D solid model corresponding to cancellous bone, is further subdivided into two subzones of distal & proximal layer of femur, which is a better approximation of FE model with real femur.

However, this method have several issues that need improvements. The real skeletal structure of femur bone includes hard and soft tissue with bone marrow, so all these should be included in future model.

Also, the physical conditions around the joint are much more complex than this model i.e. area around femoral head, neck and condylar region.

Simulating all these issues, this work may be considered as a starting phase of computational analysis of biological structures by applying finite element method.

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REFERENCES


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