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Reconstruction, Segmentation and Smoothing of Tibia and Fibula Parts from Knee Joint Assembly and RPT Estimation and Material Consumption

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ABSTRACT: Medical images are essential tools for medical practitioner and specialists to use when diagnosing problems and diseases in the body. These images from CT and MRI scans are converted into 3D CAD model and based on 3D model, reconstruction of knee joint is being made for medical applications. Hence, in this paper an attempt is made to create a 3D reconstructed anatomy structure based on real medical images of a patient so that practitioner can study the 3D anatomy structure from real medical images. The 3D slicer workbench is used for generating a 3D model of the anatomy and problems from medical images. The model was created by combining segmentation and smoothing techniques using slicer software. The segmented part is exported as STL file directly. The STL file is sliced for FDM process prototyping. The segmented part sliced for different layer heights to study the printing time and material consumption. We have sliced the model in Ultimaker CURA 4.0.0. PLA (Polylactic Acid) is used for printing Tibia and Fibula because of its biocompatibility, biodegradability, non-toxic, non-immunogenic and non-inflammatory properties towards the human body.

Key words: Segmentation, Tibia, Fibula, Knee, RPT, CURA

I. INTRODUCTION

The increasing use and improvement of occupant restraint systems have reduced fatality and severe injury rates in motor vehicle crashes (MVCs), but the protection of the lower extremity (LE) was not improved as much as that of the head and chest [1]. LE injuries still account for 36% of all AIS2+ injuries sustained by front seat occupants in all frontal crashes [2]. Even though LE injuries are usually not fatal, they can lead to costly rehabilitation and disability, which is a heavy burden for the family and community.

Tibia is the shin bone and bears the majority of weight between the knee and the ankle. Lateral to (on the outer side of) the tibia is the fibula, a smaller long bone that provides stability and assists with rotation of the ankle. The tibia is a long bone, which means it is a limb bone that is longer than it is wide.

Femur and tibia fractures are commonly seen in MVCs and cortical bones are believed to have a dominant effect on bone strength, as they serve as a damage-tolerant structural framework [3]. Aging can cause changes in the shape, size, and cortical thickness of bones and thus lead to increased incidence of bone fractures [4]. Other factors such as stature and body mass index (BMI), can also affect bone morphology [5-9].

Finite element (FE) models are powerful and effective tools to assess human impact responses in MVCs and reproduce bone fractures. Multiple FE femur and tibia models have been developed previously. References [10-12] reported detailed LE models using the geometry extracted from CT and/or magnetic resonance imaging (MRI) data. However, their models could not reflect the variation in cortical bone thickness among the population, and a method to estimate the cortical bone thickness from CT scans was not reported.

Reference [8] did a comprehensive job on the development of parametric femur FE models, and the population variation in cortical bone thickness was considered. They used a fixed global thresholding method similar to [13] to segment the cortical bone from clinical CT scans, and the thickness was determined based on the distance between the outer and inner cortical surfaces along the normal direction. However, the estimated cortical thickness values were sensitive to the specified threshold, and may introduce significant errors in thin-cortex areas.

In the field of medical image process, several cortex thickness estimation techniques based on clinical CT scans have been proposed, such as the 50% relative threshold method [14-15]. This method considered bone

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density, which was usually denoted by HU values in CT images. The threshold was set halfway from the soft tissue HU values to the cortex HU values and from the cortex HU values to the trabecular HU values. It was effective if cortex was thick enough in which case the true cortical bone density equaled to the maximum value of the density profile (expressed in HU values) along a line, but it became unreliable in thin-cortex areas and tended to overestimate cortex thickness. References [16-17] did extensive research on femoral cortical bone thickness measurement from clinical CT data based on the model derived from [14] using a model-fitting method. This technique considered the imaging system's point spread function (PSF) and required knowledge of the density (expressed in HU values) of the true cortical bone, which was assumed to be a constant value for a given subject. The bone density may vary from location to location, thus assuming the cortical bone density as constant at all measuring vertices/points seemed problematic, and the model-fitting process might not converge. Nevertheless, this was a decent technique of great accuracy. Reference [18-19] then proposed a model-based approach without profile fitting but still shared the assumption of a constant cortex density in [16-17].

Bone material content (BMC, i.e. bone mass) was calculated with three parameters measured in the profile with the help of the 50% relative threshold method. Since there were no model-fitting iterations, computation efficiency was considerably improved.

In this study, a local thresholding method was developed to quantify the thickness in cortex areas of the femur and tibia without model-fitting process or assumption of constant cortex density. Inspired by the 50% relative threshold method, on each local HU value profile, a ratio (not 50%) was employed to define a local threshold that distinguished cortex from soft tissue and trabecular bones. This ratio indicated a relative cortex density compared to the most dense part (where CT value was the highest) without the need to assume a specific cortex density value. Unlike the 'ground truth' obtained from high-resolution micro-CT scans in studies [16-17], the proposed method was validated against measurements from a post human mortem human subject (PMHS). Results were compared with the conventional global thresholding method to show validity of this method. FE meshes of a baseline model were morphed and fitted to the geometry surfaces reconstructed from 95 clinical CT scans and the cortical bone thickness at each node was computed using the proposed method. Parametric femur and tibia thickness models were developed to address the effect of sex, age, stature and BMI on cortical bone thickness distribution

II. LITERATURE SURVEY

Production of Anatomical Models from CT Scan Data by JOHN BRENAN

In this paper the latest medical data processing software tools will be used to generate models for preoperative planning and also medical training and the results reviewed. A comprehensive literature review in the field has been conducted and publications in the medical scanning, RP, preoperative planning, biomaterials, customized medical implants and jigs are presented and discussed. Several case studies that are particularly pertinent to the trials undertaken by the author have been identified and incorporated into the report and explained in detail in order to illustrate the capability, potential and flexibility of this technology within the medical sector.

Determination of muscle forces acting on the femur and stress analysis by Silke Renner, Technische Universität München

A stress analysis of the femur using the finite element software ANSYS was performed, comparing the biomechanical Pauwels' model and the "Stemmkörpermodel" in the one-legged stance.

Teaching Biomedical Engineering Design Process and Development Tools to Manufacturing Students

This study presents laboratory development efforts for a rapid prototyping and reverse engineering course taught in this ABET accredited manufacturing engineering program. The main objective of the work is to introduce biomedical design and development processes and associated tools in this manufacturing program. The driving factor is to improve the versatility of the manufacturing engineering students in addition to better marketability of the graduates in this medically oriented geographic region and beyond. The author has been developing physical and software laboratories for his biomedical engineering program. The developed laboratories are to be utilized in the design and manufacturing of biomedical devices and systems course and also included within the scope of the rapid prototyping and reverse engineering course.

Design and Development of an Offset Lightweight Polymeric Orthotic Knee Joint for Polio and Cerebral Palsy Patients BY J.K.CHAKRABORTHY

Polio patients mostly belongs to the poor class of the society and need cheap, light, high functioning orthotic calipers to be able to participate normally in daily functions of life. The concept of drop lock, gravity lock or automatic lock for calipers joint is not a very new subject as it was designed and even commercialized in the past. This design and development work claims priority to the prior caliper joints due to its unique design for injection molding that can allow changes in function, material, weight and cost. The joint is designed, analyzed, manufactured and trial tested with satisfactory results.

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Nano-Materials for Bone Implants BY Garrett Cavanaugh

An increase of geriatric patients requires improved orthopedic implant technology. Hydroxyapatite is a material naturally found in bone tissue, but the use of synthesized hydroxyapatite in orthopedic implants is limited because of its poor mechanical properties. The goal of this paper is to use nanocrystalline hydroxyapatite and epoxy resin to create composite materials that mimic bone tissue's nano-structure, test their mechanical properties to determine the influence of nanostructure and characterize the failure mechanisms using electron microscopy.

A CT-Based High-Order Finite Element Analysis of the Human Proximal Femur BY CHARLES MILGROM

The prediction of patient-specific proximal femur mechanical response to various load conditions is of major clinical importance in orthopaedics. This paper presents a novel, empirically validated high-order finite element method (FEM) for simulating the bone response to loads. A model of the bone geometry was constructed from a quantitative computerized tomography (QCT) scan using smooth surfaces for both the cortical and trabecular regions. Inhomogeneous isotropic elastic properties were assigned to the finite element model using distinct continuous spatial fields for each region. The Young's modulus was represented as a continuous function computed by a least mean squares method. P-FEMs were used to bind the simulation numerical error and to quantify the modeling assumptions. We validated the FE results with in-vitro experiments on a fresh-frozen femur loaded by a quasi-static force of up to 1500 N at four different angles. We mea- sured the vertical displacement and strains at various locations and investigated the sensitivity of the simulation. Good agreement was found for the displacements, and a fair agreement found in the measured strain in some of the locations. The presented study is a first step toward a reliable p-FEM simulation of human femurs based on QCT data for clinical computer aided decision making.

PROBLEM STATEMENT

Segmentation is done to separate the affected parts from the patient body by using thresholding method.

Smoothing is done to remove internal holes and external bloods from the segmented parts on slicer software.

Image segmentation consists of a few methods that can be used to perform image processing on a DICOM image in order to create a 3D model from it, but the right method must be chosen carefully. Furthermore, the 3D slicer workbench project template included basic 3D slicer modules that can be used to create a new project model. Hence, it is decided to use slicer software for reconstruction of 3D model of knee joint assembly by using medical scan images from CT and MRI scans.

This research is an exploratory framework geared in the direction of better understanding the application of additive manufacturing technologies in the industrial and medical field.

III. RESULTS AND DISCUSSION

Segmenting Tibia and Fibula from CT Scan Files

Scan data is imported from CT scan files into 3D Slicer software and Tibia & Fibula parts are separated from remaining parts through thresholding process, which is called segmentation. Now these Tibia and Fibula parts are exported as an STL file.

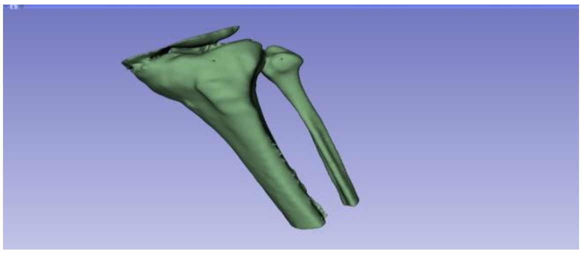

Fig 1 segmented tibia and fibula

Rapid Prototyping of Knee Joint

Estimated values of Printing Time and Material Consumption for Tibia and Fibula are obtained by importing the STL file from 3D Slicer software into Ultimaker CURA software and giving required input parameters such as layer thickness, line width, infill density etc.

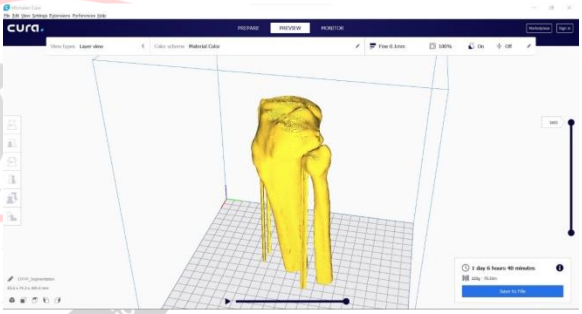

Fig 2 slicing the CAD model with 0.1 mm Layer height

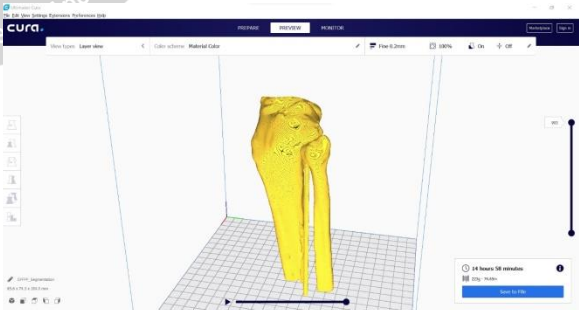

Fig 3 slicing the CAD model with 0.2 mm Layer height

Variation of Printing Time and Material Consumption Based on Layer Height:

Layer Height (mm)	Printing Time	Material Consumption	Distance Travelled by the Nozzle (m)
0.1	14hrs 9min	84g	10.61
0.2	7hrs 5min	84g	10.61
0.3	4hrs 50min	85g	10.74
0.4	3hrs 33min	84g	10.61
0.5	2hrs 58min	86g	10.88
0.6	2hrs 35min	88g	11.18

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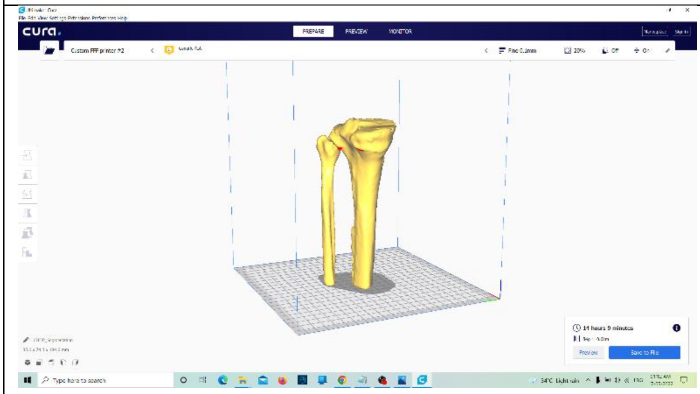
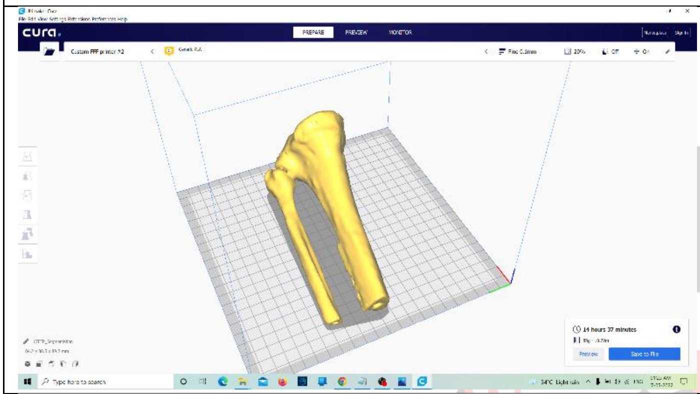
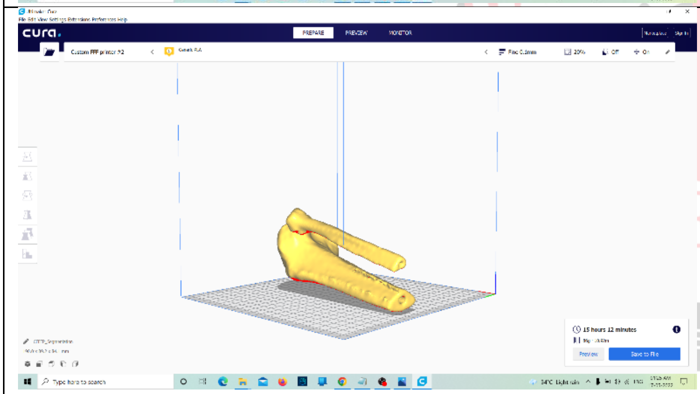
Variation of Printing Time and Material Consumption Based on Orientation: (Thickness = 0.1mm)

ORIENTATION	Printing Time	Material Consumption	Distance Travelled by the Nozzle (m)
	14hrs 9min	84g	10.61
	14hrs 37min	85g	10.72
	15hrs 12min	86g	10.92

IV. CONCLUSION

1. CT/MRI scan data of the patients was obtained from the hospital. The DICOM format of the scan data was converted to .stl file using 3D Slicer software. Prior to 3D printing, pre-processing of CAD model was done for removing extra mesh islands and to reconstruct the patches/holes in the bone model using Blender and Meshmixer software.

2. Processed model was imported to printing software (CURA) as .stl file.

3. Bone models obtained were printed using FDM printer with PLA material. The printing parameters were optimized with respect to the complexity of the bone parts for achieving the good surface quality with accurate anatomic features.

4. Complex and articulated joints such as knee joint and ankle joint were 3D printed without any error.

5. The time taken to build the implants/models on the FDM 3D printer was less than the time taken to build the same implants with other methods.

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