Reverse engineering application for 3D CAD modeling of human knee joint

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Abstract— An accurate three-dimensional (3D) model of bone knee is the most important part for implant or total replacement of knee joint. Having increasing complexity of human bone in medical science, now a day reverse engineering and rapid prototyping approach is very useful to create duplicate bone structure of existing human need in case of emergency replacement. Reverse engineering is one of the process by which 3D CAD model can be easily generated .Different techniques available for generating CAD models. From literature survey, It is conclude that CT scans provide accurate models other than different MRI or X-ray data. The present work describes the methodology applied in the development of an anatomically detailed three dimensional knee model from CT scan data using Mimics software. The final output of model is useful for fabricating artificial knee joint.

Index Terms— 3D CAD model, CT data, knee joint, Mimics (Materialise's Interactive Medical Image Control System)

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1 INTRODUCTION

1.1 Reverse Engineering:

Principles of reverse engineering:

Reverse engineering is a systematic process of acquiring the important design factors and information regarding engineering aspects from an existing product which design data is not available and complexity in design. It is a process of duplicating geometry of existing model. It is a process which analyzes a model/object specially to find out the design aspects and its functions. This is a kind of analysis which engages an individual in a process of constructive learning of the design and its functionality of systems and products. Reverse engineering method plays a significant role in the development of science and technology innovations. It often shows an effective way for learning to construct a product model or improve it.

Goals and Uses of Reverse Engineering

1. Recreating the design, making the design decision, and the information which is
2. Developed by the original design team.
3. Learning the working principle.
4. Justifications of design decisions of the original design Team
5. Redesigning the product to improvise, modify to suit the modern circumstances etc.

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6. Understanding the functionality of product in depth. Evaluating a product to understand its limitations and comparison with other products using simulation technology.

1.2 Different methods for creating 3D CAD model :

The production of a copy of an existing object of complex shape is one of the typical applications of the integration between two modern computer-based technologies, reverse engineering (RE) and rapid prototyping (RP). The method is extremely versatile and can be used in various applicative domains (e.g. replacement of anatomical parts with artificial prostheses, replication of skeletal remains).Three different acquisition techniques of images of a skull, by laser, by CT scan and by x-ray, were compared to ascertain which enabled more accurate reproduction of the original specimen. The skull was chosen due to it being the body part most often used in medico-legal investigations (for personal identification, skull-photo superimposition techniques, forensic art, etc). Comparison between the copy and the original yielded satisfactory results for all three techniques.

There are three basic techniques are:

1. Online technique: online technique use x-ray scan images to construct 3D CAD modeling using different configurations of the algorithm according to the number of X-ray images, accuracy required and the information available.
2. Mimics software: Mimics (Materialise's Interactive Medical Image Control System) is Materialise's software for processing medical images and creating 3D models. Mimics uses 2D cross-sectional medical

images such as from computed tomography (CT) and magnetic resonance imaging (MRI) to construct 3D models, which can then be directly linked to rapid prototyping, CAD, surgical simulation and advanced engineering analysis.

3. Laser scan technique: 3D laser scanner used to create 3D model of knee joint. but for to less cloud data acquired accuracy of 3D model does not provide good result for implant surgery. However, CT scanning demonstrated some advantages over the laser technique, as it provided a cleaner point cloud, enabling shorter pre-reproduction processing times, as well as data on the internal parts, which resulted in the reproduction of a more faithful copy.

1.3 Medical application:

Medical scan technology has an important place in the area of bone and tissue reconstruction. Implants and prostheses can be tailored to meet a patient's exact requirements, helping a wide range of people, including victims of bone disease, cancer, congenital defects and traumatic injuries. The data from non intrusive scans, such as CT, MRI and x-ray is used to create a 3D model allowing technicians to perfect the shape, performance and integration of the implant into existing structures within the body.

Several research organizations use Rapid Form's 3D imaging technology to convert CT, MRI and x-ray scans into CAD models for advanced neurosurgical and biomechanical research, and to build rapid prototype copies of the anatomy. Stereo-lithography takes these images and converts them to polymerized resin 3-D models allowing doctors to hold the information in their hands and examine all of the data.

1.4 Anatomy of the human knee joint:

Due to complexity of knee joint of human bone vary from person to person so to create 3D model design is crucial part for implant design. Anatomy of human knee joint shown in fig.1
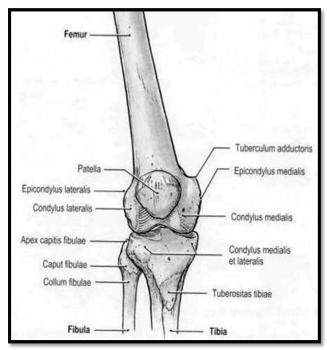

Fig. 1: Bones of the human knee joint [2]

2 LITERATURE SURVEY

2.1 Literature Survey on reverse engineering application for 3D CAD modeling of human knee joint :

1) Yan-ping lin et al. (2004),They found The CAD model formed the data base of customized artificial joints applied in clinic medicine, in which we can select a suitable kind of artificial knee joint model to customize for the patient. For different patients, we just need to change the local data of the corresponding CAD model to meet the different requirements. The dimension and shape of the patient joint, we can customize the length of the prosthesis stem, the size of the prosthesis to satisfy the patient at most.[3]

2) B. Starly at al. (2005) , has done work on the development of biomimetic bone structures which in turn would be used in the design of heterogeneous scaffold structures. The CT/MRI image based reconstruction provides a technique in which the outer shape of the scaffold structure can be retrieved for appropriate anatomical fitting and compatibility.CAD models are used as the basis for preparation, multi material scaffolds can also be fabricated for tissue engineering applications.[4]

3) Bradleyab and Currieab (2005) , Integration of RE projects with geometric modeling courses is one way to highlight the existence of workable RE techniques. The general population may not be increasingly exposed to the technology, but we can be sure that it is at work behind the scenes in a growing number of applications for customized products, made to suit an individual's anatomy or preferences.[5]

4) Milovanović and Trajanović (2007) , Resent research has led to the development of the RP process building and improving upon artificial bone implants which are strong enough to support a new bone yet, at the same time, porous enough to be absorbed and replaced by the body. It is a very significant discovery in medicine and the first step on the way to making other complex human organs.[6]

5) J. Wang et al. (2009), they found that machining cortical bone segments prior to CT scanning is an effective method for accuracy evaluation of CT-based bone reconstruction.[7]

6) Chizari and Wang (2009), The study uses a finite element method to analyze an anatomically detailed ACL reconstructed knee of a 22 years old patient three months after operation, using data obtained from a CT scan. The model considered a kinematic constraint and parts interaction at the tendon graft and tibial tunnel were implemented.[8]

7) JianpingWang et al (2009), We found that machining cortical bone segments prior to CT scanning is an effective method for accuracy evaluation of CT-based bone reconstruction. As the contour of human bone was of complex geometry, there was no golden standard to compare the difference of complex surfaces between real human bone and replica one. During the entire geometrical reconstruction process, the CTimaging modality is knownto be of very high precision, with essentially no geometric magnification error.[9]

8) Ming-Ching Chang et al. (2010), We identify two major sources of variation: (i) the noise in depth measurements of the laser scans is significantly high and (ii) the use of point-to-point correspondence in Iterative Closest Point (ICP) is not suitable due to sampling variation in the laser scans. The complete surface mesh is constructed by fusing all the scans in the order maximizing mutual overlaps. We have proposed a reliable approach to accurately process raw laser scans to produce

a consistent ground truth dataset. By reducing the sensing and sample errors in the fusion process, the resulting model has low variation and excellent repeatability, which is useful for validating the MRI measurements of the knee cartilage.[10]

9) Sudesh Sivarasu at al. (2011), The performance of the conceptually design knee is better than the reverse engineered knee joint but the best combination is that of reverse engineering over which conceptual design has to be applied for making the ideal artificial knee.[11]

10) Kamala and Kumara (2013), CT/MRI images helped to get the more accurate geometry of distal femur and proximal tibia bone and the concept of reverse engineering in order to improve the implant design and make it more customized.[12]

11) Jayesh J. Dange et al. (2013), All measured dimensions from the CAD solid model of distal femur are found to be approximately same as that measured from the input CT dimension and find methodology to develop 3D CAD model from CT via use of CAD tools.[13]

12) Sherekar and Pawar (2014), Depending on the size and complexity of the biomodel, RP fabrication times vary between a few hours to two days, which maybe unacceptably long for emergency cases. by using RP cost and time expenses are justifiable for custom implant fabrication applications, e.g. for orthopedic surgery, simply because in such cases the utilization of conventional manufacturing methods, implies significantly higher fabrication time and cost. Furthermore, the customization of the implant assures accurate fitting, reduces operating time and enhances quality.[14]

2.2 Finding from literature:

From the literature survey , to create 3D CAD modeling for human knee joint using different techniques provide different result of accuracy for different 3D model but due to complexity of knee joint and variation of knee dimension vary from person to person in case of implant surgery. So to create accurate 3D CAD model for implant surgery CT scan data provide accurate result due to large data point acquire available which provide accurate model for artificial knee joint model. So I have done work to create 3D CAD modeling from CT scan data of 25yr old male patient's knee joint using Mimics software and its application for implant surgery is very useful approach in emergency case of total knee replacement.

3 3D CAD MODELING OF KNEE JOINT:

A 3D anatomically detailed model of the knee was created using density segmented Computed Tomography (CT) scans (DICOM standard images). This technique geometrically defines the knee bone structure and the encapsulated soft tissues configuration. The geometrical complexity of the knee structure implies the use of reverse engineering tools e.g. CT scanning, in order to obtain a model that accurately simulates the biomechanical behavior of the knee, the fixation zone and the ligament.

3.1 3D modeling methodology:

The complex mechanical behavior of the knee and the necessity of obtaining accurate results for Post validation with experimental values imply an adequate modeling of the knee structure in terms of 3D anthropometrical characteristics and material constitution. The anthropometrical data was obtained from a CT scan of the knee. The DICOM images generated in the CT scan were then processed with the Mimics 10.01 soft-

ware to obtain the primary 3D model using density segmentation techniques. The generated primary 3D models were then processed and assembled as geometrical data files. Finally, the model was exported as .stl file. The model was then prepared for the analysis by definitions of loads, boundary conditions, material constitutive models, kinematic constraints and mesh discretization processes.

3.2 Medical image data generation :

A CT scan was performed on 25 years old male using CT equipment. Scans were performed on the knee at the neutral posture where there is the least tension or pressure on tendons, muscles and bones. The scans were made up of 420 cross-sectional "cuts" with a slice distance of 1 mm and a field of view (FOV) of 18.70 cm. The images were exported from the CT equipment in the DICOM format with an image area of 512x512 pixels. The high image resolution associated with the reduced distance between slices assures a good geometrical definition of the primary 3D models in the future density segmentation operations. Fig. 5 shows a single slice of a gray value image (DICOM format) of the reconstructed knee.

3.3. 3D reconstruction :

For the reconstruction of the primary 3D anthropo- metrical models (bone structure and encapsulated soft tissues) the Mimics10.1 medical imaging density segmentation software was used. The DICOM image files generated in the CT scan are constituted by pixels with different gray intensities. The different intensity fields correspond to different material densities in the anatomic knee structure, namely, soft tissues and bone. Note that in a CT scan it is possible to distinguish the tendon graft (ligament) structure. The separated 3D reconstruction of each bone segment was accomplished with manual editing Operations of the density masks. The reconstruction of the encapsulated soft tissues was faster and easier due to the high difference of densities between the soft tissues and the surrounding air. The spaces between bones normally occupied by cartilages and synovial liquid were not segmented. The different phases accomplished for the 3D reconstruction using density segmentation techniques with the Mimics10.01 software are presented below.

1) Importing the medical data

The Mimics software allows automatic importation of the 420 slice images generated in the CT scan. A pixel size of 0.3652 mm was automatically calculated accounting the present image resolution (512x512 pixels) and the acquisition FOV (field of view). The slice distance was correctly determined corresponding to 0.4mm. The pixel size and the slice distance guarantees the coherent dimensional reproducibility of the models generated during the segmentation process. To minimize the project size and maximize the productivity of the 3D reconstruction process, a crop operation was conducted in order to eliminate the slice images of the left knee, concentrating the modeling efforts in the right knee area. This is the very first step where the images were imported and converted scan data through "Import Images" from the "File" menu, then changed orientation. The orientation parameters are necessary to display the images correctly in MIMICS. Then MIMICS software generates automatically coronal and sagittal images, and the result is shown in Fig. 2.

2) Organize images

If there more no of CT images then it may take more time for further process and unnecessarily it will create problem in reconstruction of 3D model. So we have to simplify the number of CT images to reduce the workload and improve the efficiency through "Organize Images". In the "Organize Images" interface we can choose images as per our requirement in MIMICS project which should be visible and used while working with MIMICS. If you look at the images you will notice that the ones that correspond to table positions –49.5 and –48.5 do not contain any information about mandibular bone. The operation is shown in Fig.3.

Fig. 2: A single slice of a gray value image of an knee joint of a 25 years old male using CT scan (left).

Fig. 3: Organize images

3) Thresholding:
As different organizations will have different gray value in CT images, so it is required to set accurately the threshold value. We can observe the CT images to view the required part of the extracted organizations when set the threshold value. The threshold value should be kept as lower as possible to avoid the noise. A good threshold value for Mimi is about 270 (Hounsfield scale). Thresolding process shown in Fig. 4
CT images are a pixel map of the linear X-ray attenuation coefficient of tissue. The pixel values are scaled so that the linear X-ray attenuation coefficient of air equals -1024 and that of water equals 0. This scale is called the Hounsfield (HU) scale. Thresholding based on Hounsfield scale was used to separate each part of the knee including bones and the encapsulated soft tissues volume. In order to include all the cortical and trabecular bone at the knee bone structure and exclude the cartilage regions, a lower limit of 485HU and an upper limit of

1467HU were defined. The soft tissues region was generated accounting a range of -188HU to 3071HU. In the thresolding the bone structure are selected which can see with green color. In this process we select the bone structure for which we want to generate 3D model. We select only that area of the knee to generate the model. So thresolding is the selecting process of the bone structure
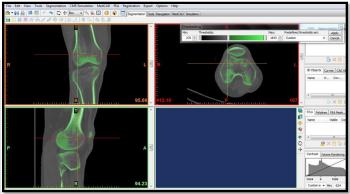

Fig. 4: Thresolding process.

4) Region growing
This command is used when the selected region is to be taken from whole figure as in below figure it shown by cyan colour which will be taken into consideration rather than taking whole part. The region growing process allows splitting the segmentation in different and separated parts.Corresponding each part to one mask that can be distinguished by the different applied mask's colors. For that geometrical separation to happen, the adjacent masks must not be connected with any residual pixel. These operations were performed in all slices generated at the CT scan. For the complete definition of the bone knee structure and soft tissues, different regions (tibia, femur, patella, fibula, tendon graft and soft tissue) were defined. Fig. 5 shows the views of an region growing process on the ligament.
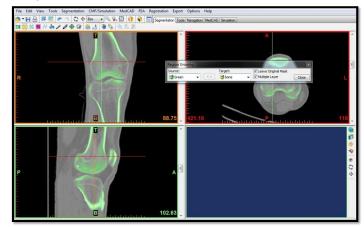

Fig. 5: Region growing process

5) Cavity filling and edit mask
In thresolding and region growing all the bone structure cannot selected easily so the model generated will not be accurate as only surface bones are selected. This happens due to density difference. So cavity is filled for each layer so that we can easily generate the 3D CAD model. Fig. 6 shows the cavity filling process for each layer. Here we can manual edit the

functions which are performed on the active mask. We can draw, erase, or restore the image with a certain threshold value indicated below. The drawing cursor can be a rectangle or a circle (ellipse) and can have different sizes, or you can use the lasso tool to draw a shape. If the holes in the femur are more it will create more trouble. So we need to modify carefully all
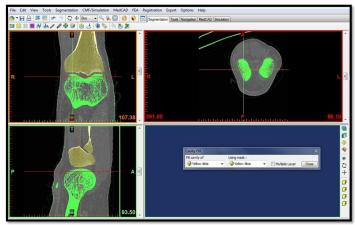

Fig. 6: cavity filling process

CT images carefully and fill all the holes in the femur. The holes are due to the setting of thresholding of CT images, not the original. So it can't affect the follow-up calculations. Fig 7 shows the edit mask process for each layer.
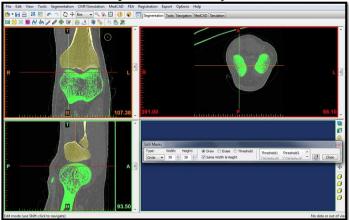

Fig 7 shows the edit mask process for each layer.

6) 3D reconstruction

After having done all above steps "Calculate 3D" from the "Segmentation" Menu. The 3D structure of the femur can be visualized clearly. The generated region masks were used to develop 3D models for each the bones and encapsulated soft tissues volume. The 3D reconstruction is based on 3D interpolation techniques that transform the 2D images (slices) in a 3D model. For this reconstruction case, gray values interpolation was used associated with the accuracy algorithm for achieving a more accurate dimensional representation of the knee structure. Shell and triangle reduction, respectively, were used for eliminating small inclusions and reducing the number of mesh elements. Each region was then reconstructed to obtain all the bones and encapsulated soft tissues volume that geometrically defines the knee structure. The relative position of the different parts constituting the primary model assembly of the knee model is shown in Fig. 8

7) Smoothing

As the model generated by this process is not accurate. The surface of the model is rough. So to create smooth model the smoothing is done. Number of iteration is done with selecting Smoothing factor between 0 to 1. Finally, the accurate 3D model is generated. Fig 9. Shows smoothing of 3D model.
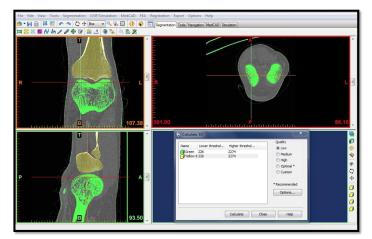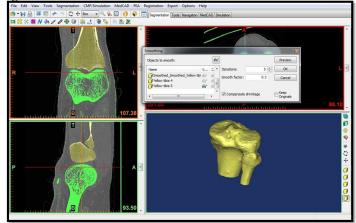

Fig. 8: 3D reconstruction of knee model

Fig. 9: Shows smoothing of 3D model.

8) Exporting file

After creating the 3D CAD model this model must be exported for further analysis in appropriate format. In MIMICS file is generated in .stl format. In .stl format the tessellation line is generated for each layer for easy further analysis. This file is used as input for different type of analysis and fabricating rapid prototyping model.

4 CONCLUSIONS:

Using the MIMICS software 3D CAD model for different bone of human knee joint are generated. Figures 10 and 11 show the models for femur and tibia & fibula respectively. From above result concluded that the accuracy and finishing of model using Mimics provide short time for model creation from CT scan data. This 3D model of knee joint complexity which is not provide good accuracy by other 3D modeling techniques. From the 3D CAD creation using reverse engineering approach following benefits achieved.

1. Shorter model creation time.

2. 3D model can be materialize with different material in case of implant knee joint Replacement.

3. Further these models can kinematic analysis in case of total knee replacement.

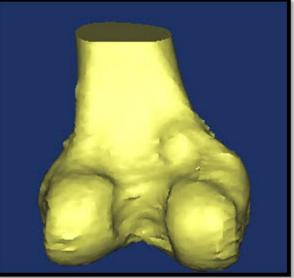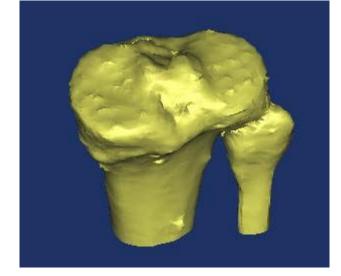4. Reduced production cycle time of knee model fabrication.

Fig. 10: Femur 3D CAD model

Fig. 11: 3D CAD tibia and fibula model

Future scope of 3D CAD modeling using Mimics and its future direction:

3D CAD modeling of human knee joint in Mimics 10.01 software using Reverse engineering approach which is useful for kinematic analysis of knee joint on finite analysis. The above created 3D model is used for implant surgery in case of total knee replacement which is created by slicing 3D CAD model and fabricates using rapid prototyping techniques.

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