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3D Printing of Human Anatomical Models for Preoperative Surgical Planning

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Abstract

Rapid Prototyping (RP) is an emerging technology, especially in a Three-Dimensional Printing (3DP) application. 3DP is used in many fields such as aeronautical, automotive, architecture, medical, and many others. 3DP can be effectively used in anatomical education for medical students who are pursuing their undergraduate degrees. It can also be used for pre-operative surgical planning by experts before surgery. Some complex organs of the human body which cannot be seen visible even after dissection of the cadaver can be printed using a 3D printer which provides haptic studies on organs and bones to students. These 3D printed parts can be used in pre-operative planning such as analysis and diagnosis formulation of affected organs. Further, it can be used in explaining the operative procedures to patients which helps them to understand and co-operate with the medical procedures. Therefore, this project aims at 3DP of complex organs and bones for anatomical studies and pre-operative planning procedures. As a first step in the project, some of the human bones were printed and analyzed for its quality.

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1. Introduction

Rapid Prototyping (RP) is a technology that will construct scale models of the prototype from its 3D Computer-Aided Design (CAD) data. Unlike the subtractive process which will remove material to fabricate a part, 3D Printing (3DP) is based on an additive process that adds layer by layer material to the substrate for constructing the whole model. In manufacturing sectors, a lot of time required for fabricating a prototype, patterns, and molds with many complex processes. To reduce the manufacturing time and to avoid the complexity, industries have started using 3DP techniques to produce a complex pattern, molds, and prototypes. In subtractive process, tool movements are planned for material removing from work piece to attain the desired shape. Compare to subtractive process like milling, turning and machining, AM technology has the most capabilities to get the complex geometries such as anatomical structures. RP provides cost-effective models of the designs that will be used to realize the product before the fabrication of expensive prototypes. Various types of RP techniques include Stereolithography

(SLA), Selective Laser Sintering (SLS), Fused Deposition Manufacturing (FDM), Laminated Object Manufacturing (LOM) and Ballistic Particle Manufacturing (BPM). [1][2]

3D printing is a technique that will print the molten material layer by layer to form an entire 3D structure of a physical part. The 3D model created by CAD software will be converted to .STL format. The .STL format was developed by Hull at 3D systems and it is being used as the gold standard for the data transfer between CAD software and the 3D printer [3].

Medical applications of 3D printing include printing of customized implants and prostheses like titanium mandibular prosthesis, Polyetherketoneketone (PEKK) skull implant, orthopedic implants, maxillofacial, spinal, hearing aids, Invisalign braces, neuroanatomical models and dental implants. Many researchers have tried to print knee meniscus, heart valve, spinal disk, cartilage tissues, bone, artificial ear, artificial liver and bio-resorbable tracheal splint [4].

For example, 3D printing of a prosthetic socket with respect to the patient's residual limb was done using the rapid

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prototyping technique. The patient's limb was scanned using the 3D scanner and digital data was processed using TracerCAD software and SolidView Pro and then after rectification, it was printed using Z corporation Z402 3D printer [5].

An anatomical study is very important for the postgraduate specialist to get surgical training. It is the required field of study for students practicing medicine. The knowledge obtained from anatomical study can be effectively used in the examination and diagnosis studies. This knowledge can be further used in explaining the operative procedures clearly to patients. Anatomical errors lead to litigation problems. Anatomical knowledge obtained from anatomical studies will avoid those errors. It provides the students to have haptic studies on 3D anatomy.

Various teaching aids have been used for anatomical studies such as dissection by students, prosecution and demonstration, didactic teaching, models, technologies (Computer Aided Learning (CAL), slides and videos), living anatomy and radiological imaging. Among those aids, dissection is the foremost and effective teaching modality for teaching anatomy. Unavailability of dissection facilities may hinder the anatomy education for students[6]. Even though effective methods are there, multi-modal teaching may facilitate the students in a deep understanding of the anatomical features.

3D printed parts of bones can aid the teaching process for anatomical studies. Some of the complex organs/bones may not be visible even after the dissection. The students may have difficulty in studying those parts. Hence, those parts can be printed and used for anatomical studies. Xiangxue Kong et al. have printed the complex structure of the hepatic segment. The hepatic segment is difficult to study for medical students because of its complexity (entwined and branching ducts), hence 3D printed part of the hepatic segment helps students to understand the structure effectively [7]. 3DP of organs/bones provides a haptic study for better understanding. 3DP of human bones/organs is cost-effective since the original cadaver cost is very high.

3D printed parts of the brain and skull can be used for neuro-surgical planning and used to explain procedures to patients before surgery. For epilepsy surgery, the placement of the electrode is a complex procedure. As for the musculoskeletal fields, cardiovascular 3D printing enhances the diagnostic work-up of complex congenital heart diseases, as well as surgical and interventional procedural planning and simulation. 3D printing is also used to fabricate patient-specific anatomical phantom to study disease progression and cardiovascular device interaction. If the patient-specific 3D model is obtained, then it can help in surgical planning by professionals [8].

Bone is an important part of the human body and it provides structural support to the body. The bone study helps students to understand the important anatomical features so that they can choose the correct implants with respect to the patient and to pre-plan the operative procedures effectively. 3D printed parts of the human bone can be used for study and planning purposes. Therefore, this project aims at developing low-cost 3D printed parts of the entire skeleton for anatomical study and patient-specific models for surgical planning and patient communication. 3D printing improves patient

engagement in understanding their own diseases and participating in their own decision-making, and improves communications with patients and their families [9]. The 3D slicer interface used for converting MRI/CT scan to .stl format is shown in **Error! Reference source not found.**

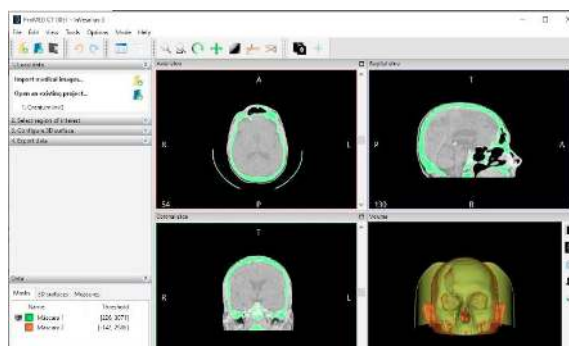


Fig. 1. DICOM from MRI/CT scan to .STL format conversion

2. Methodology

Bone models used in this study were obtained from the MRI scan data of the patients under observation. These MRI scans were used to build an .STL file for 3D printing. The framework of 3D printing of scanned parts are showed in figure 2.

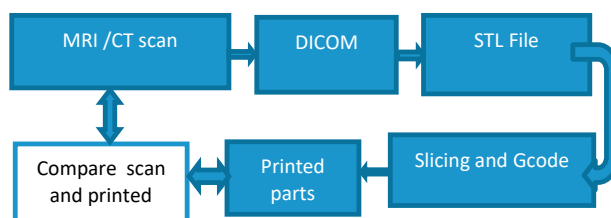


Fig. 2. Framework of 3dprinting of scanned parts

The DICOM (Digital Imaging and Communications in Medicine) file which has the CT-Scan of the full skeleton system was obtained. But, only few bones were the region of interest. needed was few bone parts. Using the crop volume tool, the exact volume which has to be processed was extracted. After defining the working volume, the model

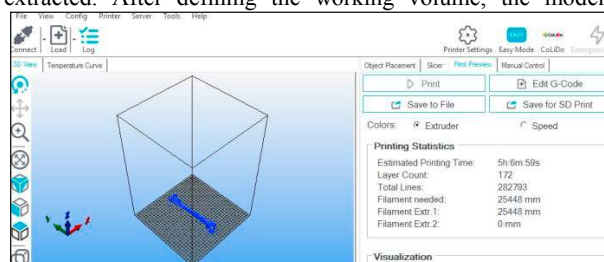


Fig. 3. 3D slicer interface used for converting .STL file to Gcode format

editor of the program was used to create a label map of the model. There are few tools used for processing such as a threshold effect tool that allows selecting a range of gray

colors. This is very useful with the bones since they have a distinctive contrast between white and gray surroundings.

Other parts such as ligament parts, blood vessels or nerves has white tone. Other tools are for erasing undesirable parts or paint others that should have been painted. By using these tools, the model was improved by filling holes that may appear or remove parts that are not from the model.

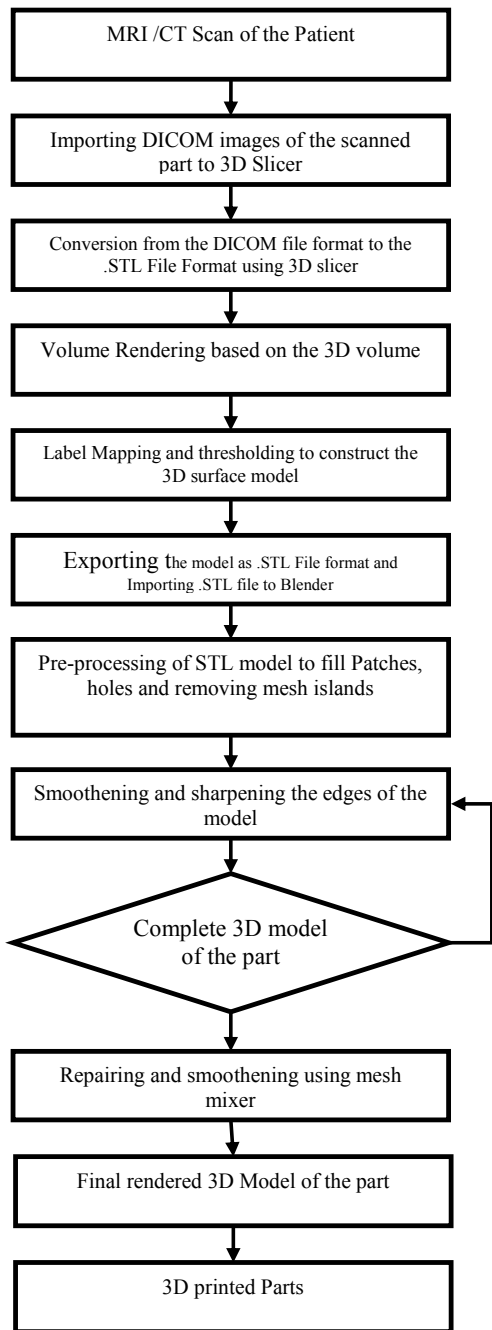


Fig. 4. Flow chart for present methodology

The DICOM format files were converted to .stl files using 3D slicer program as shown in Figure 3. After the generation

of surface model from the 3D slicer, the surface model still has some patches/holes which were processed using various CAD tool to generate the complete CAD model without any patches/holes.

All models can be exported then as.STL files[10]. Various additive manufacturing techniques had been used in fabricating educational medical models. Most of these techniques used the Fused Deposition Modeling (FDM) based method for developing these models. The methodology used in the present study is shown in Figure 4.

In the present study, FDM was used to fabricate human anatomical models. PolyLactic Acid (PLA) based filament was used for the present work with conditions for 3D printing given in Table 1.

Table 1. Parameters used in FDM printer

S.No	Parameters	Value
1	Filament Diameter	1.75 mm
2	Extruder temperature	205 °C
3	Bed temperature	60 °C
4	Nozzle Diameter	0.4mm
5	Print speed	60mm/s
6	Infill density	20%
7	Material used	PLA

The printer used for this study is Prusa i3. It is the newest and current 3D printer design by RepRap core developer. Along with this, Repetier-Host was used in this for ALL-IN-ONE software solution with multi Slicer Support. For this study, the Slic3r slicer was used. After slicing, all extruder movements and support structures can be seen.

With this, the control of the whole model, for a particular area or individual layer can be visually seen and fault data can also be extracted.This drastically avoid the defects and potential problems before printing the next layer thus save a lot of time and money.

3. Creation of Printable Medical 3D Model: From CT Scan to 3D Printable STL File

MRI/CT scanning uses DICOM as the standard format for storing the scanned data of the patient. DICOM is the standard image format set up by National Electrical Manufacturers Association (NEMA) which is mostly used for diagnosing purpose. DICOM format consists of two fields such as header field which contains the informations such as the name of the patient, type of scan and the dimension data and other field is the image data where it contains the 3D data of pixel/voxel of the image scanned for the organ of the patient. DICOM images (CT scan) of the scanned skeleton of the patient were obtained[11].

3D slicer is the open source software for medical imaging application [R]. It is used for post-processing the medical images and 3D viewing of the scanned images (Volume rendering). 3D Slicer was used to convert DICOM format of the scanned data into .stl file which was used for 3D printing. 3D printable models were printed using freeware software. Freeware software programs such as Blender and Meshmixer were used to perform complete inspection and pre-processing of the .stl files before printing.

3.1 Conversion of DICOM format to .stl file using 3D slicer

With the default settings in the 3D Slicer, .stl files of the 3D printing models of human bones were imported successfully. Patient ID is loaded for further study over the 3D slicer window with the three boxes showing that the axial (transverse), sagittal, and coronal views of the imaging study. Then, volume rendering was done based on the 3D volume rendered from several 2D projections of the organ that scanned. displayed in the slicer window. From the 3D volume, the 3D surface model was created. Using the default selection, Generic Anatomy Colours were used to create a label map that denotes the parts exactly. To bring up a choice of label maps, the threshold effect tools are used for selecting the bone through the green rectangle. It was also needed to define the minimum threshold range for the part available. By leaving the default maximum threshold range at 4095, the other settings of the threshold were modified. Based on the selection, a "label map" was created that encompasses the bone part that to be 3D printed [12]. This will leads to the creation of a 3D surface model which was saved as an .stl file format. The file format .stl file still needs further processing before printing.

3.2. Additional cleanup of .stl file using Blender

In a blender, the .stl file was imported to the processing window. The CAD model contains several disconnected mesh islands from the main object. These disconnected mesh islands in the skeleton object were cleaned to generate an editable mesh of the object. Initially, the entire mesh was selected, thus the skull appears orange. Expand the selection to include all connected vertices of the object has turned orange, but the disconnected mesh islands are still black. Upon inverting the mesh of the object, only the disconnected mesh islands should be shown highlighted in orange. Highlighted ones are cleaned for generating the skeleton object. Modifiers are functions that applied to the mesh to give the smooth appearance[13]. Using the modifier menu and select smooth from the deform column. The correct selection set the Repeat field to 30. So, blender took a few seconds to perform the smoothing function.

3.3. Processing using Mesh mixer before 3D printing

Meshmixer was used to get the smoothed .stl file without any patches. Analysis of the mesh was done for locating the defects that could cause problems during 3D printing. After analysis, Meshmixer tools were used for modifying the defected .stl file to get the smoothed one. Finally, a defect-free high-quality .stl file of the part from a CT scan was obtained.

4. Results and Discussions

Increased use of 3D printing technology in the production of customized phantom model of the human body parts for anatomic study is possible through the use of software such as Materialize, Mimics, and 3-Matic, etc.. This process is cost effective and the model has high quality. The total time used in the 3D printing was known through the slicer tool. It is used to plan the operation of the 3D printing approximately to

complete the production on time. In terms of quality, the bone models produced using the 3D printer are much lighter in weight than other methods since PLA has less density than other polymer. PLA took much longer time to complete the printing for giving the high surface quality of the parts and they can retain their strength and shape for a long time. These technologies have numerous advantages to offer the medical professionals and patients with regard to pre-operative planning models and customized medical implants. Conventional implants do not have high surface quality and over the long usage, the debris from the implants affects the tissues around the implants and creates prolong pain to the patients. 3D printed customized medical implants can avoid the pain created to the patients since it has high surface quality and strength. This research gives the methodology for conversion of CT/MRI scan data into 3D CAD model. The CAD model (.stl file) was printed using a low-cost FDM method. This can serve as an inroad to the development of customized implant from patient's own CT/MRI data and creating phantom models for anatomic and anthropometric studies, pre-planning procedures (3D templating) and to use models for explaining the operating procedures to patients by surgeons which will help the patient to build their confidence to go through the medical procedure (effective patient-surgeon communication).

Bone parts that was obtained from CT/MRI data of the patient's data were processed using 3D slicer, Blender and Meshmixer and printed using 3D printer were shown below with their applications.

4.1 Skull

The structure of the skull is always one of the most complicated areas of anatomy. Skull base models were used for endoscopic training, for planning needle insertion during neurosurgery and education in temporal bone anatomy. The 3D skull model was generated with the help of data received from the MRI/CT scan. Fabrication of these freeform shapes by other manufacturing techniques is quite difficult. Therefore, to build these models Additive Manufacturing is an effective tool. The Figure 5(a) and Figure 5(b) shows the 3D CAD model that converted from MRI/CT scan and the 3D printed model of the skull.

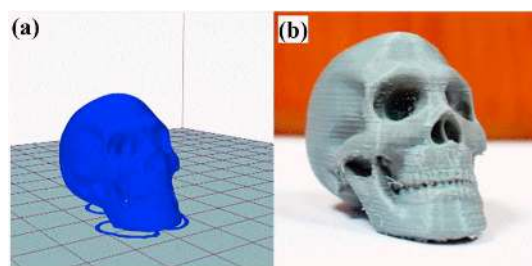


Fig. 5. (a) CAD file of the human skull before printing; (b) printing human skull model

4.2 Spine

Huge challenge in the medical field is the treatment of spinal conditions. The spine is having very complex shape and fabrication of the spine phantom models and implants are

very difficult using the conventional manufacturing methods. But, it is possible using 3D printing with higher quality. In present work, 3D printing has allowed the fabrication of spinal implants/ model for a preoperative study that is precisely designed to fit each individual patient's anatomy. Figure 6(a) shows the CAD model of the spine and Figure 6(b) shows the 3D printed spine model.

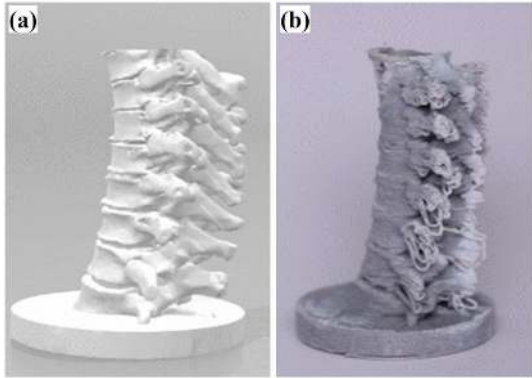


Fig. 6. (a) CAD model of the spine; (b) 3D printed spine model

4.3 Hip

The hip is a synovial joint formed by the head of the femur and the acetabulum, a cup-shaped cavity on the lateral surface of the pelvis. The manufacturing of this joint is also a complex process and the testing procedures are very complex as material changes [14]. AM allows to print these parts easily and this part can further be used for anatomical studies. The Figure 7(a) shows the CAD model of acetabulum and Figure 7(b) shows the 3D printed model of acetabulum.

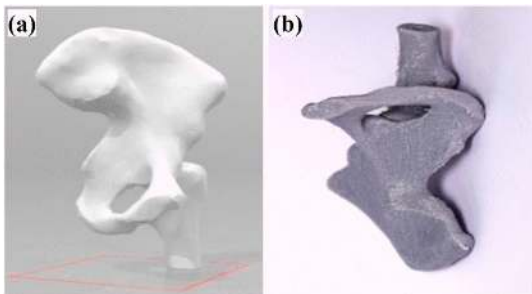


Fig. 7.(a) CAD model; (b) 3D printed model of acetabulum

4.4 Femur

Femur is the longest and weight bearing bone of the human body. The shape of the femur is based on Free Form Surface (FFS). To manufacture/fabricate FFS, requires lots of skill and efficient manufacturing technology. The femur head

is one of the main parts of the femur and it connects to the socket of the acetabulum. It helps in the locomotion. Distal end of the femur connects with the knee joint. It becomes essential to fabricate femur with much precision such that the 3D printed model can be perfectly used as a teaching aid and used for pre-planning procedures during Total Knee Replacement surgery[15]. CAD model and 3D printed model of the femur are shown Figure 8(a) and 8(b) respectively.

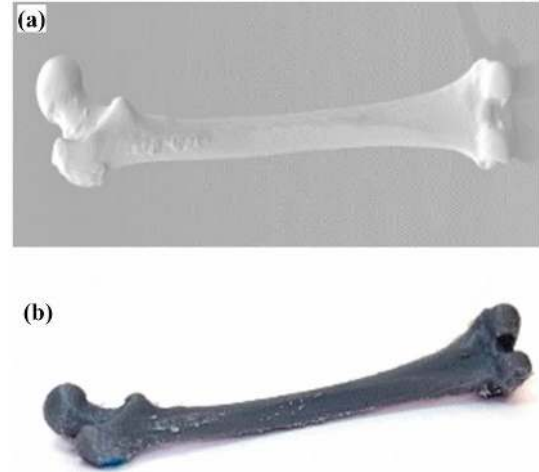


Fig. 8. (a) CAD model of the femur; (b) 3D Printed model of the femur

4.5 Tibia and Fibula

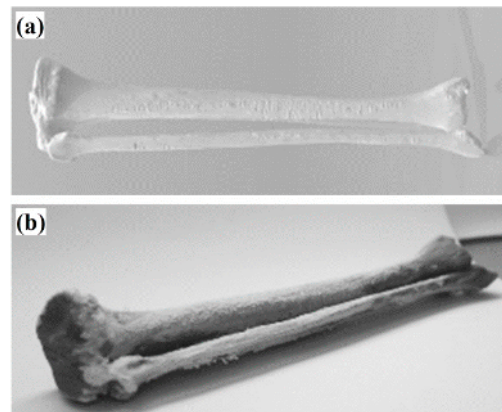


Fig. 9.(a) CAD model; (b) 3D Printed model of Tibia and Fibula

Tibia is the longest and strongest of the two bones in the lower limb. Fibula or calf bone is located on the lateral side of the tibia and it is connected with the proximal and distal portion of the tibia. Fibula is the smaller of the two bones. Tibia and fibula connects with the knee joint at their proximal region and connects with the ankle bones at their distal end[16]. Articulated tibiofibula joint is replicated accurately using 3D printing. The 3D printing model is shown in the Figure 9.

4.6 Knee joint

The knee is the intermediate joint of the inferior limb. It is one of the most complex and the largest joint of the human body. It consists of distal end of femur, knee cap/patella, proximal tibia and fibula. Knee joint model can be used for anatomic studies. CAD model and 3D printed model of the articulated knee joint are shown in the Figure 10(a) and 10(b) respectively.

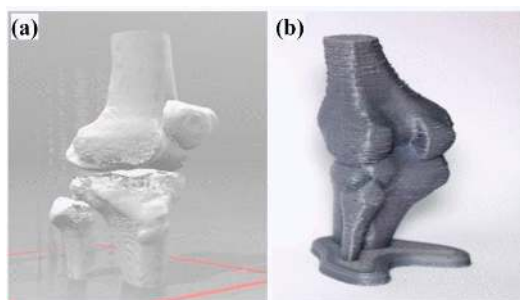


Fig. 10. (a) CAD model; (b) 3D printed Knee joint model

4.7 Ankle Joint

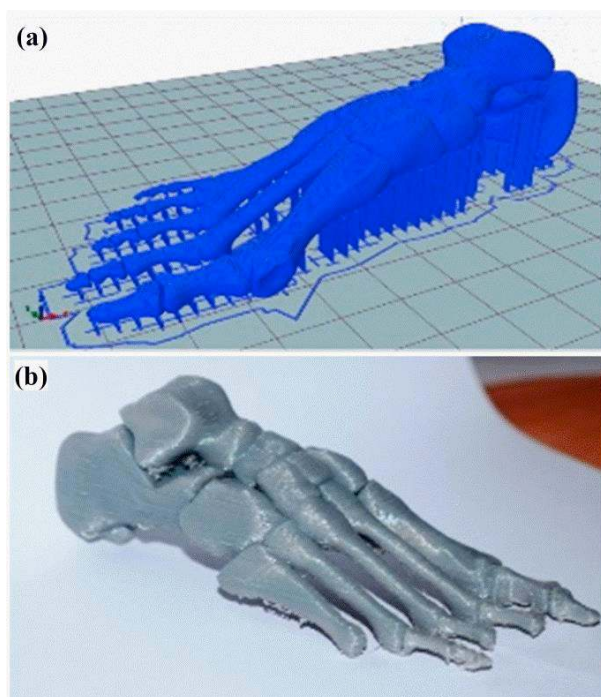


Fig. 11. (a) CAD model of the ankle joint; (b) 3D Printed foot model

Ankle joint is the joint in which leg (tibia and fibula) and foot (talus) articulate each other. It is formed by the junction of the tibia and fibula with the talus (or ankle bone). Further, the ankle joint consists of many subparts. Fabrication of all these parts together is only possible using 3D printing. 3D printed model is shown in Figure 11.

5. Summary and Future work

- 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.
- 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.
- Processed model was imported to printing software (CURA) as .stl file [17].
- 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.
- Complex and articulated joints such as knee joint and ankle joint were 3D printed without any error.
- 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.
- Future work from this research is to broaden this examination to include new materials that are biocompatible, to use other AM technologies, to redefine measurement procedure, to address other related AM research problems and to find new material that meet the current recommendation of the FDA and can be used on existing and emerging 3D printing machines.
- Further research is to explore materials and 3D printer that can be used for 3D printing delicate organs like the kidney, liver, etc. so that 3D printed organ can be produced for patients who requires organ transplant due to liver and knee failure.

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