

Cad Modelling of Human Ankle from CT and MRI Scan to Study the Bone Dislocation and Planning Operation Methodology by Using Slicing Software

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ABSTRACT: Recent findings show that 3DP is a versatile technology platform for numerous materials for mass customizable bone regeneration devices that are also getting approval from different regulatory bodies worldwide. After a brief introduction of different 3DP technologies, 3DP of different materials and devices for bone regeneration. From cell-based bioprinting to acellular patient-matched metallic or ceramic devices, 3DP has tremendous potential to improve the quality of human life through bone regeneration among patients of all ages. 3D printing provides the end user with design freedom, part customization and the ability to print complex parts on demand. A case study on the various process parameters of 3D slicing and printing in bone regeneration of human ankle is presented here.

Key words: Ankle, Bone Dislocation, Slicing, 3DP, AM

I. INTRODUCTION

3D printing is to manufacture any 3D data designed with CAD programs using a printer, by adding layers of material to a 3D physical part. 3D printing can be defined as additive manufacturing (AM) or layered manufacturing. 3D printing which has some techniques like selective laser sintering (SLS) material jetting, stereolithography (SLA), material extrusion and binder jetting etc. can be used for different materials and areas. It is interesting for many areas due to its success in the production of complex parts and the saving of material and time thanks to high-speed production. The effects of the developing technology can be seen in every field, from medicine to industry. 3D printers have become a part of this developing technology. Although it is thought to be a very new technology for us, what is actually new is that they are now more accessible and affordable than before. It is thought that 3D printing will move forward day by day thanks to the different facilities that provides for many different sectors. This technology, which is preferred especially for many applications in the field of health, provides great benefits especially for medical imaging and dental imaging, since it can largely manage studies such as medical device design and production that define the patient-specific anatomical structure. Applications using biocompatible materials such as the creation of tissue without any damage with living cells, blood vessel production, dental implants and special medical prostheses are just some of the contributions of the 3D printer to the biomedical field. In addition, this

technology is also being researched in order to fix or replace defective organs such as kidneys, heart. Moreover, with this technology, organs that will perform the same biological functions as the original organs can be created. Thanks to this technology with organ and tissue printing, the future will be provided for many patients, and there is now a growing research effort focussing on the use of its research in a variety of biomedical applications. 3D printer technology has become a preferred application in many sectors, especially in recent years its use in biomedical applications has attracted attention. In this study, 3D technology is introduced and various 3D method are referred. The superior properties of the method and its use in biomedical applications are mentioned. The use of the method in surgical applications, medical imaging, pharmaceutical industry, production of patient-specific medical prostheses and implants, vet medicine applications, skin engineering and stem cell studies and organ printing were explained. In addition, this study includes the benefits of this technology which is expected to become widespread in the biomedical applications, the current challenges that need to be developed, trends and future opportunities

II. BIOMEDICAL 3D PRINTERS

It can be expressed with many definitions such as “additive manufacturing” and “layered manufacturing”. Although it has more than one definition, as we explained in our previous study, it is the method of adding main materials to layers that usually overlap to produce parts. Printing

process basically has some steps, and the first step is modelling. Generally, computer-aided (CAD) software is preferred in 3D modelling of the part to be manufactured. The object to be manufactured can be prototyped on the computer. If, it was previously prototyped by someone else, it could be downloaded to the computer or if the part to be produced is an existing object, it can be produced after scanning. After the modelling step, the model of the part is sliced into printable layers. The last step is printing. During the printing step, an object is manufactured by adding another layer on top of layers. Thus, production takes place in a layered structure. Thanks to this technology, prototyping which takes several months using traditional methods, can be reduced to a few days or hours, saving time and costs, as the requirements of traditional manufacturing such as moulds, a long production line are not needed. In addition, it provides design freedom that enables designers to create parts with geometric and structural complexity, as it is feasible to produce objects that are impossible to produce using conventional methods. Moreover, some limitations in traditional methods are not valid for the technology so the removal of various limitations, the method offers a different way of thinking and the ability by removal of various limitations to directly address people's imagination has been effective in the day-to-day development of this technology. In the printing process an idea, a need is first transformed into a model and then into an object and thanks to this system, manufacturing can be performed easily and fastly. Fig.1.1 shows the modelling and slicing steps for the printing of the humerus bone, which forms the bone structure of the arm region between the shoulder and the elbow to define the surface of the bone model and send it to the 3D printer in order to print, it must be converted to an STL file. The stereolithography file format, abbreviated as "STL", is obtained by dividing the surfaces of 3D designed models into many triangles in a mathematical order. STL format identify surfaces as a collection of triangles. The surface is created with simple triangles that fit together like a jigsaw puzzle. Thus, the step-by-step printing process is performed. This technology includes many methods in itself. Some of the frequently preferred techniques are powder bed fusion (Selective laser melting, selective laser sintering etc.), material extrusion, SLA etc. The differences between the techniques are on account of the method of processing the layers, the material used. When choosing one of the 3D technology methods, the material and used method properties used should be considered and the most suitable method should be selected. 3D printing methods can be classified according to the physical state of the main material, solid, liquid or powder. Different methods are used for different types of materials. This classification is shown in Table 1a. 3D printing technology can be applied to metal, ceramic, composite and polymer materials. The most commonly used metal materials are stainless steel, titanium, magnesium, aluminium, Cr Co alloys. In

addition, the processing of unique materials such as titanium aluminides can be achieved with EBM. In addition to the benefits it provides, it is thought that the use of more metal alloys will increase in different applications.

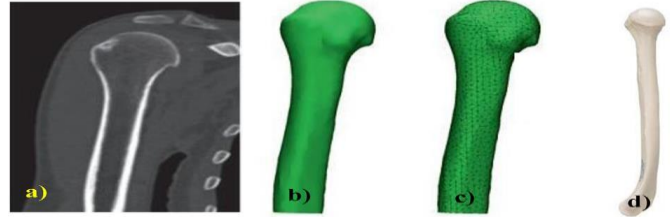


Fig.1.1 Production Stages of Humerus Bone With 3D Printer; A) Imaging of Humerus Bone with The Help of Computerized Tomography, B) Modelling, C) Slicing the Model for Printing, D) Printed Humerus Bone.

Classification of 3D printing methods according to the material used and the solid, liquid and powder form of the material.

3D printing method		Material type		Material				
		Liquids	Powder	Solid	Met al	Cera mic	Polyme r	Photopoly mers
Powder bed fusion	SLS		x		x	X	x	X
	SLM		x		x		x	
	EBM		x		x	X		
VAT- polymerization	SLA	X				X		X
Directed energy deposition	DED		x		x			X
Material jetting			x					X
Binder jetting			x		x	X	x	

Metal materials, especially Ti and Cr Co alloys, are preferred in biomedical applications, mostly because of their mechanical properties, biocompatibility, thermal, magnetic and electrical conductivity and generally high temperature resistance. Although metals have many advantages compared to polymers and other materials due to their properties such as laser absorption power and stability at higher temperatures, it can be said that this method is new for metals, while polymer materials have been used for 3D printing for years. Polymer is the first material group produced with this technology and still constitutes a large part of the materials today. Polymers are preferred in various 3D printing technologies, just like using resin as the necessary supporting structure in the SLA method. Acrylonitrile butadiene styrene (ABS), polyamides, polylactic acid (PLA), polycarbonates (PC), resins are the most commonly used polymer materials with this technology. Especially in medical applications, SLA method is preferred for poly (ethylene glycol) diacrylate (PEGDA) and periodontal ligament (PDL) polymers while material extrusion for ABS, polycaprolactone (PCL), polycarbonate (PC), polylactic acid (PLA), poly (lactic acid). SLS technique is preferred for acidcoglycolic acid (PLGA), polyvinyl alcohol (PVA), polyether ether ketone (PEEK), and binder spraying methods are preferred for polyvinyl and silica.

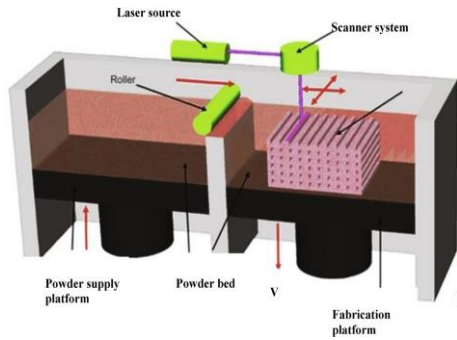


Fig.1.2 Model for SLS Method

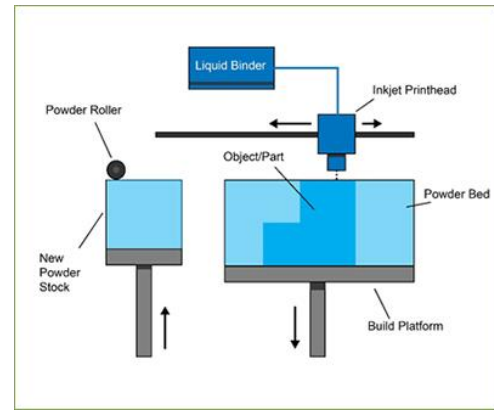


Fig.1.6 Material Jetting

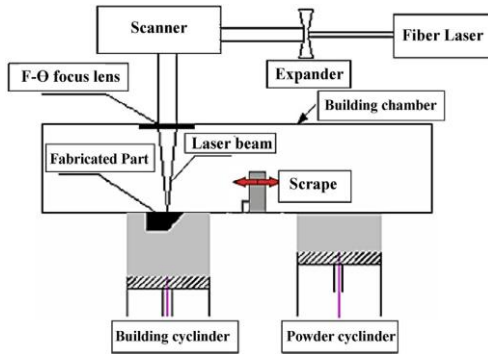


Fig.1.3 SLM Working System

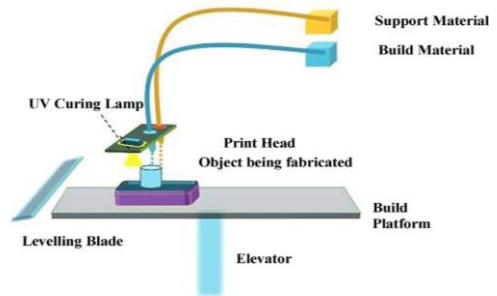


Fig.1.7 Binder Jetting

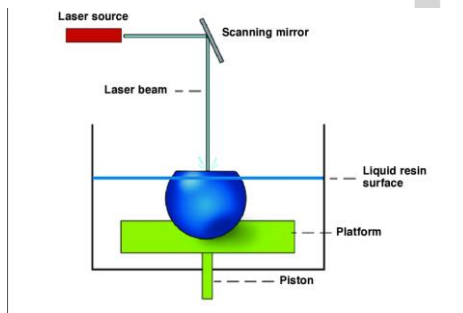


Fig.1.4 Stereolithography

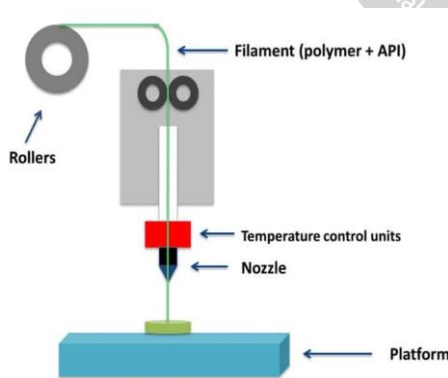


Fig.1.5 Material Extrusion Process

3D PRINTING TECHNOLOGY IN BIOMEDICAL APPLICATIONS

Recently the use of 3D printing in the biomedical applications has been interesting for lots of researches, and many Fig1.2 Model for SLS method. Fig1.3 SLM working system. 1434 journal of materials research and technology 2021; 14:1430 e1450 companies around the world have contributed to the increase in the use of this manufacturing method in the medicine with their laboratories and scientific researches. This technology offers significant benefits for biomedical applications and devices owing to the ability to manufacture the optional product according to specific patient needs. For example, many instruments used in surgery are currently produced by forging or casting methods and by using the mould required for the part, with special surface coating for desiderated surface properties and mechanical properties. These procedures need uneconomic machine and equipment, so distinct implants or patient specific are unaffordable and seldom produced. Machining of titanium alloys is more difficult as it has low elastic modulus, high mechanical strength and low thermal conductivity compared to 314L stainless steel. For this reason, patient specific implants are uneconomic to manufacture from these materials. These methods generate large material waste, and it is not possible to manufacture functional grade implants, so it is a miracle opportunity in order to the manufacturing of various functional biomedical equipment. Biomedical is a branch of technology that deals with the production of all material, apparatus and devices that can be used for diagnosis and treatment in medicine.

Artificial kidneys, heart, dental implants, knee prostheses, lenses, pacemakers and hip etc. this includes biomedical applications. Printing for these medical applications allows the customised complicated geometry of implants and upon request production, which can result in a significant attenuation in expense and stock. Also, the unit cost remains constant for all product since any special tooling for any product not to be necessary for 3D printing. This expense assessment forms the basis and purpose of this method for biomedical orthopaedic implants. Since this technology has many advantages, its use in biomedical applications is increasing day by day. It is used in biomedical applications such as implants and tissue engineering. It is predicted that its use in these application areas will increase in the near future, as shown in Fig. 2.1. Today, it is preferred for many different applications, especially in the medical sector, as shown in Fig. 7. Despite some remarkable achievements, the development of organs tissue with this method goes on pose important challenges. From cancer treatment to patient-specific prostheses; In many areas of medicine, inventions strengthened with 3D printing are sought to improve the quality of life or save patients life.

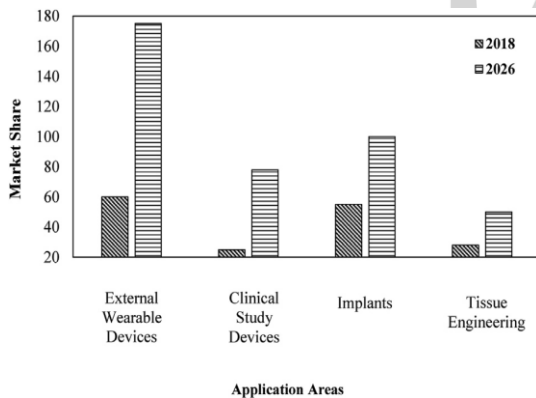


Fig.2.1 Forecast of The Increase in The Use Of 3D Printer Technology in Biomedical Applications

1. SURGICAL APPLICATIONS
2. MEDICAL DEVICES
3. PATIENT-SPECIFIC IMPLANTS
4. PATIENT-SPECIFIC PROSTHESES
5. VET MEDICINE
6. TISSUE ENGINEERING AND STEM CELL TECHNOLOGY
7. ORGAN PRINTING

BIOMEDICAL IMAGES FOR FINITE ELEMENT MESH DEVELOPMENT

3.1 X-RAY IMAGING

X-ray imaging is one of the oldest transmission-based techniques which uses ionizing radiation to take 2D images of exposed tissues by sending X-ray's beams through ROIs. These X-ray beams are absorbed in different amounts depending on the density of the material through which it is passing. These densities are expressed

using the Hounsfield (HU) scale values, named after Sir Godfrey Newbold Hounsfield (Aug. 1919eAug. 2004), as shown in Fig. 9.1. The values are measured based on a scale where radio density of water at standard pressure and temperature is defined as zero HU, while radio density of air on the same scale is defined with 1000 HU. The formula for calculating HU value based on this scale is shown in Eq. (3.1e)

$$HU = 1000 \times \frac{\mu - \mu_{water}}{\mu_{water} - \mu_{air}}, \quad 3.1e$$

where μ ¼ original linear attenuation coefficient of substance, μ_{water} ¼ linear attenuation coefficient of water, and μ_{air} ¼ linear attenuation of air. In a typical transmission-based imaging technique, the emitted X-rays pass through ROIs, which affect the level of energy reaching to the detector, depending upon the type of tissue or organs encountered along the path. Tissues having low Hounsfield scale values darken the film such as lungs and fat, while tissues having higher Hounsfield scale values lighten the film and provide white spots such as hard bones. Therefore, the denser the tissue, the brighter the image will be as the detector will return weak signals. Similar tissues can provide different X-ray images depending on the hardness or penetrating ability of X-rays, which is adjusted by selecting the voltage for the emitter. But longer emissions of these X-rays can be harmful as they ionize the biological tissues. The most common clinical uses of X-rays are detecting fractured bones, dental cavities, swallowed objects, and breast mammography. Conventional X-ray techniques provide flattened 2D images which cannot be used to generate 3D segmented regions of tissues.

3.2 COMPUTED TOMOGRAPHY IMAGING

CT, or computer axial tomography (CAT), uses multiple X-ray projections taken from different angles to produce detailed cross-sectional images of ROIs. Similar to X-ray imaging, when these beams pass through different dense tissues, it gets Fig. 4.5 Hounsfield number for different human tissues. Biomedical Images for Finite Element Mesh Development 391 weaker after absorption and the final intensity is measured by the detectors providing different contrast imaging of tissues. Since the same cross section is scanned at different angles, it can be used to reconstruct a 3D image of the tissues. By adding more than one detector, the processes can be faster and more accurate. CT imaging is commonly used to diagnose presence of tumors, colon cancer, bone injuries, and internal bleeding.

3.3 MAGNETIC RESONANCE IMAGING

Magnetic resonance imaging (MRI) generates cross-sectional images of the tissues by using a strong magnetic field to magnetize protons within the tissue. The basic principle of MRI imaging is to align the nuclei of atoms which have a spin and exhibit magnetic moment. Magnetic

field intensity lies between 0.1 and 3.0 T, a standard unit of magnetic flux density named after Nikola Tesla (Jul. 1856-Jan. 1943). The image contrasts are achieved by using different pulse sequences and by changing the imaging parameters relative to longitudinal relaxation time (T1) and transverse relaxation time (T2). The signal intensities on the T1- and T2- weighted images correspond to specific tissue characteristics. Irrespective of the difference between T1- and T2-weighted images, proton density weighing is also used to get contrast between soft tissue images. The major difference between MRI and other transmission-based techniques, such as CT and X-ray, is that MRI is based on signals sent by the tissue while the others use an external source such as X-rays to get the contrasts. With CT, detailed anatomical details can be achieved, while with the MRI tissues having different biological functions can be distinguished more clearly. MRI imaging is generally used to evaluate abnormal tissues, spinal injuries, brain abnormalities, tendon or ligaments tears, etc.

3.4 POSITRON EMISSION TOMOGRAPHY

Positron emission tomography (PET) is a nuclear imaging technique which uses a dye-like substance having radioactive tracers to identify cellular level changes in the tissue. Computer analysis of tracer concentration in the tissue along with a CT scan helps in generating a 3D image. PET is primarily used in clinical oncology for medical imaging of tumors, and in the diagnosis of neurological diseases, e.g., Alzheimer's and multiple sclerosis, as it is able to collect diagnostic information which cannot be acquired by other methods. This imaging modality is sparingly used in FE model development as it is quite expensive.

3.5 ULTRASOUND IMAGING

The principle behind ultrasound imaging is to record the reflection of sound waves penetrating through different tissues and reflecting back from boundaries of structures having different densities and velocities of sound-wave propagation. The velocities of ultrasound waves vary in different substances. The contrast images of different tissues are generated based on these sound-wave propagations. Depending on the reflection-echo quality, ultrasound images may be noisy and have spatial deformities. There are different methods to get these contrast 2D images such as B (brightness)-mode, M (motion)-mode, or D (Doppler)-mode. Ultrasound imaging is mainly used in fetal scans during pregnancy, and to evaluate symptoms of pain, swelling, or infections. The contact between the transducer and the adjoining surface is very crucial and refined by using gel-like substances or water-filled plastic bags.

Although large numbers of medical modalities are available, the task of segmenting the detailed geometry of all human organs, such as bones, soft tissues, muscles, and

veins, through medical images provided by different modalities is not straightforward. One single imaging technique cannot be used to acquire all 3D geometry information due to the limitations associated with each technique. For example, CT images can be used mainly for segmenting bone, since they have a unique spectrum in terms of Hounsfield scale values which provides white shades during a scan. The similar attenuation of the signal is not provided by soft tissues, which will show up as several overlapping grey spectrums of fat, skin, muscles, etc. The CT, or Hounsfield, number described as the density are assigned to a voxel in a CT scan on an arbitrary scale on which water has density 0, air 1000, and compact bone $\rho > 1000$. Most of the soft tissues have a CT number closer to water; therefore, the boundaries of adjacent soft tissues cannot be easily separated in CT scan.

MRI technique can provide excellent soft-tissue contrast as it uses a magnetic field which aligns orientations of protons (nuclei of hydrogen atoms) and is abundant in water and fat. Therefore, in general, 3D geometry of bones is segmented through CT scan images, while the soft tissues, such as heart, lungs, and abdominal organs, are segmented with the help of MRI images where the distinction between the such as PET, single-photon emission computed tomography (SPECT), contrast CT, or contrast MRI can also be used to distinguish the boundaries of adjacent soft tissues more clearly, if required.

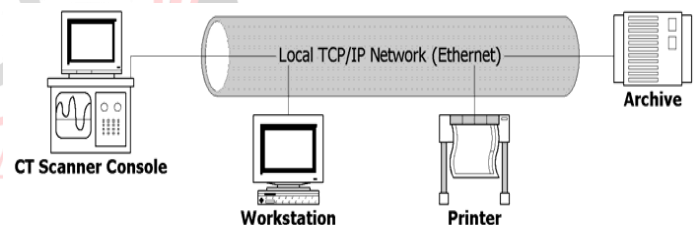


Fig.3.1 A Standard DICOM Network.

3.6 DIGITAL IMAGING AND COMMUNICATIONS IN MEDICINE (DICOM)

DICOM is a worldwide information technology standard established in 1993. The standard covers file format and transfer protocol, permitting exchange of data regardless of hardware origin. Devices that make up a DICOM system are:

- Hardware modules, such as CT and MRI scanners
- Picture Archiving and Communication Systems (PACS)
- Reporting and post processing workstations
- Printing services

3.6.1 DICOM Process

- A CT scan is performed
- The scanner console generates a set of images from the unprocessed data.

3. The CT console forwards the study to a PACS
4. Data is reformatted; this creates images from the original study.
5. These images are returned to the archive and merged with the rest of the study.

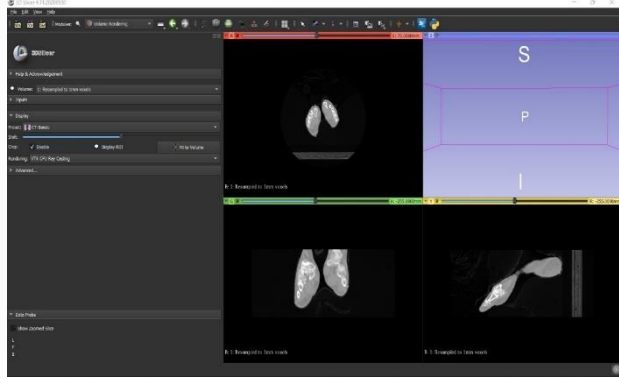


Fig.4.4 Loading DICOM Files

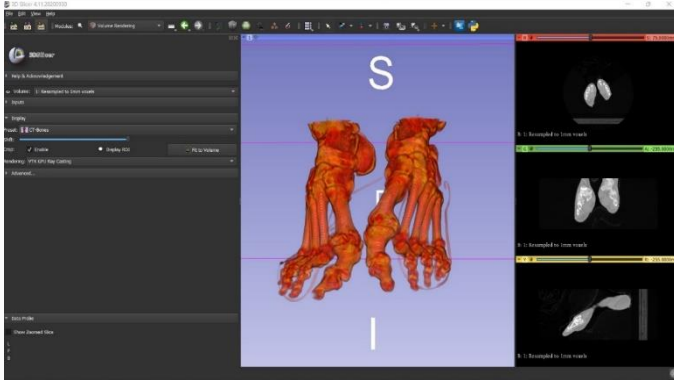


Fig.4.5 CT Bones

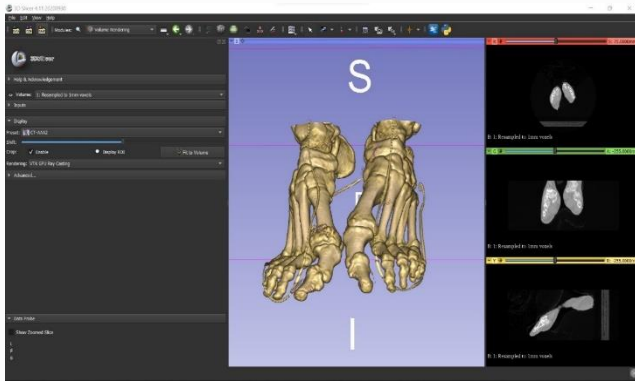


Fig.4.6 CT AAA2 View

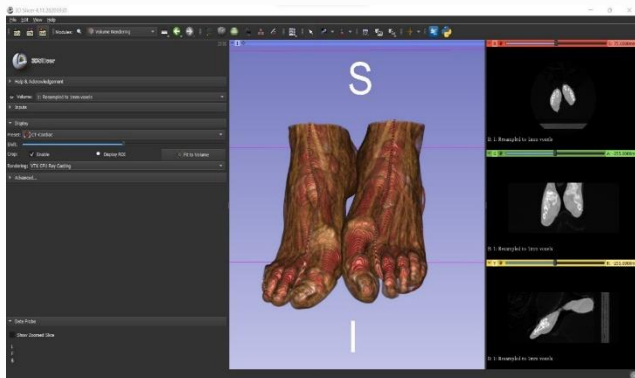


Fig.4.7 CT Cardiac View

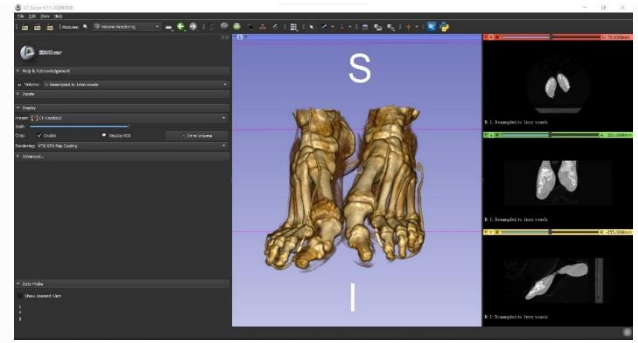


Fig.4.8 CT Cardiac2 View

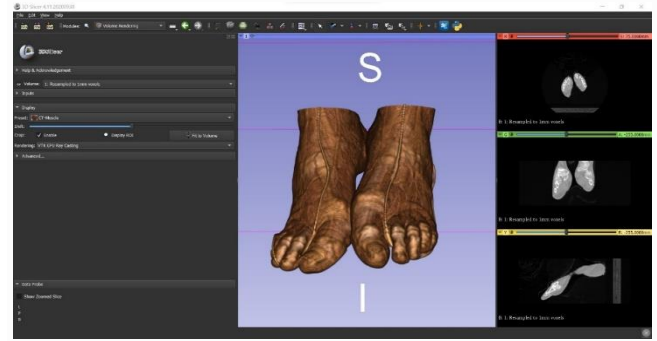


Fig.4.9 CT Muscle View

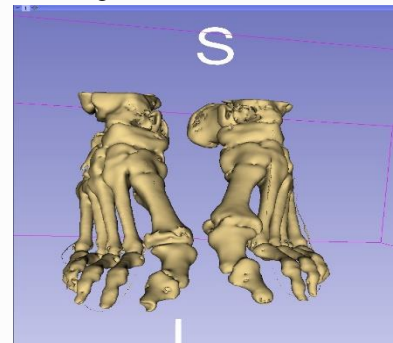


Fig.4.10 Thresholding of Ankle

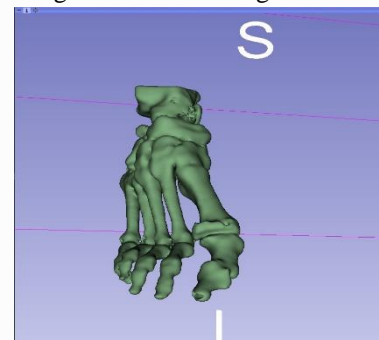


Fig.4.11 Segmentation of Part

SLICING OF HUMAN ANKLE USING ULTIMAKER CURA SOFTWARE

5.1 ULTIMAKER CURA

Cura is an open-source slicing application for 3D printers. It was created by David Bram who was later employed by Ultimaker, a 3D printer manufacturing company, to maintain the software. Cura is available under LGPLv3 license. Cura was initially released under the open source Affero General Public License version 3, but on 28 September 2017 the license was changed to LGPLv3. This change allowed for more integration with

third-party CAD applications. Development is hosted on GitHub.^[3] Ultimaker Cura is used by over one million users worldwide and handles 1.4 million print jobs per week. It is the preferred 3D printing software for Ultimaker 3D printers, but it can be used with other printers as well.

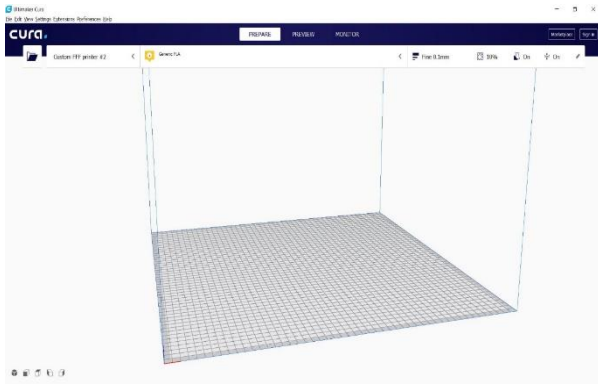


Fig.5.1 CURA User Interface

5.2 SETTING UP CURA

5.2.1 Overview

Ultimaker Cura indicates relations between custom settings with icons that indicate their relation. Settings visible to the user can be linked, automatically calculated, unavailable or hidden. This is the full list of icons and indicators used in the custom mode.

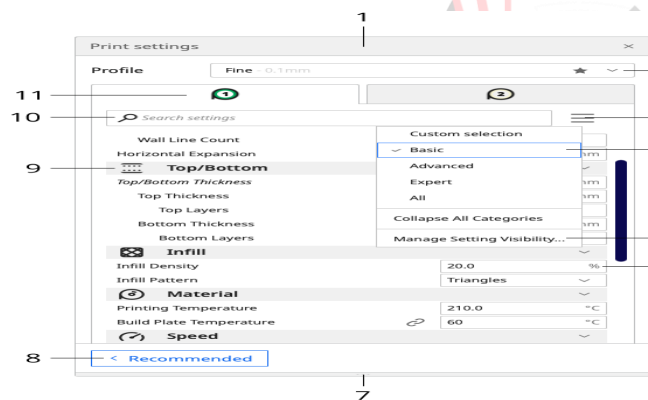


Fig.5.2 Segmented Part

1. Linked setting - Settings with this icon are linked between extruders, the setting will always be equal between all extruders
2. Greyed out setting - This setting is overwritten by a child setting. Reset the child setting to alter this setting
3. Gear icon - Opens the setting visibility preferences
4. Information icon - Shows a hidden setting influences the printing strategy. This only occurs when you accidentally change a setting and hide it afterward
5. Categories - Can be collapsed to hide them temporarily when focusing on different aspects.
6. Reset icon - Resets the value to its default or parent setting.
7. Calculated icon - Indicates the setting is normally calculated from a parent setting.

5.2.2 Setting Filter

Ultimaker Cura has a lot of settings that are easiest to find using this filter. Simply start typing to filter both already visible and hidden settings.

1. **Setting filter.** Only settings with the phrase 'layer' are visible
2. **Active settings.** These are displayed solid. They will still be visible after clearing the filter
3. **Hidden settings.** These are displayed greyed out. They will remain hidden after clearing the filter
4. **Tooltip.** Shows useful setting information when hovering the mouse over a setting
5. **Quick menu.** Right-clicking a setting has options to copy the settings' value, hide/show it and to open the setting visibility preferences

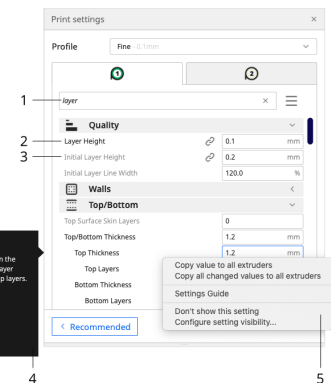


Fig.5.3 Printing Parameter Setup module

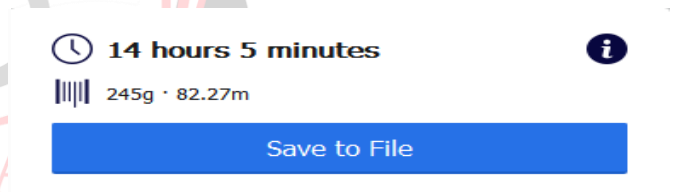


Fig.6.13 Optimized Values of Print Time, Mass of Material Consumed and Spool Length

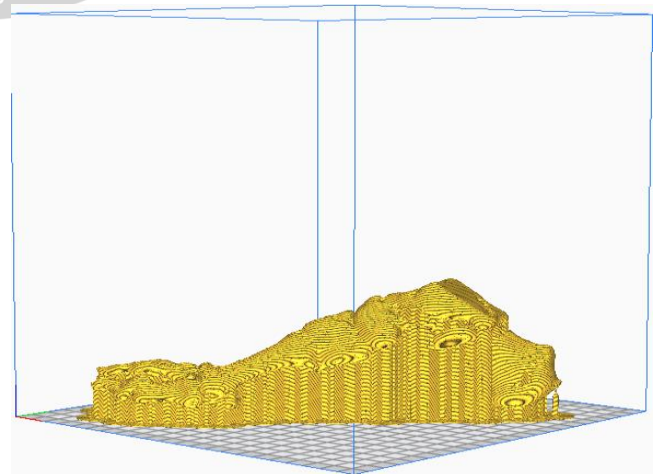


Fig.6.14 3D Slicing of Human Ankle Showing Orientation of X, Y&Z Planes with Generated Supports and Optimized Printing Parameters Using Cura Software (Right Side View)

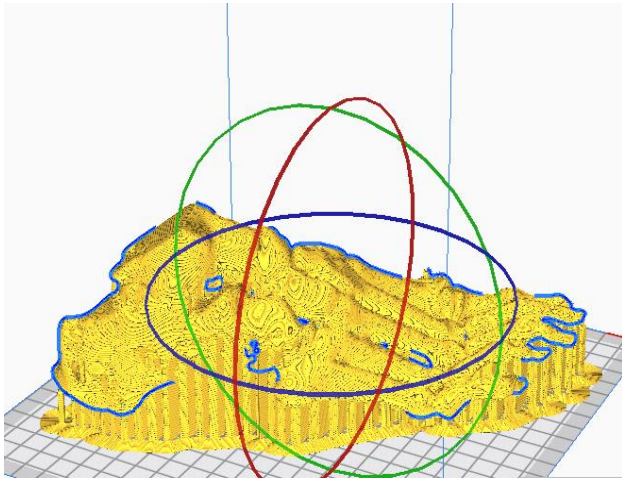


Fig.6.15 3D Slicing of Human Ankle with Generated Supports and Optimized Printing Parameters Using Cura Software (Left Side View)

III. CONCLUSION

By using conventional methods to perform reconstructive surgeries on patients, there are so many risks involved like misalignment of implants due to geometrical and dimensional inaccuracies, the implanted parts may push onto the nearby tissue or blood vessels in the future, the time for which the patient remain in surgery is longer which would increase the chances of infection and other ailments and also the place on the patient's body where a doctor must provide an incision to perform surgery is also approximate.

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 Mesh mixer software. Processed model was imported to printing software (CURA) as .stl file to slice the model with different layer height to capture the fine details of the ankle model.

Bone models obtained were optimized for 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 ankle were 3D printed without any error with least possible time and using minimum amount of material by optimizing printing parameters.

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 and patient will remain in surgery for comparatively less time than conventional methods. 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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