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Additive Manufacturing Fixture Box for Bone Measurement

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Abstract

Bone is unsymmetrical, porous and complex structure as well. Therefore, it is very challenging to measure its dimensions by both contact and noncontact methods using Co-ordinate Measuring Machine (CMM). Especially, in recent years, bone measurement data is highly needed for various medical applications (anatomical study, fabrication of implant, surgery, etc.). Total Knee Replacement (TKR) is nowadays becoming popular in bringing back of injured person to normal life. TKR needs exact three-dimensional (3D) data for making functionally-satisfactory implant which in turn almost eradicating post-surgical management. In order to acquire 3D bone data it obviously needs an aiding device (precise holding and rotating device for bone measurement). In this, a site-specific rotating box with gears was indigenously designed, developed and manufactured using Poly Lactic Acid (PLA) as material through 3D printing. The additively-manufactured fixture box was used to hold and rotate (0.2^{o} resolution) the bone precisely to obtain the three dimensional data and further imported it to Computer Aided Design (CAD) system for generating 3D model of knee joint. For verification and validation purpose; measurement done by fixture box aided CMM was compared with results measured by Vernier calliper. It showed reasonably close in agreement which pave the way in furthering this research.

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Keywords: Bone; Knee joint; Co-ordinate Measuring Machine; 3D printing; Implant

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1. Introduction

Our day to day life is based on physical movements of the human body which can be done with the help of different types of joints made with bone. Bone is a light weight porous material having greater strength. It gives protection to delicate internal organs in the body. It is an active connective tissue made up of minerals and collagen (a protein) and supplied with blood. It acts as a reservoir for calcium and phosphorous minerals. Long bones like femur and tibia have greater length than width. Hollow space inside the bone is called bone marrow cavity. Yellow marrow stores fat and red marrow produces blood cells. If any damage occurs, it can repair itself.

Nowadays, bone measurement data is needed for various applications like anatomical study of various intricate features in complex shaped bones, patient specific implant modeling and bone repair surgeries like Total Knee Replacement (TKR) and Total Hip Replacement (THR) etc. There are three types of arthritis: osteoarthritis, rheumatoid arthritis, and post-traumatic arthritis. The osteoarthritis will affect hip and knee joint severely. TKR and THR surgeries are increasing in number nowadays. Revision surgeries after primary surgeries are increasing currently because of the unsuitable implants erection and wrong-site surgeries. These problems are happening due to improper preplanning. Recent statistics of revision surgeries in the USA show that the primary and revision of TKR have increased drastically in a decade [1]. Therefore, an error -free system is necessary for orthopaedic surgical applications.

Bone measurement data is used to identify geometric variations of bone with respect to different regions around the world to model patient-specific implants with better accuracy. Several femoral parameters like femoral head offset, femoral head center, femoral head diameter, femoral neck length are identified from bone measurement data for effective design of implants [2]. Bone repair surgeries like TKR and THR need bone reference data of a patient for preplanning and execution. Different types of scans like X-ray, Magnetic Resonance Imaging (MRI) and Computed Tomography (CT) are done before the bone surgery.

TKR needs perfect 3D data of a bone for modeling the implants. For modeling entire knee joint, dimensions of femur, tibia and patella have to be known. But, femur and tibia are the long bones in the human body and having complex structure. It is very difficult to measure the femur and tibia using Co-ordinate Measuring Machine (CMM). Therefore, an aiding device is needed to measure the bone using CMM. Hence, a rotating fixture box could be used to hold bone. The Additive Manufacturing (AM) technique is believed to be the most appropriate one for fabricating the rotating fixture.

American Standard for Testing Materials (ASTM) defines the additive manufacturing as “a process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies.” Various synonyms of AM are: additive fabrication, additive processes, additive techniques, additive layer manufacturing, layer manufacturing, and freeform fabrication. AM machine can be divided into three broad areas: solid-based, liquid based and powder bed systems [3]. AM technique can be used to convert digital 3D model into a final product.

Major AM processes include Fused Deposition Modeling (FDM), Ink Jet Printing (IJP), Laminated Object Manufacturing (LOM), Laser Engineered Net Shaping (LENS), Stereo lithography (SLA), Selective Laser Sintering (SLS), Three-Dimensional Printing (3DP). Three steps in AM process are the conversion of digital 3D model into a standard AM file format, transfer of file from computer system to AM machine where the part model can varied to suit the printing process, building of part as layer by layer [4].

3D printing is a process of rapid prototyping of a 3D CAD models created by CAD software. 3D printing is a technique that will print the molten material as layer by layer to form the entire 3D structure of a physical part. The CAD program created by CAD software will be converted into .STL format. The .STL format was developed by Hull at 3D systems and it is being used as standard across globally for the data transfer between CAD software and the 3D printer [5].

Medical applications of 3D printing includes printing of customized implants and prosthesis like titanium mandibular prosthesis, PolyEtherKetoneKetone (PEKK) skull implant, orthopedic implants, maxillofacial, spinal, hearing aids, invisalign braces, neuroanatomical models and dental implants. 3D bio-printing is a current trending research in medical field. Many researchers have tried to print knee meniscus, heart valve, spinal disk, cartilage tissues, bone, artificial ear and liver and bio-resorbable tracheal splint [6].

The main usage of CMM is to obtain 3D data for constructing a parametric model of the object and for inspecting the surface profiles of machined materials for error analysis. While retrieving the dimensions of the sample for 3D modelling, the CMM can be able to trace only one surface at a time [7]. So, we need a CAD software for processing each surface plane dimensions to produce an entire 3D model. If it is a complex shaped profile, it is very difficult to trace the dimensions with respect to each other surface plane and post-processing.

So this paper is aiming to use AM of a fixture box for bone measurement. Femur dimensions are measured by CMM using rotating fixture box. The measured data will be processed and the 3D model will be generated using CAD software. The schematic of the entire process is shown in figure 1.

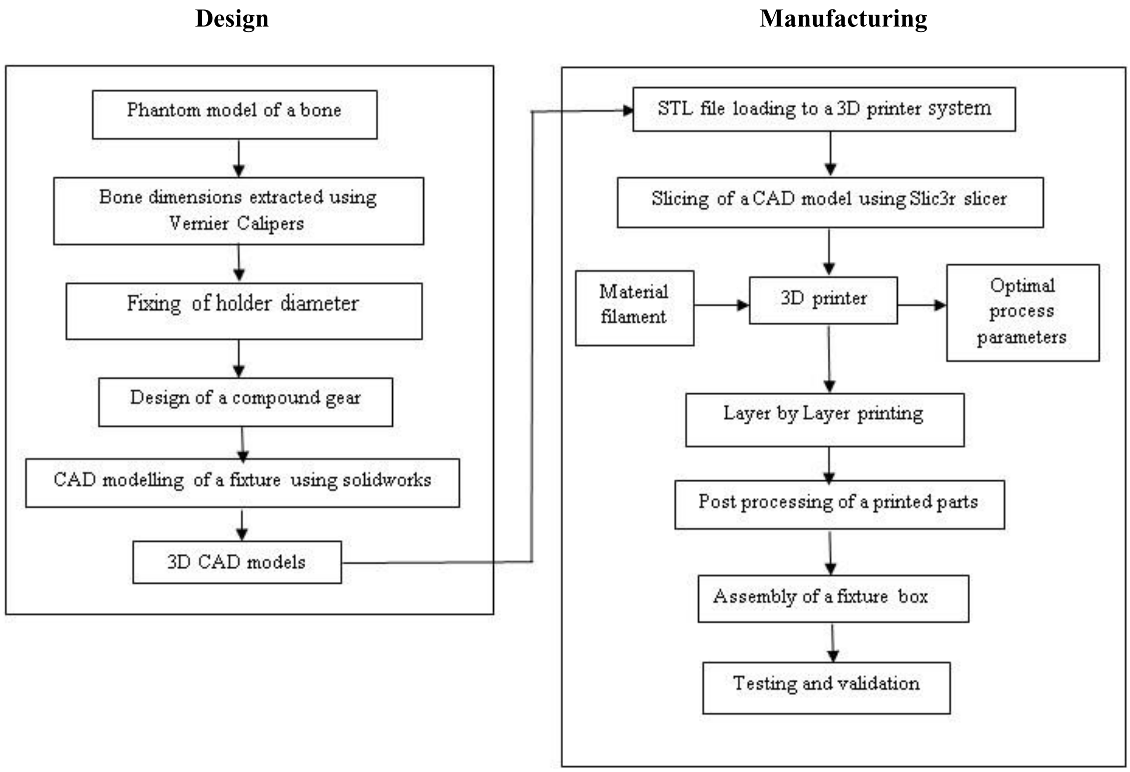

Fig. 1. Flowchart for design and manufacturing of a fixture box

2. Design of a fixture box

To make a 3D model of a knee joint (femur, tibia and patella), there is a need for measuring the dimensions of it. A CMM can be used to take measurements on human bone to make the 3D model of it. For 3D modelling the bone, a bone phantom model was used.

In order to design the holder for bone, the distal femur and proximal tibia dimensions are necessary. The Vernier calliper was used to take the dimensions of the bone. Distance between lateral condyle and medial condyle which is a large dimension has been taken as reference for fixing the diameter of the holder. Hence, CAD model of the holder has been created with this diameter. Since bone has a very complex profile, it is very difficult to take measurement in every surface plane of a bone using CMM. So, there is a need for developing fixture to hold the bone in correct plane to take measurements in CMM. Then, points corresponding to each surface plane can be obtained using CAD software to generate a 3D model.

For making measurements in each surface plane, the bone has to be rotated with respect to corresponding degree. So, the fixture with bone has to rotate from 0° to 360°. The fixture with gear reduction principle has to get resolution of 1°. For getting this resolution, herringbone compound gear with gear ratio of 1:25 was designed. Two large gears with each 50 teeth and two small gears with each 10 teeth were used. The Herringbone gear CAD model was shown in figure 2 (a). The gear ratio of a herringbone gear is given in below equation (1),

$$Gear\ ratio = \frac{N_1 N_3}{N_2 N_4} = \frac{1}{25} \tag{1}$$

Where N_1, N_2, N_3 and N_4 are the number of teeth in gears respectively.

For designing bone holder, dimensions of femur and tibia were taken using Vernier calliper. With respect to diameter of a distal femur and proximal tibia, holder diameter was fixed. To hold bone with certain grip, 6 Allen screws were used to provide 6-point contact. The bone holder CAD model was shown in figure 2 (b).

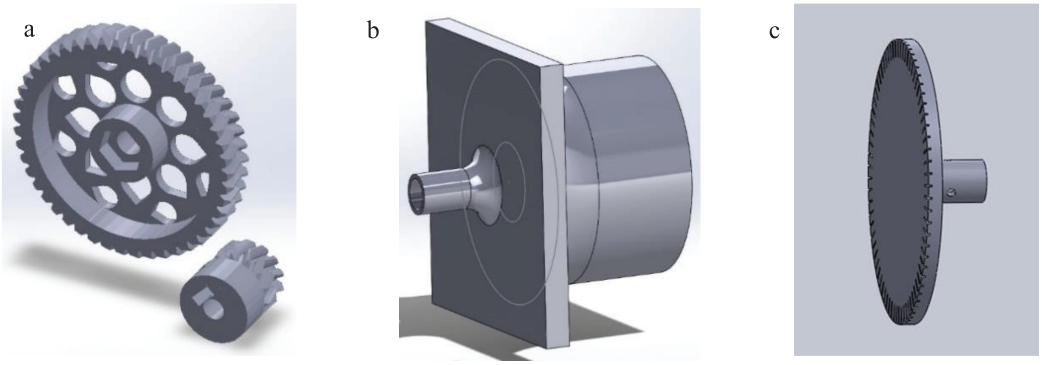

Fig. 2. (a) Herringbone gear (b) Bone holder (c) Input handle

The Input handle was designed with 72 divisions marked over 360° circle. So, each division correspond to 5°. For rotating each division at input, will give 0.2° at the output because of the gear reduction. The Input handle's CAD model was shown in figure 2(c).

3. Development of a Fixture box

The handle, gears and bone holder were printed using 3D printer facility available in Manufacturing Engineering Section (MES) at IIT Madras. A Prusa i3 (iteration 3) 3D printer-based on FDM was used for printing the components of fixture box. FDM is based on laying down semi-liquid state thermoplastic material layer by layer from extruder over the substrate. The building material should be melted 0.5ºC more than its melting temperature so that it will be cool down, solidified and welded to the previous layer permanently. The overhanging features of a model can be printed with supporting structures which can be made with low cost material so that it can be removed easily after printing. Some of the current systems include water dissolvable supporting structures [8]. Materials like Polycarbonate (PC), acrylonitrile butadiene styrene (ABS), PolyPhenylSulFone (PPSF), PC-ABS blends, and PC-ISO are used in this process [9]. A plastic material wire is fed into the extruder to produce a part. Each layer is laminated to the previous layer. Likewise, an entire 3D model will be created [10].

The Prusa i3 consists of five NEMA 17 stepper motors, single metal sheet style frame, heated bed, thermistor and extruder. Different kinds of material can be used with prusa i3 like PLA (polylactide), Acrylonitrile Butadiene Styrene (ABS) and copper-PLA (copper fill). For printing components of fixture box, PLA was used as a printing material. PLA is a biodegradable, corn-based plastic that prints at nozzle temperatures of ~180ºC and baseplate temperature near room temperature [11]. Material properties of the PLA are given in Table 1.

A Repetier-host was used as a host software for prusa i3. The parameters are given in Table 2. The 3D CAD model which was created using software was imported to the repetier host. It has positioned the STL files in virtual heated bed and slice them using Slic3r slicer into horizontal layers of varying thickness. A support structures can be created if it is needed with respect to a modelled part. STL files were automatically converted to G-code for generating tool path movements. Then, the entire data was exported to the FDM machine. After printing, the support structures were removed from the main part. For assembling purpose, three aluminium shafts each of length 15mm were used.

Table. 1. Material properties of a PLA

Properties	Value
Density	1.25 g/cm^3
Elastic Modulus	3.5 GPa
Elongation at break	6%
Flexural Modulus	4 GPa
Flexural strength	80 MPa
Glass transition temperature	60°C
Heat deflection temperature At 455 KPa	65°C
Melting onset (solidus)	160°C
Shear Modulus	2.4 GPa
Specific heat capacity	1800 $J/kg-K$
Strength to weight ratio	40 $kN-m/kg$
Tensile strength: Ultimate (UTS)	50 MPa
Thermal conductivity	0.13 $W/m-K$

Table. 2. Pruza i3 parameters

Parameter	Value
First layer height	0.35 mm
Other layer's height	0.40 mm
Fill density	20%
Fill pattern	Honeycomb
Top/bottom fill pattern	Rectilinear
Fill angle	45°
Speed for printing moves	
Perimeter	80mm/s
Small perimeter	45 mm/s
Infill	70 mm/s
Solid infill	30 mm/s
Support matter	60 mm/s
Speed for non-print moves:	
Travel	130 mm/s
First layer	20 mm/s
Specific temperature	180°C to 225°C
Extruder temperature : first layer	200°C
Extruder temperature: other layers	190°C
Heated Bed (MK 3) thickness	3 mm
Heated Bed temperature: first layer	60°C
Heated Bed temperature: other layers	55°C

The shafts were inserted into the gear's collars. The knurling operation was done to hold the gear with the shaft. The Allen grub screws were also used to hold the gear with the shaft rigidly. The input handle and bone holder were attached to the input shaft and the output shaft, respectively. The entire assembly was covered using Acrylic box with six ball bearings for providing frictionless rotation of shafts. The entire assembly is shown in figure 3.

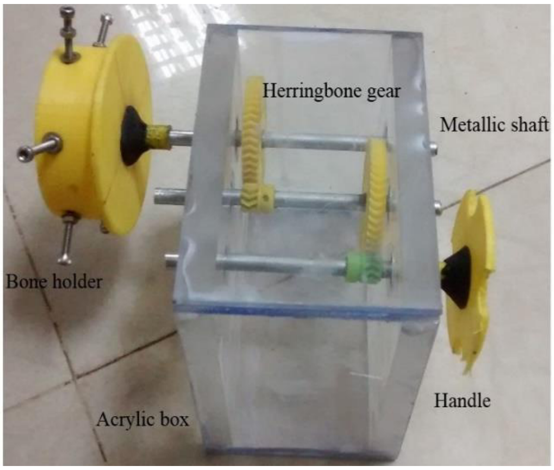

Fig. 3. Fixture box

4. Experiments

There are three types of bone in a knee joint. They are femur, tibia and patella. These bones are unsymmetrical and complex in shape. For measuring purpose, human bone phantom models were used. Experiments were done using the CMM for these phantom models. For initial experiments, femur alone was used for measurement and validation. O-inspect 442 Zeiss CMM was used for measurement. CALYPSO was the reference measuring software used by this CMM.

4.1. Measurement of a femur by CMM without fixture box

First experiment was done without fixture. The femur was placed over the glass pallet in the CMM. Initially, contact probe was used for the measurement. Since femur is having complex shape, probe slippage has occured while traversing over complex profiles. Then, Non-contact measurement was done using optical sensor in the same CMM. Measurement was done in four surface planes; $0^{\circ}, 90^{\circ}, 180^{\circ}$to 360°. Using optical sensor, only profiles of femur has been extracted for four planes. The CALYPSO software was used to export points to text file. The point cloud was imported in CAD software's for processing and modelling.

4.2. Measurement of a femur by CMM with fixture box

To get a profile and the surface features of a femur, both contact probe and non-contact optical sensors were used for measurement with fixture box as an aiding device in same plane. Measurements were made in four surface planes $0^{\circ}, 90^{\circ}, 180^{\circ}$to 360°. Markings were done over the bone for contact measurement as shown in figure 4. The fixture box was used to hold bone in respective angle. Different views are shown in figure 5 (a,b,c,d). Both contact and non-measurements were done to generate point cloud for each surface plane. CALYPSO was used as a measuring software for both the experiments. For one surface plane, it took almost 4 hours for both contact and non-contact measurement. For whole experiment, it took 16 hours of time for measurement.

Fig. 4. Femur phantom model with markings for contact measurement

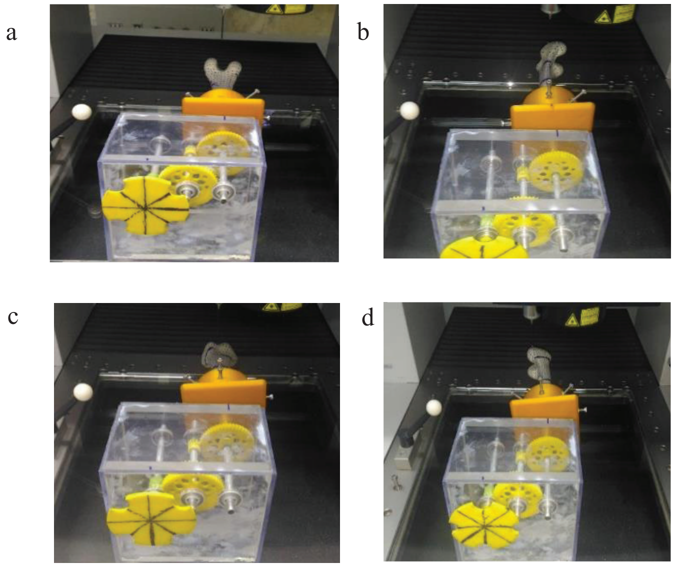

Fig. 5. Bone measurement at (a) 0º plane (b) 90º plane (c) 180º plane (d) 270º plane

5. Results and discussions

5.1. 3D model generated from measurement without fixture box

Two softwares, AutoCAD and Solidworks were used for modelling. The points extracted from measurements were plotted in AutoCAD using spline technique. All overlapping entities have been trimmed and deleted. Perfect boundary was created using spline and arc technique. All the points were aligned to the origin. Likewise, the boundaries were created for all views using the above procedure. All the views have been saved in separate drawing files. These views were imported in Solidworks and 3D model was generated using lofting and extruded cut techniques. The 3D model of the femur is shown in figure 6. The resultant 3D model generated from above experiment is having good profile but not having surface features.

Optical sensor are difficult to use in measuring the complex surface profiles. Again contact measurement was used for next level of experiments. If contact measurement has to be done that means, there is a need for suitable fixture box for holding the bone in fixed position. As probe imposes some mille-newton force over the object for taking co-ordinates, there is a requirement for holding device. Otherwise, probe damage may occur.

Fig. 6. 3D model from non-contact measurement

5.2. 3D model generated from measurement with fixture box

Filtering was done before importing to CAD software to remove data's other than XYZ co-ordinates. The scan to 3D add-in as the special feature in Solidworks was used to import point cloud files without writing any macros. This has mesh preparation wizard and surface wizard for creating 3D model.

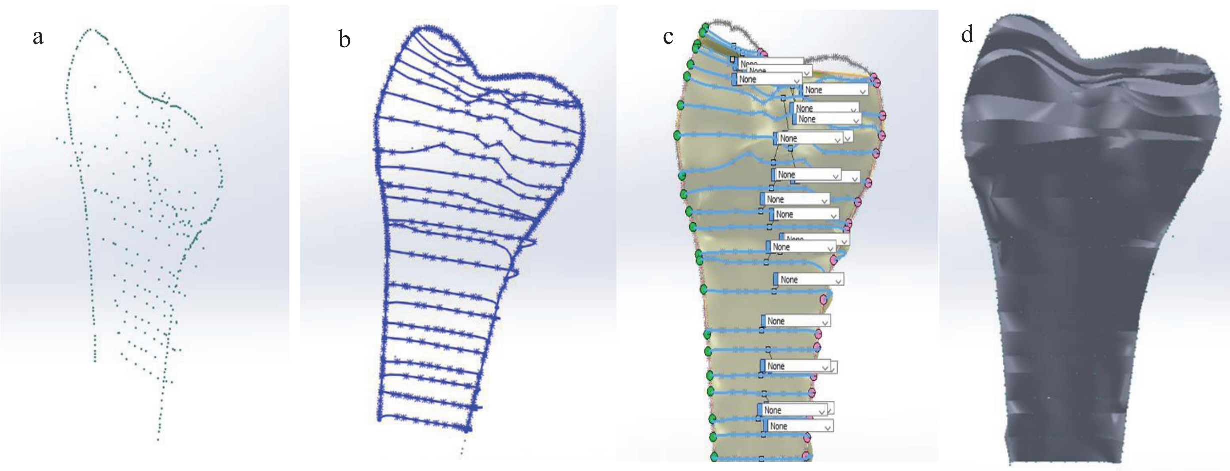

Fig. 7. (a) Femur point cloud (b) 3D splines (c) Boundary surface creation (d) Surface model at 0º

As measurements were made in top plane for all angles, the data points with respect to each angle was oriented to its original plane. Then, the points were converted into splines. Using boundary surface and lofting technique, surface models were generated. The steps of 3D modeling are shown in figure 7 (a, b, c, d). The model obtained using the contact measurements points has given both profile and surface features compared to the model obtained from non-contact measurement which has given only the profile. These models features were in close proximity to the features in original bone phantom model. The surface model of femur at different planes are shown in figure 8 (a,b,c).

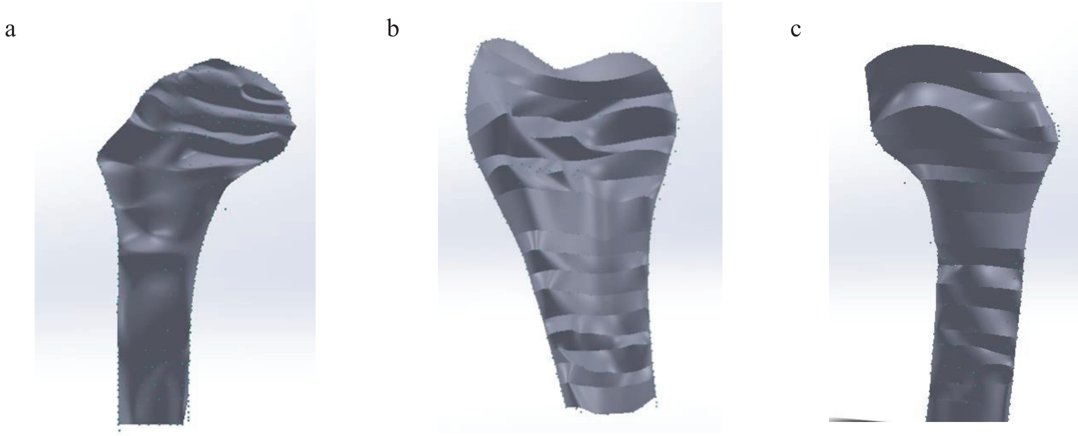

Fig. 8. Surface model of a femur (a) at 90º (b) at 180º (c) at 270º

6. Conclusions

Both contact and non-contact based CMM techniques were used to measure the complex profile of the femur bone with the support of fixture box. The fixture box was used as an aiding device to help the measurement of complex profiles and the results were clearly indicating that there is a necessity for using fixture box to extract the measurement data as an error free. Reverse engineering based FDM technique was used to fabricate the fixture box to hold and aid the measurement of the femur bone smoothly. A new systematic approach was designed and implemented to measure the complex profile of the bone and the results were presented.

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