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3D printed human humerus bone with proximal implant prototype for arthroplasty

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***Abstract*---**Human shoulder joints are susceptible to failure due to Osteonecrosis. It occurs at the humeral head region thereby collapsing it. For repair, resurfacing arthroplasty is used which involves reshaping of the humerus bone head and preparing an implant. But it is a tedious process to prepare the bone implant conventionally. This article presents developing prototype of a customized implant on human humerus bone that can act as an alternative to the conventional manufacturing of implants. 3D scanning technology is employed for acquisition of data of humerus bone in the form of point cloud which acts as an input for its modeling. Morphometric measurements of the bone are used to develop the resurfacing implant for proximal humerus. The humerus head is reshaped using Boolean operations and assembled with resurfacing implant. CATIA software is used for CAD modeling and related operations. Static structural analysis is performed on humerus bone and reshaped humerus bone with implant in ANSYS software to know its behaviour during different loading conditions. Fused Deposition Modeling technology has been used for 3D printing of humerus bone and its implant. However, the procedure for geometric modeling of such complex shape bone and its proximal implant has not been well defined. Work presents an approach for the development of CAD model of humerus bone with its

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implant and its prototype development using FDM based 3D printing. The prototypes of reshaped bone and resurfacing implant are then printed at 80% scaled downsize in Makerbot Replicator 2X 3D printer and later assembled. The methodology employed is useful for orthopaedic surgeons for humerus surgeries and bone prosthesis development providing an avenue to understand its anatomical structure and implant fixation in the proximal region of the humerus bone. Outcome of achieving a customized proximal implant in terms of shape and size using 3D scanning and 3D printing technologies is really interesting.

***Keywords*---**humerus bone, proximal implant, 3D printing, 3D scanning.

Introduction

Demand for personalized and tailored implants in orthopaedical surgeries and its offshoot is increasing. This has necessitated to know the geometrical form and fit of the human bone. Thus, it is vital to Therefore, it is vital to construct precise bone geometry swiftly (Stojkovic et al., 2010). Human humerus bone is one such bone which is lengthiest as well as complicated in shape and geometry. Ventral and dorsal views of a human humerus bone is exhibited in Figure 1.

Figure 1. Humerus bone - ventral and dorsal position

Each person has unique geometry of humerus bone. Multitude of parameters including environmental are responsible for the development of bones in humans viz. gender, age, ethnicity etc. Illustrating the geometry of this bone is a tough undertaking due its complex form and fit thereby making it a great task in modeling. Conventional CAD softwares do not offer much when it comes to modeling of such complex bone models. Precise modeling of bones is possible through reverse engineering technique (Popa et al., 2006; Lokanadham et al., 2013; Somesh et al., 2011). Bone model is generally prepared utilizing imaging techniques like CT and MRI scan which is then used for simulation. Nareliya & Kumar (2012) investigated mechanical behaviour of bones by retrieving finite element analysis of a bone joint from CT and MRI scans. Femur bone is modeled in softwares like Solidworks, CATIA and MIMICS. Masood et al. (2013) and Singh et al. (2013) reported that CAD model of bone developed based on measurements of bone and modeling is not so precise than the one developed through advanced imaging. Typical CAD software like CATIA has been used for modeling of bones based on scanned data obtained from laser scanning of physical bones. These softwares often provide an interface for accommodating various file formats like STL which is employed for 3D printing process. 3D printing softwares divide CAD model into layers; generate support structures and the necessary G-code for printing of the part (Chandramohan & Marimuthu, 2011).

Methodology

In this article, a methodology to develop complex biological parts precisely and quickly is presented. This can be useful to surgeons while performing similar surgeries on other body parts. Figure 2 displays the methodology adopted in this work. Human humerus bone of a male subject is used. Point cloud data is obtained by scanning the humerus bone using a Artec 3D scanner. Data is further utilized in CATIA software for building model of humerus bone. Morphometric measurements of humerus head are taken and the patient specific implant is developed. Based on the implant dimensions, the humerus bone is reshaped for proper fixing of implant. The static structural analysis is performed on humerus bone and reshaped bone with implant, to know the behaviour of the bones. Finally the reshaped humerus bone and implant 3D printed models are developed in 3D printer.

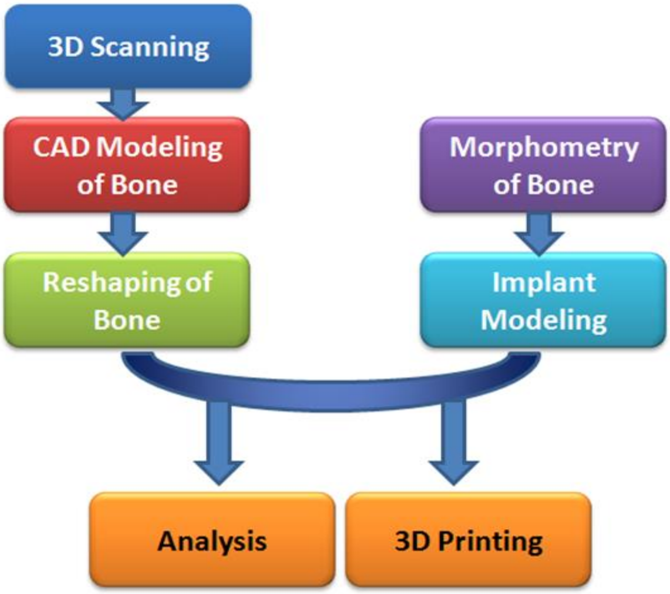


Figure 2. Methodology

3D scanning of bone

3D scanning is a typical reverse engineering technique for acquisition of model data using a scanner. 3D scan essentially ends up in providing output as a set of points in space called as the point cloud data (Sobota et al., 2009). 3D scanners are known for positioning themselves in space using reflective targets. Scanning software calculates its position when it is able to see atleast four targets of the positioned model which is then utilized for building its point cloud. Further these points are converted into usable form employing appropriate transformation methods (Hebert, 2001; Etxaniz et al., 2008). In this work, humerus bone of a male subject is scanned using a light scanning technique based Artec 3D scanner. Humerus bone is placed on table such that it receives projected light thereby securing the coordinates of multiple points at once. The 3D scanner is moved around the object to get the scan data at different angles. More number of scans makes the object complete and perfect.

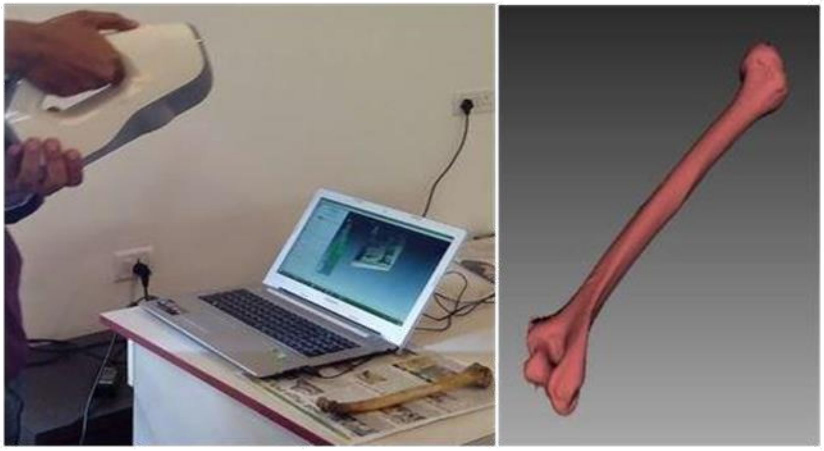


Figure 3. 3D scanning of humerus bone and its scanned model

Data processing

Generally an accurate and precise 3D scanner lead to an accurate model. Data points are linked to each other to form a network of triangles thereby resulting in a mesh. Bone surface is obtained by aligning the scans from different angles and combining it into one continuous mesh. Additional scanned data other than the humerus bone is then removed. Various tools are used to fill the unscanned part and smoothening the meshed model. Light reflected during the scanning process creates holes in model. Scanning process and the output model is depicted in Figure 3. Output model is saved as point cloud data in ASCII file format. Obtained data is utilized for developing CAD model of the bone in CATIA software.

CAD modeling of bone

CAD model of human humerus bone is obtained by generating a digital model of bone geometry from 3D scanned data. CATIA software is employed for this purpose. Figure 4 portrays the various stages in CAD modeling of bone and models obtained i.e., (a) point cloud model, (b) mesh model, (c) surface model and (d) solid model respectively. It utilises point cloud data as an input. First, surface model of bone is prepared using digitized shape editor module. Result obtained from reverse engineering i.e., 3D scanning is in digitized form. Digitized shape editor allows to perform operations on this data. Neighborhood value of 2.512 mm is employed for generating mesh using imported point cloud data.

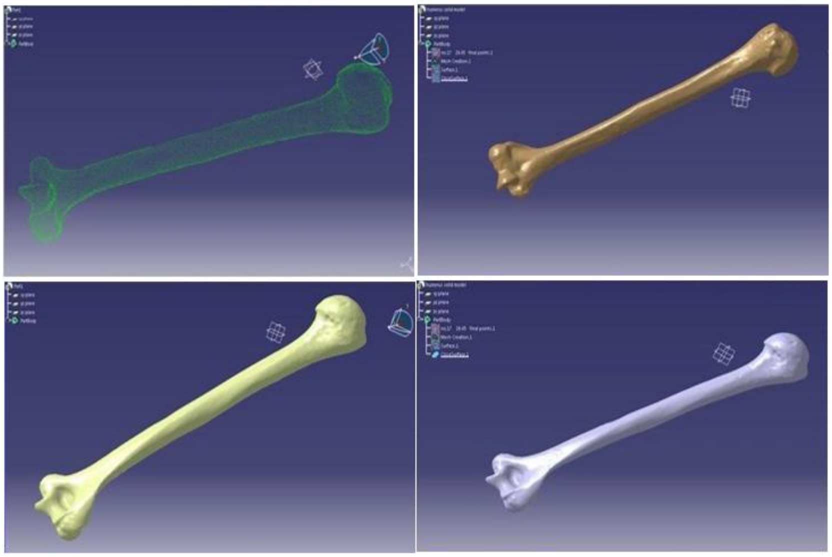


Figure 4. Humerus bone models (a) Point cloud (b) Mesh (c) Surface (d) Solid

Meshed model of bone obtained from 3D scanning depicts holes and irregular surface due to overlapping of cloud points. Removal of internal overlapping points is difficult due to closed boundary. Activate and remove tools are then used to select and remove particular area. Cloud points can be filtered using filter tool which also helps in decreasing additional points for bringing homogeneous distance between points. Corrupted triangles, duplicated triangles, non-manifold edges, etc. are analyzed using mesh cleaner tools. Meshed model is imported to surface reconstruction module. Surface model of bone is created using automatic creation for developing its solid model. Vaselinovic et al. (2011) and Naaji (2004) reported that creating a 3D solid model from 3D surface is tough if characteristic region methods are employed. CATIA software has best tools and options that aid in developing a solid model. Close surface tool is utilised in part design for generating the solid mode of bone.

Modeling of resurfacing implant

Modeling of implants is vital for humeral resurfacing arthroplasty. The implant dimensions depend on shape and dimensions of the head of humerus. Every arthroplasty surgery requires acquiring dimensions of the bone and selecting a proper implant for it. For this purpose, morphometric measurements of the bone are taken and the implant is developed for humeral resurfacing arthroplasty (Jensen, 2007).

Morphometry of humerus bone

Anatomical head sizing of humerus is crucial for development of the implant for resurfacing arthroplasty. Humeral head gauges are used to measure the head diameter and height which are the two prime parameters in design of an implant. Morphometric measurements indicate head diameter as 44 mm and height as 15 mm. The implant is designed in CATIA software using these values.

Implant modeling

Shoulder joint is a type of ball and socket joint. The socket is fixed and ball is rotatable. Similarly, the humerus head can rotate in scapula bone. Hence, the cap implant of humerus head is modeled like a half sphere using sketch tools and Boolean operations in part design workbench of CATIA software as shown in Figure 5. 3D model of implant cap is modeled with the outer diameter as 44 mm and inner diameter as 38 mm. The internal surface of the half sphere is modeled as flat. Apical flat on under surface of the implant allows better fit and intimate contact with humerus bone. Next stem of the implant is designed. The flat portion is selected as reference and 12 mm diameter of circle is drawn on it and extruded up to 30 mm by using pad. The sharp edge of the 3D printed stem, when implanted may damage the muscles of human hand and lead to severe pain during its movement in any direction. In order to overcome this, a taper of 45° is provided at the edge of the stem by using the groove tool. Taper prosthesis is believed to give the most similar trends as real bone and also for better mechanical press fit (Abdullah et al., 2010). The rotational stability of implant is an important parameter in designing of an implant. The cruciform shape can improve the rotational stability (Jensen, 2007). The cruciform shape is drawn and developed on implant stem by using the pocket tool. The sharp outer edge of the implant cap can damage the humerus bone after surgery, which may develop pain while moving the hand. The edge fillet is created with 0.5 mm radius at outer edges of implant cap. 3D model of the implant cap is shown in Figure 5.

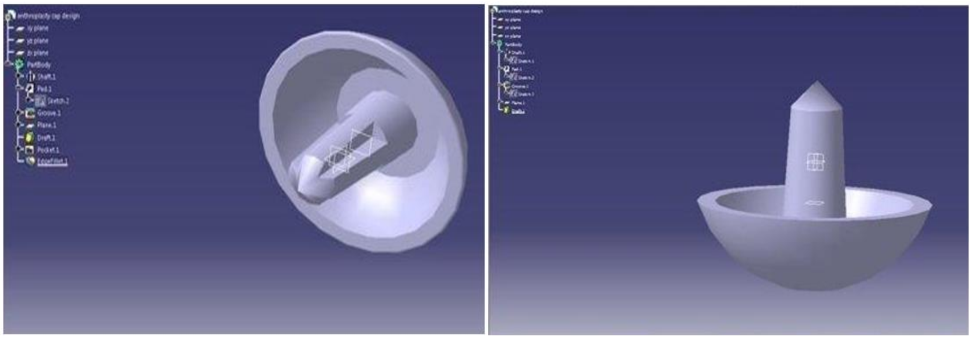


Figure 5. Views of modelled cap implant

Reshaping of humerus bone

Reshaping of the humerus bone at proximal head is needed for proper fixing of the implant during arthroplasty surgery. Boolean operations are used to develop the reshaped bone in CATIA software. In order to reshape the humerus bone, material removal & addition operations are performed. Material removal involves creation of a circle on a plane which is then used to remove material up to a depth of 15 mm from the surface of humerus head through pocket tool. One plane is created at this location. It is difficult to know the centre point of the irregular outer section after removing of material. The maximum lengths in X, Y directions are measured and the centre point is created on plane of irregular outer section. This point is chosen as a reference point of humerus bone head to develop half sphere surface model with 38 mm diameter & 16 mm height. The resurfacing implant has a flat portion on internal surface. The pocket option is used to remove the material up to 3 mm depth for developing the flat portion on humerus. The flat portion is created on spherical shape of humeral head. The flat surface of the head is selected as the reference and a V-bottom type of hole is developed with 12 mm diameter & 24 mm depth. A 30° taper is provided using draft tool. The implant stem is developed with cruciform shape. For proper fitting of the implant stem with the bone, similar cruciform shape is created by adding material to hole. The internal shape of hole is same as compared with external shape of the implant shape as shown in Figure 6.

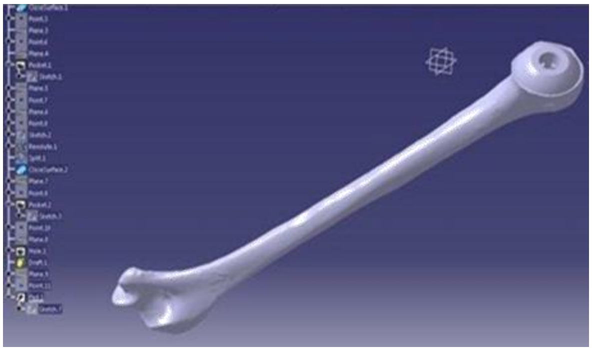


Figure 6 Reshaped humerus bone model

Assembly of reshaped bone with implant

The reshaped humerus bone and implant models are imported into assembly design workbench in CATIA software by using existing component tool. Manipulate position tool is used to place the models in required position. The coincidence tool is used to coincide the axes of the reshaped bone. Surface contact tool is used for developing the contact between the models of humerus bone and implant. Using the contact constraint tool, contact is made between the faces of both the models. The assembly process and assembled reshaped bone with implant are displayed in Figure 7.

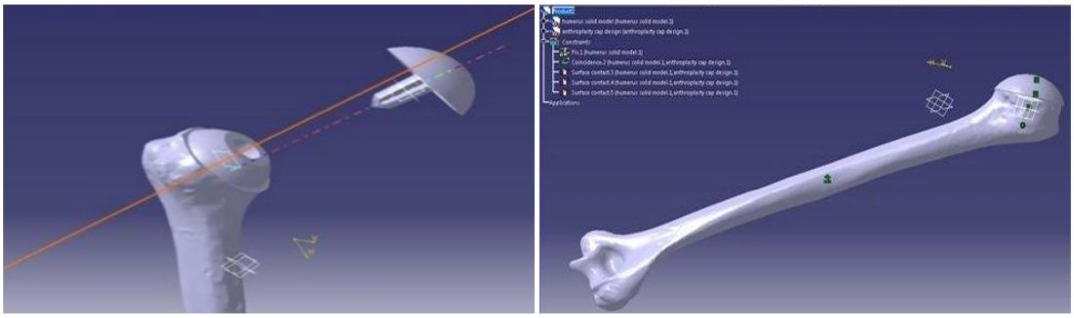


Figure 7 Assembled reshaped bone and implant

Analysis

Humerus bone

The .IGS file format file of humerus bone is imported in ANSYS software. The human humerus bone is a sort of composite material containing compact and spongy tissues. The material of the bone is anisotropic and not homogeneous. It is difficult to assign real properties to the bone. As reported by Shireesha et al., (2013), Zadpour (2006) and Sharma & Yadav (2014), material properties are assigned to solid humerus bone considering it as homogeneous and isotropic. The humerus bone material properties are presented in Table 1.

Table 1
Humerus bone material properties

Properties	Value
Young's modulus (GPa)	17.2
Poisson ratio	0.3
Bone density (kg/m^3)	1900

Humerus bone with implant

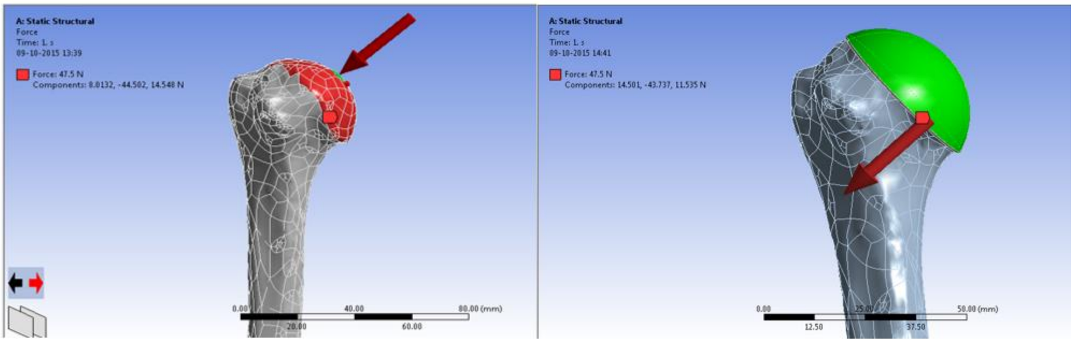
STP file of assembly of humerus bone with implant is imported in ANSYS software. The model has two different parts, one is reshaped humerus bone and other resurfacing implant. Both humerus bone and its implant have different material properties. Humerus bone properties as exhibited in Table 1 are assigned to the bone model. The resurfacing implants are manufactured commonly with titanium alloy i.e., Ti6Al4V. Hence material properties of Ti6Al4V as displayed in Table 2 are assigned to implant model.

Table 2
Ti-6Al-4V material properties

Properties	Value
Young's modulus (GPa)	115
Poisson ratio	0.3
Density (kg/m^3)	4430

Meshing, loading and boundary conditions

The triangular surface mesh is generated in ANSYS software. The distal region of humerus bone is selected as fixed support and load to be applied on humerus proximal region. Terrier (2010) reported that weight of arm of a human of 75 kg body weight is 37.5 N (5% of the body weight). Additional loads need to be applied on these models. The loads of 10 N, 30 N and 50 N are added to 37.5 N of arm weight are applied on both models as shown in Figure 8.



A: Static Structural
Force
Time: 1. s
09-10-2015 13:39
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Components: 8.0132, -44.502, 14.548 N

A: Static Structural
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09-10-2015 14:41
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Components: 14.501, -43.737, 11.535 N

Figure 8 Loading and boundary conditions on bone models

3D printing of reshaped humerus bone

3D printing is layer-by-layer additive process for fabricating prototypes. For prototype demonstration, Fused deposition modeling (FDM) based Makerbot Replicator 2X 3D printer and Makerware software is used in 3D printing of bone and implant. These are printed individually with ABS material. The STL file format of the reshaped humerus bone is given as an input in the software. The co-ordinates of humerus bone are not same as the co-ordinates of build platform and also the size of humerus bone is more than the build platform. Hence, it is required to move the model in proper orientation and also required to scale down. To obtain the maximum size of the model, the model is placed in an inclined position on the build platform. Due to build volume constraints, the model is scaled down to 80% by using the scaling option. The parameter settings in 3D printer are important to obtain a good quality prototype. The parameter values of layer height, shell thickness, number of shells, infill structure, infill percentage and build plate temperature are shown in Table 3.

Table 3
Print parameters

Layer height (mm)	Shell thickness (mm	Number of shells	Infill structure	% Infill	Build plate temperature (°C)
0.1	0.1	2	Hexagonal	20	120

These input parameters are used in 3D printing of humerus bone. Depending on the orientation of model, the supports are created and slicing is prepared. The humerus bone model is printed by laying material slices with hexagonal infill pattern. The horizontal lattice structure is useful to reduce the weight and save the material. Figure 9 shows the exact replica of 3D printed model of reshaped humerus bone.

Figure 9 3D printed prototype of humerus bone

3D printing of implant

STL file of implant is imported in the Makerware software. The orientation of implant on platform is important for accurate printing of the model shape. The cap of implant is placed over the platform and the stem is perpendicular to the build platform. Figure 9 shows the exact replica of 3D printed model of reshaped humerus bone.

Figure 10 3D printed prototype of implant

Results and Discussion

Analysis

Comparative analysis is performed on CAD model of humerus bone as well as humerus bone with implant for obtaining insights on their behaviour. Static analysis is performed in ANSYS software to know stress, strain and deformations in the models when different loads are applied. Stress, strain and deformation behaviour on humerus bone are depicted in Figure 11. Comparison of stress, strain and deformation on humerus bone and humerus bone with implant models is displayed in Figure 12. The stress developed in humerus bone with implant is more than humerus bone model. With loading of 87.5 N, the maximum stress of 79.7 MPa is observed in humerus bone with implant model. It is noted that the stress value is increasing when the load increases. The stress increasing rate is more in humerus bone with implant. More strain is observed in humerus bone with implant as compared to humerus bone. Strain values are increasing gradually with increase in the load. When load of 87.5 N is applied, the maximum strain of 5.7e-3 is observed in humerus bone with implant model. The stress and strains are higher in reshaped humerus bone with implant as compared to humerus bone. The reason for increased stress and strain values in bone with implant model is due to the dissimilarities in the densities of natural bone and the implant. Due to this higher density, the implant induces greater stress and strain in natural bone at contact region which has resulted in higher stress and strain values. The deformation is less in humerus bone with implant as compared to humerus bone. Maximum deformation is developed at proximal region of humerus bone. When load of 87.5 N is applied, maximum deformation of 4.6 mm is observed at proximal region of humerus bone.

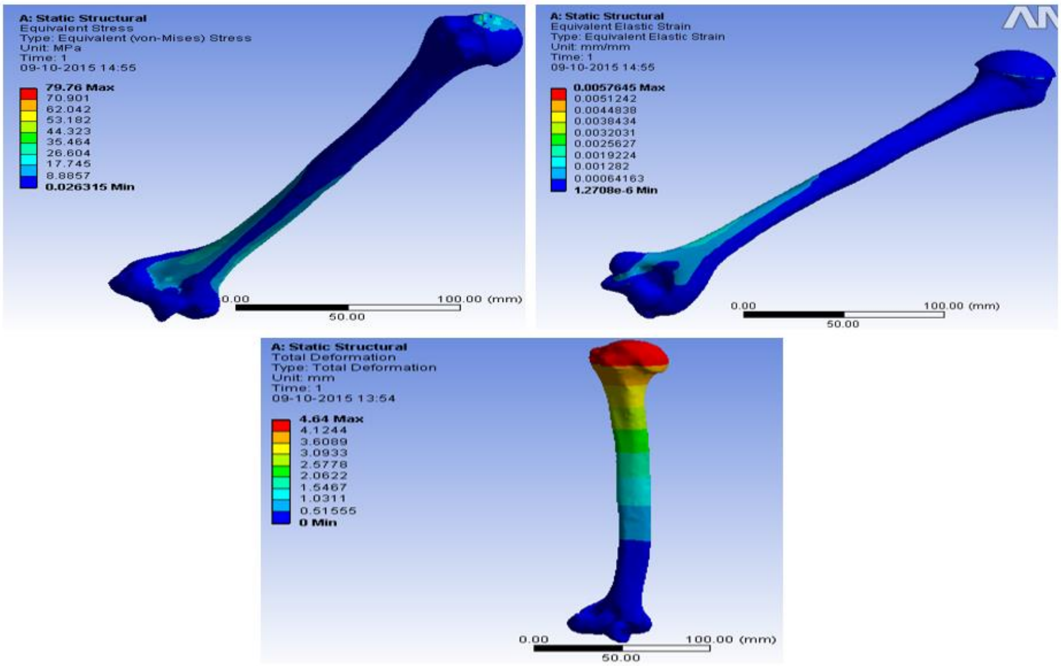

Figure 11 Stress, strain and deformation in humerus bone

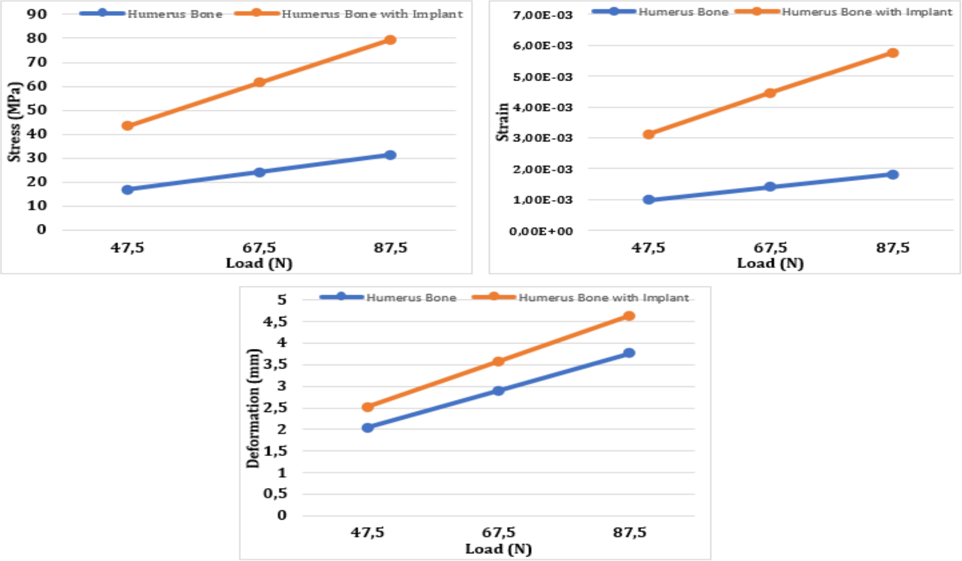

Figure 12 Comparison of stress, strain and deformation in humerus bone and humerus bone with implant models

3D printing and assembly of humerus bone and implant

3D printing of humerus bone and implant is performed on FDM Makerbot 3D printer using Acrylonitrile Butadiene Styrene (ABS) material. The 3D printed reshaped humerus bone model is scaled to 80% of its size due to machine build volume constraints. Hence, the implant model is also scaled down to 80% for achieving a perfect fit with the reshaped bone. Parameters used in printing of the reshaped humerus bone and implant are displayed in Table 3. 3D printing of reshaped humerus bone took 6 hr 21 min of time whereas that of cap implant took 51 minutes of time. Figure 13 shows views of 3D printed model of reshaped humerus bone in comparison to original bone.

Figure 13 Posterior, anterior and side view of 3D printed reshaped bone and humerus bone

The fixation of proximal implant with humerus bone in real time surgery is very important. The printed models of humerus bone and implant surfaces are cleaned and assembled together as shown in Figure 14. It is observed that the implant perfectly fits in to the reshaped bone.

Figure 14 Assembled 3D printed humerus bone with proximal implant prototype

Conclusion

A procedure for modeling of complex human humerus bone and its proximal implant has been discussed in detail. Point cloud data of human humerus bone is acquired through 3D scanning technology which is then used for modeling of humerus bone. Process for reshaping of the bone and preparation of the proximal implant is presented. The implant is modeled in CATIA software using the morphometric measurements of the humerus bone. The static analysis is performed on humerus bone and humerus bone with implant and the stress, strain and deformation results are compared. For the different loads applied, the humerus bone and bone with implant did exhibit similar mechanical behavior. 80% scaled down models of reshaped humerus bone and implant are printed in Makerbot 3D printer. Scaling down is due to the constraints in build specifications of the printer. Methodology presented and 3D printed models would provide orthopaedic surgeons a direct way of understanding the anatomical structure of humerus bone and implant fixation to proximal region of the humerus bone as well as an alternative for quick and customized implant fabrication. Methodology adopted can be beneficial to other surgeons who are into the implant surgeries.

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