Design and fabrication of dental implant prototypes using additive manufacturing

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Abstract- Tissue engineering possesses some unique qualities which can help to treat different orthopedics diseases and problems caused by any trauma or accident. Additive manufacturing technology has gained ground in printing scaffolds and implants compatible in the biological system using biomaterials. These can be used in surgical planning and for satisfactory accuracy. A patient specific implant design can be manufactured by this technology. This research deals with the challenge of designing the dental implant using open source available applications and a commercial three-dimensional printer. A methodology has been described to attain the accurate design in the designing applications and in also their printing. The steps involved the conversion of CT or MRI Digital Imaging and Communications in Medicine (DICOM) raw image data to a virtual 3D structure by Materialise Mimics 20.0. The 3D structure is meshed in the open source application via. Autodesk Meshmixer. Simplify 3D was used to transfer the data to be printed, to the 3D printer. The obtained prototypes of the dental implants were satisfactory in design and the same methodology can be used to build any dental implant with compatible biomaterial.

1. Introduction

3D printing also known as “Additive manufacturing” or “Rapid prototyping” deals with the manufacturing of 3D structure in a layer-by-layer manner. The AM technology is not new as it started in the 1980s. Many industries started testing the limits of this technology and resulted in its expansion. Now, AM has also gained its reach in the tissue engineering as it can produce very complex parts. This technology was referred as Rapid Prototyping in the beginning as it was able to rapidly manufacture varieties of industrial parts before their final release or for commercial purposes. The basic principle of this manufacturing technique is generating a physical prototype directly, using 3D CAD data. The whole model is produced in the layer-by-layer fashion, there is just little difference among other approaches in term of bonding and type of material used in the processes. The advantage in using this technology is that the wastage of material is very less and this helps also in the reduction of manufacturing cost. [1] Tissue engineering deals with the practice of combining different methods and materials, cells and biological, biomechanical and biophysical factors, which helps in the recovery or restoration of new or existing functional tissues. Tissue Engineering aims to manufacture tissues, organs and biological devices by 3D printing which can be extensively used in medical applications. Y.C. Fung founded tissue engineering in 1984, by a proposal submission to National Science Foundation for an Engineering Research Center named “Center for the Engineering of Living Tissues”. Tissues engineering has been producing scaffolds and allowing them to deliver cells or help in the restoration of cells or tissues. There were two tissue engineering approaches which were used. First, in which the scaffolding was used as a cell supporting device, in which the cells were seeded. The second approach involved the scaffold being used as a device which delivers a drug or increases the growth factor. This allows the gathering of cells at the scaffold placement site which results in the appearance of tissues throughout the matrix [2].
Dental Implant is the artificial replacement for the teeth or the fixture over the crowns for fixing. Dental Implants are mostly successful as these are being used for many years. Samy Tunchel et al. (2016) did a review clinical study on 3 years of follow-up in which a total number of 82 patients were enrolled, including 44 males and 38 females with age range from 26-67 years. 110 3DP/AM titanium dental implants were implanted. After 3 years with implantation, 6 implants failed out of 110 and 104 implants came out as successful surviving implants [3]. Different biomaterials can be used for the fabrication of the implants. Most generally used materials are Titanium, Titanium alloys and Zirconia. Shyh-Yuan et al. developed a zirconia dental implant using two-staged sintering process in the three-dimensional slurry printing system (3DSP). For forming binding burnout, the rigid green region was heated up to a temperature of 600° C and 1540° C respectively, for sintering the dental implant part of zirconia [5]. Wahyudin P. Syama’s review tells that the development of medical implants has three different characteristics: low volume, complexity and highly customized feature. Titanium and its alloy are most commonly used biomaterials because of their weight ratio, high strength, corrosion resistance, low density and mechanical strength [7]. Nanomaterials supported the event of technology not solely have higher characteristics than raw materials however even have distinctive characteristics of scaffolds and supports differentiation, adhesions of cell, and rapid increase in number of cells, and various studies have resulted into possibility of application for nanomaterials in hard tissue i.e. bone and dental tissue formations in orthopedics [6].

3D printing improves the precision and reduction in surgery time. According to a total of 2,889 patients were benefited because of 3D printed objects. Most printed frequently objects were surgical guides and anatomic models, 45% models were professional models. With the use of a desktop 3D Printer, cost can be reduced to a greater extent, for example laboratory and shipping expenses, and apart from that there is an increase in the surgical guides for better accuracy [8]. 3D printer could produce very complex or intricate structural geometries too that are not easily achievable by any milling machine nor other conventional machining processes, and when compared to other methods of manufacturing dental implant, this appeared to be the fastest method [9, 10].

1.1. Fused Deposition Modeling (FDM)
FDM is the type of an additive manufacturing technique in which a raw material is forced from the heated nozzle. The heated material then gets solidified over the bottom of the printer’s platform or bed. The platform is formed of hard plastic, metal or ceramic. The model is printed in form of layers from down to up direction. FDM has a mechanism which forms support(s), in cases of complex or hanging structures also known as print struts (support structure). Once the process is complete, the struts are removed from the model. The material in building these struts are same as the material used for the model but a different material can also be used. Some printers also have a second extruder performing the same task of support as in Fig. 1.

![Figure 1. Schematic Diagram of the FDM process](image)

2. Methodology and Material
The four steps used in the fabrication of the dental implant are shown in Fig. 2. The received data of CT or MRI is converted into an STL file i.e. stereolithographic file. The 3D structure obtained from the CT/MRI images is meshed in form of triangles.
Figure 2. Flow Diagram of the FDM process in current research.

According to Fig. 2, the received data of CT or MRI is converted into an STL file i.e. stereolithographic file. The 3D structure obtained from the CT/MRI images is meshed in form of triangles. This STL file is used in some designing application in order to make an accurate and customized design. The number of triangles in order to make the design printable, is adjusted. The design is then sliced into layers with is interpreted and understood by the 3D printer by the same application or any slicing application. The 3D printer takes the directions of the nozzle from the sliced data. Later, the completion of the process results into the manufacturing of a physical model. The same steps have been used in the manufacturing of the required dental implant in the present research work.

The material used in the printing of the dental implant prototype is PLA (Polylactic Acid). It is a thermoplastic polymer which is extracted from the resources like corn starch or sugarcane. The physical properties of PLA are Melt flow rate (g/10 min) of 4.3-2.4, Density (g/cm³) of 1.25, Haze of 2.2 and Yellowness index of 20-60. The mechanical properties are Tensile strength at yield (Mpa) of 53, Elongation at yield (%) of 10-100, Flexural modulus (Mpa) of 53. The thermal properties are HDT (ºC) of 40-45 and 135, GIT (ºC) of 55-56 and melting point of 120-170[4]. Characteristic of PLA is similar to polypropylene (PP), polyethylene (PE), or polystyrene (PS) and is also biodegradable.

Figure 3. CT Scan View in Mimics Medical 20

The first step was to take the CT Scan data and import it into the Materialise Mimics 20.0 software. As the images were imported in the software, the images from all three axis i.e. X, Y and Z have been shown in three small different dialog boxes. The images from these three axes are then analyzed to form a 3D view as presented in Fig. 3.
For the selection of maxilla and the mandible region, a mask had to be created. In creating the mask, the range had to be selected to define the type of tissues being hard or soft as shown in Fig. 4(a). In this case, the mask created was for the hard tissues, since maxilla and mandible are bones. Therefore, the predefined threshold was set to Bone (CT) and the minimum/maximum HU was varied to select the regions as in Fig. 4(b). Then the quality of design was chosen as optimal one. After calculating the mask region and setting the masking threshold, the mask was applied. A 3D structure of the selected threshold tissues was obtained. This 3D model was ready to be moved to the second step as a STL file.

The STL file was opened in the Autodesk Meshmixer for the second step of analyzing the problem, and printing the implant. According to the American Dental Association, Endosteal and Subperiosteal implants are the two types of implants which are safe. Endosteal implants are those that are directly implanted with surgery into the jawbone. The crown implant is attached over the post-individually, or on adventure. And the subperiosteal implants are those that consist of a metal frame fitted over the jawbone. Once the gum heals, then the dentist fixes the artificial replacement teeth over them. In the present research, Subperiosteal implant was to be designed over the maxilla with partial edentulism problem as shown in Fig. 5(a). The STL file of the maxilla and mandible was optimized in Meshmixer. The left teeth portion of the maxilla appeared appropriate but right side had partial edentulism or toothlessness problem, that looked improper and damaged.

Figure 4. (a) Mask Threshold and (b) Calculating the Mask Region

Figure 5. (a) 3D Model of CT Scan and (b) Mirrored 3D Model
So, for the repair, the symmetry was followed over the design in which the healthy region was mirrored over the damaged region. The left mirrored image was put over the right side to obtain a symmetrical form in the denture structure as shown in Fig. 5 (b). When compared with the mirrored model as shown in Fig. 6 (a) and Fig. 6 (b), the three teeth were selected from the mirrored model and were separated to an object. This object was then processed by some surface smoothing and filling. These were done to place the implanted teeth for a perfect fit. The third step involved the conversion of set parameters in UltimakerCura for Creality CR-3040S 3D Printer. The layer height was set to 0.1 mm, extrusion to 100%, printer speed to 60 mm/sec, temperature 200° C and nozzle diameter was 0.4 mm and bed length was 300*300*400 mm. Then the slicing was done automatically by the software according to the given parameters. The fourth step was to transfer the sliced design data to the 3D printer. It took 25-30 minutes in the printing of these dental implant prototype. The model was compared to the virtual design. The design resulted in high precision and a good fit to the printed maxilla.

3. Results and Discussion

The entire human body exhibits mirror symmetry known as bilateral symmetry. Meshing and creating a 3D structured STL file were not a much difficult task in the Autodesk Meshmixer. However, as compared to other paid applications the parameter changes resulted in very good quality and printing ease.

The above Fig. 7 (a) shows a particular patient’s problem of edentulism in which the defected part has been removed. For this, a bridge of teeth as a whole dental implant was created which has to be later fixed over the lower portion maxilla bone where the toothlessness is visible as in Fig. 7 (b). Dental surgery is required for the implantations to be made. CT Scan used was of a specific patient, therefore, the implant was also patient-specific (Reference: ’Dr. Aditya Gupta, 3rd Dimension Imaging, Civil Lines, Allahabad, U.P, India), and can be used only for that specific patient, whereas the same will vary from patient to patient as everyone’s anatomy and body is unique in itself. So, the
denture of crown teeth was placed and screwed so as to hold the denture at its place repairing the symmetry and the shape of the full denture.

*Note: The name of the patient has not been disclosed due to privacy reasons.*

4. Conclusion
The achieved highlights of this study were evaluation of CT data, exporting the implant as an STL file for 3D printing and meshing with the assistance of an open source applications such as Autodesk Meshmixer with Ultimaker Cura and Materialize Mimics Medical 20.0. The Dental Implant taken from a real case study had the problem of edentulism, which can be solved using a prototype of Dental Implant, printed from FDM 3D Printer with the compatible biomaterials. Generally, titanium, zirconia, and their alloys are used as the compatible biomaterials. Designing of the Implants was obtained from CT Scan, further taking it for meshing and then printing. This technique of printing can reduce the time of surgery for giving a better understanding of the real-time surgery operation over the human body and these free accessible applications can increase design accuracy with possible minimal expense.

From the above research, the points can be summed up:
- The open source meshing application provided a straightforward and economical approach to design a custom-built patient-specific implant prototype for defect restoration by a surgery based on the 3D maxilla and mandible model.
- The reflected model will make sure the form of the model to be very close as to the real part and will also make a right fit on the edge of the defect.
- Three manual steps were required, with choosing the anatomically symmetric points to generate the median plane and reflecting over the defective region, which seems easier and simpler than the former ways.

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