3D printing- creating a blueprint for the future of orthopedics: Current concept review and the road ahead!

Vaibhav Bagaria*, Rakesh Bhansali, Prashant Pawar

Sir HN Reliance Foundation Hospital, Mumbai, India

ARTICLE INFO

Article history:

Received 28 May 2018

Accepted 13 July 2018

Available online 23 July 2018

Keywords:

3D printing
Arthroplasty
Orthopedics
3DGraphy
Bio printing
Metal printing

ABSTRACT

The use of 3D printing in Orthopedics is set to transform the way surgeries are planned and executed. The development of X rays and later the CT scan and MRI enabled surgeons to understand the anatomy and condition better and helped plan surgeries on images obtained. 3DGraphy a term used for 3D printed orthopedic patient models and Jigs has gone a step further by providing surgeons with a physical copy of the patient's affected part that can not only be seen but also felt and moved around spatially. Similarly 3D printed Jigs are patient specific devices that are used to ensure optimal screw trajectory and implant placement with minimal exposure. While the use of 3D printed models and Jigs have now become routine, a similar revolution is happening in the field of designing and printing patient specific implants. Metal printing along with enhanced capability to print other biocompatible materials like PEEK and PLA is likely to improve the current implant manufacturing process. On the horizon is another interesting development related to this field – 3D Bio printing. Printing human tissues and organs is considered the final frontier and impressive strides have been made in printing bone graft substitutes and cartilage like material. This paper is an overview of all the current developments and the road ahead in this invigorating field.

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1. Introduction

3D printing was originally called “rapid prototyping”. It was primarily meant to create prototypes of industrial designs in a quick and inexpensive manner. The technology used was radically different from conventional methods, which were primarily casting or machining. The method used was additive manufacturing or layered manufacturing in which the material passed through an extruder, and its layers were deposited on top of each other in a pre designated manner and fused to form the final product. This three-dimensional product creation was computer control driven and hence very accurate. Currently there are various technologies available for additive manufacturing and these are collectively referred to as 3D printing in popular vernacular language.

In 1984 Charles Hull, the co founder of 3D systems, set the foundation for this industry, when he filed a patent for stereolithography fabrication system.¹ In this system of manufacturing the layers were added by curing the photopolymers with ultraviolet

light lasers. Charles Hull invented STL (Stereolithography) file format, introduced the concept of digital slicing and infill strategies and defined this particular printing process as a “system for generating three-dimensional objects by creating a cross sectional pattern of the object to be formed”. It was in the year 1988 that the technology most commonly used in 3D printing today – Fused Deposition Modeling (FDM) involving special extrusion of plastic material, was developed by Scott Crump and commercialized by Stratasys.² The patent for this technology expired in the year 2009, and led to an exponential growth in the field with numerous low cost machines being available to end user.

1.1. Various types of 3D printing technologies used for biomedical applications

There are three key types of rapid prototyping technologies used for biomedical applications: Extrusion (Nozzle), Laser, and Printer based (Fig. 1). Of these Nozzle based FDM, laser based SLA and SLS are more commonly used and are described below. Inkjet printing is multi coloured and used for educational and teaching purposes.

* Corresponding author. Dept Of Orthopedics, Sir HN Reliance Foundation Hospital, Mumbai, India.

E-mail address: Drbagaria@gmail.com (V. Bagaria).

Fig. 1. Various types of 3D printing.

Fig. 3. SLA process.

1.2. Nozzle based Fused Deposition Modeling (FDM)

In the FDM the product is manufactured by extrusion of tiny beads or streams of material that immediately harden post extrusion to form solid layers (Fig. 2). A filament of material usually thermoplastic or metal wire is fed into the extrusion nozzle head that heats up this filament and extrudes it out turning the process off and on depending on the design giving it the desired shape.³

1.3. Stereolithography (SLA)

This is a fast and very accurate technique to manufacture the desired products.⁴ The technology works by converting a special type of plastic typically a liquid photopolymer into a solid three-dimensional object in a layered fashion. The photopolymer is turned into semisolid with heat and it then hardens on contact. The whole process uses ultra violet laser triangulated on to surface using X and Y Scanning mirrors (Fig. 3).

1.4. Selective Laser sintering (SLS)

This type of printer can be used to print plastic, metals and ceramic. In this the laser draws the shape of the desired object fusing it together with upcoming layer when a second set of the

powder in desired shape is laid down by the laser (Fig. 4). It can be used to create extremely accurate representation as the accuracy is limited only by the laser and the fineness of the raw material powder.⁵ Selective Laser melting also called, as SLM is a subtype of SLS and used mainly for metal printing and implant manufacturing.

1.5. Materials available for biomedical use

The various materials that are used for 3D printing are listed in the table below.^{6–9} Of these for preparation of 3D Models and Jigs –

Fig. 2. FDM machine printing a 3DGraphy model of Acetabulum.

Fig. 4. SLS process.

ABS, Nylon and PLA is used. ABS is the most common, it's tough and non-toxic but it has high melting point and can have unpleasant fumes while printing. PLA is easy to print and is biodegradable however its strength degrades over time and the print has a rough texture. Nylon is tough and inexpensive, but has high temperature requirements. As for metal printing, various approved materials like 316 L, Ti4ALV 6 and Co – Cr alloys are used for printing. Bio plotters can print a variety of biocompatible materials ranging from natural to synthetic products common being Alginate, Chitosan, Collagen and PLA.

Type of Materials Used for 3D printing

1. Acrylonitrile butadiene styrene (ABS)
2. Poly Lactic Acid (PLA)
3. Nylon
4. Poly Vinyl Alcohol (PVA)
5. HDPE
6. T Glass/PETT
7. Metal filaments
8. Wood Filaments
9. Conductive Filaments
10. Carbon Fiber Mix
11. Flexible Filaments

1.6. Overview of 3D printing biosphere

For the biomedical use, 3D printing has 4 important uses – First and most common is the development of anatomically bio similar model based on imaging of the patient. These *3DGraphy* models help understand the anatomy and the condition better and surgeons can use it to simulate the intended intervention for a better execution. This is also called as *3DGraphy*.¹⁰ The next in chain is developing patient specific tools or jigs that help in executing surgery with more accuracy and in many cases with minimal invasive techniques. Implant printing has picked up over last one decade with reduction in cost of metal printers. Similarly 3D Bio printing is still in infancy although impressive strides have been made in the field of cartilage and bone graft substitute printing (Fig. 5).

2. 3D bio-models or 3DGraphy

3D printed anatomical models added a new dimension to the imaging evaluation of a patient's condition. A new term called as *3DGraphy* is often used to refer to these anatomical models and they offer a distinct advantage over available radiographic techniques such as X-rays and CT Scans. While the conventional radiographic modalities allowed the clinicians to find the anatomical anomalies and pathology, software based reconstructions added more information by extrapolating these into a 3rd spatial dimension. With advent of *3DGraphy*, clinicians could not only see but also feel and spatially manipulate them. These *3DGraphy* models allowed them to simulate the surgical intervention and plan inventory. Most papers on the subject reported a favorable outcome in terms of reduction in surgical time, improved operative accuracy and a better inventory management.^{11–14} (Table 1).

Fig. 5. 3D printing Biosphere – Various Applications of 3D printing in Medicine.

2.1. Creating 3D printable files

The first challenge with the printing of these *3DGraphy* model was the conversion of medical data files into 3D printable formats. With standardization of protocols like one described by the author – MRCP: Medical rapid Prototyping Computer Tomography Protocol, the process became more smooth lined and accessible.¹⁵ The availability of many free and paid software ensured that even surgeons with working knowledge of computers can now create a 3D printable file from their own desktop. The commonest softwares used are Osirix (free and paid versions available); Slicer (free version) and MIMICS (paid version by Materialise Inc). Typical Flowchart of the process is as follows:

Table 1

The list of common areas for which the 3DGraphy has been useful.

Common Orthopedic conditions for which 3DGraphy Models are ordered
Peri articular fractures Like Tibial Condyle; Plafond and those around Elbow
Acetabular fractures
Complex Hip arthroplasty with acetabular defects
Sacroiliac Fixations
Complex Spinal Deformity
Maxillofacial fractures and Deformity
Pediatric Deformity
Osteotomy planning

2.2. Simulating on 3D bio-models

Depending on the area of interest, the type of material is chosen. For most Orthopedic simulations, ABS is preferred. The surgeons can ream, pass screws and pre-contour the plates and implants. It also gives residents and fellows to practice difficult cases (Figs. 6 and 7). The same model can be sterilized and kept on the operating table with simulation drawn for immediate intra operative referencing (Fig. 8). All this ensures an improved surgical outcome with improved fracture reduction accuracy and correct implant positioning apart from reducing the overall surgical time.

3. 3D tools: jigs & trajectory guides

Patient specific cutting blocks had been already popularized by some Knee replacement manufacturing companies. While most companies have some form of this particular instrumentation system in their armamentarium, Visionaire by Smith Nephew and Signature by Biomet are the most popular. The cutting blocks for tibia and femur are 3D printed in Nylon and the input is either MRI and CT that are processed using the proprietary software developed by Materialise Company.

Fig. 6. 3DGraphy Model of an acetabulum with fracture of posterior wall and posterior column.

Fig. 7. Templating and pre-contouring a Recon plate for acetabular fracture (on opposite non fractured side).

The use of patient specific jigs in complex trauma started a bit late but is now gaining rapid popularity. It has borrowed heavily from dental applications where these are used to print trajectory guides for dental implantation. Once again the leader in providing the back end service was Materialise, with time however multiple companies like Blue sky are increasingly adopting this technology. Other inexpensive but technologically demanding way is to create negative mold using slicer and/or blender software.

These patient specific jigs allow surgeons to perform surgery with small incision and in many cases in a percutaneous fashion. The jigs are made in ABS and can be customized as per the intended implant usage. Of the most versatile uses, the one involving use of these jigs to fix anterior column of acetabulum through a posterior mini open approach and Jigs for high tibial osteotomy have become very popular.^{16–18}

4. 3D metal printing & implant manufacturing

4.1. Basics

Selective Laser Melting (SLM) and Direct Metal Laser Sintering (DMLS) are the most common metal 3D printing technologies. Both of these use a laser to scan and then selectively fuse/melt the metal powder particles that bind to each other in a layered fashion. The raw materials for both come as powder or in a granular form. The major difference between the two technologies is their ability to print different materials based on the individual technologies. While SLM can print only a single metal, SMLS allows printing various alloys as well as the powder with variable melting points can also fuse at molecular level in this particular technology. The layer height for metal 3D printing varies between 20 and 50 μm and depends on the raw material properties like flow ability, particle size, shape and distribution. The modern metal patterns have an amazing accuracy of less than 0.1 mm making them ideal for high precision press fit orthopedic scenarios (Fig. 9). One of the key highlights here is the extremely small degree of wastage of raw material typically less than 5%.^{19–21}

Metals suitable for printing: Both SLM And DMLS can print a variety of metal and their alloys including Stainless steel, Aluminum and its alloys, Titanium and alloy, Cobalt Chrome and Nickel alloy -Inconel. Even precious metals like Gold, Silver, Platinum and Palladium can be printed; their use being limited to Jewelry designing and manufacturing. The cost of the raw material metal powder depends on the alloy and as a benchmark for 316 L medical grade steel is between 300 and 400 USD per Kg.

Fig. 8. Acetabular reaming and templating acetabular socket on 3DGraphy model.

4.2. Post processing

In order to improve mechanical properties, Osseo integration and tribology, various post processing techniques may be adopted. These include removal of the loose powder and support structures, thermal annealing, surface blasting, CNC machining, micro machining and polishing. One or more of the above can be adopted depending on the nature of requirement, for e g: A wedge to fill in the acetabular defect may have rough surface finish with an Osseo-integrative blast coating and on the other hand a bearing surface may require thermal annealing and polishing to reduce the wear.

5. Bio-printing

5.1. Basics

3D printing gives a unique versatility by enabling combination of various cells, growth factor and supporting material in sophisticated ways in a desired spatial orientation to create a biological tissue. The bio printing materials are now available in several biocompatible and bio-enabler forms and are typically called as bio inks. There is tremendous interest and explosion in popularity of research involving this in the field of regenerative medicine. In orthopedics two tissues are readily amenable to 3D printing - the cartilages and the bone.²²

5.2. Cartilage printing

Cartilage disorders today form one of the biggest burdens of treating orthopedic surgeons. For large cartilage defect – autologous chondrocyte implantation: a 2-stage procedure is considered gold standard. The success however depends on the quality and

quantity of the patient's autologous cells. Given the fact that the cartilage is immune-privileged and that the heterologous cells can be used in grafting, human derived induced pluripotent cell lines (iPSC) are increasingly being investigated for their potential use in cartilage 3D printing. For support material Nano fibrillated Cellulose (NFC) compositions with either Alginate (A) or hyaluronic acid (HA) hydrogels are being tested. NFC has shown to provide necessary structural and mechanical support conducive for physiological mimetic environment.^{23–25}

Bone Printing: Complex trauma, non-unions, tumors and congenital anomalies often result in situation where there is need of extraneous source of bone other than autologous bone grafts. The materials that are commonly used include Hydroxy apatite and Tri Calcium Phosphate (TCP). The use with growth factors like Bone morphogenic protein (BMP) has enhanced their properties.^{26,27}

5.3. The road travelled and the road ahead

3D printing is set to revolutionize many aspects of the way orthopedics is currently practiced. While the very basic printing of anatomical models also known as 3DGraphy has nearly become mainstream, use of patient specific jigs are being increasingly used for complex situations. With falling prices of metal printing, patient specific implants are likely to be norm for revision surgeries and critical bone defects. Tissue printing like the cartilage and bone printing are at the moment in realm of research and further developments will be keenly watched not only in orthopedics but by the entire regenerative medicine field.

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