3D Printing Technologies for Medical Applications: Review of 3D printing customized implants and prostheses

Brent Weber

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Brent Weber
Fundamentals of Computational Intelligence
Flinders University

Webe0064@flinders.edu.au

Abstract

3D printing technology is continuing to evolve rapidly with many applications in the medical industry, including in the production of customized implants and prostheses. The ability to produce a 3D printed implant or prosthesis, in place of a handmade version, has significant time, cost, convenience and quality benefits. The history, technology behind the process, benefits, limitations and future directions will be investigated in this paper.

1 Introduction

Three-dimensional (3D) printing, also referred to as additive manufacturing, is a layered manufacturing process, in which a physical model is created by overlapping layers of material (Yan et al., 2018). These materials can include metals, ceramics, plastics, liquids, powders and living cells (Ventola, 2014). The process uses digital information as the basis for producing the physical model, and as such, is heavily reliant on computer technology.

Reduced manufacturing costs of 3D printers and improvements in their speed and accuracy have resulted in a rapid expansion of the 3D printing industry in recent times (Yan et al., 2018). It is still a relatively new technology however, and one of the most exciting applications is within the medical field. Some of these applications include: personalized pre-operative planning; improving medical education; bioprinting skin and organs; and the production of customized implants and prostheses (Aimar, Palermo, & Innocenti, 2019).

This paper will investigate the history, technology behind the process, benefits, limitations and future directions of using 3D printing technologies to create customized implants and prostheses.

2 History of 3D printing technologies

3D printing was invented in the early 1980s by Charles Hull which he gave the term printing Stereolithography (STL) (Schubert, van Langeveld, & Donoso, 2014). He established 3D Systems in 1986 and created the .STL file format, which was the link between computer aided software (CAD) and the 3D printer, known as a "Stereolithography apparatus" at the time (Gross, Erkal, Lockwood, Chen, & Spence, 2014). These files contain information such as the thickness of layers, texture, colour, and shape of the object to be printed, which have been interpreted from the CAD data (Schubert et al., 2014).

Fused deposition modeling (FDM), a relatively cost-effective and simple additive manufacturing technique, was developed by Scott Crump at Stratasys in 1990. The first apparatus termed "3D printer" was patented by MIT professors Michael Cima and Emanuel Sachs in 1993 (Gross et al., 2014). Since then, 3D printers for commercial applications have been developed by a number of other companies.

3 3D printing technology for customized implant and prosthesis production

There are a number of key steps to be followed in the process of producing a printed customized implant or prosthetic. These include choosing the target area, creating a 3D digital model, enhancing the digital file to optimize it for the intended use, and selecting the 3D printer and the materials it will use (Aimar et al., 2019).

The first of these steps is to select the anatomical area of interest and acquire an image of that area. This can be done by utilizing a number of technologies including computerized tomography (CT), x-rays, and magnetic resonance imaging (MRI) (Gross et al., 2014). These radiographic images are in two-dimensional (2D) format and can be converted to a 3D digital model using CAD software (Ventola, 2014). Modifications to the design model can be made at this stage which is then converted to a .STL file which is a format optimized for data transfer between the CAD software and 3D printer (Gross et al., 2014). The .STL file uses triangulated sections to store information about the surface of the 3D model, defining the coordinates of the vertices in a text file (Gross et al., 2014). The file is then “sliced” into horizontal cross sections via software in the 3D printer. These sections are printed to build the prostheses as a series of layers, from the base layer to the top, using the provided raw materials (Aimar et al., 2019).

There are many different methods of 3D printing, each with their own advantages and disadvantages. These use a variety of materials and printer technologies. Selective laser sintering (SLS) and Fused Deposition Modeling (FDM) are 3D printer technologies which are most commonly used in creating customized implants and prostheses(Ventola,2014).

An SLS printer can be used to create delicate and detailed 3D metal, ceramic and plastic objects from powdered material. A laser is used to fuse the powder in the shape of the object one layer at a time (Ventola, 2014).

An FDM printer releases beads of heated plastic from a printhead which is similar to an inkjet printer. The object is built in thin layers which bond together and harden as the plastic cools. FDM printers can use a variety of plastics and are generally more common and less expensive than SLS printers (Ventola, 2014).

4 Benefits of 3D printing customized implants and prostheses

One of the earliest uses of 3D printing in medical applications was for the production of dental implants and custom prosthetics, dating back to the early 2000s (Ventola, 2014). As such, the use of this technology in this application can be considered relatively mature when compared to other applications such as bioprinting.

There is a large variety of custom implants and prosthetics that can be manufactured using 3D printing. Some of these include: implants to replace bone such as rib, jaw, spine and skull; joint replacement implants for knees and hips; and prosthetic limbs such as hands and feet (Carlota, 2019). These can be constructed from a variety of materials including metals, polymers, ceramics or combinations of these (Yan et al., 2018).

There are a number of benefits that 3D printing offers in place of traditional methods used to construct customized implants and prostheses. One of the most important is the ability to produce items that are tailor made to the patient, both in terms of anatomy and pathology (Jamroz, Szafraniec, Kurek, & Jachowicz, 2018). Replacement prosthetic limbs, for example, are able to fit better, resulting in improved comfort and functionality.

Another benefit is the ability to create complex structures with a high degree of accuracy. This has implications for orthopedic implants, where previously, surgeons had to physically modify the implant or surrounding bone to achieve the desired fit (Ventola, 2014). This allows for better recovery due to reduced trauma to the body, as well as minimizing surgery time.

The ability to produce items cost-effectively is another important benefit that 3D printing offers. The setup costs compared to traditional manufacturing are much less which is ideal for making one-off, custom made implants and prosthetics (Schubert et al., 2014). The production costs for smaller and low volume items are also reduced making it useful for this application (Ventola, 2014).

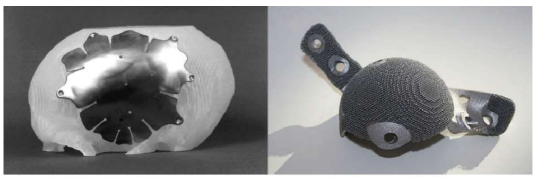
Traditionally, implants and prosthetics are fabricated using machining technology. Casts of defects may need to be made and the manufactured item may also require milling for a better fit. All these processes are time intensive. 3D printing can be done in real-time resulting in shorter production cycles (Yan et al., 2018).

5 Limitations and future directions

As discussed earlier, the use of 3D printing to produce customized implants and prostheses can be considered to be relatively mature. However as with all technology, there are always improvements which can be made for the future.

One of the main limitations that currently exists is in the type of materials used to create the implant or prosthetic. An example of this is that many of the metals used have a high elastic modulus, meaning they are highly resistant to elastic deformation. This can result in an elastic mismatch between the implant and the bone it is grafted to, leading to potential bone stress problems (Yan et al., 2018). Research and development of alternative materials is an important direction for the future of 3D printing in this application. New materials can also be developed to simplify the manufacturing process. An example of this is the use of stereolithographic resin (Fig. 1(a)), which has been used to create a model of a cranial defect from which a custom cranial titanium (Ti) implant could then be manufactured (Yan et al., 2018).

Another future improvement is in the technology of the 3D printing process itself. For example, SLM Solutions in Germany have used a selective laser melting (SLM) process to create a high-strength and lightweight Ti hip implant (Fig. 1(b)) for an Australian patient. This and future 3D printing technologies have the potential to produce higher quality implants with lasting health and cost benefits for both patients and health professionals.



(a) (b)

Fig. 1. (a) Stereolithographic resin model of a full skull with a custom Ti plate in place; (b) hip implant fabricated by SLM Solutions in Germany (Yan et al., 2018).

6 Conclusion

3D printing is still a relatively new manufacturing method which has expanded rapidly in recent times and will continue to do so as new technologies emerge (Yan et al., 2018). The use of computer technology underpins the process as digital information is used in each step of creating the physical model.

The use of 3D printing to create customized implants and prostheses is one of the earlier uses of this technology for medical applications (Ventola, 2014). It continues to provide a number of benefits including the ability to produce complex and highly accurate items, that can be tailor made to the recipient (Jamroz et al., 2018). Other benefits include low production costs and fast turnaround times (Yan et al., 2018).

Current limitations can arise from incompatibilities between the material of the 3D printed objects and the human tissue they are connected to. The research and development of new materials and printing technologies is important for the mitigation of these issues, and to further enhance the cost, quality and efficiency benefits that 3D printing customized implants and protheses provides.

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