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Three dimensional (3D) printing in Orthopaedics: Scope of application and future perspectives

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Abstract

Three dimensional (3D) printing also known as additive manufacturing has the potential to change the paradigm of Orthopaedic practice. Modern times have witnessed exponential growth in 3D-printing technology as well as its uses. A wide spectrum of printers are now available, ranging from the desktop printer to high end manufacturing units. The ability to use a plethora of materials and create almost limitless geometric shapes with varying surface topography makes this method of production highly appealing. Certain inherent advantages include easy customizability, small production runs, less wastage of material, smaller footprint. Challenges such as lack of data, absence of established government regulations and cost considerations remain, but one can expect these to be overcome as the economy of scale plays out and the medical fraternity becomes more accommodating of the new technology.

Keywords: Three dimensional printing, Recent Advances, Arthroplasty, Spine, Tumor Implants

Three dimensional (3D) printing is also known as Additive Manufacturing (AM) or Rapid Prototyping. It involves the creation of objects in a sequential layering fashion which differs from the traditional 'subtractive manufacturing' where a large block of raw material is gradually broken down or processed to create the desired product. [1-3] Recent times have witnessed an explosive growth of 3D printing technology especially with the development of desktop printers. Certain inherent advantages of this technology are easy prototyping, allows for small batch production, real-time modification, smaller footprint and customization of product. [3]

Evolution and Workflow

The first report on rapid prototyping was published by Hideo Kodama in 1981. [1,4] Later in 1984, Charles Hull developed the novel STL format which allows for the rendering of three dimensional objects by a computer and the subsequent printing of the object by sequential layering. He is widely considered the inventor of 3D printing. [1,5] The first modern 3D printers were introduced in 1988 by Stratasys company which have later evolved to the desktop printer which was created in 2001. The first step in the workflow requires the creation of an STL (Standard Triangle or Standard Tessellation Language) file. This can be created de novo using a computer, by scanning any existing object by a 3D scanner, from a 3D image library or from the DICOM (Digital Imaging and Communications in Medicine) images. The data from the above sources are modelled into an STL file. This process is called as tessellation, where the surface of the object is defined by multiple identical geometric shapes usually polygons. The more the number of polygons, higher is the resolution and better the accuracy.

The next step involves segmentation where the STL file is sliced into multiple layers. The number of layers is directly proportional to the resolution and the thickness of each layer is inversely proportional. [1] This layered STL file is known as a G-CODE. Essentially the G-CODE allows the printer to convert the digital data within the STL file into a sequence of two dimensional cross-sections. The last stage involves printing, where the 3D printer successively fuses together each layer to generate the final product. [1,3,5]

Types of 3D printing technologies [1,2]

Fused Deposition Modelling (FDM)

This is the most widely used technique in which the material is extruded through a nozzle where it gets heated and is deposited in layers onto the plate or platform. The movement of the nozzle allows incorporation of different shapes and designs. The material is deposited onto a platform that gradually lowers. Typically

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plastic polymers such as polylactic acid (PLA), acrylonitrile butadiene styrene (ABS) are used with this type of technology. This is a low cost technology but generally lacks accuracy and speed.

Stereolithography (SLA)

The process works by vat photopolymerization where a container of liquid photopolymer resin is converted by the action of visible or ultraviolet light into semisolid form that hardens on contact. Only a few such resins are available for use. Highly accurate but lacks strength and durability.

Selective Laser Sintering (SLS)

The process is known as Powder bed fusion where a solid object is created from powdered material by heating using high powered lasers. Can be used to print glass, ceramics and metal products including titanium, cobalt-chromium objects. Subtypes include Direct Metal Laser Sintering (DMLS), Selective Heat Sintering (SHS), and Electron Beam Melting (EBM)

Bioprinting

Work similar to FDM printers. The material deposited may include only cells or an additional compatible medium such as collagen which serves as an extracellular matrix.

Budget level or entry level printers are usually FDM printers, whereas professional or industrial ones utilize SLS or SLA technology.

Orthopaedic Applications

Anatomic models

3D printed models of various skeletal structures can be created by computer aided design (CAD), image library or from the DICOM data. They can be valuable adjuncts for teaching trainee doctors, for preoperative planning of challenging cases and for patient education. [3] One need not depend on two dimensional images such as those available with conventional imaging studies for planning difficult surgeries. Such models give excellent orientation of anatomy and allow for modification of surgical technique/implant as per the requirement of the case. [6]

Surgeons can also prebend plates or make other necessary modifications on the anatomical model and save time in the operation theatre. True size models allow surgeon to get a proprioceptive feel of the bony anatomy which allows for better rehearsal of surgical procedures. With improvements in technology, accurate rendering of pathological bone quality such as osteoporotic bone is possible. This is vital for patient education which also improves compliance. [3, 7]

Prosthetics

With the advent of desktop 3D printers, amputees can print their own prosthetics. This offers a low-cost and accessible solution to conventional prosthetic manufacturing with the added benefit of customization. [1,3, 8] STL files encoding prosthetic designs are available online and can be used to develop functional prostheses at a fraction of the cost compared to conventional professional prosthetics. [1] By combining 3D printing with myoelectric technology one can create customized robotic upper limb prosthetics. Manufacturing fully customizable prosthetics by the conventional processes is usually more expensive as well as time consuming. It is important to note that open source designs are not regulated or extensively tested unlike established traditional prosthetics.

Orthotics

Majority of the commercially available braces are in a limited number of sizes which are designed to fit a large number of the population. However, with the advances in 3D printing, user centric orthotics can be created. This allows to accommodate the unique biomechanical metrics of each individual, that can improve the comfort, ease of use and the overall results. Also modern 3D printed orthoses are waterproof. [1,3]

A pilot study conducted by Chen et al. showed that results of 3D printed short arm casts were comparable to contemporary immobilization techniques for distal radius fractures. [9]

Patient Specific Instrumentation

3D Printed cutting jigs or guides which are customized for the patient by using DICOM images pertaining to the patient's anatomy have the potential to facilitate surgery by decreasing the operative time, improving accuracy of the surgical procedure, reduced radiation exposure and preventing iatrogenic injury to adjacent structures.

These are especially suitable for complex deformity corrections that require intensive preoperative planning. [2,3] Studies conducted using 3D printed guides for distal radius malunion have reported good results. [10] Customized cutting guides are also increasingly being used for arthroplasty procedures. Theoretically using a patient specific guide should lead to better postoperative alignment with reduced surgical time. However, the results are mixed and it remains unclear whether they definitively improve clinical outcomes. [11,12] Even with the use of specific cutting guides, deformity corrections remain technically demanding procedures. Accuracy of correction is also influenced by proper positioning of the guide, depth of the osteotomy cut and other technical factors unrelated to the cutting guide. Specific jigs are also useful in spine surgeries by allowing accurate pedicle screw placement, reducing risk of iatrogenic injury, decreasing procedure time and radiation exposure.

3D printed patient specific (PS) blocks are an alternative to navigation system and conventional systems in total knee arthroplasty (TKA). However the increasing acceptance and utilization of robotic systems which circumvent the additional cost of making individual cutting guides, the role of PSI in knee arthroplasty may decline in the future. Custom instrumentation doesn't have to be disposable and patient specific, it can also be manufactured to be surgeon specific. Those who require specialized instruments for personalized surgical techniques can manufacture them by 3D-printing instead of the conventional methods. [2]

Arthroplasty Implants

Three dimensional printing of titanium arthroplasty implants can enable modification of porosity to optimize osseous ingrowth. Implant companies have started using this technology for their primary as well as revision products. One such example of titanium 3D-printed implant is the REDAPT revision acetabular cup developed by Smith & Nephew, London, United Kingdom. [2] Recent studies have demonstrated good results of 3D printed triflange acetabular implants in patients with acetabular defects. [13-15]

Spine Implants

High performance plastic polymers like poly-ethyl-ether-ketone (PEEK) and metals like titanium can be 3D printed as interbody cages for use in spine surgeries. Modifications of shape, rigidity and material composition by additive manufacturing has led to development of innovative cage prototypes for spine surgery. [2] It is possible to closely mimic the compressive modulus of native bone using 3D-printed fusion cages with certain studies reporting fusion rates of close to 99% at 1 year. [16] A systematic review conducted by Burnard et al. reported improved clinical outcomes on comparing 3D-printed with off the shelf implants. But the authors also warn of significant preoperative work, additional financial burden and intensive coordination that is needed to manufacture them. [17]

Patient Specific (Custom) implants

The development of patient specific custom implants can revolutionize patient care. It provides a personalized fit, that accounts for the patient's native anatomy and pathological condition that a conventional mass produced implant cannot. [3] It is possible to produce implants with open porous structure and with reduced modulus of elasticity that closely matches that of the bone. [2, 18] Implants with variable stiffness and structural properties which help to reduce stress shielding of the bone can also be produced. [19] Thus highly specific implants that vary according to patient's bone density and the site of implantation can be manufactured. This can be beneficial when dealing with cases with significant bone defect secondary to trauma, infection, revision procedures or tumors. It has widespread utility in the field of orthopaedic oncology, where following resection, the resultant defect can be imaged and a highly customized implant can be created by computer aided design (CAD) which is subsequently 3D-printed. This process requires active cooperation and coordination between the surgeon, the engineering team and the implant company. [3] Custom implants have been granted United States (US) FDA approval but they can only be used on a case-by-case basis to manage unique conditions that cannot be treated with currently available commercial implants. [20] Liang et al. have described successful results with 3D-printed pelvic implants following tumor resections. [21] By changing the surface geometry and porosity of the implant, one can improve the osseous ingrowth and help in better incorporation.

Future Perspectives

Bioprinting

Bioprinting uses living cells combined with a scaffold which is then 3D printed as a tissue. This procedure distributes cells, biological materials and other growth factors in a layered manner to create tissue analogs. [2,3] The bioactive scaffold or medium which can be used for this purpose includes metals, bioceramics, polymers, hydrogels and other composites. [1] These scaffolds can be implanted with pluripotent stem cells to fill defects. Bioprinting of bone or bone substitutes has significant clinical implications. Calcium phosphate is a commonly used material for 3D printed bone scaffold. Certain challenges faced by bioprinting include retaining viability during manufacture, ensuring sterility and safety, and achieving adequate cell density. Another obstacle is achieving adequate perfusion of the implanted tissue in vivo. [2] Bioprinting has also opened the gateway to tissue engineering which aims to regenerate, restore or replace injured tissue. [1] Creation of scaffolds with heterogeneous surface geometry and porosity can replicate highly complex native biological structures such as the muscle-tendon complex. This may allow for 'true' soft tissue reconstruction in the future. [2, 22]

Four dimensional printing [3]

This incorporates the use of smart materials to create self-changing proteins which are capable of self-repair. These changes are brought about by a change in the environmental condition such as temperature, pH etc. [23]

Conclusion

Three dimensional printing can allow for creation of almost unlimited 3D shapes of increasing complexity of geometry which enables customization. An increasingly wide variety of materials can be used such as metals, polymers, plastics and even living tissues. Even though cost considerations remain, one can expect to see reduction of expenses with more widespread use. Other limitations that are inherent for any new technology include lack of published long term data and lack of government regulations. In spite of the obstacles, additive manufacturing has progressed manifold especially with regards to its potential applications in the medical field. Although definitive long term data regarding clinical significance and improvement in outcome is still unavailable, orthopaedic surgeons both young and old should be aware of the multitude of possibilities that exist due to advancements in 3D printing.

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