Three-dimensional printing in orthopedics – what an orthopedic surgeon should know

Ahmed S. Barakat[a], Mohamed Alhashash[b]

[a]Department of Orthopedics and Traumatology, Cairo University, Cairo, [b]Department of Orthopedics and Traumatology, Alexandria University, Alexandria, Egypt

Correspondence to Ahmed S. Barakat, MD, Department of Orthopedics and Traumatology, Faculty of Medicine, Cairo University, Cairo, Egypt. Tel: +49 152 2652 9829; fax: +20 223 682 030; e-mail: ahmedsamir222222@live.com

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Background

In complex situations, regular on-shelf orthopedic implants are not suitable or sufficient to ensure the expected biomechanical or biological function, and customized implants could theoretically offer a solution. Preoperative planning, procedure rehearsal, patient teaching, and three-dimensional (3D) bioprinting are other uses of the fast-spreading 3D printing technology.

Aim

This review deals with the status and future uses of 3D printing and its various applications in orthopedic surgery. In the past decades, enormous technological progress in the field of radiological data acquisition, processing, and 3D printing technologies led to an explosive advancement of this promising industry.

Materials and methods

A literature review of the recent and relevant publications with a special focus on the various orthopedic applications of 3D printing technology was done.

Conclusion

3D printing offers already a valid yet still an expensive solution in certain orthopedic indications. Soon, orthopedic surgeons will be able to use this emerging technology more frequently as more and more companies offer cheaper rapid prototyping manufacturing solutions. Nevertheless, the technology still needs improvement, and many issues such as accuracy, long-term survivorship, and legal liability for the customized implants are still not fully solved.

Keywords:
3D printing, additive manufacturing, bioprinting, individualized orthopedic implant manufacturing, organ printing, rapid prototype manufacturing, stereolithography, tissue printing and engineering

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Introduction

Chuck W. Hull was credited to have invented three-dimensional (3D) printing and patented the process he termed stereolithography in August 1984 [1]. Anecdotally, 3 weeks before, a group at the French General Company, now Alcatel-Alstom, filled their patent for a similar process, but they were told by their employer that there was no business perspective [2]. However, it was a Japanese researcher, Dr. Hideo Kodama, in 1981 who described two manufacturing processes, which are considered the predecessors of contemporary additive manufacturing (AM) [3].

Basically, 3D printing can be divided into three major procedural steps: image acquisition, image postprocessing, and rapid prototyping (RP) [4].

Image acquisition

The images are preferably taken by computed tomography (CT), but also MRT, single-photon emission CT, and even ultrasound-based systems have been described [4]. Despite the intrinsic radiation exposure, CT-based data acquisition is faster and shows better isotropy when compared with MRI enabling superior spatial reconstructions. Isotropy describes the voxel length size in the *z*-axis, which should ideally equal those of the *x*-axis and *y*-axis [5].

To obtain good images high-resolution 1 mm or slice thickness or less with almost isotropic voxel size cuts are taken. A voxel [*vox* ('volume') and *el* (for 'element')] can be imagined as a volumetric pixel in a 3D grid and are preferred when displaying regularly sampled spaces that are nonhomogeneously filled. This contrasts with polygons, which can sufficiently represent simple 3D structures with large empty or homogeneously filled space. This is essential to minimize step artifacts and partial volume effects during image reconstruction [6].

Image postprocessing

Medical image data are most commonly stored in the common digital imaging and communications in medicine format in the picture archiving and communication system. This standardization allows for rapid data exchange between the data acquisition unit and the end user whether he/she is in the same medical facility or hundreds of miles away. Image postprocessing essentially comprises the use of high-end workstations with dedicated computer-aided design software to convert 2D images into an appropriate 3D model. This is achieved most commonly by maximum intensity projection and volume rendering and their subsequent modifications [7,8].

The created 3D model on the workstation monitor is then adapted to the clinical needs with the proper software. To communicate with the actual 3D printer, these data have again to be converted into special digital formats, namely, stereolithography format (also known as Surface Tessellation Language or Standard Triangle Language format), initial graphics exchange specification, or virtual reality modeling language formats.

RP and AM

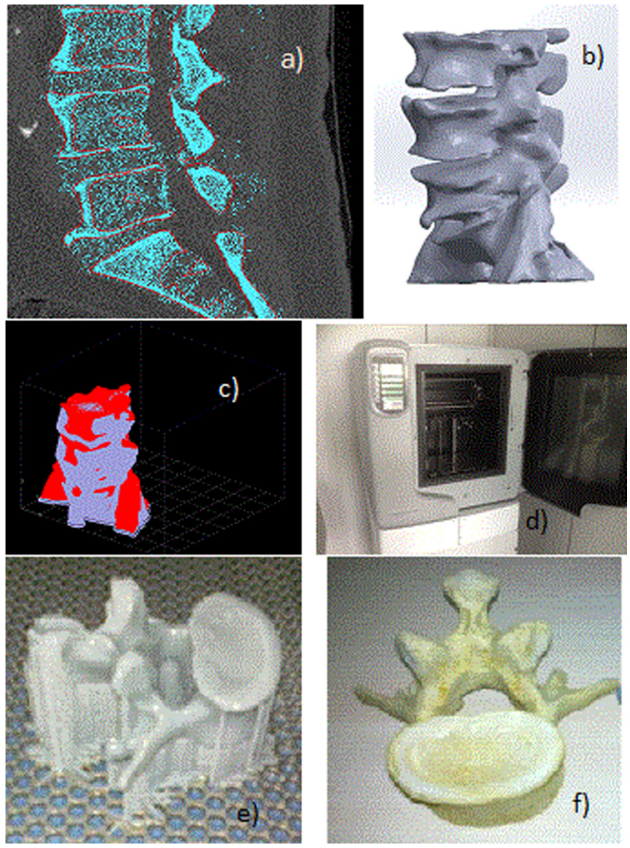
The term RP has been coined by the automotive industry, where a fast manufacturing of cheap prototype parts and models is of vital economic importance. Basically, the stereolithography format, initial graphics exchange specification, or virtual reality modeling language data files serve as a blueprint for the 3D printing machine, which stacks layer on layer to build the object in a technology that is termed AM. This contrasts with the traditional subtractive manufacturing, which literally mills the desired object out of a solid material block. Other traditional manufacturing principles are stamping, fabrication, and casting. Difficulties encountered in subtractive manufacturing in the production of complex and delicate 3D structures has been largely overcome by the additional manufacturing technology. By accurately sintering granules layer-by-layer by the printing machine, the object is quickly printed, allowing for high details, the recycling of unused granular material powder, and the feasibility to handle materials such as medical grade titanium, which by default have difficult manufacturing properties [9,10].

Hence, AM has evolved for direct component and product manufacture and remains not only reserved for RP, thus advancing the competitiveness and flexibility of the manufacturer, as on-demand custom needs could be met more promptly [11] (Fig. 1).

3D printing techniques

3D printing can be classified according to the used technique, the used material, and the application process, namely, drop-on-drop (PolyJet printing) or continuous deposition [(fused deposition modeling (FDM)] [12].

Figure 1



(a) DICOM file of sagittal view of lower lumbar spine. (b) Stereolithography format file of the same lower lumbar spine. (c) Printer model file. (d) HP designjet color 3D printer CQ655A, HP Inc. (Palo Alto, California, USA) serves as output device using acrylonitrile butadiene styrene (ABS) plastic (Courtesy of Medicon eG, Tuttlingen, Germany). (e) Patient-specific lower thoracic vertebra with supporting structures during PolyJet 3D printing. (f) Final D11 vertebral after removal of support structures. (Courtesy of M3DP UG, Magdeburg, Germany). DICOM, digital imaging and communications in medicine format.

The commonly used techniques include stereolithography apparatus (SLA), selective laser sintering (SLS), multijet printing (MJP), PolyJet printing, color-jet printing (CJP or binderjet), digital light processing, direct metal laser sintering, FDM, laminated object manufacturing, and electron beam melting [9,12]. The employed material can include thermoplastic, metal powder, ceramic powder, eutectic metals, alloy metal, photopolymer, paper, foil, plastic film, and titanium alloys [12,13].

SLA is a common medically applied technology and uses an ultraviolet (UV) laser for curing a bath of photosensitive resin located on a vertically moving platform. Digitally controlled layer-by-layer curing is achieved by special mirrors, which focus the UV on the resin. Final dry curing is achieved in a separate UV chamber [12].

Being light and robust but slightly brittle, it is considered the most suitable technology for medical applications. Choi *et al.* [14] verified its relative accuracy when comparing 16 linear measurements taken to compare an original skull to an SL manufactured model with the mean deviation being 0.62±0.5 mm (0.56±0.39%). Schicho *et al.* [15] reported similarly good results when comparing CT and SL measurements, with a mean of deviation of 2.5 mm (range: 0.8–3.2 mm).

Again, UV light is used in MJP to cure simultaneously applied acrylic photopolymer and wax acting as support. Yet, being the most precise technique, it provides relatively frail products, and at 65°, shape distortion occurs [12].

Resembling the former MJP technique, PolyJet printing consists of immediate curing of very thin photopolymer materials, which are applied layer wise. An easy removable gel-like material is used as the supporting material [12]. The accuracy was investigated in a dry mandible model and reported as a dimensional error of 2.14% [16].

Digital light processing is liquid based and projects an image on the light-curable material present in a container, offering the fastest method with outstanding surface details. Nevertheless, the printer and the available materials are quite expensive [12,16].

SLS uses a CO_2 laser to heat previously applied powder material to obtain a solid layer. Thereafter, the details of this layer are obtained by laser movement along the x and y axes. The holding tray then shifts downward, and a new layer is fabricated. Sandblasting removes the residual powder from the prototype, which appears porous and abrasive, yet being very accurate with errors in the range of 0.1–0.6 mm [17].

Direct metal laser sintering resembles SLS printing but uses a solid-state Yb-fiber optic laser, enabling the system to build excellent fabricates. Variable melting temperatures enable the processing and alteration of metallic powder material such as titanium, stainless steel, aluminum, cobalt, and nickel alloy. No postprocessing of the product is needed as no support substance is used.

The color-jet printing (CJP or binderjet) selectively injects a binder substance onto the powder layer, which is like SLS prespread by rollers. The print head then injects a solution that hardens the powder particles to form the desired product. The unused powder is de-powdered and can be reprocessed. Additionally, the material properties such as hardness, brittleness, and surface roughness can be influenced by additional hardening by, for example, cyanoacrylate and epoxy. Fast production speed, relatively low cost, and excellent accuracy make this technique attractive [12,17].

FDM is also solid based. Layers of heated thermoplastic, such as acrylonitrile butadiene styrene, are extruded from special printer nozzles and deposited layer-by-layer. Owing to the relatively prolonged hardening time, support material is needed, which is removed mechanically or chemically at the end of the process [12]. Owing to its porosity, its use as a graft scaffold has been reported [18,19].

Applications

Uses of the fast-spreading 3D printing technology comprise custom implant and organ/tissue manufacturing, preoperative planning, procedure rehearsal, and patient teaching (Fig. 2).

Customized implants have been recently used in different orthopedic indications. Dai and colleagues reported on 10 patients after hemipelvectomy, who received a custom prosthesis manufactured by RP. After 21 to 48 months, the six surviving patients were reported to have good hip function, although two had early hip dislocations and three had wound healing issues [20].

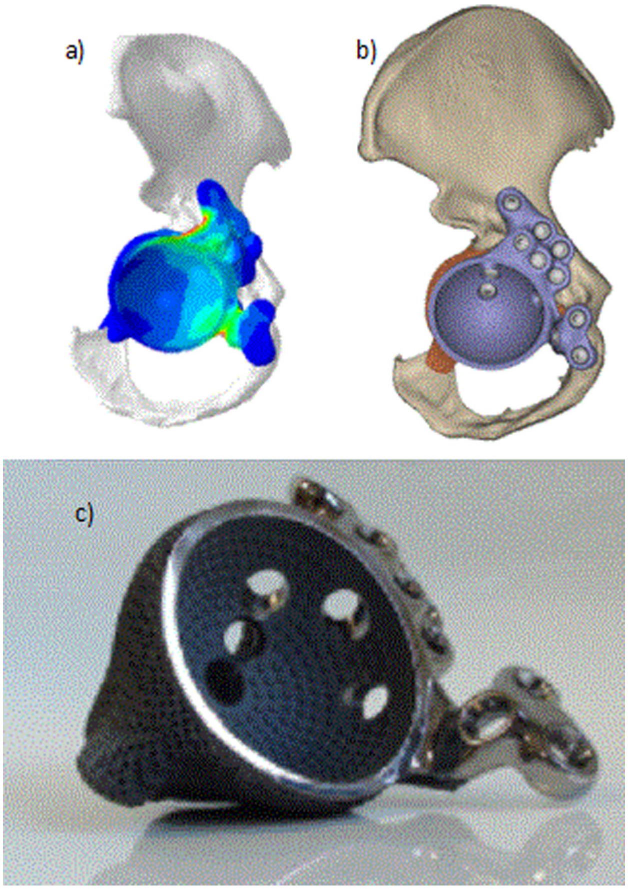
Harrysson *et al.* [21] reported on a customized cementless total knee femoral component that would have better stress distribution and thereby better biological and biomechanical properties.

Paiva *et al.* [22] used SLS to build a stereographic model to plan and simulate the complex spine surgery in a 12-year-old with Ewing's sarcoma at C4.

By SLS, Hurson *et al.* [23] produced 3D models of 20 acetabular fractures and examined the intraobserver and interobserver accuracy of diagnosis of consultant and trainee surgeons. Especially younger surgeons testified a better understanding of the fracture geometry.

Kalita and colleagues examined controlled porosity polymer-ceramic composite scaffolds for enhancing in-growth of bone cells. Their mechanical stability, cytotoxic, and proliferative features proved the

Figure 2



(a) After having obtained a computed tomography of this 15-year-old girl with neurofibromatosis and prior extensive hip surgery, a triflange patient-specific cup was designed (b) using Mimics and 3-matic software. (c) Eventually a titanium cup was printed to match the anatomical defects using 3D printing technology from Mobilife aMace (Courtesy of Materialise Belgium, Leuven, Belgium).

ceramics' usability even when considering the high content of polypropylene (PP) polymer in relation to tricalcium phosphate (TCP). In-vitro testing verified their excellent cell growth and nontoxicity during the first 2 weeks [18].

Hutmacher *et al.* [19] showed complete 3D-filling with cellular tissue within 3–4 weeks, proving the proliferation and differentiation of fibroblasts and osteoblast-like cells and production of cellular tissue in an entirely interconnected 3D polycaprolactone matrix.

Yang and colleagues produced 50 patient-specific spine models of patients with adolescence idiopathic scoliosis for preoperative planning and compared operation time, perioperative blood loss, transfusion volume, and postoperative complication rate with 76 age-matched non-3D-planned patients with adolescence idiopathic scoliosis. They report a significantly shorter operative time and significantly lower blood loss with lower transfusion requirements in 3D-planned patients, but there was no significant difference when comparing the postoperative complication rate [24].

Starosolski *et al.* [10] emphasized the use of 3D printing for patient/parent education in pediatric orthopedic disorders.

Bioprinting technology is a recent yet still an evolving technology in which mesenchymal cell-laden hydrogel structures are stacked by inkjet printing or laser-induced forward transfer to form viable 3D structures with adequate biological properties, such as porosity and cytocompatibility [25].

The vastly growing bioprinting technology could have potentially a democratizing effect as organs-on-demand could become a graspable reality soon, thereby obviating the need for organ transplantation from deceased or living donors. Its advantages also include the absence of rejection reactions and the theoretically unlimited availability of virtual donor organs.

Copyright and liability

Nevertheless, various problems arise, such as organ patent licensing, legal liability, and cost-bearing issues, whether by the society or the affected individual, calling for strict regulations [26].

Additionally, 3D printing technology could lead to the manufacture of imitated low-standard medical implants and products owing to the widespread availability of printing devices and material and so far the lack of stringent national and international regulatory and monitoring instances [27].

Liability question arises whether to hold the printing facility, that is, the physician/hospital or third party responsible in case of patient injury as the sources of failure could be manifold as a corrupt original file, corrupt printer or printing material and faulty application of the customized end-product [28].

Outlook

The dream of having the ability to produce customized on-demand implants, as well as teaching and training models, has substantialized in developed countries more and more into a real option. Large medical facilities now have the capability or access to this game-changing technology. Owing to the steady decrease in cost, a drastic spread, even in third world countries, is expected to occur soon.Organ printing of viable and vascularized organ tissues such as liver, kidney, or bone is one of the most important frontiers in modern medicine, although still in the early development phase, it could change transplantation medicine dramatically [27].

In theory, stored stem cells taken early in life could serve as individualized data sets for future organs that could be quickly printed when needed.

Experimental external in situ printing was already performed when 3D-printed keratinocytes and fibroblasts were used to heal a large skin defect [29].

Another future trend is the personalized polypill which entails the customized in-hospital printing of a single multidrug containing pill leading to better patient compliance and cost-efficiency [30].

Conclusion

3D printing offers already a valid yet still an expensive solution in certain orthopedic indications. Soon, orthopedic surgeons will be able to use this emerging technology more frequently as more and more companies offer cheaper RP manufacturing solutions. Nevertheless, the technology still needs improvement, and many issues such as accuracy, long-term survivorship, and legal liability for the customized implants are still not fully solved.

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Conflicts of interest

There are no conflicts of interest.

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