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Overview study on challenges of additive manufacturing for a healthcare application

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Abstract. Additive manufacturing is a rapidly evolving manufacturing technology bringing numerous and wide opportunities for the design team involved in the process by creating intricate and customized products with saving labor, time, and other expenses. Innovative AM methods and numerous practical applications in aerospace, automotive, medical, energy, and other industries have been developed and commercialized through extensive research over the last two decades. One embraced industry among others that benefited from the advances of AM is the healthcare industry. This paper focuses on addressing the challenges and opportunities in Additive manufacturing for healthcare. Although there are advanced possibilities in AM, there are also numerous issues needed to be overcome. The paper is based upon the current state-of-the-art review and study visits. The purpose of this work has been to identify the opportunities and limitations associated with additive manufacturing in healthcare applications and to highlight the identified research needs.

1. Introduction

The most advanced technology, additive manufacturing (AM) is used for manufacturing intricate geometries and structures by building layer-upon-layer utilizing 3D model data [1]. In contrast to traditional subtractive technologies, which produce components by removing material from a bigger raw part, AM techniques fabricate components by adding a material single layer at a time. Since the part is built based on the cross-section of the geometry of the part, AM significant lowers material waste, shortens the manufacturing time, and removes the requirement for the majority of manual procedures that require a skill. For instance, it is reported that by adopting AM methods rather than conventional machining, raw material wastage in the metal industry was decreased by up to 40% [2].

Though the technology is referred to as additive manufacturing due to its current role as a method of fabrication of functional parts, the technology, in other contexts, is also referred to as 3D printing, rapid prototyping and manufacturing, digital fabrication (manufacturing), layer manufacturing, desktop manufacturing, on-demand manufacturing, direct manufacturing, and solid free from manufacturing, which are all the terms used to describe additive manufacturing. Because no cutting tools are used, the fabrication process is also commonly referred to as the toolless process [3]. Other techniques like laser forming (Incremental sheet forming) are similarly used in the customization of medical products to build structures layer by layer but they cannot be considered as AM techniques as they add the form rather than the material. By adding materials without deleting them, AM maximizes material savings.

Since the inception of the Stereolithography apparatus (SLA) based 3D printing in the 1980s as a tool of rapid prototyping, many other variants of the technology emerged based on the source of power (electron beam, laser, etc.), the material type (ceramic, metal, and plastic), and the configuration or state of the feedstock (filament, resin, powder, bar). The American Society for Testing and Materials (ASTM) committee ASTM F42-Additive Manufacturing [4] has categorized AM techniques into seven broad groups as illustrated in Figure 1. Figure 2 further illustrates the material processing technique used to deposit the printing layers in each of the standardized categories.

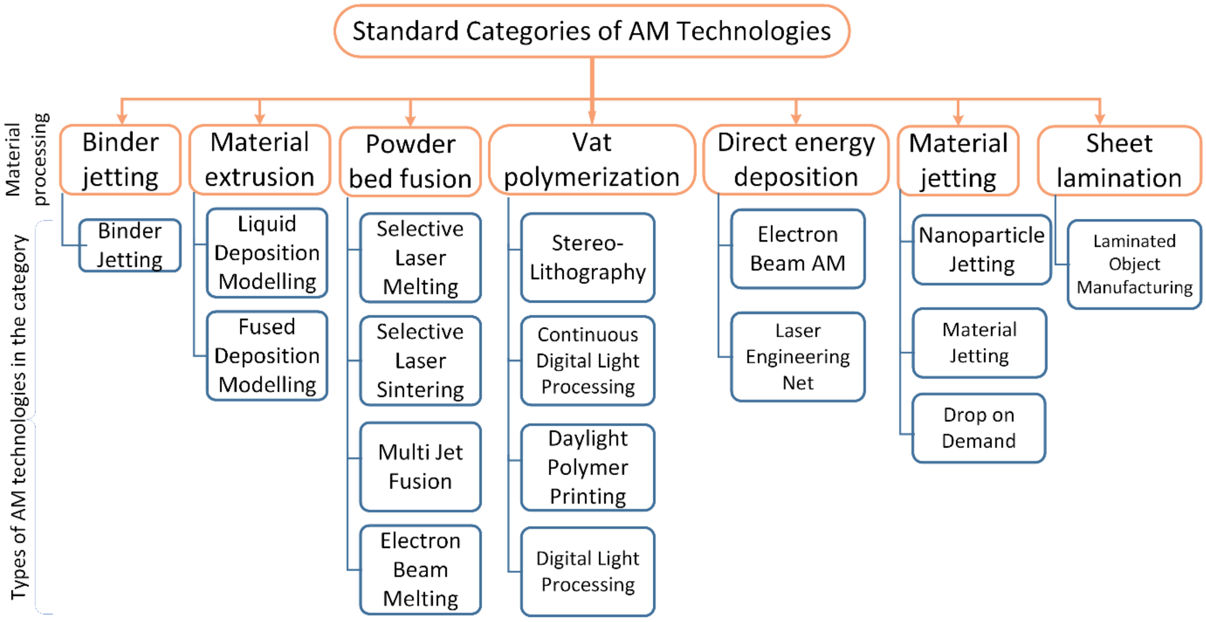

Figure 1. The seven standardized categories of additive manufacturing techniques

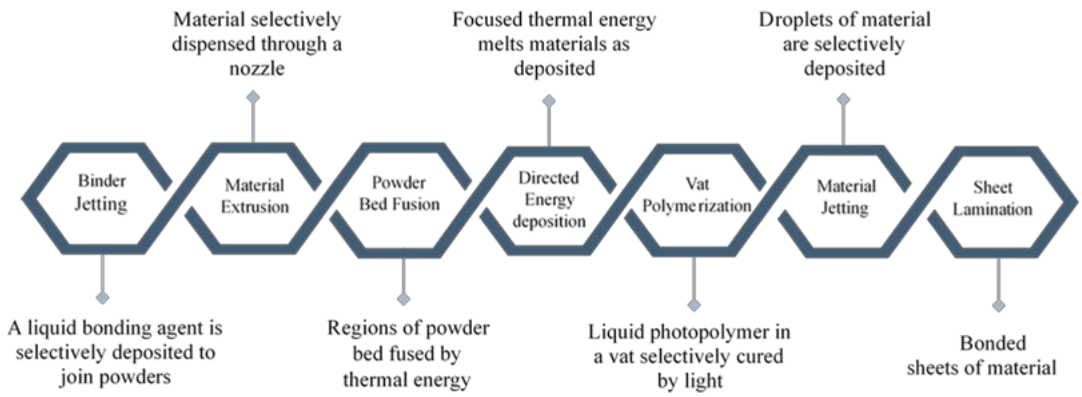

Figure 2. Methods of material processing in the standardized AM techniques

Among the earlier users of the innovative solutions that AM provides, we find the aerospace industry, the automotive industry, the energy sector, and the medical sector. In the last mentioned, in particular, many breakthroughs have been occurred in the medical field using the design freedom it provides. Among others, AM has advanced and continues to immensely advance medical applications, with bioprinting cardiovascular applications, such as 3D-printed heart valves, being the current focus of this method [5-7]. While the basic principles of additive manufacturing haven't changed, there are now more resources available to explore these technologies, which will lead to new medical applications [8, 9]. Despite new opportunities that the technology opens in particular in the field of medicine and biomechanics, issues such as incomplete vascular networks in manufactured grafts (physical organ models), the need for a big multi-specialist team, restrictions in layer height of generated models, and (medical) bioethical concerns about using 3D printed devices in humans are still research and application challenges.

This article presents an overview study of the opportunities and challenges faced when additive manufacturing technology is implemented with a particular focus on its trends of application in the medical sector. The core aim of the review is to explore the potential areas of future research on the application of topology optimized design and prediction of material behavior for medical devices that can be fabricated using AM technology. In Section 2, an overview of the key process step and the application of additive manufacturing in the aerospace and the automotive industry, which the authors assume to exceed that of the medical sector, are presented. Section 4 focuses on the AM applications, processes, technologies, etc. from the perspective of the interest in the healthcare sector. The concepts and research work presented in this section are further explored and discussed in Section 5 where the focus is on highlighting the current challenges facing the widespread application of this technology in the healthcare sector. Finally, Section 6 briefly presents the conclusions withdrawn based on the study.

2. Key processing steps and applications of AM technology

As stated earlier, the novelty of AM technology lies in its ability to transform 3D model data in digital form directly to a 3D physical object. This process is quite common to almost all of the available technologies, though the way these processing steps are executed using different mechanisms based on the energy used, the material being processed, and the state of the material. This general step is illustrated in Figure 3.

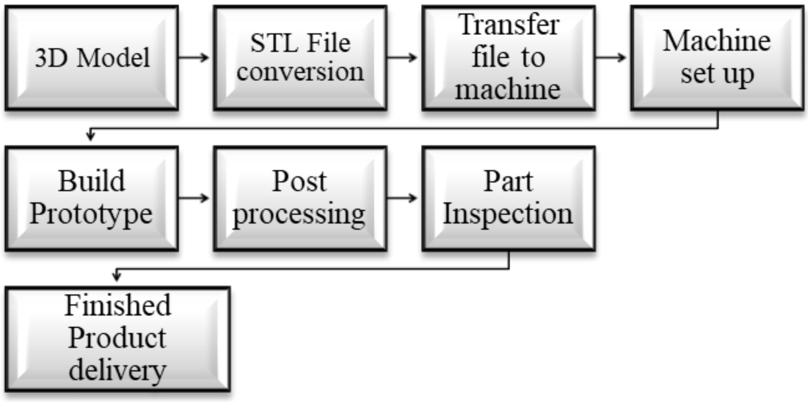

Figure 3. General steps of transforming 3D model data to a 3D object in AM

Employing the processing steps illustrated in Figure 3, the development of novel, advanced additive manufacturing techniques has accelerated significantly, resulting in an increasing number of industry applications. AM is particularly well suited to manufacturing low volumes of goods, especially for components with complex geometry, when compared to subtractive manufacturing. Customized implants for hip and knee prostheses are one example of how AM methods can be used to increase customization. Additive manufacturing is widely being used and explored in energy, marine, aerospace, automotive, and medical industries, as well as industrial spare parts.

Aerospace: Aerospace innovation has always attempted to reduce the cost and weight of components whilst maintaining the highest safety standards. Typically, aerospace components have complex structures and are built of advanced materials such as nickel superalloys, titanium alloys, and ultra-high-temperature ceramics that are costly, difficult, and time-consuming for manufacturing. This makes AM suitable for Aerospace applications. These potentials of AM technology in the aerospace industry, particularly in enabling fabrication of topology optimized components leading to less weight has attracted recent research environment. Table 1 summarizes a few of the reported research works.

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Table 1. Additive manufacturing applications in aerospace

No.	Description	Reference
1.	Additive manufactured being used for end-user components	[10]
2.	Boeing F/A-18 forward fuselage parts manufactured by Selective laser sintering	[11]
3.	GE Aviation passenger jet engine (LEAP) utilizing 3D Printed nozzles	[12]
4.	NASA exploring to manufacture space objects through 3D printing	[13]
5.	TWI hired LMD process for a combustion chamber of helicopter engine manufacturing	[14]

Automotive: The automotive business relies on new product development, yet this can be an incredibly expensive and time-consuming activity. Because of its ability to shorten the development cycle and lower manufacturing and production costs, AM has become a key tool in the automobile industry's design and implementation of automobile parts. In addition to the production of limited quantities of luxury or high-performance automobile parts, the design freedom makes it ideal for the production of gearboxes and driveshafts [15]. Structural composites such as turbocharger turbines, engine valves are other examples of additive manufactured automotive parts [16]. Further benefits of adopting AM for automobile parts include shorter product development and manufacturing times leading to lower total costs [17]. However, some significant challenges of AM in the automotive industry are reported including (i) - thermal stresses generated in additive manufactured components, which influence their performance and repeatability [18], (ii) - the surface finish and the dimensional accuracy [19], (iii) unsuitability for large volume production of parts [20]. Table 2 summarizes some of the additive manufacturing technologies and their application in the automotive industry [21].

Table 2. Additive manufacturing technologies suitable for the fabrication of parts for the automotive industry

AM technology	Materials manufactured
Stereolithography	• Transparent prototypes for tooling devices and engine components • Hydraulic and pneumatics prototype • Bumpers and body kits for vehicle manifold and engine covers
Fused Deposition Modelling	• The design and prototyping of vehicles • Dashboard, fuel doors, and cluster physical design • Emission filter, housing units, and filter housing
Electron Beam Melting	• Turbine blades, Pump impeller • Frame construction • Wheel rims, Variable density system
Selective Laser Sintering	• Prototypes of Gears, low volume parts • Fuel tanks, Grills and fenders, Heat exchangers

Energy: The energy sector is nowadays focusing on renewables such as solar and wind, and clean energy like hydrogen that are believed to reduce environmental impact while also decreasing the reliance on fossil fuels. To put it another way, fuel cells are one of the most "green" energy sources because of their higher efficiency, minimal emissions, and higher power density. The portable power supply, automobile system, and distributed energy system are only a few of the possible uses. However, the expensive cost, as well as the low durability of fuel cells, prevent their general implementation. As a result, the fabrication of diverse components for the energy sector using AM approach has been focused and Table 3 lists some of the AM technologies used in the sector.

Table 3. Additive manufacturing technologies employed for the fabrication of parts in the energy sector

AM Technology	Materials	Energy Application	References
Directed Energy Deposition	Inconel 718	Nuclear, energy, Oil & gas	[22]
	Oxide dispersion strengthened 14Cr stainless steel	Nuclear energy	[23]
Powder Bed Fusion	316L stainless steel	Nuclear, energy, Oil & gas	[24]
	Graphite-Carbon fiber bipolar plate	PEM fuel cell	[25]
Materials Extrusion	Holey graphene oxide	Li-ion batteries	[26]
	Yttria-stabilized Zirconia electrolyte	Solid oxide fuel cell & electrolyzer	[27]
VAT Photopolymerization	Microfluidics device	Micro fluidic fuel cell	[28]
	Lithium iron phosphate	Micro-battery	[29]

3. Overview of AM for healthcare

The medical field was the first to implement AM technology [30] due to the flexibility it provides through design freedom. This interest emanates from the fact that creating a part with AM procedures just requires its 3D digital model, which is not demanding with the advent of the digital era we are in.

A new analysis by Grand View Research, Inc., indicates that the worldwide healthcare additive manufacturing industry is estimated to be worth USD 6.4 billion by 2028 and to increase at a compound annual growth rate (CAGR) of 21.8 percent from 2021 to 2028 [31]. The use of advanced technology; availability of a vast range of materials such as plastics, metals, and polymers; design flexibility, the ability to produce complex geometries, including honeycomb structure and cooling channels are the propellers of additive manufacturing market rise in medical applications. Furthermore, the growing elderly population implies that there exists an increased need for orthopedic surgeries including knee and hip implants for replacement. Additionally, increased use of dental implants in combination with an increasing demand for prosthetics is another significant driver projected to lead the market. With the above-mentioned technological, economical, and societal conditions, this section will explore the healthcare-related applications, benefits, and methods (processes) of realization of additive manufacturing.

3.1 Applications of AM in healthcare

Five broad categories of application of additive manufacturing in medicine can be identified, as illustrated in Figure 4 [32] [33].

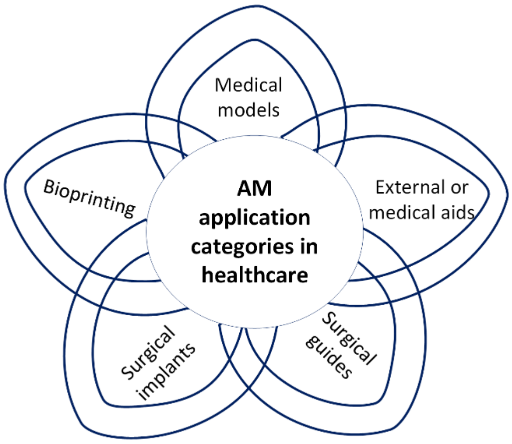

Figure 4. Applications of AM Healthcare

Bioprinting: 3D Bioprinting was patented in 2003 and it is utilized for printing organs and tissues [34]. The three-dimensional tissue-like structures can be formed by layering cells on a biocompatible scaffold and distributing them layer-by-layer. In this procedure, cells are delivered to a biocompatible scaffold through the use of a 3D printer to build tissues that resemble three-dimensional structures [35]. The cells then can be developed through the matrix or scaffold, which can be printed using a 3D printing technology such as fused deposition modeling (FDM) [36]. One powerful element of the technology is creating personalized designs from the geometry of the patient that is acquired through medical imaging or 3D scanning. Particular attention may be needed that the procedure must be sterile, or parts must be sterilizable after printing. Moreover, cell growth in vitro or in vivo may be required prior to final application. Vitro models in 3D bioprinting enable researchers to better understand the interactions between cells and the environments [37]. Observing cellular interactions could bring fresh insights in a variety of fields, including cancer research.

Researchers have also indicated an effective approach to print scaffold that retains the microstructure while also increasing repeatability [38]. Though bioprinting is based on scaffolds, it has significant issues, such as cell degradation with time and low cell-to-cell interactions. Ozbolat [39] proposed the idea of printing cells without a scaffold, which could be extremely useful in the future of tissue engineering and regenerative medicine. It may potentially be possible to use living bioprinted liver tissue and heart valves for investigation and medication development purposes in the future [40, 41].

Medical aids: Orthoses, prostheses, and splints are all examples of medical aids. AM may supply a customized device to aid in healing and ensure that damage repair is as precise as possible. External to the body, additive-manufactured parts can be combined with everyday appliances to allow for better personalization [42]. As the traditional methods for making prosthetic sockets were time-consuming, taking two to three days to produce one socket, additive manufacturing can improve this process. The study reported in [43] shows that the time required is decreased to less than four hours when AM technologies are employed. Another case is the therapy of dental malocclusion using AM to create a mold for one or more transparent and removable prostheses [44, 45]. Additionally, this class includes noninvasive positioning guidelines, such as an auricular template for craniofacial implant position [46].

Medical Models: Pre-and post-operative training and education are mostly based on medical models. Using medical models, anatomical objects can be rebuilt with a higher level of details and accuracy, and hence simulation for better surgical planning and imaging using medical imaging and reverse engineering (RE) [47]. For intricate surgical operations, models can also be utilized for the communication of personnel, training of students, and counseling of patients and families. Different aspects of the models, such as material properties, anatomical accuracy, and haptic response, are crucial depending on the requirements. In surgical teaching models, a real haptic reaction of bone is especially desirable [48].

External Aids (tools): AM can help to produce patient-specific tools that will assist with efficiency and enable and increase the effectiveness of medical operations, and in addition, it can aid in drug production [49]. This category includes the manufacture of operation-specific equipment such as custom-fit surgical guides and preforms. A prototype of a mandible fracture reduction instrument is an example of a surgical tool [50]. Oral appliances, which are created entirely by AM are other examples of this class of application [51]. Devices in this class come in touch with body fluids, mucous membranes, or tissues for a short period, and are thus intended for temporary or short-term usage [52]. They are intrusive but not implantable. The material must be sterilizable, and the surface requirements vary by use. Most of these products are invasive surgical.

Implants: The possibility of providing customized implants with improved clinical and cosmetic outcomes and biocompatibility materials with high mechanical qualities with the use of AM, combined with medical imaging and RE, offers great promise. Tissue compatibility requirements are strict, and approval processes are lengthy. Membrane properties may impact cell adhesion. Recent research has looked at embedding materials inside implants, for example, as a medicine delivery mechanism [53]. In customized implants, AM is a good choice since the typical procedure requires capturing a patient's anatomy such as medical models. It is then used as a design reference to allow patient-specific fitting

3.2 Advantages and recent developments of AM in the health industry
Given that every patient is unique, AM offers a significant perspective for use in medical applications that are personalized and customized. As explained above, tissue and organ fabrication, anatomical models, development of customized prosthetics and implants, medication dosage forms discovery, and administration is among the most applied biomedical uses of additive manufacturing. It also enables substantial customization based on the unique patient data and requirements. This technology also ensures that the implant is perfectly fitted and saves both time and cost [51]. Figure 5 depicts the benefits of AM in healthcare applications.

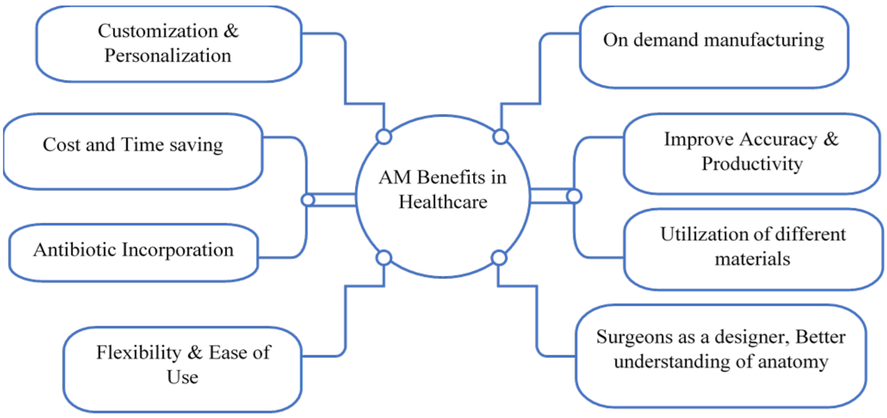

Figure 5. Benefits of AM in healthcare applications.

3.3 AM processes in Health
A common procedure for personalized (unique) medical devices begins with capturing images or digitizing the patient's geometry. Typically, magnetic resonance imaging (MRI) and computed tomography (CT) are employed to capture model data. Ultrasound, laser scanning, and positron emission tomography are just a few of the other techniques that are utilized to acquire patient data. Digital print files created from 2D radiographic images such as CT scans, MRI, and X-rays can be customized anatomically, medically, and structurally. Thus, specific patient virtual models are created in three-dimensional (3D) parts using specialized software 3D CAD [3]. Once the virtual model is prepared, the data is then translated to a Standard Triangulate Language (STL) format [54] or the latest additive manufacturing file format for rapid prototyping machines [55]. The typical process flow of AM in health is seen in Figure 6.

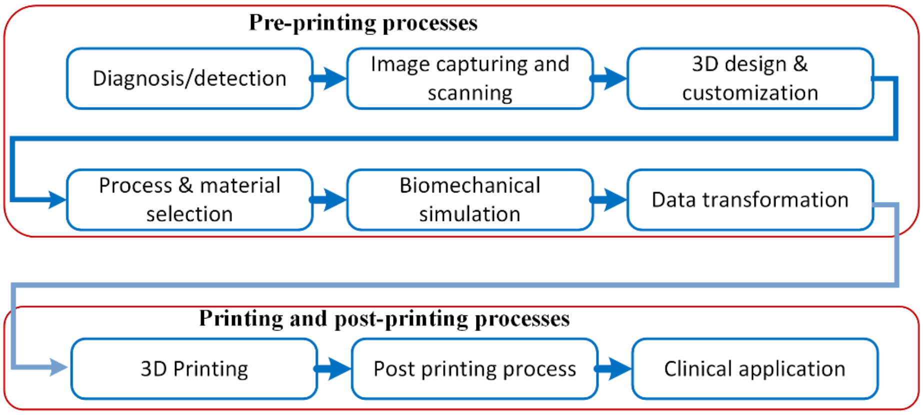

Figure 6. The typical workflow of AM in Health

3.4 AM methods in healthcare

According to the forecast [31] for the year, 2021 to 2028, the major healthcare additive manufacturing technology outlook will be stereolithography, electron beam melting, deposition modeling, laser sintering, laminated object manufacturing, jetting technology. Table 3 shows an overview of different methods of AM used mostly in healthcare applications [56, 57].

Table 3. Different methods of AM used mostly in healthcare applications

AM Process	AM technology	Materials	Application
Material extrusion (MEX)	Fused deposition modeling (FDM)	Thermoplastic polymer (ABS, nylon, PC, AB), plastics	- Rapid prototyping exoskeleton - Antibiotic delivery systems - Scaffolds - Medical devices - Porous structures
Powder bed fusion	Selective laser sintering Selective laser melting Electron beam melting	Polymer, Metal, Ceramic	- Joint Implants - Scaffolds (Tissue Engineering) - Craniofacial Implants - Vertebral body replacement - Cervical - Porous dental Implants - Hip and Knee implants - Press-fit
Vat photopolymerization	Stereolithography (SLA)	Photopolymers (resin)	- Dental Implants and models - Bone, - Hearing aids
Sheet lamination	Laminated object manufacturing	Plastic, paper, sheet metals	- Orthopedic modeling of bone surfaces

Direct Energy deposition	Laser metal deposition	Metals, titanium, cobalt chrome	-	Repair existing parts and build very big (large) parts
Material Jetting	Multi-jet modeling (MJM)	Polymers, plastics	-	Dental implant guides and casts, medical models

4. Discussion on specific challenges future perspectives

Though it is in its early stages, AM can create realistic teaching or training models, pharmacological or pathophysiological experimental models, personalized medical equipment, and devices, as well as bioartificial tissue or organ grafts for use, for instance in implantology. Generally, the purpose of 3D printing in healthcare applications is to enable physicians to serve more patients without sacrificing results.

The literature study shows that there is a significant amount of untapped potential that can be realized through bioprinting and other emerging technologies, including to help in solving the organ donor shortage. To realize this potential, scalability and affordability are the forefront challenges while also utilizing innovative print methodologies. Demand for faster printers with higher resolution than what is currently available is the key constraint that needs to be overcome. Instead of optimizing a single manufacturing process for the manufacture of a fully functional organ, it may be more beneficial to integrate procedures that imitate the natural organ's structural heterogeneity, structural tissue hierarchy, and functionality.

Prosthetic mini tissues that can be used to test the response of therapeutic and/or toxic pharmaceuticals as well as predict these responses while potentially decreasing the costs of drug discovery and allowing more discovery to occur through the use of bio-printed organs is the most likely application for bio-printed organs to appear shortly.

Even though file formats are being processed and different advancements are underway to improve the medical imaging that enables the transfer of medical image data in the form of MRI, CT scan, and other forms to a usable format for use in 3D printing machines, it is still challenging as every patient is unique and need unique treatment. In general, medical imaging consists of three main steps: (1)image acquisition, (2)image post-processing, and (3)3D printing [58]. Post-processing converts DICOM images into STL files, which are made up of thin layers ranging from 0.5 mm to 2 mm thick. Thus, sending the file to the printer to print. The DICOM image may be clear to the doctor but not to the patient. 3D printing can overcome this limitation.

Making a model from a 3D printer's DICOM image has limitations including errors introduced during the step-by-step development of the 3D model. These inaccuracies cause the CAD data to deviate from the real 3D model. In [59], it is demonstrated the inconsistencies in data transfer and created a 3D model. The size of both the model and the software used to determine the errors. The printer used also contributes to the inaccuracies. Polyjet is reported to be more accurate than SLS and 3D inkjet printers [60]. In addition, the achievable surface finish can also dictate the type of technology to be used. For instance, SLA is recommended for an excellent surface polish, while FDM is if cost is an issue, and a relatively accurate model may be employed.

Multi-material printing is another issue in AM for healthcare. Currently, printing 3D models with different materials (multi-material) are possible with some AM technologies. The benefit of printing multilateral is that a model can now contain different portions representing bone, organs, and soft tissue, giving surgeons and doctors a better grasp of how a patient's body will feel when utilizing a model for surgery or education.

Further challenges are related to material structural strength. Due to the layer-by-layer nature of the AM process, final products are known to have high strength in the X (length) and Y (width) planes but are feared to lack similar strength in the Z plane (depth). While the layer-by-layer method has demonstrated sufficient strength for a variety of applications, concerns persist that AM products may be less structurally sound than those produced through conventional manufacturing [61]. Moreover, limitations of speed and size, lack of standards, unavailability of enough expertise, lack of awareness about the risks associated with each application, etc. can be mentioned as some of the existing challenges in the wider application of this technology.

Regardless of the above-mentioned challenges, AM will be crucial in the future of healthcare practice, and it will change the way medical models are made. Among others, an implant made with this technology can replace traditional scaffold fabrication processes. The models help the surgical and physician teams plan better surgery. It can quickly produce complex geometry and custom fittings and implants. This is required for the creation of diverse medical devices and surgical training models provided that further research overcomes the existing application challenges.

5. Conclusion

A brief overview of the role and challenges of AM technology for healthcare application is presented in this article. As this is an actively researched area, the review presented in this article is far short of a detailed review. As a matured technology, it is easy to observe that 3D printing is a game-changing technology in various spheres of healthcare and has shown to be an extremely beneficial technology up to the point of widespread use. It gives sufficient reason to envision a world in which one can just push a button and a machine will automatically print out medication and products for patients, as well as customized goods according to each person's demands. Someday, one will be able to get a new bodily part produced on demand. More progress is being made, although it will still take some time.

Future work in this direction will involve conducting a more detailed literature review and develop methods and mechanisms that can advance the application. Among others, the focus will be done on the smooth conversion of medical image data to a file format compatible with 3D printing, predicting material behavior in multi-material printing, and effective topology optimization of medical devices.

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