

This paper is part of the Special Issue on [Design and Manufacturing in Biomedical Engineering](#).

Guest Editor: Dr. Jashanpreet Singh, University Center for Research and Development, Chandigarh University, Punjab, India.
Prof. Dr. Chander Prakash, University Center for Research and Development, Chandigarh University, Punjab, India.

Received January 6, 2025, accepted July 12, 2025, publication date for online-first December 10, 2025.

Review

A Critical Review of 3D Printing in Bioimplants' Applications

Vikas Sharma¹, Jashanpreet Singh^{1,*} and Amanpreet Singh²

¹ University Center for Research and Development, Chandigarh University, Mohali, Punjab, India.

² Centre for Research Impact and Outcome, Chitkara University Institute of Engineering and Technology, Chitkara University, Rajpura, Punjab, India.

* Corresponding Author Email: jashanpreet.e17331@cumail.in

ABSTRACT

3D printing is rapidly revolutionizing the field of biomedical engineering, particularly in the production of customized implants. This manuscript explores the diverse applications of AM for the fabrication of implants in various medical disciplines such as orthopaedics, dentistry, and craniofacial surgery. Selective laser melting (SLM), fused deposition modelling (FDM), and stereolithography (SLA) are examined as the main additive fabrication techniques in terms of bioimplant manufacturing. It also includes a variety of biomaterials applied in 3D printing with emphasis on their mechanical capabilities, compatibility, and applicability in various procedures. With the help of digital design files and advanced printing techniques, healthcare providers can supply implants with respect to a patient's exact anatomy, resulting in better fit, high performance, and more comfort than conventional mass-produced options.

The paper also highlights the advantages of AM, such as reduced surgical period and enhanced patient outcomes because of the precise customization of implant geometries. The use of 3D printing in practice has disadvantages and major obstacles, such as production limitations, cost of production, strict regulations, and long-term clinical evidence. This review discusses the future possibilities and potential of 3D printing to enhance personalized medicine and the need for interdisciplinary cooperation to address existing barriers.

Keywords—*Additive manufacturing, 3D printing, Orthopaedics, Customized implants, Regenerative medicine, Personalized medicine.*

Copyright © 2025. This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY): *Creative Commons - Attribution 4.0 International - CC BY 4.0*. The use, distribution or reproduction in other forums is permitted, provided the original author(s) and the copyright owner(s) are credited and that the original publication in this journal is cited, in accordance with accepted academic practice. No use, distribution or reproduction is permitted which does not comply with these terms.

INTRODUCTION

Additive manufacturing (AM) or three-dimensional (3D) printing is a transformative technology used in the development of 3D objects using layer-by-layer material deposition based on 3D models.¹ The 3D printing technology has created a transformational change in medical implantology (i.e., design, placement, and management of medical implants), especially in the designing and manufacturing of orthopaedic implants.² The AM technology allows the production of patient-specific implants (PSIs) according to individual anatomic needs. Thus, it overcomes the shortcomings of the conventional implant manufacturing processes. AM directly creates a complex part from a computer-aided design (CAD), not possible with the conventional manufacturing processes based on subtractive subtraction of a material. 3D printing enables the fabrication of implants with complex geometry and improved functional characteristics based on high-resolution imaging, CAD, and layer-by-layer material deposition to provide unprecedented possibilities in medical applications with customization and precision.

The 3D printing or AM also has a profound effect on the biomedical industry, with the capability to produce complex, customized medical devices, vaccines, and tissues.³ 3D printing reduced the burden of material production, truncated the pattern of preparation, and offered a wider domain to treat diseases.⁴ In orthopaedics, 3D printing is utilized for a wide range of applications, including joint replacements, fixation devices, and spinal fusion systems. The notion of designing complex surface structures and customization of implants to the specific needs of patients has transformed the way surgical operations are planned and implemented.⁵ These customized implants not only improve surgical outcomes but also reduce complications associated with misalignment and suboptimal fit. Furthermore, the technology is rapidly evolving to address challenges, such as regulatory compliance, material biocompatibility, and scalability, making it an integral component of modern orthopaedic practices.

3D printing is an emerging technology with a lot of potential to be translational in biology and medicine.⁶

Lately, 3D living and non-living materials are under extensive scrutiny for a possible alternative to the traditionally used and proffered solutions to testing and combating antimicrobial resistance (AMR). To be able to control the cell and micro-environment accurately with the complex presence and activities of the cell, AM has a good chance to promote medical treatment. The technology used in 3D bioprinting has made cell-laden scaffolds more applicable and functional.⁷ One of the prerequisites for the evolution of 3D printing in tissue engineering is the research of innovative compatible biomaterials for use in bioprinting with fast crosslinking properties. The developers should consider the key aspects of making the technology printable so that it can enhance the coding of the fabrication process, as well as cell encapsulation. 3D printing methods could help in many medical and pharmaceutical areas, including tissue regeneration, printing organs, and drug delivery.⁸ The technology has presented itself as a game-changer in the biomedical sector, with 3D printing presenting a wide range of applications and advantages.⁹ It is very important in facilitating the increase and reconstruction of destroyed tissues. It is able to build structures (resembling the native tissue) and regenerate the tissue by precisely depositing cells, biomaterials, and growth factors. It will facilitate the production of complex cellular structures and even working organs in the future. This is when multi-type cells and biomaterials are combined in three-dimension (3D) to produce functional structures. In medical engineering, 3D printing has taken the form of a more potent production stage.⁹ These techniques are very helpful to produce a variety of complex and specialized biomedical products of high precision, layer by layer of materials, biomolecules, and living cells.

The selection and manufacturing process of the tissue engineering materials is an important factor in the context of compatibility, sensitivity, and interaction with other organs in case of a failed organ replacement.¹⁰ A versatile range of biomaterials, such as polymers, hydrogels, ceramics, composites, and metals, can be achieved by 3D printing.¹¹ It makes possible the construction of complex structures with high resolution and accuracy. Implants and prostheses are manufactured using 3D printing, which

means that they are exact to the anatomy of the patient.⁹ This has the potential to result in more compatibility with the surrounding tissues and enhances long-term performance. Customized prosthetics and orthotics are also developed using this technology; this offers a superior fit, additional comfort, and enhanced functionality. 3D printing provides the opportunity of rapid prototyping prosthetic and orthotic design, in which designers and clinicians are able to test and update the design instantly by following the patient input, so that the resulting devices are superior and more humane in use. 3D printing has its prospects in the perspective of mechanical engineering through the finite element analysis of implants, that is, a computational technique of modelling how implants respond to different loads to optimize their design and functionality.¹² Furthermore, the implants are now done through 3D printing, thus enabling a unique implant with intricate geometries to suit patient's specific requirements.

This paper explores the diverse applications and benefits of 3D printing in orthopaedic implants, with a focus on its role in enhancing surgical precision, improving patient outcomes, and advancing sustainable manufacturing practices. Additionally, this paper highlights the challenges

facing the widespread adoption of this technology and the future directions that hold promise for overcoming these barriers. Through a comprehensive analysis, this review paper elaborates the pivotal role of 3D printing in the development of personalized medicine and the practice of high-quality orthopaedic surgery through a broader analysis.

3D PRINTING TECHNIQUES FOR BIOMEDICAL IMPLANTS

The integration of the concept of 3D printing or AM in biomedical implants has transformed the development and fabrication of medical equipment.¹³ Different methods of 3D printing have been developed, which are characterized by their own inimitable benefits. These methods increase the efficiency and placement of bioimplants into the human body.¹⁴ It discusses five major 3D printing methods applicable in the designing of biomedical implants: powder bed fusion (PBF), binder jetting, material extrusion (M/E), directed energy deposition (DED), and stereolithography (SLA). Table 1 demonstrates the 3D printing methods and materials applied to bioimplants.

TABLE 1. 3D printing techniques and materials for bioimplants.

S. No.	Technique	Materials	Application	Benefits	Drawbacks	References
1.	Selective laser sintering (SLS)	Polycarbonate (PC), polyurethane (PU), etc.	Customized implants, surgical tools, prosthetics, etc.	High strength, durability, and complex geometries	Expensive, limited resolution, and rough surface finish	15-17
2.	Stereolithography (SLA)	Photopolymerizable resins such as acrylates, epoxies, and polyurethanes	Dental models, prosthetics, surgical guides, etc.	High-resolution, smooth surface finish, and accuracy	Expensive, limited material selection, and potentially toxic photo initiators	18
3.	Fused deposition modelling (FDM)	Poly(lactic acid (PLA), polyethylene terephthalate (PET), polyethylene oxide (PEO), etc.	Customized implants, surgical guides, prosthetics, etc.	Low-cost, versatile, and easy to use	Limited strength and stiffness, poor resolution, and rough surface finish	19-21
4.	Electrospinning (ESP)	Polycaprolactone (PCL), poly(vinyl alcohol (PVA), collagen, etc.	Tissue engineering, wound healing, and drug delivery	High porosity, biocompatibility, and fiber diameter control	Limited mechanical strength and complex 3D structures	22-24
5.	Inkjet printing (IJP)	Hydrogels, synthetic polymers, bioinks, etc.	Tissue engineering, drug delivery, and regenerative medicine	High flexibility, scalability, and control over composition	Limited mechanical properties, resolution, and stability	25,26
6.	Digital light processing (DLP)	Poly(ethylene glycol) diacrylate (PEGDA), GelMA, Polyurethane (PU)	Tissue engineering, drug delivery, and surgical planning	High resolution, accuracy, and speed	Limited material selection, biocompatibility, and mechanical properties	27,28

Powder Bed Fusion

One of the most common 3D printing techniques is powder bed fusion, which involves the process of melting or sintering powdered materials through layer-by-layer selectivity into solid objects.²⁹ Figure 1 presents a schematic diagram of PBF. It works particularly well in applications involving biomedical implants for producing complex geometries that closely mimic natural bone structures. The technique commonly utilizes titanium (Ti) and cobalt–chromium (Co-Cr) alloys that are considered biocompatible metals because of their strong, durable, and biocompatible nature with human tissues. A major advantage of PBF is its ability to allow the development of porous structures, leading to facilitated osseointegration. In the osseointegration, an implant properly connects with the surrounding bone, which reduces the complications related to stress shielding. Therefore, the surrounding bone is resorbed.²⁹ For example, PBF can be used to create implants in a trabecular lattice structure that allows oriented in-growth of bones, enhancing the effective life and functionality of orthopaedic implants. Also, the PBF can create complex internal architectures and allows manipulating implants to be more suitable to fit biological functions; this has made it gain popularity in orthopaedic and dental surgery.

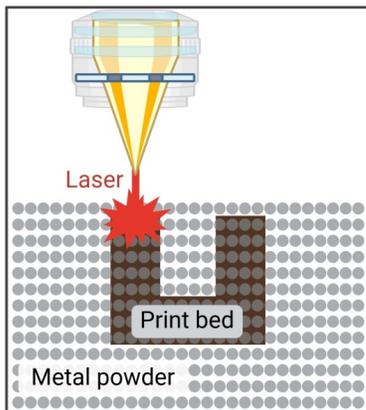


FIGURE 1. Schematic diagram of powder bed fusion (PBF) technique.

Binder Jetting Technique

Another 3D printing method is binder jetting technology (BJT), in which powders are fused with the help of a liquid agent,³⁰ as schematically shown in Figure 2. The technique

offers high accuracy in producing intricate forms and has little waste of materials. BJT can specifically be applied in biomedical engineering to make ceramic and metal implants. Multi-material constructs can also be produced by BJT. Thus, it allows dissimilar properties within the same implant to be combined together, for example, using bioactive ceramics with metals to facilitate improved bone healing.³¹ For instance, a dental implant made by combining Ti, providing good mechanical strength, with bioactive glass, offering osteoconductivity, using BJT integrates more favourably with the tissue of the jawbone. In addition, BJT has the ability to scale to mass production, so it provides an inexpensive solution in manufacturing patient-specific implants in larger volumes with high fidelity to patient anatomy.³²

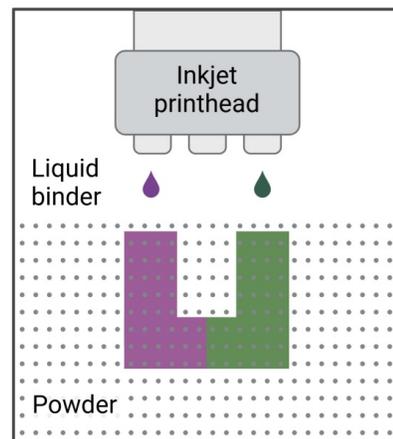


FIGURE 2. Schematic diagram of the binder jetting technique.

Material Extrusion Technique

In biomedical applications, one of the most accessible and widely adopted procedures of 3D printing is the material extrusion technique (MET).³³ It consists of extrusion of a thermoplastic or bioink material through a nozzle to stack the layers side by side, as exemplified in Figure 3. MET (in bioimplants) is especially successful in creating polymer-based implants that require flexibility and biocompatibility. MET is customized easily depending on the information of the patient through medical imaging techniques, such as computed axial tomography (CAT) scan and magnetic resonance imaging (MRI). The mechanical properties and tissue integration of composite filament applications, which are constituted of polymers

and bioactive fillers, are increased with the use of MET. Polymer scaffolds, 3D-printed and impregnated with hydroxyapatite (HA), had the ability to imitate natural bone structure and ensured a good ambience in terms of proliferation and regeneration of cells.³⁴

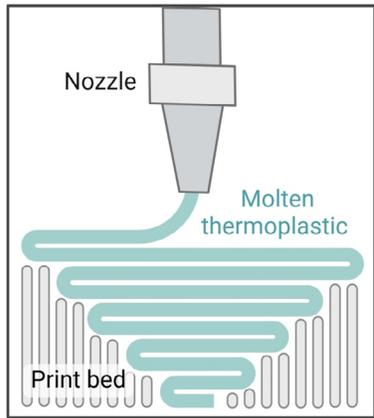


FIGURE 3. Schematic diagram of the material extrusion technique (MET).

Directed Energy Deposition

Directed energy deposition (DED) involves focused energy sources, such as lasers or electron beams, to melt deposited materials on the substrate, as shown in Figure 4.^{35,36} DED is advantageous in repairing the existing implant or in post-processing the implant after formation. In biomedical applications, DED is used to make large-scale implants of tailored properties by varying the composition of materials throughout the deposition sequence. This ability has led to the production of functionally graded materials in which properties vary gradually throughout the implant. This allows these materials to adapt more effectively to physiological loads and perform better with time.³⁷ Furthermore, DED has the potential to manufacture patient-specific osteotomy instruments and orthopaedic implants that can fit the anatomical demands of the patient.³⁸

Stereolithography

Stereolithography (SLA) involves the use of ultraviolet (UV) light in curing photopolymer resins progressively into solid objects.¹⁸ SLA is acknowledged due to its high-resolution printing and smooth finish of the surface, as presented in Figure 5. Thus, it has been used for

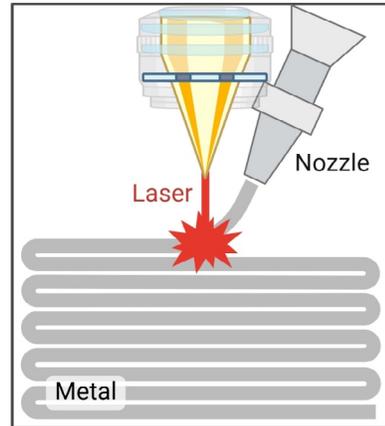


FIGURE 4. Schematic presentation of the directed energy deposition (DED) technique.

creating highly complex models required in bioimplants, particularly in the fields of dentistry and craniofacial surgery. Moreover, new developments in biocompatible resins have increased the scope of SLA to be used in manufacturing temporary implants or tissue-supportive scaffolds. For instance, with the help of SLA technology, it is possible to make cranial plates that are perfect to be shaped on defects and traumas in the skull as a result of trauma or surgical operations. It decreases the period of recovery and increases patient satisfaction.

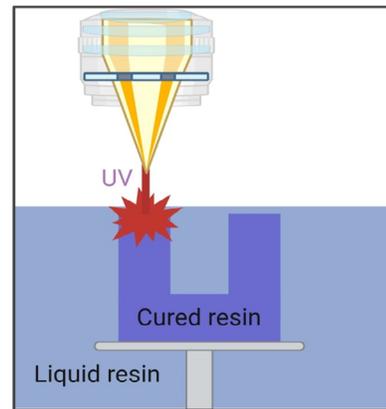


FIGURE 5. Schematic presentation of stereolithography (SLA) technology.

One new way to make one-of-a-kind products is using 3D printing. In the biomedical industry, the most common 3D printing methods include extrusion printing/bioprinting, SLA, powder deposition printing (such as FDM), laser-assisted printing (such as selective laser

sintering [SLS] or selective laser melting [SLM]), and direct ink writing (DIW)/inkjet bioprinting.^{39,40} The first method of creating 3D objects was SLA. This method often makes use of thermoset photopolymers. The process of solidifying liquid resins allows the generation of object models. The area of 3D printed ceramic biomedical devices has reported extensive use of these approaches.⁴¹ Composites made of SLA have potential applications in the fields of dentistry and cardiovascular medicine. Another 3D printing technology is digital light processing (DLP), which largely uses the same light source as SLA but with a different printing approach.²⁷ The DLP manufacturing really shines for developing conductive products for the electrical industry. That means conductive polymer systems are a viable option for the method's first components.

MATERIALS FOR 3D PRINTING OF BIOMEDICAL IMPLANTS

Metallic Materials

Various types of 3D printing metallic materials (Figure 6) are as follows.

Titanium and Its Alloys

Owing to their high specific strength, good corrosion resistance, and excellent biocompatibility, Ti and its alloys have been utilized extensively in biomedical implants since the 1970s.⁴² Ti exhibits an α -phase (hexagonal), close-packed lattice structure at ambient temperature, and if heated to 883 °C, the β -phase with body-centered cubic structure appears. An increase in β/α transus temperature is one way that alloying elements, such as aluminium (Al), carbon (C), and oxygen (O), prolong the α -phase, and a decrease in the transus temperature is another way that molybdenum (Mo), tantalum (Ta), and niobium (Nb) employ.⁴² Thus, α , near- α , ($\alpha + \beta$), and β type alloys are the four primary categories into which Ti alloys accrue. Ti alloys can have their grain size changed by plastic deformation, and osseointegration is enhanced in alloys with smaller grains, because there are fewer atoms per grain and a higher surface energy. Specifically, as contrasted with traditional Ti-64 (with a high strength-to-weight ratio) variations—ultrafine-grained commercially pure titanium (CP-Ti) and Ti-64 alloys (with

a grain structure in the submicrometer to nanometre range)—exhibit far superior vascular and bone cell adhesion.⁴³ The formation of a passive TiO₂ coating by CP-Ti and Ti-64 occurs naturally. This film contains OH⁻ ions, which interact with the mineral components of the bones and enhance osteointegration. Ti-64 is used by half of all biomedical implants, but it's not without its fears. It contains cytotoxic Al and vanadium (V); thus, new alloys without these elements have been developed specifically for implant applications.⁴⁴

Gallium Alloys

In contrast to solid metals, gallium (Ga) alloys have a wide range of medicinal uses, such as nerve reconnection, vascular embolization, tumor therapy, and flexible interconnects.⁴⁵ Metal thiolate complex functionalization of Ga alloy nanoparticles has opened new avenues for drug delivery.⁴⁶ Antennas and electrodes used in biological applications benefit from Ga alloys' self-healing properties. For instance, when a Ga alloy-filled channel is cut, the alloy forms a protective oxide that stops liquid metal from escaping or dripping out. When the two pieces are rejoined, the liquid metal eventually combines, and electrical conduction is normalised. Additionally, the channel is able to mechanically mend itself if it is composed of a self-healing polymer.

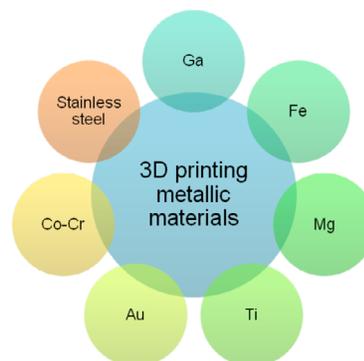


FIGURE 6. Various types of 3D printing metallic materials.

Iron

Proteins in hemoglobin and myoglobin are responsible for carrying oxygen to the tissues. Other proteins and

enzymes involved in metabolism contain iron (Fe), an important trace element for nearly all living things.⁴⁷ It is known that the elevated Fe concentrations are poisonous. The outstanding mechanical properties of Fe-based materials make them an attractive option for biodegradable implants.⁴⁸

Magnesium and ITS ALLOYS

In addition to its role in energy metabolism and protein synthesis, magnesium (Mg) aids in the regulation of blood sugar and maintenance of bone strength. The kidneys filter out excess Mg after its absorption in the digestive tract.⁴⁹ Infection and formation of hydrogen bubbles are two issues when using Mg alloys as implants. The solution to this is to nucleate Mg alloy as metallic glass, an amorphous, one-phase structure, which eliminates hydrogen bubbles. Because of its flammability, 3D printing of Mg scaffolds requires an inert or vacuum environment.⁴³

Gold

The many desirable properties of gold (Au) include its high infrared reflectance, ductility, electrical conductivity, and thermal conductivity, which make it an ideal material for use in engineering.⁵⁰ Owing to the high cost of Au, only electroplated objects are used. Ocular prosthetics, especially for the surgery of the upper eyelids, endovascular stents, soluble injectable compounds to treat or prevent bacterial infections, and restorative dentistry (implants, fillings, gold wire fixings, and supports) are among the many uses of Au.

Cobalt–Chromium Alloys

Medical implants made of Co-Cr alloys have been used since the 1930s. Compared to stainless steel, Co-Cr alloys offer superior corrosion resistance and wear resistance.⁵¹ As this alloy contacts the human body, Cr creates a protective Cr_2O_3 coating, which makes it very biocompatible. Some implants, such as Co-Cr-Mo manufactured implants, discharge ions of Co and Cr into the bloodstream because of their metal-on-metal bearings.⁵² After 4–5 years of implantation, some patients with metal-on-metal hip prosthesis have reported severe reactions because of cobalt toxicity. Treatment of the laser with the alloy and calcium phosphate coating of the prosthesis might be

applied as one of the methods to make the process of osseointegration faster and further improve the surface characteristics of the implant and stimulate the development of new bone tissues.⁵³

Stainless Steel

Stainless steel alloys consist of Fe and Ni alloys with chromium content $\geq 11\%$. By manipulating the doping and heat treatment of stainless steel, one can influence its mechanical properties. Owing to its biocompatibility, low cost, ease of manufacturing, and widespread availability, austenitic stainless steel, such as stainless steel 316L, is used in the majority of biomedical applications. Co-Cr alloys form a protective oxide layer on stainless steel surfaces.

Polymer-Based Materials

Figure 7 shows various types of 3D printing polymeric materials. The following sections present a detailed discussion on polymeric 3D printing materials.

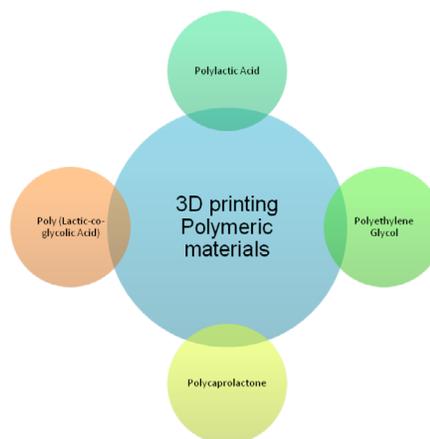


FIGURE 7. Various types of 3D printing polymer-based materials.

Polylactic Acid

Corn starch, tapioca roots, and sugarcane are some of the renewable natural resources used to make polylactic acid (PLA). It melts at the moderate temperatures of 160–180 °C, and is biodegradable.⁵⁴ Its mechanical qualities and high level of biocompatibility have made it a US Food and Drug Administration (FDA)-approved implantable medical device. Liu et al. etched and coated the PLA fused deposition modelling (FDM)-printed scaffold with polydopamine

(PDA) to investigate the topographic shift brought about by etching that affected cell adherence, growth, and proliferation.⁵⁵ Both in vitro and in vivo studies demonstrated that the etched and PDA-coated scaffolds were superior to the unetched scaffolds in terms of cell proliferation, growth, cell viability, and bone regeneration.

Polyethylene Glycol

A synthetic biocompatible polymer with hydrophilicity and solubility in a range of liquids, polyethylene glycol (PEG) is also known as polyethylene oxide (PEO). Compared to other materials, PEG's compressive modulus is higher because of its larger molecular weight. The mechanobiological evaluation of PEG and its composites involves combining tendon extracellular matrix (tECM) with PEG diacrylate (PEGDA) by SLA printing to produce a stronger and more porous scaffold.⁵⁶ While tECM makes the synthetic polymer more biocompatible, PEGDA provides the scaffold with its physical and mechanical strength.

Polycaprolactone

The US FDA has authorised polycaprolactone (PCL), a synthetic aliphatic polymer used in tissue regeneration. It is inexpensive and easy to obtain. Its biocompatibility and slow disintegration rate have made it a popular polymer-based material. PCL's decreased cytotoxicity and inflammation in vivo are due to its breakdown rate. Mechanically, two types of cervical cages are characterised: first, with a ring form, and the second with a porous rectangular shape, and their static and fatigue properties are SLS-printed. The structural properties are impacted by the geometry and design of the cages, as demonstrated by mechanical characterization through static and dynamic loading of cages.

Poly Lactic-Co-Glycolic Acid

Two different monomers, namely PLA and PGA, combine to form poly lactic-co-glycolic acid (PLGA). Its use as a biodegradable polymer in healthcare is approved by the FDA. Polycondensation or ring-opening of PLA and PGA are two methods for its synthesis. PLGA is very easy to process with good biocompatibility. The incorporation of nano-titania and PLA into a composite scaffold improves its mechanical characteristics and stimulates bone cell

function by simulating macro- and nano-structures of real bone.⁵⁷ Liu et al. extruded a scaffold from the composite material using an aerosol-based printing process.⁵⁷ According to the authors, cell adhesion was highest for surfaces with roughness similar to that of real bone. In vitro tests showed that osteoblasts interacted with 3D scaffolds, infiltrated bone cells, and proliferated.

Ceramic Materials

Oxide ceramics contain metal oxides and are known for their excellent thermal and chemical stability. The following are some examples of ceramic materials used in bioimplant applications.

Alumina

Alumina (aluminium oxide [Al_2O_3]) is widely used due to its hardness, corrosion resistance, and electrical insulation properties. It is commonly found in cutting tools, substrates for electronics, and dental applications. Alumina is renowned for its hardness and wear resistance, making it ideal for applications such as dental implants and industrial cutting tools.⁵⁸ Its ability to maintain structural integrity at high temperatures allows it to be effectively processed using techniques such as SLS and binder jetting, enabling the creation of complex geometries that meet demanding performance requirements.

Zirconia

Zirconium oxide (ZrO_2) is a high-strength ceramic with low thermal conductivity, which makes it particularly suitable for applications requiring durability and resistance to thermal stress. Oxide ceramics, including zirconia, have very high melting points and are widely used in electronics, aerospace, and chemical processing. Zirconia is especially important in 3D printing for the dental field, where excellent mechanical properties, such as toughness, aesthetics, and biocompatibility, are desired. It is commonly used in crowns, bridges, and orthopaedic implants due to its durability and natural appearance. Advanced 3D printing techniques, such as SLA and DLP, allow high-resolution fabrication of dental restorations, expanding their role in biomedical applications.⁵⁹ Research on zirconia processing continues to optimize its properties and enhance clinical performance.

The 3D printed models can be prepared from diverse materials, such as metals, plastics, ceramics, etc. The materials that are usually compatible with particular processes include Ti, Co-Cr alloys, and stainless steel; they are usually compatible with electron beam melting, selective laser melting, and direct metal laser sintering. Some of the ceramic materials, such as Al₂O₃, hydroxyapatite, and calcium phosphate, are also used for 3D printing. JBT and MET are commonly used methods of printing ceramic materials. Polymeric materials, such as PLA, PCL, and polyethylene (PE), are widely used in the medical field. Natural polymers include collagen, alginate, silk, fibrin, hyaluronic acid, chitin, chitosan, gelatin, and polysaccharides.⁶⁰ Properties of natural polymers help to maintain the extracellular matrix composition of tissues and make them suitable for constructing scaffolds.

Despite their low mechanical strength, ceramic materials are very biodegradable and have excellent bioactivity.⁶¹ Materials, such as Ti and stainless steel, are often used in the medical field. FDM is now the method of choice for fabricating models in 3D printing.⁶² Compared to other methods, it offers several benefits, including affordability, user-friendliness, and thermal and mechanically sound products. Human tissues, bones, and blood vessels are created using 3D bioprinting technology and biomaterials. Hydrogels, bio-glasses, bio-ceramics, and other similar materials are used in bioprinting. Hence, the biomedical sector is strongly associated with 3D printing for creating scaffolds, implants, etc. Tissue engineering and organ transplantation are two areas where bioprinting is finding many uses. This method of bioprinting makes use of a variety of technologies, including thermal inkjet, micro extrusion, and laser-assisted printing.⁶³

APPLICATIONS OF 3D PRINTING IN BIOMEDICAL IMPLANTS

The AM technology has many benefits that contribute largely to the manufacture of implants. The customization is one of the most outstanding advantages as it can produce patient-specific devices according to their anatomical requirements. Such a high degree of personalization has

the potential to result in better surgical outcomes and patient satisfaction. Furthermore, AM helps to achieve waste reduction because of its layer-by-layer principle that helps to eliminate the wastage of materials, compared to old subtractive manufacturing.¹³ This also makes the process sustainable as well as reduces production costs. Moreover, with AM, it is easy to conduct rapid prototyping, which means that it is easy to perform one or a few iterations of the device's design and form, and thus development cycles can be made faster. This hierarchical ability shortens the development of innovation, which results in more efficiently designed and higher-quality implants. The technology has revolutionized medical device manufacturing, as it is now possible to manufacture patient-specific implants and prosthetics to improve surgical registry and patient satisfaction. As illustrated in Figure 8, some uses of implants of 3D printing include hand and arm applications, bone and joint applications, implantable devices applications, and inside and outside use applications. Among the most remarkable strengths of 3D printing is the possibility to print individually fitted implants on the basis of the unique anatomical scan; this makes the process extremely precise. Thus, it is less prone to complications brought about by improperly designed and manufactured devices.⁶⁴ Moreover, 3D printing can also be used to aid rapid prototyping, in which the prototypes can be iterated and tested for developing new ideas without long lead times of manufacturing. This ability also helps in hastening the invention of new products in the fields of orthopaedic implants, dental products, and heart stents.⁶⁵ In this case, Ti cranial plates can be 3D printed in a shorter period, thus reducing the time previously needed for reconstruction surgeries using conventional methods. Additionally, the incorporation of bioprinting technologies has provided more opportunities in the production of functional tissues and organs.⁶⁶ By culturing living cells on top of one another with biomaterials, researchers are able to create tissue constructs that appear similar to natural organs. This can be used in the field of organ transplantation, where the availability of organs is very limited, thus solving the problem of grafting, and also contributing to the field of regenerative medicine.

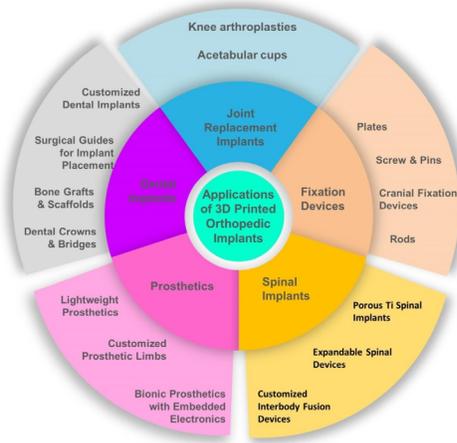


FIGURE 8. Various implant applications of 3D printing.

Orthopaedic Implants

The development of AM technology has contributed to the quality and effectiveness of orthopaedic implants, resulting in increased improvement of surgical results and patient satisfaction, as shown in Figure 9. The material innovations present one of the greatest changes, and the use of biocompatible materials. In the same context, advancement in making Ti implants has resulted in high strength and also being favorable in terms of integrating with bone tissues. The materials used are safe to interact with human tissues, which also reduces possible rejection and complications. Moreover, advancement in the field of biocompatibility has led to the search for other bioactive ceramics and polymers. This has also contributed to the performance and durability of orthopaedic implants. Wu et al. investigated the possibilities of 3D printing in the design of orthopaedic implants with a focus on the ability to develop complex-geometry implants with patient specificity for high mechanical and biological performance.⁶⁷ The authors found these parameters suitable for the success of implants in terms of lower porosity and pore size, which results in bone ingrowth and the mitigation of stress shielding. García-Ávila et al.⁶⁸ presented a dynamic topology optimization method for the design of transtibial orthopaedic implants, using high-speed AM processes, such as continuous liquid interface production (CLIP). The authors explained the inclusion of biomechanical data using gait cycle forces into the design process, thus resulting in lower load distribution

and high implant stability. The authors further demonstrated that significantly lightweight implants could be achieved by porous metamaterials formulated on triply periodic minimal surfaces (TPMS) and without the loss of isotropic behavior.

Fixation Devices

The use of fixation devices for orthopaedic and cranial surgeries is redefined by the nature of 3D printing technology. Additive manufacturing has significantly enhanced the customization, precision, and overall performance of critical medical components which includes plates, screws, pins, cranial fixation systems, and rods. These innovations have removed the shortcomings of conventional manufacturing through patient-specific solutions, greater functionality, and better surgical results.

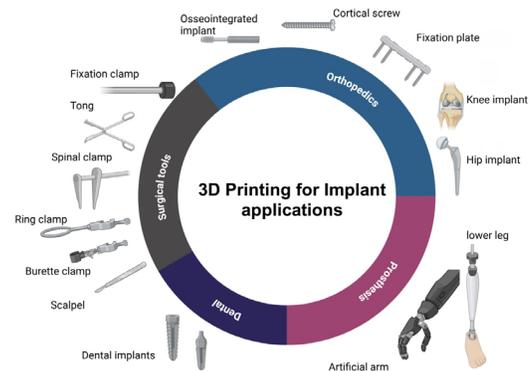


FIGURE 9. 3D printing in biomedical applications.

Plates

3D printing has benefited the production of plates used in fixing the bones. The conventional plates usually need adjustments by the surgeon during the surgery to generate the anatomical shape of the patient. This factor increased the length of the surgery and lowered its accuracy.⁶⁹ With the help of 3D printing, plates are made and adapted to the exact geometry of the bone, which is a good fit and distributes load more efficiently. The new technology with 3D printing makes it possible to print plates with complex internal lattice structures, of less weight, and of the same mechanical strength. Such small patient-specific plates reduce the irritation of neighboring tissues and accelerate recovery. Liu et al. studied the development of a 3D-printed

permanent implantable porous tantalum-coated bone plate that can be used to fix a fracture.⁷⁰ They also found that the porous coating of Ti improves osteogenesis and osseointegration, and is mechanically compatible with human bones. In animal studies, the rate of fracture healing is higher, as a better callus develops with Ti-coated plates, compared to conventional and porous Ti plates. The research highlighted the possibilities of combining 3D printing and chemical vapor deposition to develop superior orthopaedic implants. Oraa et al. discussed the case application of 3D technology in the field of orthopaedics, considering derotation tibial osteotomy.⁷¹ The authors illustrated the process of creating and printing their own cutting guides and osteosynthesis plates using 3D printing. Their method showed accurate corrections in bone deformities using virtual surgery planning and personalized implants to achieve the best possible outcome of surgery. The method demonstrated the increasing use of 3D printing in customized orthopaedic care.

Screws and Pins

Bone stabilization requires screws and pins, which have to be designed using 3D printing so that they are better than the original ones. AM enables the screws and pins to be manufactured both lengthwise and width-wise perfectly, with the best pattern of threads and surface texture that would enhance their grip and stability on the bone. Second, high-tech and biocompatible materials, non-reactive to the human body, can be used to create these devices from Ti or composite polymers. Customized screws and pins are especially useful in complicated fractures or deformities where more standard components are unlikely to provide sufficient support. Figure 10 shows the fitting of Ti interbody cages and anterior plate fixation in the cervical spine. Miao et al.⁷² examined the use of 3D printing technology in the calcaneal fracture repair of the paediatric population using percutaneous reduction and cannulated screws. The authors proved that preoperative planning using a 3D printing model improved surgical precision and results. Sampath Kumar reported that the angle of Böhler, calcaneal height, and length showed significant improvement following surgery.⁷³ In addition, the clinical outcome assessed by the American Orthopaedic Foot and Ankle Society (AOFAS) with a hindfoot score

was 94.1, which indicates good postoperative function. Although a few complications were noted, both surgeons and patients expressed higher satisfaction. This study highlights the value of 3D printing in the visualization of fractures and supporting surgical planning.



FIGURE 10. Cervical spine X-ray illustrating anterior discectomy and fusion at C5–C7, utilizing Ti interbody cages and anterior plate fixation.⁷⁴ (Permission under the CC BY 4.0 license).

Fixation Devices

The neurosurgery cranial fixation devices are needed when cranial bones are fixed after trauma or surgery.⁷⁵ These devices have seen transformative improvement through 3D printing, where they have been subjected to radical innovations.⁷⁶ The benefit is the possibility to develop patient-specific devices that fit the specific shape of the skull, eliminating complications and guaranteeing a perfect fit. Moreover, custom prototypes of cranial fixation devices produced by 3D printing could be endowed with properties to promote osseointegration (porosity), resulting in better long-term results because of lighter weight and high strength.

Rods

Rods are an essential part of spine and long bone surgeries to ensure the structure and alignment of a patient. The geometries and surface finishes of rods are focused on using 3D printing to enhance their mechanical behaviors and compatibility with the body. Patient-specific rods can be adjusted to fit specific dimensions that correspond to the requirements and help in minimizing intraoperative

changes. Also, Ti alloys are used in rods because of their strength and lightweight properties, which minimize stress on the surrounding tissue. Figure 11 shows the integration of patient-specific implants and bone cements with distraction osteogenesis. The successful use of custom-designed parts was observed to achieve maintenance of alignment and gradual bone transport.⁷⁶

It is a part of a larger pattern in orthopaedic and spinal surgery, in which the 3D-printed rods and implants are custom-designed to match specific anatomy. The use of rods to stabilize spinal and long bone surgeries is important for maintaining structural integrity and restoration of shape. 3D printing has made it possible to create rods that have new geometries and treatments to enhance the mechanical properties and compatibility with tissues. The rods are also customized to specific patients regarding length and curvature, so that less or no adjustment is needed during the procedure. Moreover, the material used to make rods (Ti alloys) makes them strong and, at the same time, light to reduce stress on neighboring tissues. Figures 11A and 11B indicate the intraoperative use of PSI and vancomycin-loaded Refobacin 12 bone cement used to execute the defect.⁷⁶ Manipulation of the wound after the operation was performed using vacuum sealing drainage (VSD), sparing skin grafting, and progressive cement removal as a part of the bone transport procedure. The X-rays indicate proper alignment of fractured fragments and had 1.74-mm valgus and 1.14-mm angles of anteversion. The Ilizarov fixator was stable (Figure 11C and 11D).

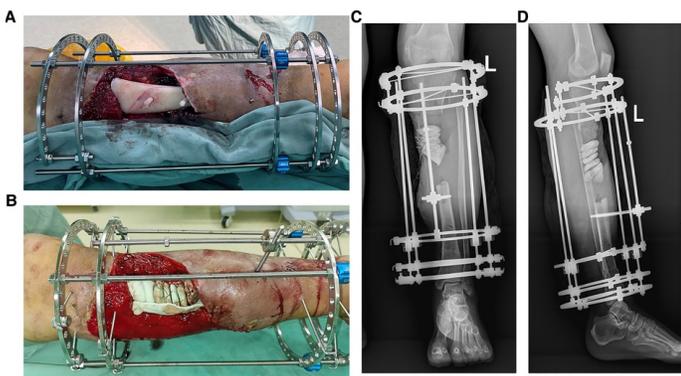


FIGURE 11. Intraoperative patient-specific instrument placement and postoperative X-rays in case 1 using Ilizarov distraction osteogenesis. (A) PSI maintains fracture alignment; (B) pie-shaped

bone cements inserted for gradual removal during transport; (C) postoperative AP X-ray shows 1.74° valgus angulation; and (D) lateral X-ray shows 1.14° anteversion.⁷⁶ (Permission under the CC BY 4.0 license).

Joint Replacement Implants

Specifically, knee arthroplasties, acetabular cups, and other implants of joint replacement applications have gained a remarkable transformation, individualization, and effectiveness offered by AM. Various joint replacement implants are discussed as follows.

Knee Arthroplasties

3D printing has become a game-changer in knee arthroplasty by enabling the production of highly customized implants tailored to individual patients' anatomy. Traditional knee replacement procedures often rely on standardized implants that may not perfectly match a patient's unique bone structure, potentially leading to discomfort or reduced mobility. By employing 3D scanning and printing technologies, surgeons can now design implants that precisely replicate a patient's knee geometry. This customization enhances joint alignment, reduces wear and tear, and minimizes the risk of post-operative complications.⁷⁷ Figure 12 presents the overall process of designing and applying 3D-printed PSI into orthopaedic surgery.⁷⁸ A preoperative planning (Figure 12A–12D) is made using a CT scan and shows the precise modelling of the distal femur and proximal tibia of the patient, which is reconstructed accurately. The 3D models reconstructed (Figure 12E) are inserted with osteotomy markers that help in making surgical incisions. On the models (Figures 12F and 12G), the fit of PSI is checked to ensure accuracy prior to surgery. Throughout the process, the PSI is placed on the bone to advise capacities in the operation (Figures 12H and 12I), which increases precision in the surgery. As comparison of the scheduled and actual osteotomy volumes (Figure 12J) verifies, the bone cuts are very close to the preoperative plan, which proves that the PSI is effective in enhancing surgical results. Furthermore, the ability to preprint surgical guides based on patient-specific data allows for greater accuracy during the procedure, reducing operating time and improving the overall outcome.



FIGURE 12. Design and intraoperative use of 3D-printed PSI: (A–D) CT-based preoperative planning for femoral and tibial reconstruction; (E) 3D models of distal femur and proximal tibia with osteotomy markers; (F and G) PSI fit verification; (H and I) intraoperative placement of PSI; (J) real-time comparison of planned versus actual osteotomy volume.⁷⁸ (Permission under the CC BY 4.0 license).

Acetabular Cups

In hip replacement surgery, acetabular cups serve as a crucial component for restoring joint function and stability. 3D printing has introduced groundbreaking improvements in the design and functionality of these implants. By leveraging AM, acetabular cups can now incorporate porous structures that mimic the natural trabecular bone architecture. This porosity not only facilitates superior osteointegration that helps the bone grow into the implant but also guarantees a long-term stability and durability of the implant. Furthermore, advanced materials that cannot be (or are more difficult to) 3D printed are used; for example, Ti alloys offer a greater strength to biocompatibility as well as corrosion-resistance.⁷⁹ Such innovations increase the life duration of implants and decrease the chance of revision surgeries.

Prosthetics

3D printing has facilitated innovative solutions in several categories of prosthetics. AM techniques are of great use to develop lightweight prosthetics, customized prosthetic limbs, and bionic prosthetics with embedded

electronics. These developments have not only made prosthetics more accessible and useful but also improved the lives of people with impaired limbs.

Lightweight Prosthetics

One of the contributions of 3D printing is to design lightweight and strong prosthetics. The conventional materials used in developing prosthetics are quite cumbersome, for instance, heavy metals or dense polymer, and are usually inconvenient to the individuals using them. Titanium alloys are mixed with other materials to produce advanced polymers and subsequently printed to attain low weight and increased strength.⁸⁰ Also, a lattice structure facilitated by 3D printing is of lesser weight and does not compromise the mechanical integrity of prosthetics. The innovation is especially useful for paediatric patients or for those who need prosthetics for longer periods, so that lightweight equipment is less tiring and comfortable for use in daily life situations.

Customized Prosthetic Limbs

One of the most essential characteristics of the contemporary prosthetic design is customization, and 3D printing has allowed the creation of highly customized prosthetic limbs. With the help of 3D scan technology, the design of the prosthetics is adjusted to the peculiarities of the patient's anatomy in order to make them fit and increase functionality. Such elaboration leads to better mobility and decreases discomfort due to poorly fitting instruments. Besides, this capability to weave aesthetic inclinations, for instance, color, texture, and style, contributes to the user's individualistic spirit and mental health. Customized prosthetics are especially impressive in the case of people who have complex needs, for example, athletes or people with partial limb deviations.

Bionic Prosthetics with Embedded Electronics

The next level of use in prosthetics through 3D printing is the creation of bionic prosthetics with wired electronics. Such devices combine sensors, actuators, and microprocessors that allow users to conduct complex life-simulated movements with high accuracy. 3D printing facilitates the incorporation of intricate internal components into the prosthetic framework, ensuring

compact and seamless designs. Moreover, the technology supports the creation of flexible, conductive materials for sensor placement and connectivity. The result is a new generation of prosthetics that responds to muscle signals or even neural inputs, allowing for intuitive control and interaction with the environment.⁸¹ Such bionic prosthetics represent a significant leap toward restoring near-natural limb functionality for users.

Hip Implants

3D printing technology has emerged as a transformative force in the production of hip implants, significantly enhancing the customization and effectiveness of these critical orthopaedic devices.⁷⁹ Hao et al. compared X-rays taken one week after surgery with those taken 12 months later for radiographic evaluation.⁸² The authors conducted the study on three different patients, and in all cases, implants were held firmly. The authors found no signs of implant loosening or osteolysis around the implants (Figure 13). The patient-specific acetabular cups and femoral stems are designed in accordance with the specifics of a patient. With the aid of cutting-edge imaging technology such as CT scans or MRIs, a surgeon is able to create implants that work seamlessly in a patient's hip joint and offer greater stability and decrease the probability of complications such as dislocation or problems with the loosening of implants. This not only improves the fit but also aids better osseointegration, or the process of bone fusing to the implant, thus leading to a long life and long use of hip replacement.

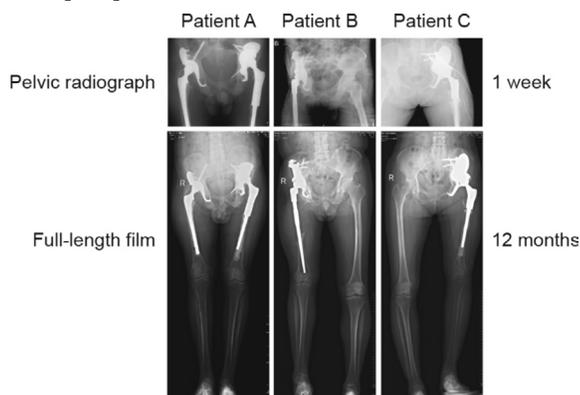


FIGURE 13. X-rays showing prosthesis evaluation after 1 week and 12 months that demonstrating stable fixation without any

signs of loosening after 12 months.⁸² (Permission under the CC BY-NC-ND license).

Spinal Implants

Porous Spinal Implants

Use of 3D printing technology in biomedical engineering has unlocked new possibilities in casting spinal porous Ti and other implants. These implants are developed with interconnective porous designs to resemble the natural architecture of the bone and vitalize osteogenesis and advance bone incorporation. The pore size and porosity are very significant, compared to mechanical properties and biological performance, which can be controlled precisely using techniques such as selective laser melting (SLM).⁸³

Optimizing these parameters ensures that the implants provide sufficient mechanical support while facilitating nutrient exchange and cellular integration.⁸⁴ The recent studies have demonstrated that porous Ti scaffolds with pore sizes of around 600–700 μm and higher porosities are more conducive to osteogenic activity and bone formation, making them ideal for spinal applications where load-bearing and biocompatibility are paramount. Using a 3D printer, Li et al. designed and tested elastic two-component polymer-metal discs for the lumbar spine with varying stresses.⁸⁵ The layered structure with a 10- μm algorithm depicts the microscopic structure in Figure 14(a, b). Along the same lines of parallel grooves are the surface strands that have grown on the sheets. Surface strips with different structures enhance mechanical characteristics. According to the scanning electron micrographs, the cut sheets are sufficiently rough to adhere to a polymer cage that has been attached using adhesive bio resin. Arthroplasty, which involves the removal and replacement of damaged vertebrae, together with a bioactive ceramic covering, has been suggested as a solution to the problems caused by the current degenerative disc disease (DDD) therapies. In order to lessen the impact on the nearby components, bead connection techniques are devised.

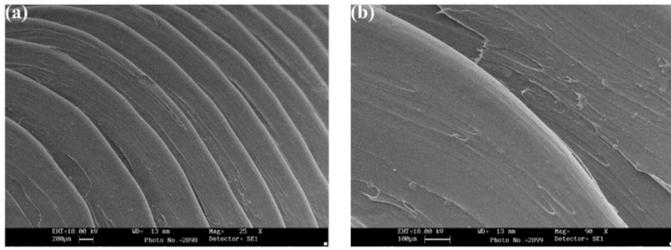


FIGURE 14. Scanning electron microscope (SEM) pictures of PLA polymer used to construct L4 and L5 intervertebral discs at (a) $\times 25$ and (b) $\times 90$.⁸⁵ (Permission under the CC BY-NC-ND license).

Interbody Fusion Devices

Customized interbody fusion devices represent a significant advancement in personalized spine care, leveraging 3D printing technology to create implants tailored to individual patients' anatomy. By utilizing medical imaging data and advanced manufacturing techniques, such as SLM and electron beam melting (EBM), these devices are designed to match the unique curvature and dimensions of a patient's spine. Owing to the presence of Ti in these implants, the strength-to-weight ratios are high and also favor biocompatibility. Ti alloys allow implants to use complex porous ways of manufacturing to promote osteoinduction and osteoconduction.⁸⁶ Customization is helpful in enhancing accuracy in surgery and achieves a better fit and embeds the implant with precision, resulting in improved clinical outcomes through reduced complications in the form of implant migration or subsidence. This is a patient-customized technique, which means a revolutionary change in spinal surgery because it is in line with the objectives of making the practice of medicine more personal, efficacious, and focused.

Dental Implants

The 3D printing technology is changing the face of dentistry, especially in the manufacturing of dental implants. This new technique makes it possible to produce individual implants adapted to individual anatomy for a closer fit and more convenience. However, standardized implants are produced with traditional treatment procedures that do not fit a patient, thus causing potential problems. Conversely, there are also 3D-printed dental implants, which are custom-designed by digital scanning

and CAD, and tailored to enhance both aesthetics and functionality.² Besides increasing durability, the choice of material serves to improve osseointegration and the coupling of the implant and the jaw bone.⁸⁷ Moreover, the 3D printing technology saves clothing design and production time, and also curtails wastage, as minimal tooling and molds are required with such a process, which makes on-demand production possible. Such efficiency is translated into reduced costs and a faster turnaround period among dental laboratories so as to cater to patients in a better way.⁸⁸ Furthermore, 3D printing allows the creation of intricate shapes that are hard to attain by using conventional techniques. For example, it is possible to make implants with different porosities to ensure a natural bone structure in which implants would integrate and distribute the load in a better manner.⁸⁹ The capacity to build well-defined models also helps in preoperative planning, thus the dentist is able to simulate the process and enhance surgical precision. Consequently, the patients experience shorter recuperation periods and fewer after-surgery modifications, thus making their experience better.⁹⁰

Shi et al. explored the application of 3D inkjet printing for fabricating zirconia ceramic teeth.²⁶ Their study utilized high-permeability 3 mol% yttria-stabilized tetragonal zirconia polycrystal (3Y-TZP as the primary material. The zirconia ceramic ink, with a 55 vol% solid phase, demonstrated shear-thinning behavior favorable for the printing process. After sintering at 1,500 °C for 54 h, the printed samples achieved a density of 98.5%, a hardness of 14.4 ± 0.1 GPa, and a transverse rupture strength of 520 ± 20 MPa, conforming to ISO 13356:2015 standards. This method proved to be efficient, cost-effective, and suitable for producing complex geometries, compared to traditional manufacturing methods.⁹¹ Mohammed et al. developed the zirconia ceramics-based dental prostheses using DLP 3D printing, as shown in Figure 15.²⁸ Alqutaibi et al.² presented a detailed overview of advanced AM in the framework of implant dentistry with the focus on the contribution of 3D printing technologies, such as Vat photopolymerization (VPP), PBF, and multi jet fusion (MJT) to manufacture dental implants and prosthetics. They emphasized the benefits of such technologies which

is increased precision, minimized waste, and the possibility of creating complex geometries. The optimization of printable material and the necessity of post-processing to obtain the required mechanical and biological qualities were other observable issues⁹².

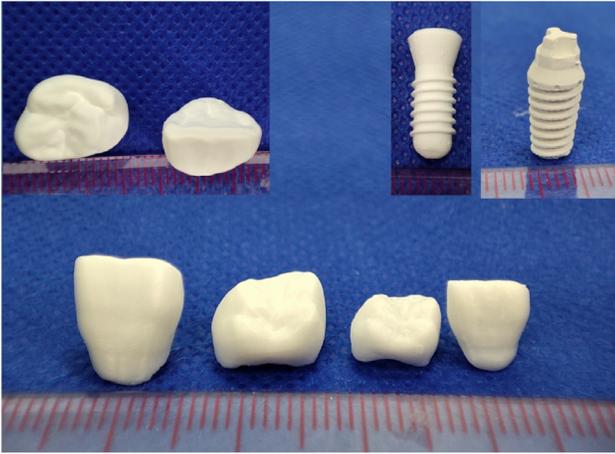


FIGURE 15. 3D-printed dental prostheses.²⁸ (Permission under the CC BY-NC-ND license).

Craniofacial Implants

The 3D printing technology has proved to be quite revolutionary in neurosurgery, especially regarding cranial implants used during cranioplasty procedures.⁹³ Such an innovative approach enables the production of individualized implants perfectly fitting to individual anatomical peculiarities of the patient, thus providing a great improvement in both functional and aesthetic results. It starts with high-resolution CT scans of the skull, which are consequently employed to make a complex 3D model. This is reflected to provide the complete mirror of the skull, making it symmetrical and fit, perfect as an implant. With the help of this technology, surgeons create patient-specific implants from biocompatible materials, such as Ti or polyether ether ketone (PEEK), which are known to be strong and resistant to corrosion and can be used with human tissue.

The advantages of employing 3D printing in cranial implants are numerous. It enables quick prototyping and production and cuts down the production time of implants, which previously took weeks instead of a few days. This expedited process is essential in emergency

cases, where prompt intervention is required after traumatic brain injuries or brain surgery. Moreover, complex geometries in 3D-printed implants favour integration with the surrounding bones and reduce complications, such as stress shielding. Further, preoperative modelling techniques help surgeons to plan their strategy in a better manner, consequently shortening the surgery time and complications. It has been demonstrated that operating with 3D-printed molds achieves good results, such as a low level of bleeding and quick recovery.

Moreover, recent developments resulted in the FDA approving 3D-printed PEEK cranial implants, which is an important step in customized medicine and the increased usage of such technology in cranial reconstruction.⁹⁴ Mishchenko et al. explored the application of 3D printing and the usage of plasma electrolyte oxidation (PEO) to generate personalized Ti implant in the context of craniofacial reconstruction.⁹⁵ The experiment used Ti6Al4V alloy in producing customized implants, which were then processed using PEO to increase surface bioactivity. The conducted PEO process used electrolyte calcium phosphate at 250 V, subsequently resulting in the formation of a bioactive oxide layer, which enhanced osteoblast proliferation and osseointegration. Successful implantation in patients with craniofacial defects that entailed fewer postoperative complications and greater aesthetic and functional results was indicated in clinical application. In complex craniofacial structures, the significance of surface modifications in obtaining bone and soft tissue integration was mentioned by the authors. Yousefiasl et al. prepared 3D-printed bioactive chitosan-based scaffolds applicable to bone tissue engineering of craniofacial origin.⁹⁶ Such scaffoldings were supplemented by the concentration of hydroxyapatite, which enhanced the same in terms of porosity, bioactivity, as well as strength. The addition of hydroxyapatite enhanced osteoconductivity and cell survival, and 5% hydroxyapatite scaffolds were found to perform optimally in the presence of cell proliferation.

The study emphasized the potential of such scaffolds for regenerating craniofacial bone defects, affording their biocompatibility and ability to support stem cell growth

and differentiation. A case study was conducted by Mishchenko et al. on the improvement of surface properties of craniofacial reconstruction using 3D personalized implants.⁹⁵ In their study, a 48-year-old male (patient P) was admitted with a mandibular defect, which caused facial deformity, partial secondary adentia, and functional disability. The defect was due to failed ameloblastoma surgery, which necessitated segmental resection and tibial graft harvesting, but developed infection, graft necrosis, and exposure of the fixation plate. The delayed iliac crest segment was grafted, and a patient-specific, 3D-printed Ti implant treated with PEO was installed, as shown in Figure 16. Subjective use was evident postoperatively, covering aesthetic appearance, facial balance, lip seal, speech, and psychoemotional well-being. The biocompatibility of Ti implant guaranteed proper integration with lasting positive results regarding functioning and appearance, irrespective of high-risk infection zones and various comorbidities.

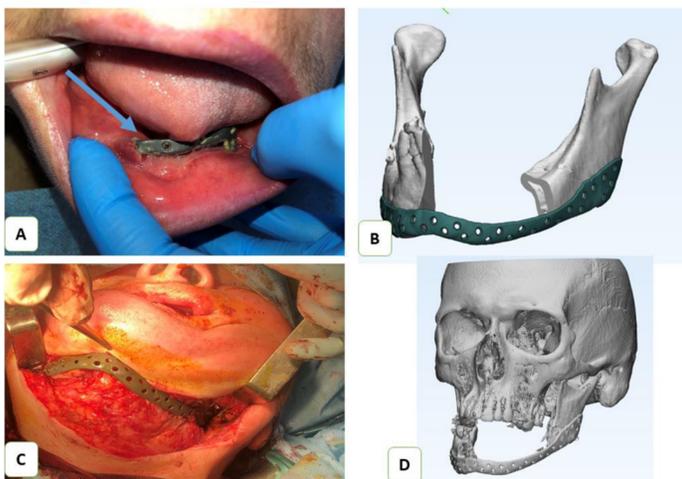


FIGURE 16. Patient P. A: Graft fragment erupted into the oral cavity (blue arrow); B: 3D model of the patient-specific implant (PSI); C: Intraoperative view of mucous membrane defect in the lower jaw; D: Postoperative CT scan showing restored mandible configuration and joint function.⁹⁵ (Permission under the CC BY-NC-ND license).

Cardiovascular Stents and Implants

3D printing technology is increasingly utilized in the production of stents, which are critical devices used to support blood vessels and maintain patency in various

medical conditions, particularly cardiovascular diseases.⁹⁷ One of the primary applications of 3D printing in stent production is the ability to create customized stents that are tailored to the specific anatomy of individual patients. By using advanced imaging techniques, such as angiography and CT scans, healthcare providers design stents that fit precisely within the targeted blood vessel, ensuring optimal support and reducing the risk of complications, such as restenosis (re-narrowing of the vessel). This customization not only enhances the effectiveness of the stent but also improves patient comfort and outcomes.

Besides customization, 3D printing is also used to manufacture stents with geometries not possible through traditional models of manufacturing. This allows adding features such as variable strut thicknesses and distinctive lattice styles, which maximize flexibility and conformability as well as strength. The dynamics of blood flow and turbulence are improved by such designs, which result in improved healing responses. Additionally, 3D printing enables fast prototyping, which enables design to be iterated based on clinical feedback, resulting in more efficient end products. The possibilities of applications of biocompatible materials and drug-eluting coating also increase the functionality of 3D-printed stents by inducing healing and obviating thrombosis (blood clot formation).⁹⁸ The use of 3D printing in the production of stents is a great development in the field of vascular interventions, as it provides a customized solution that helps patients and surgical outcomes in a greater way.

With the current technology, such as angiography or CT scans, medical practitioners can make a stent that perfectly fits the target blood vessel, such that it provides optimum support and the chances of complications are minimized.

Hatami et al. examined the aspect of using 3D and 4D printing technologies to produce cardiovascular stents.⁹⁶ Their study emphasized the capability of these processing methods of AM to manufacture patient-specific stents in intricate geometries with superior biocompatibility and drug-releasing capabilities. The authors focused on

the future of 4D printing, where stents would change in real-time, reacting to environmental triggers, such as heat and moisture, supporting easy deployment and a smooth flow into the vascular system.

Yuan et al. developed 3D-printed melatonin-loaded esophageal stents (MESs) and used them to treat corrosive esophagitis (CE).⁹⁹ They tested stents of different designs by the SLA technique. A stent of Pagoda shape was found with better retention and drug-release characteristics. The MESs ensured that entry of melatonin to the oesophageal tissues was done effectively, thereby decreasing oxidative stress, inflammation, and oesophageal stenosis in a rat model. The results also showed that the stents are biocompatible and should be safely degraded in the gastrointestinal tract, which promises higher levels of therapeutic applications in oesophagus injuries.

Surgical Devices and Tools

The technology of 3D printing is being used increasingly for creating surgical equipment and tools, transforming the very nature of surgery, as well as for improving the overall care of patients.¹⁰⁰ Some of the most common uses include manufacturing modified surgical equipment to fit special surgical needs or the preferences of a surgeon. The customization enables instruments that are ergonomically perfect to fit in the surgeon's hands, thus leading to better dexterity and control of instruments while performing surgery. For example, 3D-printed surgical instruments can be made in such a way that they meet the needs of different surgical practices better because of their ergonomic handles and special tips that meet the demands of specific surgical techniques and improve precision and decrease fatigue during a long procedure.

The other important use of 3D printing in surgery is the anatomical model created during preoperative planning. Before the surgeon enters an operating room, patient-specific models based on imaging information (e.g., CT or MRI scans) are used, so that the surgeon can visualize all aspects of the complex anatomy. This advanced planning makes it possible to devise effective strategies and achieve more productive surgeries marked by shorter operation periods and fewer spillages. Moreover, they can be used as training models that enable medical professionals to

practice surgical procedures in a simulated environment without involving actual patients. It is also possible to continually improve tools and models according to clinical feedback, with rapid prototyping capabilities providing tools and models to be at the cutting edge of innovation.

Kessler et al. studied the release of monomers in surgical guide resins produced with various 3D printing methods, and were focused on the elution of methanol and water.¹⁰¹ They found that the release of monomers greatly varies in terms of printing method and the type of resins. Monomers, such as methyl methacrylate (MMA) and hydroxyethyl methacrylate (HEMA), among others, were found to be in high concentration in methanol and low concentrations in water. Notably, the maximum concentrations of the released monomers in Nextdent SG were obtained when these materials were fabricated using SLA devices. The result highlighted the most significant evidence of the type of printer and the material of resin when applied to reducing the amount of chemical exposure in surgical operations. Li et al. developed a photocurable gel that can have superior tear resistance to be used in 3D printing of flexible wearable devices and surgical mock-ups.¹⁰² The gel utilized a double network with covalent and hydrophobic cross-linking that significantly improves its mechanical properties, such as toughness, tear resistance, and conductivity. The addition of sodium chloride and glycerol to the gel revealed better anti-drying and anti-freezing effects, which allowed using the gel in a wide range of environments. Their results demonstrated the possibilities of using such a gel to develop customized surgical models and wearable biomedical devices with enhanced durability and flexibility.

CHALLENGES IN ADDITIVE MANUFACTURING OF BIOMEDICAL IMPLANTS

Although AM has numerous benefits, there are various challenges to the universal use of the technology in producing implants. The first major impediment is regulatory barriers, because the process of regulating medical equipment slows down innovation and delays market entry of new products. Compared to conventional manufacturing methods, there are few limitations to the

materials that are used in AM.¹⁰³ Such limitations may limit the type of implants that could be produced efficiently. Besides, it is a significant challenge to provide quality control because the printing conditions change, and this process may influence the consistency and reliability of different batches of implants.

Regulatory and Standardization Issues

The regulatory landscape of AM in the biomedical sector is complex and evolving. Regulatory bodies such as the FDA have begun to establish guidelines for the approval of 3D-printed medical devices. However, these regulations are often not fully developed or standardized across different regions. The lack of clear guidelines leads to inconsistencies in product evaluation for safety and efficacy, thus potentially delaying the introduction of innovative technologies into the market. Furthermore, the absence of standardized testing protocols poses a significant barrier. Each AM technique produces varying results based on parameters, such as material choice, printer settings, and post-processing methods.¹⁰⁴

Without standardized criteria for assessing the mechanical properties and biocompatibility of printed implants, it becomes challenging to ensure that devices meet necessary performance benchmarks.¹⁰⁵ Regulatory challenges can be resolved by investing in and developing new instruments, devices, and technology for patients (Figure 17). This inconsistency hinders collaborations between manufacturers and healthcare providers, as differing standards may complicate the integration of new technologies into existing medical practices.

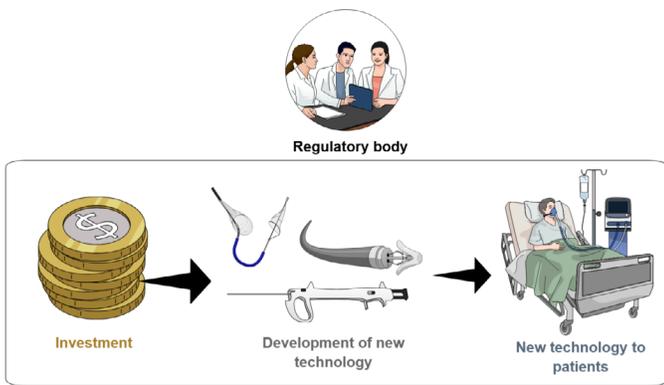


FIGURE 17. 3D printing in biomedical applications.

Material Limitations

Material selection is critical in the AM of biomedical implants. While AM allows for a wide range of materials, such as metals, polymers, and ceramics, each material has specific limitations that can impact its suitability for medical applications. For instance, biocompatibility is a primary concern, and materials must not elicit adverse biological responses when implanted in the body. Mechanical properties such as strength, elasticity, and the capacity to resist fatigue have to match the needs of the implant site. Generally, the performance of the existing materials is also lacking. Ti alloys, because of their strength-to-weight ratio and resistance to corrosion, may have poor osseointegration characteristics compared to natural bone.¹⁰⁶ Moreover, polymers that are applied to AM processes are not always provided with the mechanical strength required to be of load-bearing capacity or are subject to degradation due to prolonged exposure to the physiological environment. Consequently, the current research continues to consider the possible development of new biomaterials that fulfil the strict requirements of numerous uses and are compatible with AM.

Process Repeatability and Reliability

Repeatability and reliability of a process used in AM are another important issue. The AM processes are very variable compared to the established traditional manufacturing process, which usually adopts predictable, well-proven techniques. Such variations may cause discrepancies in the quality of the implants used, and this is truly daunting in biomedical applications where the safety of patients is at the forefront. A robust quality control is needed during the manufacturing process so as to enable it to tackle this problem. Adoption of real-time monitoring software that monitors important parameters such as temperature variations during print, the ability of layers to stick together, etc., may help to have consistent results. Advancements in simulation tools that predict the influence of process parameter variations on the final product properties are helpful in significantly improving manufacturing reliability. By providing insights into the expected outcomes, these tools enable manufacturers to optimize process parameters, reduce trial-and-error experimentation, and design their production systems

in the most efficient and cost-effective manner before large-scale implementation.

Besides, AM offers a lot of potential to transform biomedical implants by customization and efficiency, although there are some serious challenges. Regulatory and standardization questions are also important to achieve efficacy and safety in diverse markets.

Similarly, the material compromises faced are defeated by conducting new research to make implants more functional. Moreover, high standards of implant production require advanced techniques of monitoring and simulation to achieve high levels of repeatability and reliability in the implant production process, thereby supporting high-quality standards.¹⁰⁷ However, with these challenges addressed, the biomedical field can fully leverage its benefits through the use of AM technologies.

FUTURE TRENDS AND INNOVATIONS

The future of AM in medical implantology is promising with several exciting directions. The research relating to the future discovery of biocompatible materials could be focused on increasing the longevity of implants. Also, the usage of AM with digital technologies (e.g., advanced imaging techniques such as CT scans) can increase the level of customization because implants are now designed to the requirements of patients.¹⁰⁸ Moreover, point-of-care manufacturing has huge possibilities, and the manufacturing of tailor-made implants on demand has the possibility of transforming surgical procedures by removing delays and making the treatment more effective as a whole. With the help of the directions developed in the market, AM has a chance to leave a significant impact in the field of medical implantology by addressing current challenges.

Advanced Materials for Additive Manufacturing

In order to increase functionalities and the use of AM, the development of advanced materials is essential. With the growth of advanced AM technologies, the demands of new materials are increasing, which not only respond to the mechanical and thermal requirements of the processes used in multiple applications but also possess certain

functionalities. Various studies on AM have dealt with nontraditional materials, such as metals, non-ceramics, composite polymers, and high-performance alloys. For instance, carbon fibers reinforced within polymer matrices have demonstrated much enhanced mechanical properties. Thus, it is possible to produce lightweight components with better mechanical strengths for automobile and aerospace applications.¹⁰⁹ Additionally, the future materials made from AM can support the manufacturing of multi-functional structures possessing a combination of different properties in the same component. This comprises the synthesis of biomaterials that are biocompatible and allow tissue integration in the case of medical implants and metamaterials that are naturally uneven in their mechanics. Investigation of these new materials is necessary to fill the existing gaps in AM.

Multi-Material Additive Manufacturing Processes

Multi-Material Additive Manufacturing (MMAM) technology is a remarkable improvement to the AM technology because this has enabled developers to manufacture parts with diverse material qualities in the same construct.¹¹⁰ This allows more complicated shapes to be created that are able to optimize performance by using various materials in the areas where they can function the best. For instance, a combination of soft and hard materials can result in an implant replica in the natural behavior of biological tissues, leading to an improvement in comfort and functionality.

Multi-materials are introduced to support the techniques such as FDM and SLS. FDM has the potential to lay down different filaments with dual or multi-extrusion nozzles. SLS can stack timelines of dissimilar materials as a means of creating the desired material gradients.¹¹¹ The ability to process multiple materials provides not just more freedom to design but new avenues to customize and personalize products, such as biomedical engineering products. The ongoing research is expected to provide MMAM a dominant part in improving the practicality and usefulness of 3D printed implants.

Use of CAD Design in Additive Manufacturing

Additive manufacturing or 3D printing is largely affected by CAD. The integration of AM and CAD results in increased efficiency of product development.¹¹² Rapid prototyping with CAD leads to multiple design iterations, resulting in increased production in a short time and less cost. The process translates CAD models into machine-readable models to achieve successful printing results. Three prerequisites to produce quality printed parts are geometric accuracy, feature resolution, and surface roughness. Moreover, dedicated software applications help to make necessary optimizations in designs as far as additive processes are concerned, which deal with support structures, material consumption, etc. Finally, this results in unique and tailored solutions that are hard to achieve in traditional manufacturing.¹¹³

Optimization of the Additive Manufacturing Process using CAD

The potential of CAD is to optimize the AM process by improving efficiency and accuracy in designing. One of the primary functions of CAD in this context is converting 3D models into machine-readable formats, which results in efficient and accurate 3D printing.¹¹⁴ This process is completed by preparing the model, part orientation, and using supporting structures to make the model stable during printing. Moreover, advanced CAD applications simplify the slicing process by slicing the 3D model into layers so that a 3D print can be built sequentially. These layers are adjusted in thickness based on experimental requirements, ensuring optimal print quality. A notable feature of CAD is to support for DfAM (Design Framework of Additive Manufacturing) principles for the optimization of designs. It promotes the designing of lightweight and intricate geometries that cannot possibly be produced by conventional production methods, resulting in high material wastage and expenses.¹³ Also, compatibility with simulation systems enables engineers to check designs in different conditions for the best performance. Before commencing the full-scale production, the printing success can be demonstrated through preliminary trials and simulations. These achievements allow manufacturers to validate the process, optimize printing parameters, and ensure product quality and reliability prior to real

production. Overall, the AM process, which includes design, production, and the final output, is greatly accelerated by CAD. This process significantly elevates innovation and efficiency in product development.

Integration with Artificial intelligence and digital twin technology

The integration of AM with artificial intelligence (AI) and digital twin (a virtual copy of a real system) technology transformed the approach for the products designed and manufactured, thereby optimizing the performance and efficiency.¹¹⁵ Huge data sets can be processed using AI algorithms to determine patterns and to optimize parameters such as print speed, temperature, and material flow. Such optimization increases process efficiency, minimizes waste, and provides high product quality. The application of digital twins enables a manufacturer to simulate and track the real cycle of an AM process. Digital twins can be used to predict failures, prioritize maintenance activities, and gain knowledge for better performance, which is achieved using live data from sensors. This combination of AI with digital twins provides better decisions and also reduces the cycle time of innovation to iterate on new designs quickly. This results in a good prototype and tests the designs locally before committing to building a real one. The combination of advanced materials, multi-material processes, and AI integration can create a revolution in AM. These developments ensure that product performances boost the industry and reduce the problems of material constraints and process maintenance. As experimental advancements in AM progress, it can unlock new possibilities for innovative engineering and production methods.

Integration of 3D Printing with Artificial Intelligence in Cardiology

Advances in the field of cardiology are achieved through the introduction of AI and 3D printing, thus allowing a more precise, efficient, and customized treatment.¹¹⁶ Imaging data acquired from different techniques like CT, MRI, and echocardiography can be enhanced through AI-based processing to ensure accurate models for 3D printing.

The cardiac structures are sorted out with the help of machine learning (ML) algorithms to allow the optimization of imaging resolution and create effective replications of

cardiovascular structures of the patient to show proper anatomy. Such accuracy is invaluable in preoperative planning, especially in complicated situations, so that the course of action is planned with more fidelity. AI also streamlines the 3D printing process by automating procedures in design or even material selection. Predictive algorithms allow tailoring the devices with patient-specific data, when it comes to designing stents and valves, which focus on the geometry of the heart and the dynamics of the blood flow. Monitoring after and during printing by AI results in quality control, and AI can even locate discrepancies. The combination of these innovations and the capability of AI to simplify the process has the potential to maximize results in cardiac care by providing efficient, speedy, and patient-centered solutions.

CONCLUSION

Additive manufacturing has transformed the medical implant manufacturing industry by providing highly customized and patient-specific solutions. The technology has made surgery more accurate and effective in different areas of medical practice, such as orthopaedics, dentistry, and craniofacial surgery. 3D printers are able to produce complex shapes with the help of advanced imaging and digital designs that were not possible with other traditional processes. 3D printing results in improved fitting of implants, shorter surgery period, as well as recovery, coupled with sustainable manufacturing methods that minimize material waste and production inefficiencies. However, even with these advancements, the adoption of 3D-printed implants still faces many challenges. The major obstacles are approval by regulatory bodies, material restrictions, and long-term biocompatibility. The ongoing research for new biomaterials and integration with imaging technologies addresses these issues for more precise and accessible solutions. As these innovations evolve, 3D printing is set to play a pivotal role in customized medicine, transforming surgical practices and enhancing patient care, thus marking a new era in the field of medical implantology.

AUTHOR CONTRIBUTIONS

Conceptualization and Methodology, V.S. and J.S.; Literature Review, V.S. and J.S.; Formal Analysis, V.S. and J.S.; Writing–Original Draft Preparation, V.S. and J.S.; Software, J.S.; Writing–Review & Editing, A.S. and J.S.; Visualization, V.S.; Supervision: J.S.

CONFLICTS OF INTEREST

The authors declare no conflicts of interest.

ETHICS APPROVAL AND CONSENT TO PARTICIPATE

Not applicable.

CONSENT FOR PUBLICATION

Not applicable.

REFERENCES

1. Jiménez, M., Romero, L., Domínguez, I.A., et al. Additive manufacturing technologies: An overview about 3D printing methods and future prospects. *Complexity*. 2019;2019(1):9656938. <https://doi.org/10.1155/2019/9656938>.
2. Alqutaibi, A.Y., Alghauli, M.A., Aljohani, MHA., et al. Advanced additive manufacturing in implant dentistry: 3D printing technologies, printable materials, current applications and future requirements. *Bioprinting*. 2024;42:e00356. <https://doi.org/10.1016/j.bprint.2024.e00356>.
3. Kumar, S.A. and Tushar, J. Review of 3D printing applications in biomedical engineering: A comprehensive analysis. *J Clin Biomed Sci*. 2024;14(4):129–137. <http://dx.doi.org/10.58739/jcbs/v14i4.110>.
4. Li, J., Liang, D., Chen, X., et al. Applications of 3D printing in tumor treatment. *Biomed Technol*. 2024;5:1–13. <http://dx.doi.org/10.1016/j.bmt.2023.03.002>.
5. Gupta, R.S., Lal, B., Bhagat, A.C., et al. Medical imaging for patient-specific implants. In: *Biomedical Implants*, Dwivedi, R.K., Chauhan, P.S., eds. CRC Press: Boca Raton, FL; 2024. pp. 39–60. <https://doi.org/10.1201/9781003375098-4>.
6. Doganay, M.T., John, C.C., Tozluyurt, A., et al. 3D printed materials for combating antimicrobial resistance. *Mater Today*. 2023;67:371–398. <http://dx.doi.org/10.1016/j.matod.2023.05.030>.

7. Derakhshanfar, S., Mbeleck, R., Xu, K., et al. 3D bioprinting for biomedical devices and tissue engineering: A review of recent trends and advances. *Bioactive Mat.* 2018;3:144–156. <https://doi.org/10.1016/j.bioactmat.2017.11.008>.
8. Huang, G., Zhao, Y., Chen, D., et al. Applications, advancements, and challenges of 3D bioprinting in organ transplantation. *Biomater Sci.* 2024;12(6):1425–1448. <http://dx.doi.org/10.1039/d3bm01934a>.
9. Song, Y., Ghafari, Y., Asefnejad, A., et al. An overview of selective laser sintering 3D printing technology for biomedical and sports device applications: Processes, materials, and applications. *Opt Laser Technol.* 2024;171:110459. <http://dx.doi.org/10.1016/j.optlastec.2023.110459>.
10. John, P., Antony, I.R., Whenish, R., et al. A review on fabrication of 3D printed biomaterials using optical methodologies for tissue engineering applications. *Proc Inst Mech Eng Part H J Eng Med.* 2022;236(11):1583–1594. <http://dx.doi.org/10.1177/09544119221122856>.
11. Bhatti, S.S., and Singh, J. 3D printing of biomaterials for biomedical applications: A review. *Int J Interact Des Manuf.* 2023; <http://dx.doi.org/10.1007/s12008-023-01525-z>.
12. Kennedy, S.M., Vasanathanathan, A., Jeen, R.R., et al. Impact of mechanical engineering innovations in biomedical advancements. *Vitr Model.* 2024;3(1):5–18. <http://dx.doi.org/10.1007/s44164-024-00065-4>.
13. Javaid, M., Haleem, A., Singh, R., et al. Role of additive manufacturing applications towards environmental sustainability. *Adv Ind Eng Polym Res.* 2021;4(4):312–322. <https://doi.org/10.1016/j.aiepr.2021.07.005>.
14. Jadhav, T., Kamble, N., Padave, P. A review on additive manufacturing for bio-implants. *Int J Eng Res Technol.* 2019;8(11):609–614.
15. Olakanmi, E.O. Selective laser sintering/melting (SLS/SLM) of pure Al, Al–Mg, and Al–Si powders: Effect of processing conditions and powder properties. *J Mater Process Technol.* 2013;213(8):1387–1405. <https://doi.org/10.1016/j.jmatprotec.2013.03.009>.
16. Olakanmi, E.O., Cochrane, R.F., Dalgarno, K.W. A review on selective laser sintering/melting (SLS/SLM) of aluminium alloy powders: Processing, microstructure, and properties. *Prog Mater Sci.* 2015;74:401–477. <https://doi.org/10.1016/j.pmatsci.2015.03.002>.
17. Way, A.C. SLS reliability considering autogenous self-sealing in tension governed reinforced concrete water retaining structures. PhD Thesis, Stellenbosch University, Stellenbosch, South Africa, 2021.
18. Ravi, P., and Patel, P. Stereolithography (SLA) in pharmaceuticals. In: *Additive Manufacturing in Pharmaceuticals*. Banerjee, S. Springer: Cham, Switzerland; 2023; pp. 97–123. https://doi.org/10.1007/978-981-99-2404-2_3.
19. Chen, Y.W., Moussi, J., Drury, J.L., et al. Zirconia in biomedical applications. *Expert Rev Med Devices.* 2016;13(10):945–963. <https://doi.org/10.1080/17434440.2016.1230017>.
20. Mzali, S., Elwasli, F., Mezlini, S., et al. Experimental investigation of tribological behavior of FDM-PLA surfaces. *Proc Inst Mech Eng Part L J Mater Des Appl.* 2025;239(4):760–775. <https://doi.org/10.1177/14644207241312974>.
21. Bhandari, S., Lopez-Anido, R.A., Gardner, D.J. Enhancing the interlayer tensile strength of 3D printed short carbon fiber reinforced PETG and PLA composites via annealing. *Addit Manuf.* 2019;30:100922. <https://doi.org/10.1016/j.addma.2019.100922>.
22. Wendels, S., and Avérous, L. Biobased polyurethanes for biomedical applications. *Bioact Mater.* 2021;6(4):1083–1086. <https://doi.org/10.1016/j.bioactmat.2020.10.002>.
23. Mousa, H.M., Abdal-Hay, A., Bartnikowski, M., et al. A multifunctional zinc oxide/poly(lactic acid) nanocomposite layer coated on magnesium alloys for controlled degradation and antibacterial function. *ACS Biomater Sci Eng.* 2018;4(6):2169–2180. <https://doi.org/10.1021/acsbio materials.8b00277>.
24. Song, J., Winkeljann, B., Lieleg, O. Biopolymer-based coatings: promising strategies to improve the biocompatibility and functionality of materials used in biomedical engineering. *Adv Mater Interfaces.* 2020;7: 2000850. <https://doi.org/10.1002/admi.202000850>.
25. Zub, K., Hoepfener, S., Schubert, U.S. Inkjet printing and 3D printing strategies for biosensing, analytical, and diagnostic applications. *Adv Mater.* 2022;34(31):2105015. <https://doi.org/10.1002/adma.202105015>.
26. Shi, Y., and Wang, W. 3D inkjet printing of the zirconia ceramic implanted teeth. *Mater Lett.* 2020;261:127131. <https://doi.org/10.1016/j.matlet.2019.127131>.
27. Swetha, S., Sahiti, T.J., Priya, G.S., et al. Review on digital light processing (DLP) and effect of printing parameters on quality of print. *Interactions.* 2024;245(1):178. <https://doi.org/10.1007/s10751-024-02018-5>.
28. Mohammed, M.K., Alahmari, A., Alkhalefah, H., et al. Evaluation of zirconia ceramics fabricated through DLP 3d printing process for dental applications. *Heliyon.* 2024;10(17):e36725. <https://doi.org/10.1016/j.heliyon.2024.e36725>.

29. Murchio, S. Hierarchical multifunctional cellular materials for implants with improved fatigue resistance and osteo-integration. PhD Thesis, University of Trento, Trento, Italy, 2023. <https://iris.unitn.it/handle/11572/379289>.
30. Mostafaei, A., Elliott, A.M., Barnes, J.E., et al. Binder jet 3D printing—process parameters, materials, properties, modeling, and challenges. *Prog Mater Sci.* 2021;119:100707. <https://doi.org/10.1016/j.pmatsci.2020.100707>.
31. Banothu, D., Kumar, P., Reddy, R. Advancements in 3D printing for metal bio-implants: a comprehensive bibliometric and scientometric analysis. *J. Mechanic. Continua Math. Sci.* 2024;19:9–28. <https://doi.org/10.26782/jmcms.2024.11.00002>.
32. Singh, A.B. Transforming healthcare: a review of additive manufacturing applications in the healthcare sector. *Eng Proc.* 2024;72(1):2. <https://doi.org/10.3390/engproc2024072002>.
33. Placone, J.K., Engler, A.J. Recent advances in extrusion-based 3D printing for biomedical applications. *Adv Healthc Mater.* 2018;7(8):1701161. <https://doi.org/10.1002/adhm.201701161>.
34. Yuan, X., Zhu, W., Yang, Z., et al. Recent advances in 3D printing of smart scaffolds for bone tissue engineering and regeneration. *Adv Mater.* 2024;36(34):2403641. <https://doi.org/10.1002/adma.202403641>.
35. Svetlizky, D., Das, M., Zheng, B., et al. Directed energy deposition (DED) additive manufacturing: physical characteristics, defects, challenges and applications. *Mater Today.* 2021;49:271–295. <https://doi.org/10.1016/j.mattod.2021.03.020>.
36. Ahmad, M., Javaid, M., Haleem, A. Enhancing biocompatible metal alloy fabrication for bio implants through laser-based additive manufacturing (LBAM). *Biomed Anal.* 2024;1(1):73–85. <https://doi.org/10.1016/j.bioana.2024.02.001>.
37. Kundu, M., Kadambi, P., Dhattrak, P. Additive manufacturing of bio-implants using functionally graded materials. In: *AIP Conference Proceedings*. International Conference on Recent Innovations in Science and Technology (RIST 2021) 19–20 June 2021, Malappuram, India, 2021, Paul, V., Deepanraj, B, eds., AIP Publishing: Melville, New York; 2022. <https://doi.org/10.1063/5.0082039>.
38. Tilton, M., Lewis, G.S., Manogharan, G.P. Additive manufacturing of orthopedic implants. In: *Orthopedic Biomaterials: Progress in Biology, Manufacturing, and Industry Perspectives*. Li, B.Y. Webster, T. Springer: Cham, Switzerland 2018; pp. 21–55. https://doi.org/10.1007/978-3-319-89542-0_2.
39. Rakić, B., Ratković, A., Mrvić, J. Potential impact of 3D printing in redesigning supply chain—example of medical industry. In *International Symposium (symorg 2016) Reshaping The Future Through Sustainable Business Development And Entrepreneurship*, Zlatibor, Serbia, June 10–13, 2016; University of Belgrade, Faculty of Organizational Sciences: Belgrade, Serbia, 2016.
40. Sharma, V., Singh, J.P., Hussan, K., et al. Machine learning approach for predicting the machining characteristics of additive manufactured ABS material. *Proc Inst Mech Eng C J Mech Eng Sci.* 2024; 239(1):129–144. <https://doi.org/10.1177/09544062241283330>.
41. Jiang, L. Application and innovation of 3D printing in medical equipment maintenance. *Glob Clin Eng J.* 2024;6(4):15–23. <https://doi.org/10.31354/globalce.v6i4.181>.
42. Ballor, J., Li, T., Prima, F., et al. A review of the metastable omega phase in beta titanium alloys: the phase transformation mechanisms and its effect on mechanical properties. *Int Mater Rev.* 2023;68(1):26–45. <https://doi.org/10.1080/09506608.2022.2036401>.
43. Velásquez-García, L.F., Kornbluth, Y. Biomedical applications of metal 3D printing. *Annu Rev Biomed Eng.* 2021;23(1):307–338. <https://doi.org/10.1146/annurev-bioeng-082020-032402>.
44. Khulief, Z. Tribological, Electrochemical, and Tribocorrosion Behaviour of New Titanium Biomedical Alloys. PhD thesis, University of Sheffield: Sheffield, UK, 2018.
45. Li, G., Liu, S., Xu, Z., et al. Recent advancements in liquid metal enabled flexible and wearable biosensors. *Soft Sci.* 2023;3(4):37. <https://doi.org/10.20517/ss.2023.30>.
46. Yang, X., Yu, Y., Lai, Q., et al. Recent development and advances on fabrication and biomedical applications of GA-based liquid metal micro/nanoparticles. *Compos B Eng.* 2023;248:110384. <https://doi.org/10.1016/j.compositesb.2022.110384>.
47. Gupta, C.P. Role of iron (Fe) in body. *IOSR J Appl Chem.* 2014;7(11):38–46. <https://doi.org/10.9790/5736-071123846>.
48. Gąsior, G., Szczepański, J., Radtke, A. Biodegradable iron-based materials—what was done and what more can be done? *Materials (Basel).* 2021;14(12):3381. <https://doi.org/10.3390/ma14123381>.
49. Pasternak, K., Kocot, J., Horecka, A. Biochemistry of magnesium. *J Elem.* 2010;15(3):601–616. <https://doi.org/10.5601/jelem.2010.15.3.601-616>.

50. Grimwade, M. The metallurgy of gold. *Interdiscip Sci Rev.* 1992;17(4):371–381. <https://doi.org/10.1179/isr.1992.17.4.371>.
51. Bandyopadhyay, A., Traxel, K.D., Avila, J.D., et al. In: *Bio-materials Science*. Wagner, W.R., Shelly, E., eds. Elsevier: Amsterdam, the Netherlands; 2020; pp. 257–269. <https://doi.org/10.1016/B978-0-12-816137-1.00020-9>.
52. Milošev, I. CoCrMo alloy for biomedical applications. In: *Biomedical Applications*. Djokić, S.S. Springer: Cham, Switzerland; 2012; pp. 1–72. https://doi.org/10.1007/978-1-4614-3125-1_1.
53. Sahasrabudhe, H., Bose, S., Bandyopadhyay, A. Laser-processed calcium phosphate reinforced CoCrMo for load-bearing applications: processing and wear induced damage evaluation. *Acta Biomater.* 2018;66:118–128. <https://doi.org/10.1016/j.actbio.2017.11.022>.
54. de Albuquerque, T.L., Júnior, J.E.M., de Queiroz, L.P., et al. Polylactic acid production from biotechnological routes: a review. *Int J Biol Macromol.* 2021;186:933–951. <https://doi.org/10.1016/j.ijbiomac.2021.07.074>.
55. Liu, S., Qin, S., He, M., et al. Current applications of poly(lactic acid) composites in tissue engineering and drug delivery. *Compos B Eng.* 2020;199:108238. <https://doi.org/10.1016/j.compositesb.2020.108238>.
56. Chen, Z., Du, C., Liu, S., et al. Progress in biomaterials inspired by the extracellular matrix. *Giant.* 2024;19:100323. <https://doi.org/10.1016/j.giant.2024.100323>.
57. Liu, H., and Webster, T.J. Enhanced biological and mechanical properties of well-dispersed nanophase ceramics in polymer composites: from 2D to 3D printed structures. *Mater Sci Eng C.* 2011;31(2):77–89. <https://doi.org/10.1016/j.msec.2010.07.013>.
58. Ben-Nissan, B., Choi, A.H., Cordingley, R. Alumina ceramics. In: *Bioceramics and their Clinical Applications*. Elsevier: Amsterdam, the Netherlands; 2008. pp. 223–242. <https://doi.org/10.1533/9781845694227.2.223>.
59. Lin, L., Fang, Y., Liao, Y., et al. 3D printing and digital processing techniques in dentistry: a review of literature. *Adv Eng Mater.* 2019;21(6):1801013. <https://doi.org/10.1002/adem.201801013>.
60. Sionkowska, A. Collagen blended with natural polymers: recent advances and trends. *Prog Polym Sci.* 2021;122:101452. <https://doi.org/10.1016/j.progpolymsci.2021.101452>.
61. Sharma, S., Sudhakara, P., Singh, J., et al. Critical review of biodegradable and bioactive polymer composites for bone tissue engineering and drug delivery applications. *Polymers (Basel).* 2021;13(16):2623. <https://doi.org/10.3390/polym13162623>.
62. Buj-Corral, I., Tejo-Otero, A., Fenollosa-Artés, F. Use of FDM technology in healthcare applications: recent advances. In: *Fused Deposition Modeling Based 3D Printing*. Dave, H.K. Davim, J.P. Springer Cham: Switzerland, 2021;277–297. https://doi.org/10.1007/978-3-030-68024-4_15.
63. Li, J., Chen, M., Fan, X., et al. Recent advances in bioprinting techniques: approaches, applications and future prospects. *J Transl Med.* 2016;14:1–15. <https://doi.org/10.1186/s12967-016-1028-0>.
64. Mulcahy, N.J. *Exploring the Feasibility of 3D Printing in the Treatment of Diabetic Foot Ulcers*. University of Limerick: Limerick, Ireland; 2024.
65. Beshchasna, N., Saqib, M., Kraskiewicz, H., et al. Recent advances in manufacturing innovative stents. *Pharmaceutics.* 2020;12(4):349. <https://doi.org/10.3390/pharmaceutics12040349>.
66. Leberfinger, A.N., Dinda, S., Wu, Y., et al. Bioprinting functional tissues. *Acta Biomater.* 2019;95:32–49. <https://doi.org/10.1016/j.actbio.2019.01.009>.
67. Wu, Y., Liu, J., Kang, L., et al. An overview of 3D printed metal implants in orthopedic applications: present and future perspectives. *Heliyon.* 2023;9(7): e17718. <https://doi.org/10.1016/j.heliyon.2023.e17718>.
68. García-Ávila, J., González-Gallegos, C.P., Segura-Ibarra, V., et al. Dynamic topology optimization of 3D-printed transtibial orthopedic implant using tunable isotropic porous metamaterials. *J Mech Behav Biomed Mater.* 2024;153:106479. <https://doi.org/10.1016/j.jmbbm.2024.106479>.
69. Wong, K.C. 3D-printed patient-specific applications in orthopedics. *Orthop Res Rev.* 2016;8:57–66. <https://doi.org/10.2147/ORR.S99614>.
70. Liu, B., Ma, Z., Li, J., et al. Experimental study of a 3D printed permanent implantable porous Ta-coated bone plate for fracture fixation. *Bioact Mater.* 2022;10:269–280. <https://doi.org/10.1016/j.bioactmat.2021.09.009>.
71. Oraa, J., Fiz, N., González, S., et al. Derotation tibial osteotomy with custom cutting guides and custom osteosynthesis plate printed with 3D technology: case and technical note. *Ann 3D Print Med.* 2023;9:100093. <https://doi.org/10.1016/j.stlm.2022.100093>.
72. Miao, K., Wang, J., Yu, K., et al. Percutaneous reduction and cannulated screw fixation assisted by 3D printing technology of calcaneal fractures in children. *J Orthop Sci.* 2022;29(1):236–242. <https://doi.org/10.1016/j.jos.2022.12.004>.

73. Kumar, S.V., Marimuthu, K., Subramani, S., et al. Prospective randomized trial comparing open reduction and internal fixation with minimally invasive reduction and percutaneous fixation in managing displaced intra-articular calcaneal fractures. *Int Orthop*. 2014;38:2505–2512. <https://doi.org/10.1007/s00264-014-2501-0>.
74. Kia, C., Antonacci, C.L., Wellington, I., et al. Spinal implant osseointegration and the role of 3D printing: an analysis and review of the literature. *Bioengineering*. 2022;9(3):108. <https://doi.org/10.3390/bioengineering9030108>.
75. Siracusa, V., Maimone, G., Antonelli, V. State-of-art of standard and innovative materials used in cranioplasty. *Polymers (Basel)*. 2021;13(9):1452. <https://doi.org/10.3390/polym13091452>.
76. Zheng, H., Wang, L., Jiang, W., et al. Application of 3D printed patient-specific instruments in the treatment of large tibial bone defects by the Ilizarov technique of distraction osteogenesis. *Front Surg*. 2023;9:985110. <https://doi.org/10.3389/fsurg.2022.985110>.
77. Choudhari, A., Gupta, A.K., Kumar, A., et al. Wear and friction mechanism study in knee and hip rehabilitation: a comprehensive review. In: *Applications of Biotribology in Biomedical Systems*. Kumar, A., Kumar, A., eds. Springer Cham: Switzerland, 2024;345–432. https://doi.org/10.1007/978-3-031-58327-8_13.
78. Wang, J., Wang, X., Sun, B., et al. 3D-printed patient-specific instrumentation decreases the variability of patellar height in total knee arthroplasty. *Front Surg*. 2023;9:954517. <https://doi.org/10.3389/fsurg.2022.954517>.
79. Meng, M., Wang, J., Huang, H., et al. 3D printing metal implants in orthopedic surgery: methods, applications and future prospects. *J Orthop Transl*. 2023;42:94–112. <https://doi.org/10.1016/j.jot.2023.08.004>.
80. Saroia, J., Wang, Y., Wei, Q., et al. A review on 3D printed matrix polymer composites: its potential and future challenges. *Int J Adv Manuf Technol*. 2020;106:1695–1721. <https://doi.org/10.1007/s00170-019-04534-z>.
81. Gentile, C., and Gruppioni, E. A perspective on prosthetic hands control: from the brain to the hand. *Prosthesis*. 2023;5(4):1184–1205. <https://doi.org/10.3390/prosthesis5040083>.
82. Hao, Y., Wang, L., Jiang, W., et al. 3D printing hip prostheses offer accurate reconstruction, stable fixation, and functional recovery for revision total hip arthroplasty with complex acetabular bone defect. *Engineering*. 2020;6(11):1285–1290. <https://doi.org/10.1016/j.eng.2020.04.013>.
83. Dziaduszezewska, M., and Zieliński, A. Structural and material determinants influencing the behavior of porous Ti and its alloys made by additive manufacturing techniques for biomedical applications. *Materials (Basel)*. 2021;14(4):712. <https://doi.org/10.3390/ma14040712>.
84. Borah, J., and Chandrasekaran, M. Experimental investigation and development of artificial neural network modeling of 3D printed PEEK bio implants and its optimization. *Research Square (preprint) 2023*; posted 14 Sep, 2023. <https://doi.org/10.21203/rs.3.rs-3204960/v1>.
85. Li, X., Heidari, A., Nourbakhsh, S.M., et al. Design and fabrication of elastic two-component polymer-metal disks using a 3D printer under different loads for the lumbar spine. *Polym Test*. 2022;112:107633. <https://doi.org/10.1016/j.polymertesting.2022.107633>.
86. Lewallen, E.A., Riester, S.M., Bonin, C.A., et al. Biological strategies for improved osseointegration and osteoinduction of porous metal orthopedic implants. *Tissue Eng B Rev*. 2015;21(2):218–230. <https://doi.org/10.1089/ten.teb.2014.0333>.
87. Bandyopadhyay, A., Mitra, I., Goodman, S.B., et al. Improving biocompatibility for next generation of metallic implants. *Prog Mater Sci*. 2023;133:101053. <https://doi.org/10.1016/j.pmatsci.2022.101053>.
88. Schito, M., Peter, T.F., Cavanaugh, S., et al. Opportunities and challenges for cost-efficient implementation of new point-of-care diagnostics for HIV and tuberculosis. *J Infect Dis*. 2012;205(Suppl 2):S169–S180. <https://doi.org/10.1093/infdis/jis044>.
89. Wu, S., Liu, X., Yeung, K.W.K., et al. Biomimetic porous scaffolds for bone tissue engineering. *Mater Sci Eng R Rep*. 2014;80:1–36. <https://doi.org/10.1016/j.mser.2014.04.001>.
90. Bernard, H., and Foss, M. Patient experiences of enhanced recovery after surgery (ERAS). *Br J Nurs*. 2014;23(2):100–106. <https://doi.org/10.12968/bjon.2014.23.2.100>.
91. Sidhu, S.S., Chanda, A., Abdel-Hady, G.M. Advances and perspective in bio-implants for commercialization. *Front. Bioeng. and Biotech*. 2023;11:1306077. <https://doi.org/10.3389/fbioe.2023.1306077>.
92. Mahajan, A., Devgan, S., Zitoune, R. *Additive Manufacturing of Bio-Implants*. Springer: Cham, Switzerland; 2024. <https://doi.org/10.1007/978-981-99-6972-2>.
93. Jegadeesan, J.T., Baldia, M., Basu, B. Next-generation personalized cranioplasty treatment. *Acta Biomater*. 2022;154:63–82. <https://doi.org/10.1016/j.actbio.2022.10.030>.
94. Pathak, K., Saikia, R., Das, A., et al. 3D printing in biomedicine: advancing personalized care through additive manufacturing.

- Explor Med.* 2023;4(6):1135–1167. <https://doi.org/10.37349/emed.2023.00200>.
95. Mishchenko, O., Kopchak, A., Chernohorskyi, D., et al. Craniofacial reconstruction using 3D personalized implants with enhanced surface properties: technological and clinical aspects. *Appl Surf Sci Adv.* 2023;16:100437. <https://doi.org/10.1016/j.apsadv.2023.100437>.
 96. Yousefiasl, S., Sharifi, E., Salahinejad, E., et al. Bioactive 3D-printed chitosan-based scaffolds for personalized craniofacial bone tissue engineering. *Eng Regen.* 2023;4(1):1–11. <https://doi.org/10.1016/j.engreg.2022.09.005>.
 97. Ullah, M., Bibi, A., Wahab, A., et al. Shaping the future of cardiovascular disease by 3D printing applications in stent technology and its clinical outcomes. *Curr Probl Cardiol.* 2024;49(1):102039. <https://doi.org/10.1016/j.cpcardiol.2023.102039>.
 98. Liu, J., Mohd Rafiq, N.B., Wong, L.M., et al. Surface treatment and bioinspired coating for 3D-printed implants. *Front Chem.* 2021;9:768007. <https://doi.org/10.3389/fchem.2021.768007>.
 99. Yuan, T., Liu, D., Li, Q., et al. 3D printing of melatonin-loaded esophageal stents for treatment of corrosive esophagitis. *Appl Mater Today.* 2024;37:102161. <https://doi.org/10.1016/j.apmt.2024.102161>.
 100. Jabeen, F. Bio implants—a review. *J Adv Med Dent Sci Res.* 2018;6(1):169. <https://doi.org/10.21276/jamdsr>.
 101. Kessler, A., Reichl, F.X., Folwaczny, M., et al. Monomer release from surgical guide resins manufactured with different 3D printing devices. *Dent Mater.* 2020;36(11):1486–1492. <https://doi.org/10.1016/j.dental.2020.09.002>.
 102. Li, H., An, J., Bao, Q., et al. Photocurable 3D printing high-strength gels for flexible wearable devices and surgical models. *Polymer (Guildf).* 2023;286:126392. <https://doi.org/10.1016/j.polymer.2023.126392>.
 103. Sharma, S., Jain, A., Gupta, V., et al. Additive manufacturing of bio-implants. In: *Additive Manufacturing for Biomedical Applications: Recent Trends and Challenges*. Dixit, A. Kumar, A., eds. Springer; Cham, Switzerland; 2024; pp. 39–54. https://doi.org/10.1007/978-981-97-5456-4_3.
 104. Chua, C.K., Wong, C.H., Yeong, W.Y. *Standards, Quality Control, and Measurement Sciences in 3D Printing and Additive Manufacturing*. Academic Press: Cambridge, MA; 2017. <https://doi.org/10.1016/B978-0-12-813489-4.00008-8>.
 105. Limaye, N., Veschini, L., Coward, T. Assessing biocompatibility & mechanical testing of 3D-printed PEEK versus milled PEEK. *Heliyon.* 2022;8(12):e12314. <https://doi.org/10.1016/j.heliyon.2022.e12314>.
 106. Abd-Elaziem, W., Darwish, M.A., Hamada, A., et al. Titanium-based alloys and composites for orthopedic implants applications: a comprehensive review. *Mater Des.* 2024;241:112850. <https://doi.org/10.1016/j.matdes.2024.112850>.
 107. Martinez-Marquez, D., Terhaer, K., Scheinmann, P., et al. Quality by design for industry translation: three-dimensional risk assessment failure mode, effects, and criticality analysis for additively manufactured patient-specific implants. *Eng Rep.* 2020;2(1):e12113. <https://doi.org/10.1002/eng2.12113>.
 108. Guzzi, E.A., and Tibbitt, M.W. Additive manufacturing of precision biomaterials. *Adv Mater.* 2020;32(13):1901994. <https://doi.org/10.1002/adma.201901994>.
 109. Das, T.K., Ghosh, P., Das, N.C. Preparation, development, outcomes, and application versatility of carbon fiber-based polymer composites: a review. *Adv Compos Hybrid Mater.* 2019;2:214–233. <https://doi.org/10.1007/s42114-018-0072-z>.
 110. Verma, A., Kapil, A., Klobčar, D., et al. A review on multiplicity in multi-material additive manufacturing: process, capability, scale, and structure. *Materials (Basel).* 2023;16(15):5246. <https://doi.org/10.3390/ma16155246>.
 111. Wu, Y., An, C., Guo, Y. 3D printed graphene and graphene/polymer composites for multifunctional applications. *Materials (Basel).* 2023;16(16):5681. <https://doi.org/10.3390/ma16165681>.
 112. Vido, M., de Oliveira, N.G.C., Lourenço, S.R., et al. Computer-aided design and additive manufacturing for automotive prototypes: a review. *Appl Sci.* 2024;14(16):7155. <https://doi.org/10.3390/app14167155>.
 113. Gao, W., Zhang, Y., Ramanujan, D., et al. The status, challenges, and future of additive manufacturing in engineering. *Comput Des.* 2015;69:65–89. <https://doi.org/10.1016/j.cad.2015.04.001>.
 114. Top, N., Şahin, İ., Gökçe, H., et al. Computer-aided design and additive manufacturing of bone scaffolds for tissue engineering: state of the art. *J Mater Res.* 2021;36:3725–3745. <https://doi.org/10.1557/s43578-021-00156-y>.
 115. Delgado, J.M.D., and Oyedele, L. Digital twins for the built environment: learning from conceptual and process models in manufacturing. *Adv Eng Informatics.* 2021;49:101332. <https://doi.org/10.1016/j.aei.2021.101332>.
 116. Wang, D.D., Qian, Z., Vukicevic, M., et al. 3D printing, computational modeling, and artificial intelligence for structural heart disease. *Cardiovasc Imaging.* 2021;14(1):41–60. <https://doi.org/10.1016/j.jcmg.2019.12.022>.