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PAPER

# A Review of Material, Design, and Techniques in 3D Printing for Medical Applications

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**ABSTRACT**

This review research assesses the numerous 3D printing methods utilized in medical applications and the materials and design methods that are associated with the current and existing technology. The article thoroughly examines the advantages and disadvantages of various techniques and materials and the difficulties of applying 3D printing technology to the medical sector. Further research and development are required to overcome current challenges since the review highlights the importance of design strategies in achieving positive medical outcomes. Overall, the article provides a thorough overview of the state of 3D printing in medical applications today and its potential to revolutionize the industry.

**KEYWORDS**

materials, mechanics, engineering, design, medical, lattices, 3D printing

## 1 INTRODUCTION

Medical implant applications for 3D printing are booming due to advances in material design and 3D printer technology. It is now possible to produce microscopic replicas of intricate biological systems, such as anatomical spine models. As 3D printers become more widely available and medical computer-aided design (CAD) software becomes more widely available, more hospitals establish 3D printing labs. Using 3D-printed models to plan surgery leads to shorter operating room times and fewer patient issues over the long run [1]–[3].

Additive Manufacturing (AM) technology uses various designing, 3D scanning, and 3D printing programs to create medical objects. Organizations produce biocompatible materials such as thermoplastics and metals for 3D printing [4], [5]. As the variety of 3D printable biocompatible materials and deposition procedures expand, unique 3D-printed electronic medical devices will be applied to individuals. It demands an additive manufacturing technique that can 3D print electronics in any shape. It is feasible to use 3D-printed structures in pharmacological and cosmetic research. One advantage of medical 3D printing is personalized medicine,

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which eliminates the necessity for potentially dangerous therapies like chemotherapy [6]–[8]. Dental models, medical implants, and other models can now be created using AM technology, including devices like cranial and orthopedic implants, hearing aids, dental restorations, surgical instruments, and external prostheses [9], [10]. This paper aims to briefly discuss 3D printing in medical applications, discuss the suitable implant material and study the progressive steps for implementation.

## 2 MATERIAL

The molecular structures of the materials and the printing method impact how those materials behave when used for 3D printing. Materials are chosen for design applications based on quantifiable characteristics and processing and testing techniques.

### 2.1 Material properties

Medical applications call for various material qualities, which 3D printing can provide. The demand for specialized material capabilities is frequently driven by medical applications, such as the need for energy-absorbing materials that are impact-resistant, colorful components with suitable textures for modeling surgical anatomy or special material properties to replicate biological tissues. There are several research summarizes recent findings in medicinal polymer materials with flexibility [11], [12], an emphasis on mechanical toughness [13], [14], further capabilities such as electrical conductivity [15], [16], and biological capabilities for biocompatibility [17], [18].

Toughness is determined by combining strength and ductility, and a tough polyurethane material was used to create a 3D-printed tensile bar with crosshatch structures in the study conducted by Miller et al. [13]. Comparisons were made between physical and chemical cross-linking [13]. Recent advances in flexible materials allow for creating prosthetics that may be customized for a person's particular physiology using scanning and fitting technology [11]. The 27-year-old study subject used 3D mapping software to create the contour of their nose using a Stratasys polyjet printer and Tango Plus flexible material with properties like rubber. Stereolithography has also been used to print complex patterns on flexible materials [12].

Biocompatibility is an essential material feature for printed objects that interact with the body or are implanted in living organisms. It means the substance must not harm the body while performing the desired function. Stratasys MED610, an acrylic-based polymer, is used to create tissue scaffolds with complex topologies. Biocompatibility requires biodegradability, non-cytotoxicity, and stimulation tissue development [18].

Thermoplastics used with conductive carbon black infill for 3D-printed chess set with an LED light have shown that they can improve electrical conductivity [15]. Meanwhile, electrical conductivity has been used to 3D print organogels to create artificial, sensorized tissue analogues. This technique used piezoresistive strain sensors and conductive threads as electrodes to create a suture training pad to quantify the trainee's performance [16].

### 2.2 Material structure

A wide variety of polymer materials are available for 3D printing, each having unique characteristics based on its molecular structure and treated differently for each printing method. Thermoplastics, which are melted during extrusion and subsequently hardened after deposition, are often used in extrusion processes for 3D printing [19]. For instance, compared to pure polystyrene, the popular thermoplastic acrylonitrile butadiene styrene (ABS) displays better chemical resistance and good impact strength [15]. ABS has variable physical properties based on its three monomers' proportions. For instance, its tensile moduli can be between 2.5 GPa to 2.7 GPa, and its density can range from 1.05 $mg/m^3$ to 1.07 $mg/m^3$. A thermoplastic alternative to ABS with remarkable ultraviolet stability and higher heat resistance is acrylonitrile styrene acrylate (ASA) [20].

In addition to these printing procedures, PLA is also appropriate for resin curing with stereolithography [14], making it feasible to create more intricate part structures than extrusion techniques. Despite being biocompatible, stereolithography printing of PLA raises several safety issues due to its toxicity. This is due to the addition of photopolymers, which are necessary for the cross-linking of monomers to create polymers in the presence of UV light, to the resin solution [17]. However, when printed and post-processed correctly, resin curing procedures are safe for use in the medical field, depending on the composition of chemical components [21].

## 2.3 Material capabilities

To identify the material capabilities for a particular application, thorough testing of various materials and process variables is necessary because the characteristics of 3D-printed objects are influenced by both the material composition and printing process [22]. For example, the processing temperature, the thickness of the printed layer, and component orientation all affect how a part responds to fused deposition modeling [23].

**Table 1.** Several material properties of measured 3D-printed parts arranged by printing method and material

| References | Materials | Printing Process | Measured Properties |
|---|---|---|---|
| [24] | Polyether ether ketone (PEEK) | FDM | Elastic Modulus: 3000–4100 MPa.<br>Tensile Strength: 58–85 MPa.<br>Temperature-dependent. |
| [23] | Polylactic acid (PLA) | FDM | Elastic Modulus: 4400 MPa.<br>Ultimate Strength: 265 MPa.<br>Yield Strength: 205 MPa.<br>Compression Testing. |
| [23] | Polycarbonate (PC); Biomaterial blend | FDM | Elastic Modulus: 2100 MPa.<br>Tensile Strength: 35–65 MPa.<br>Orientations of 0° to 90°.<br>Nozzle Temperature: 240–270°C. |

Table 1 compares several investigations on materials properties, all of which showed comparable but marginally differing mechanical properties [23], [24], like tensile strength that ranges from 15 MPa to 38 MPa. The structure of ABS, the orientation of the tested components, and the printing parameters and processing temperatures used to create the parts all contribute to the variations. Polycarbonate materials showed similar variations based on the material's manufacturing process and the chemicals utilized [23], [25]. According to one study, bio-based polycarbonate had an elastic modulus of 2100 MPa, much stronger than the 1500 MPa elastic modulus and 62 MPa strength of fossil fuel-based polycarbonate [23]. PEEK and PLA are two biocompatible materials that are frequently utilized. They have higher stiffness and mechanical strength than other polymers and may be manufactured via fused deposition modeling [24], [26]. PEEK is the more costly material, with a 4100 MPa elastic modulus, while PLA has a 4400 MPa elastic modulus. These two values are the highest of the materials in Table 1 that were inspected [15].

Recently, scaffolds for bone tissue have been investigated using 3D-printed biocompatible materials [27]–[29]. The resin prints are less stiff than the fused deposition modeling parts, but they may be made stiffer by adjusting the post-processing curing time and the curing time for each layer, as shown for lattice structures [28]. The highlighted materials in Table 1 show how processing can change a material's properties and how different processing methods allow the selection of materials with similar property ranges. Fabrication accuracy and consistency are crucial when choosing a material/process combination [15].

### 2.4 Auxetic and porous structure

Porous structures with bio-inspired designs could absorb impact energy and find use in many technical fields. It describes the various kinds of biomimetic porous structures seen in nature, classifies them, and demonstrates how they work. These structures may be altered to suit specific requirements and are produced using additive manufacturing technology. Column structures, sandwich structures, honeycombs, foams, architecture structures, and smooth cell lattice structures are a few examples of biomimetic porous structures that have been imitated for engineering applications utilizing additive manufacturing techniques. These structures can be tailored to fit specific requirements and feature distinctive architectures that increase durability and can absorb impact energy [22].

The crystal sheet lattices are presented as a new type of mechanical metamaterial, as discovered by Liew et al. [30]. In the study, the elastic performances were examined with quasi-static compression experiments and a basic volume model. In addition, elastoplastic simulations were used to investigate the structural strength in the deformation mode. Following the outcomes, it was demonstrated that reduced elastic anisotropy may be attained without a laborious regulatory procedure. Given their high surface volume ratios, flat profiles, and improved mechanical properties, CSLs have the potential to be used in lightweight and heat transmission areas [30].

## 3 3D PRINTING DESIGN STRATEGIES

3D-printed parts can be customized to offer functionality beyond just printing solid components. Investigated strategies include responsive polymers [31], multi-material combinations [32], customization [33], architected materials [34], and functionally graded materials [35], which all offer a way to enhance the performance and functionality of printed items. Layout techniques are advantageous for medicines as they extend the functional and physical characteristics of created objects beyond the materials selection and printing techniques. They offer a way to enhance the performance and functionality of printed items [15].

### 3.1 Stimuli-responsive

A coordinated arrangement of printed elements with guided state changes in response to an external stimulus, such as heat, light, or force, is necessary for stimuli-responsive designs [36]. Combining contrasting materials with varying responses to a stimulus is a popular technique for stimuli-responsive parts. A mixture of shape memory polymers creates a self-folding box due to the system's overall material reactions [31].

In a recent study, using extrusion printing, an elastomer and a glassy polymer were combined to create a rod-shaped structure to investigate the interaction of materials with various degrees of stimulus sensitivity [37]. In reaction to external heating stimuli, the glassy polymer seems more likely to alter form, resulting in over 300 percent of the failure strain. High-resolution photocuring has been done using microdisplays with incredibly high contrast and resolution, enabling the production of photo-shape memory alloys with 3D architecture [38]. One research offered a new 4DMesh technique that involved bending and shrinking a 4D print to create a surface that is not developable using a thermoplastic actuator [39].

### 3.2 Architected materials

To increase mechanical qualities for a given structural density, the structures with regular subunit patterning are made by systematically placing materials, like a lattice with unit cells having a specific topological layout [40]. By building a single unit cell out of beams first, then placing the unit cells beside each other to form a lattice structure, patterning unit cells offer a straightforward method of setting up an architectural material [41]. Due to the bigger pores introduced by the hierarchy, hierarchically architected materials have an extreme [15]. Crystal sheet lattices have a potential for customization due to the geometrical characteristics of the lattice structure, such as the size and form of the lattice cells. Additionally, they have an advantage over conventional mechanical metamaterials in that they have a smooth profile and less anisotropy, making them more appropriate for various applications [30].

A polylactic acid-based 3D-printed mandible model uses customized layouts that reflect each patient's physiology [33]. Due to the complexity of the layout options to consider when getting a patient's component fitted, automated design customization typically uses image-based approaches [42]. For example, several patients' 2D CT scan images are transformed into 3D images. Following that, to develop a product for 3D printing or other imaging processes, 3D imaging data is converted into a virtual 3D surface shape and aligned with optical scan data [43].

### 3.3 Functionally graded

Architectural materials with a material transition or gradual geometric across the structure are shown to be functionally graded materials [44]. Functionally graded materials enable a smooth transition of qualities at interfaces, reducing stress concentrations and offering durability, particularly as supports for loads [45]. In addition, functional gradients may control mass transport, fluid flow, mechanical qualities, and biodegradation more effectively. They benefit medical applications because they offer a diverse structural variety of bioinspired gradients, making them advantageous for biomedical implants [46]. The structural design has a functionally graded lattice where the thickness of the beams varies depending on where they are positioned [35].

## 4 3D PRINTING TECHNIQUES

3D printing is a process of printing objects/models using various materials and bioprinters, with software such as Octaprint, Cura, CAD, and IdeaMaker. Printers convert the '.STL' file format into separate portions [47], [48]. Several well-known fabrication techniques exist under the umbrella of 3D printing. In general, the advantages of 3D printing enable the production of intricate and unique designs that may be impossible using conventional manufacturing techniques. It can be a cost-effective technique for making prototypes or limited runs of parts. The time and money required for iterative refinement cycles during the design and testing process can be decreased with 3D printing. 3D printing can also lessen waste and its adverse environmental effects by using less material. The quality and robustness of 3D-printed products might be better than those made using conventional manufacturing techniques. More significant numbers of parts may result in higher 3D printing costs. There will be fewer materials available for 3D printing.

Application cases for 3D printing, including surgery equipment, implants, and prostheses, have all been created using 3D printing in the medical industry. It has also been employed in the aerospace and automotive industries to create lightweight and intricate parts. Models and building components have been produced using 3D printing in architecture and construction [49]. One previous paper uses 3D printing technology to fabricate a "small contraction" sensor for practical biology work, achieving high-quality and affordable fabrication compared to other technologies [50]. Figure 1 shows a few of the popular 3D printing techniques, which are selective laser sintering (SLS), stereolithography (SLA), fused deposition modeling (FDM), and binder jet printing (BJ) [51].

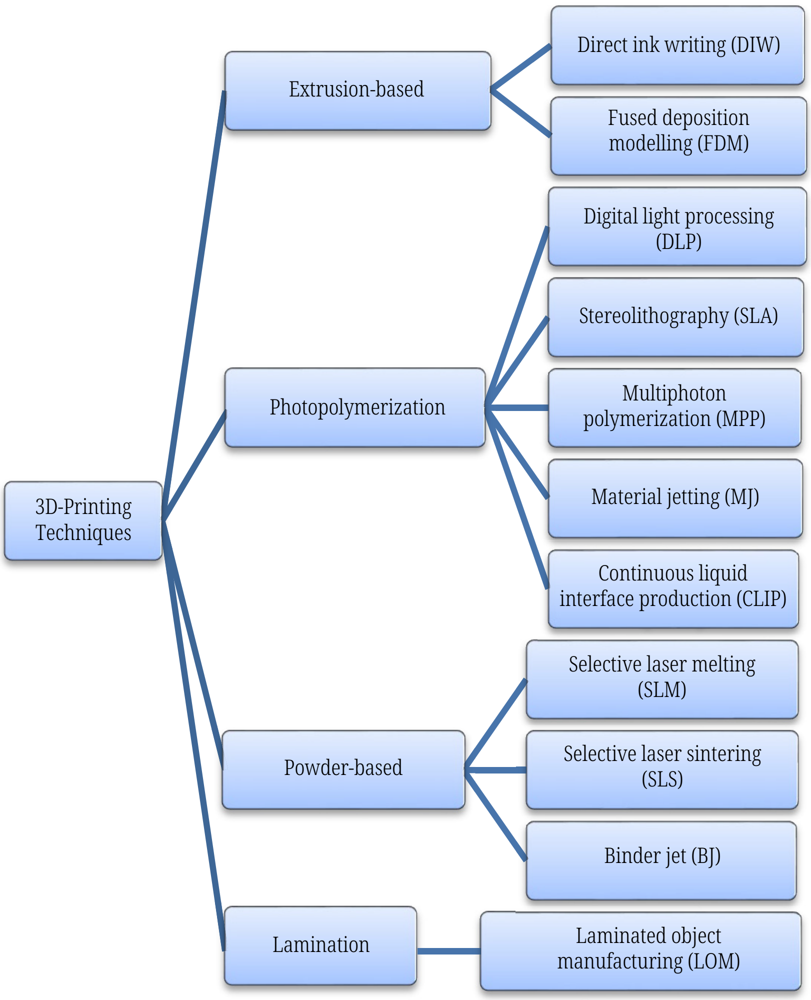


**Fig. 1.** Fundamental types of 3D printing techniques [52]

### 4.1 Fused Deposition Modelling (FDM)

Fused deposition modeling is the most common extrusion 3D printing technique [53]. In fused deposition modeling, continuous filaments of the material are fed into a printer. The filament is heated in the extruder body until it melts, then cools and solidifies. Acrylonitrile butadiene styrene (ABS), polylactic acid (PLA), thermoplastic polyurethane (TPU), and polyethylene terephthalate (PET) are examples of common printing materials. One paper briefly mentions PLA as the most commonly used material for 3D printing. However, it also notes that PLA is rigid and unsuitable for creating flexible molds [54]. Support materials include wax, breakaway substances, and water-soluble polymers like polyvinyl alcohol (PVA). The selection of process and materials elements, including build orientation, layer thickness, infill density, raster angle, printing speed, and nozzle temperature, affect how well-printed items operate [55]. If the nozzle temperature is not maintained a few degrees above the polymer's melting point, the performance of materials like PEI and PEEK may be impacted.

FDM offers several advantages, making it a preferred choice in various 3D printing applications. Firstly, it tends to be cost-effective, providing parts with sound mechanical performance [56]. Compared to other 3D printing methods, this relative affordability makes it accessible to many users. FDM's versatility is further demonstrated by its ability to print with a wide range of thermoplastic materials, including biocompatible options suitable for medical applications [53]. The simple and easy-to-use printing process of FDM contributes to its popularity among users. Moreover, FDM printers' open-build platform design allows the production of large parts, expanding the scope of potential applications. Additionally, the ability to print parts with varying infill levels allows for the customization of part strength and weight, catering to specific requirements and functionalities.

However, FDM does come with certain limitations. Its resolution could be better than other 3D printing processes, resulting in lower surface quality and less intricate detail in printed parts. The need for support structures when printing complex geometries poses challenges, as these structures can be difficult to remove and may leave surface imperfections [57]. Furthermore, FDM's restricted ability to print with high-temperature materials can limit its use in applications requiring materials with extreme temperature resistance.

Notwithstanding these limitations, FDM finds specific use cases in the medical field. Due to its low cost and ability to print with biocompatible materials, FDM is well-suited to produce prosthetics and orthotics. The ability to print custom shapes and sizes makes it ideal for fabricating surgical tools and guides tailored to individual patients. Additionally, FDM's capability to print anatomical models with varying infill levels proves valuable in surgical planning and medical education [15].

### 4.2 Direct Ink Writing (DIW)

Another extrusion-based 3D printing method is direct ink writing, also known as robocasting, which bypasses the heating needs of fused deposition modeling in favor of using an external shear force to thin viscoelastic material and deposit shear via a nozzle [58]. Designs for numerous applications, including epoxy, thermoplastics, and polydimethylsiloxane (PDMS), have been made possible through direct ink writing. Soft materials can be printed best when the process is done under ambient circumstances. The viscosity of the ink decreases as the shear stress rises, allowing for extrusion through the nozzle. The ink regains its viscosity during extrusion and creates a three-dimensional structure. According to the needs of the material, the printed item is cured in a varied environment. Different materials are printed using direct ink writing, including fiber-suspended inks [58], bio-inks [59], multi-material inks, and magnetic/electro inks [15].

DIW is a 3D printing method that offers various advantages, as highlighted in the paper [58]–[60]. Firstly, it is suitable for printing in ambient conditions, providing convenience and ease of use compared to processes requiring specialized environmental controls [58]. Additionally, DIW excels in producing parts with high resolution and accuracy, making it ideal for applications demanding fine details and intricate designs. Its versatility in utilizing various materials, including biocompatible and biodegradable options, makes DIW well-suited for medical applications, particularly in fabricating tissue scaffolds with complex geometries and tailored mechanical properties for regenerative medicine [58]. Various materials, such as bio-inks [59], fiber-suspended inks [60], electro/magnetic inks, and multi-material inks, can also be printed via direct ink writing. Direct ink writing's ability to print on a variety of materials has made it possible to create designs for a range of uses [59].

However, this technology has its drawbacks. DIW has limitations in tuning part performance during printing since it does not involve heating [58]. Moreover, the relatively slow printing process of DIW, compared to some other 3D printing technologies, may restrict its use for large-scale production. Additionally, DIW-printed parts may exhibit low mechanical strength and durability, potentially limiting their suitability for functional applications. Furthermore, DIW parts can be sensitive to environmental conditions, such as temperature and humidity, which can affect the quality of the printed components [58].

Notwithstanding these limitations, specific use cases mentioned in the paper showcase the potential of DIW in diverse applications. For instance, it can be applied to produce drug delivery systems with controlled-release properties, catering to personalized medicine applications. Additionally, DIW's ability to create microfluidic devices with precise channels and features makes it a valuable tool in lab-on-a-chip applications, advancing research and diagnostics [15].

### 4.3 Stereolithography (SLA)

SLA is a popular method for creating 3D objects because it uses a laser to concentrate a liquid polymer, solidifying and polymerizing it. It has certain drawbacks, though, like the infrequent use of clinical instruments and the presence of functional groups that endanger gene structures. In addition, due to their low impact strength and resistance, most of the polymers in this category are not considered safe for usage [58].

SLA has several benefits, including making parts with high resolution and precision, making it appropriate for uses requiring intricate features and complex geometries. Post-processing is less necessary when using SLA because it may create pieces with a smooth surface finish. SLA is appropriate for medical applications since it may use various materials, such as biocompatible and biodegradable polymers [15].

The drawbacks of SLA include its slower printing speed compared to other 3D printing technologies, which may prevent it from being used for mass manufacturing. Compared to items created utilizing other 3D printing technologies, SLA parts might be brittle and have poorer mechanical strength. SLA components may deteriorate over time if exposed to sunlight since they are susceptible to UV radiation [15]. Printing in stereolithography is not multi-material capable [18].

SLA has specific applications in producing highly accurate and detailed dental models and prostheses. Anatomical models and surgical guides can be created using SLA for surgical planning and instruction. SLA can be utilized to create tissue scaffolds for regenerative medicine applications with complex geometries and specialized mechanical qualities [15].

### 4.4 Ink-jet printing

The alternative resin-curing method is known as polyjet or inkjet printing. It employs a nozzle to deposit material droplets instantly cured by a UV beam during deposition to form a layer [61]. For fast printing of multi-material structures with support materials, polyjet printing is useful [62]. However, materials must still possess shear-thinning characteristics, restricting their accessibility [63]. With the use of mechanically effective lattice structures, it has been shown that inkjet printing might be used on biomedical equipment [62], with applications spanning from bioprinting to electronics to prototyping [27]. Lattices with a 400 m diameter were printed using polyjet technology, with fabrication errors according to the build direction and topology design. More research is required if it is acceptable for tissue engineering applications [18]. However, the technique offers the possibility of quickly fabricating adaptable structures for patients in applications like safety harnesses [15].

Arefin et al. [15] listed the advantages of Inkjet 3D printing. Firstly, it can produce high-quality and accurate parts, making it well-suited for applications requiring fine details and complex geometries. The technology's ability to utilize a wide range of materials, including biocompatible and biodegradable options, makes it particularly suitable for medical applications, such as fabricating tissue scaffolds with complex geometries and tailored mechanical properties for regenerative medicine. Additionally, Inkjet 3D printing yields parts with a smooth surface finish, reducing the need for post-processing and enhancing the overall quality of the printed components.

However, the technology also comes with certain limitations that should be considered. Inkjet 3D printing is relatively slower than other 3D printing technologies, which may limit its use for large-scale production. Furthermore, parts produced using Inkjet 3D printing may exhibit lower mechanical strength than those manufactured using other 3D printing methods [15]. Additionally, the process can be sensitive to environmental conditions, such as temperature and humidity, which may influence the quality of the printed parts. At its resolution limits, Inkjet 3D printing may result in inconsistent surfaces for the printed parts [18].

Notwithstanding these drawbacks, the specific use cases highlighted in the paper underscore the versatility and potential of Inkjet 3D printing in various fields. For instance, it can be applied to fabricate tissue scaffolds with intricate geometries and tailored mechanical properties, advancing regenerative medicine applications. Furthermore, Inkjet 3D printing proves valuable in creating drug delivery systems with controlled-release properties, catering to personalized medicine requirements. Additionally, its capability to produce microfluidic devices for lab-on-a-chip applications enhances research and diagnostics in various scientific disciplines [15].

### 4.5 Selective Laser Sintering (SLS)

SLS is a powder bed fusion technology that uses a laser to selectively fuse powdered material into a solid part [15]. The main materials are polyamides (PA6, PA11, and PA12), PEEK, polypropylene, and elastomers like TPU. In the SLS process, CO2 lasers are frequently employed. The procedure entails translating a model file into STL format, managing the laser to scan profiles, selectively sintering powder, and layer stacking cycles. The completed product is cooled and removed to ensure good quality [64]. Through exposure to a laser, a powder stock level is used in selective laser sintering to fuse one layer. It is possible to fabricate intricate parts and assemblies because the residual powder in the platform serves as a support during component production. This technique allows intricate pieces and assemblies to be created without requiring additional support material to be printed [15].

SLS is a 3D printing technique that offers several advantages, as discussed by Goodridge, Tuck, and Hague [65]. Notably, it excels in producing parts with high mechanical strength and durability, making it suitable for functional applications. SLS's versatility in using a wide range of materials, including biocompatible and biodegradable options, makes it particularly applicable in medical settings. Additionally, SLS is valuable in fabricating parts with complex geometries and intricate internal structures, catering to applications requiring precision and intricate designs. One of the major advantages of selective laser sintering is that the leftover powder in the platform acts as a support during part construction. Therefore the process does not require printing a separate support material and enables complex part and assembly fabrication [65].

However, SLS also comes with certain limitations that need to be considered. The process is relatively slow compared to other 3D printing technologies, potentially limiting its suitability for large-scale production. Furthermore, SLS-printed parts may exhibit a rough surface finish, necessitating post-processing to achieve a smoother surface. Additionally, SLS parts can be sensitive to environmental conditions, such as temperature and humidity, which may influence the quality of the printed components [15].

The specific use cases mentioned in the paper demonstrate the versatility and significance of SLS in various medical applications. For instance, it is well-suited for producing orthopedic implants with complex geometries and tailored mechanical properties, meeting the specific requirements of individual patients. SLS is also valuable in creating patient-specific surgical guides and anatomical models for surgical planning and training, enhancing precision and accuracy in medical procedures. Moreover, SLS is instrumental in generating tissue scaffolds with complex geometries and tailored mechanical properties for regenerative medicine applications, facilitating advancements in tissue engineering [57].

### 4.6 Binder Jet Printing (BJ)

Binder jet printing utilizes a jetted substance to bond powder as an alternative to laser melting [64]. Multi-colour, functionally graded materials and multi-material can be printed effectively using the binder jetting technique. It is quicker than laser melting because it injects the binding substance through several nozzles. It can print on multiple materials, including those with varying functional grades and colors [66]. The binding material not only controls the size and form of the powder but also acts as an adhesive to hold the powder together and produce a printed geometry, which influences the characteristics of the printed components [67], [68].

Binder jetting is a 3D printing technique with several advantages, as mentioned by Ziaee and Crane [66]. Utilizing multiple nozzles to inject the binding material, binder jetting has the potential to be faster than laser melting. It is an efficient process capable of printing multicolor, multi-material, and functionally graded materials [66].

Furthermore, binder jetting can process various materials, including metals, ceramics, and polymers, offering versatility in material selection. The technique excels in producing complex geometries and internal structures that are challenging or impossible to achieve using traditional manufacturing methods. Additionally, binder jetting enables the creation of parts with varying material properties using different powders and binders, leading to diverse and customizable components. It also boasts of high accuracy and resolution in the production of parts.

However, binder jetting does come with certain limitations. Parts produced by this method typically exhibit lower mechanical properties than those manufactured using other 3D printing techniques, such as selective laser sintering or fused deposition modeling. The surface finish of binder jetting parts is also typically rougher compared to parts produced by other 3D printing methods. Furthermore, the process can be slow, especially when printing large parts, which may affect its applicability for high-volume production scenarios [66].

The specific use cases mentioned in the paper demonstrate the versatility and suitability of binder jetting for various applications. For instance, it is well-suited for producing small, complex parts with high accuracy and resolution, making it ideal for dental implants or hearing aids. Binder jetting can also effectively create large, intricate parts, such as aerospace components or architectural models. Additionally, it proves valuable in generating parts with varying material properties, including composite materials or parts with graded porosity, offering a wide range of possibilities for advanced engineering and customized applications [69] (see Table 2).

**Table 2.** Materials utilized in several 3D printing techniques, along with some of its benefits and drawbacks [70]

| Methods | Materials | Advantages | Disadvantages |
|---|---|---|---|
| Fused deposition modeling | ABS, PLA, Wax blend, nylon | Used for a variety of materials, high quality, and speed. | Support was frequently needed because of the binder's porous nature and poor mechanical characteristics. |
| Stereolithography | Resin (Acrylate or epoxy based with proprietary photoinitiator) | Large parts can be built easily, with surface finish and high accuracy. | The binder's porous nature and poor mechanical characteristics frequently required assistance. |
| Selective laser sintering | Metallic powder, polyamide, PVC | High strength and high resolution. | It was frequently necessary to provide support due to the binder's porous nature and poor mechanical qualities. |
| 3D inkjet printing | Hydrogel or Photo-resin | Very high surface finishes and very good accuracy. | Poor mechanical characteristics and fragile components. |

## 5 FINITE ELEMENT ANALYSIS (FEA)

With different manufacturing factors, a lumbar cage design's performance can be predicted using FEA. FEA is a simulation technique that may speed up the product design and development process and examine the mechanics of intricate geometries. For instance, Provaggi et al. [71] conducted a study investigating how cage stiffness affected the rate of lumbar interbody fusion. In this study, the construction of a lumbar fusion cage was optimized using FEA by choosing the best materials and cage structure that could handle the highest predicted static loads. Results showed that PEEK cages had a higher failure risk than PLA cages due to their higher maximal stress at the cage endplate. Generally, to model the mechanical structural behavior under varied loading conditions, FEA is the best option. More studies on FEA are required to comprehend the PLA cage structure's mechanical properties [72].

## 6 MEDICAL APPLICATIONS

The production of 3D-printed parts is advantageous for the medical sector, and current developments in polymer 3D printing are opening up new possibilities in medicine for a dental model [73], spinal implant [74], sacral surgery planning [75], and intervertebral disc implant [76].

### 6.1 Spinal implants

After removing a boy's C2 Ewing sarcoma, Xu et al. [77] employed a 3D-printed axial vertebral body to restore the upper cervical spine. The implant was osseointegrated, and the patient had an uneventful recovery. No subsidence or displacement of the construct was visible in the CT scans [77]. For polymethylmethacrylate implants, Erasmo et al. [78] created unique 3D template molds for 16 patients undergoing cranioplasty, resulting in harmonious symmetry and no postoperative infection, bleeding, or reoperation.

The next application of 3D printing was reported by Mobbs et al. [79]. In this study, an emergency traumatic spinal injury in a 31-year-old man was treated using a patient-specific implant created using 3D printing. The implant exhibited excellent primary stability and fit throughout the surgery. The postoperative imaging also revealed cord decompression and instrument alignment.

### 6.2 Auxetic-structured intervertebral disc implant

Due to the quick developments in biomedical implant design, it is vital to use intelligent and high-performance materials to meet the continuously increasing needs of patient-specific applications. As of 1987, when Lakes [80] produced the first auxetic foam constructions, auxetic materials have generated study attention and are added to more intelligent, sophisticated materials and structures for use in the biomedical, engineering, and scientific fields. They have a negative Poisson's ratio (NPR), which enables them to grow when stretched and shrink when squeezed [81]. Bucklicrystals, a new type of 3D auxetic structure, have been created by Jiang et al. [76]. They can create outstanding auxetic effects while keeping their mechanical qualities by buckling and rotating the connected nodes [82]. However, due to the nodes that connect them, bucklicrystals have little structural stability, rendering them unsuitable for biomedical purposes. They require optimization to reach their full potential [83].

### 6.3 Surgical planning

To visualize patient-specific organ models before an operation, models for surgical planning have been 3D printed with rigid plastics like ABS and PLA. Organ models made with 3D printing are patient-specific, inexpensive, and used in a variety of medical professions, including urology [15], cardiology [84], neurology [85], and osteology [75]. Using PLA, a patient-specific sacral model might be 3D printed. This model is employed to improve surgical methods for sacral abnormalities and to instruct aspiring surgeons [75].

ABS filaments have been utilized to create patient-specific hearts to improve inflow during device implantation procedures [86]. Additionally, some previous studies have used thermoplastic polyester resins to create ventricular outflow tract and pulmonary trunk 3D-printed models that are anatomically accurate [87]. Using photosensitive liquid resins and PLA filaments, aneurysm models with rigid walls and hollow heads have been constructed in 3D printing [85]. To study hydrodynamics, patient-specific anatomy is replicated in 3D-printed aneurysm models. Models of the prostate and kidney have been 3D printed using rigid photopolymers. Modeling for a kidney with a detachable tumor can also be done individually. These printing plans give doctors the least intrusive approach to practice and prepare for surgery [15].

### 6.4 Tissue scaffolds

For tissue engineering applications, 3D polymer printing has grown in popularity. Materials, processes, and design techniques all contribute to the customization of scaffold architectures [88]. Egan et al. [74] developed a 3D-printed scaffold for spinal fusion applications to manage different topological arrangements, unit cell sizes, beam diameters, and localized reinforcements. The study compared relative trade-offs between designs using a computational approach to identify workable scaffold topologies for bone development. Additional studies have examined trade-offs by analyzing computationally generated asymmetric unit cell topologies and stimulating tissue growth [89]. Because they enable customized configurations for patients, applications of 3D printing in medicine benefit from automated processes and computational design. For medical applications of 3D printing, computational design and automated methods are advantageous since they enable customized set-ups for individual patients [15].

## 7 CHALLENGES

Even though 3D printing in surgery has several benefits, its typical use is constrained by its higher cost, the longer development time, and the paucity of data demonstrating its efficacy in regular procedures [90]. As a highly specialized process, 3D printing necessitates significant financial investments in the 3D printer, cameras, and design software. The time needed to design a single patient-specific device may also include the printing of the device, advancements in 3D modeling, and subsequent imaging procedures. Additionally, the time required to manufacture a single device for a patient might increase due to new imaging processes, the printing of the device, and developments in the 3D modeling field itself [91].

### 7.1 Implant manufacturing with 3D printing

Medical uses of 3D printing have been effective in research, but numerous obstacles remain. Essential things for researchers to think about are highlighted in Figure 2 [15].

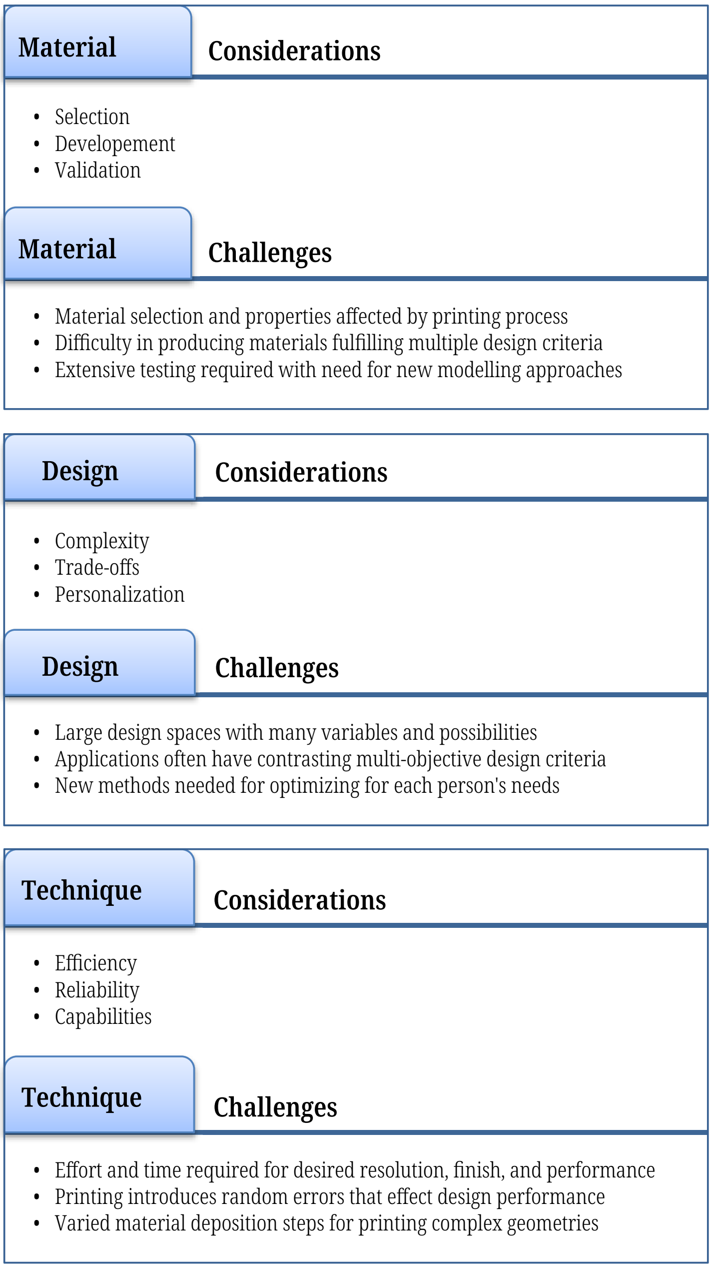


**Fig. 2.** The main research issues for 3D printing polymers with materials, designs, and techniques for medical applications [15]

The tricky part of producing a print with appropriate qualities is material selection [92]. For instance, compared to the transverse direction, fused deposition modeling provides products with superior mechanical strength [93]. This involves a trade-off between fidelity, printing speed, and resolution that impacts production planning, mechanical performance, and surface finish. Because each 3D printing method has drawbacks and trade-offs, research and development of suitable printing techniques are required [94].

By combining two biocompatible materials to improve system performance, design solutions can assist in alleviating material shortcomings. Testing and validating printed items is crucial, especially when all print process parameters are considered [95]. Only elective procedures and less urgent circumstances require the time to manufacture personalized implants. Faster printing rates, an integrated sterilization facility, and the intricate structure of the spine are considered to broaden the scope of applicability. Due to a lack of extensive cohort studies and long-term clinical trials, the advanced use of 3D-printed implants is now limited to in vivo animal models or case reports [96].

### 7.2 Patient-specific implants

By combining 3D printing technology with medical imaging data and 3D modeling, preoperative planning and customized implants that can potentially treat spinal disorders are now achievable [86]. Patient-specific implants must be manufactured in various dimensions to accommodate variations between the modeling based on preoperative clinical imaging and actual patient anatomy. The dimensions requirements or kind of implant can alter due to intraoperative discoveries, which makes it more challenging to use the implants. To address this, medical imaging technologies that are more accurate may produce images that are more closely aligned with the actual anatomy. A potential upgrade could also reduce the disparities caused by inaccurate medical aging estimation to modeling software (i.e., a compensatory algorithm) [96].

### 7.3 Ethical and legal implications

Patients must give informed consent before participating in 3D printing applications in their treatment by fully understanding the technology's use, dangers, rewards, and right to withdraw consent. Another issue that can arise is intellectual property rights, particularly if the model is built on confidential medical imaging data. Before using such data for 3D models, it is vital to obtain the necessary permits and licenses [97].

The use of 3D printing to enhance patient comprehension and informed consent is discussed in the study by Liew et al. [98]. The preoperative informed consent process was supported by a 3D-printed model to obtain patient agreement. The customized model reassured patients and increased patients' engagement in treatment choices by assisting them in comprehending the nature of the disease and the surgical procedure. This shows that by presenting a tangible picture of the patient's anatomy and pathology, 3D printing in medicine could enhance patient consent [98].

The Amsterdam UMC Ethics Committee has waived clearance for a retrospective study involving standard medical care practices and patient data in 3D printing research [102]. This raises ethical questions as appropriate standards must be observed, especially when patient data and medical information are involved. Respecting patients' autonomy and decision-making is crucial, and informed consent from all participants or parents is required. Intellectual property rights are discussed, and participants' informed consent is secured before identifying information is used. This proactive approach ensures that patients are informed about using their information in 3D printing research and addresses the legal implications of using patient-specific data [102].

The fact that the National Ethics Committee of Hungary and the National Institute of Pharmacy and Nutrition approved the study shows that it underwent a stringent ethical review procedure to adhere to requirements for using human subjects [101]. But the publication needs to detail how the study was approved or what standards were used to judge it.

Supportive evidence like 3D printed models and 3D visualization technologies are typically used to convince patients to sign the informed consent. The 3D models can clarify the potential necrosis and how the surgery would proceed [99]. The application of 3D-printed models of cerebral aneurysms was one of the initial studies that employed the 3D model to improve patient understanding conducted by Kim et al. [100]. Twenty unruptured cerebral aneurysms were divided into two groups; one received 3D printed models while the other underwent CT angiography. The 3D model was associated with greater comprehension and satisfaction in assessing the patient's knowledge and contentment with the aneurysm clipping operation [100].

# 8 LIMITATIONS

## 8.1 Regulatory approval

The regulatory approval procedure for medical equipment, particularly those made via 3D printing, is difficult and drawn out. Before clinical usage, FDA-approved devices must pass stringent testing and review to guarantee their efficacy and safety. Depending on their class and intended application, these devices may have different standards and requirements. FDA approval is required for 3D-printed medical equipment, a time-consuming and expensive procedure, including extensive testing and evaluation to guarantee safety and efficacy in clinical settings [103]. The difficulty of the approval procedure may constrain the adoption of 3D printing in medicine, and the standards that differ from regulatory approval are necessary for 3D printing in medicine to ensure that the materials, equipment and implants are safe and meet performance and quality criteria. The effectiveness and safety of 3D printing in the human body are guaranteed by this intricate procedure [104].

As the process for obtaining regulatory approval for 3D-printed medical devices changes, concerns regarding their efficacy and safety are emerging. The effectiveness and safety of these devices need to be further investigated, and regulatory organizations need to create standards and procedures for their approval [105]. Due to the bespoke nature of 3D-printed medical devices, the regulatory approval procedure is difficult and time-consuming. Authorities want safety and effectiveness data, which includes preclinical testing, clinical trials, and the submission of regulatory documents [106].

## 8.2 Cost-effectiveness

Due to initial investments in high-quality printers and materials, 3D printing is expensive and has higher production costs than conventional manufacturing processes. However, it can lower costs in some manufacturing areas by allowing for the mass production of personalized implants and devices. By reducing the need for manual labor and equipment, this customized medical solution may eventually pay for itself [107].

A major barrier to entry for healthcare providers, particularly in low-resource settings, is the high cost of printers and materials, which makes it difficult to implement 3D printing in medicine [105]. Medical device 3D printing can be expensive, especially when custom implants are involved. Materials, equipment, labor, and regulatory compliance affect the price. Using cost-effective materials, improving manufacturing efficiency, and optimizing the printing process can all help to lower costs [106]. Although it can save tooling and mold costs, 3D printing is still expensive, especially for personalized implants. It's crucial to weigh its cost-effectiveness against traditional production methods to assess its suitability for medical applications [103].

3D printing is not frequently used since it is expensive and time-consuming. It calls for specialized materials and tools, resulting in complex models or devices that could need many hours to build [104]. Medical facilities might need help to afford 3D printing due to the high cost of the materials and equipment, especially for complicated medical items. However, as technology develops, costs are projected to decrease [108], [109]. Barcik et al. [49] established a framework for developing tailor-made instruments for experimental preclinical surgeries, reducing time and financial investment. This technique was successfully applied during sheep model implantations of an active fixator [49].

### 8.3 Scalability

Although 3D printing technology allows for the scalable production of customized implants, this is not true for medical devices. Manufacturing procedures must be developed and studied further to increase productivity and workflows. As technology advances, it might become more scalable, potentially having a greater impact on healthcare. Manufacturers must overcome challenges while adhering to regulatory requirements and prioritizing patient safety during development and approval [107]. Large-scale medical applications, such as personalized implants, are restricted by 3D printing's scalability for mass production, but it may not be practical to produce large quantities of devices [103].

Due to lengthy procedures, object size and complexity restrictions, and time-consuming processes, 3D printing in medicine faces scalability challenges. Research is required to create quicker, more effective processes and investigate new materials. The quality and consistency of printed objects can be impacted by the need for more standardization in 3D printing processes and materials, making it difficult to ensure that they adhere to requirements and are secure for patient use [105].

Thanks to additive manufacturing technology, custom implants can be made with complex geometries and excellent reproducibility, but scaling relies on infrastructure and resource accessibility. Infrastructure and resource availability are constraints on the scalability of 3D-printed medical devices. The process depends on specimens, skilled labor, and infrastructure. Resources must be increased, the printing process must be improved, and manufacturing efficiency must be raised [106].

The slow and time-consuming nature of 3D printing limits its ability to be scaled up for the mass production of medical devices. It must be improved before it can be produced on a large scale. Scalability may also be restricted by the size of the printer, which also affects the size of the implant or medical device produced [108]. Concerns about producing numerous customized implants or devices in large quantities are brought up by 3D printing's scalability in the medical field. Although it permits highly customized devices, mass production may not be feasible, and the cost of creating these devices may be prohibitively high [104].

### 8.4 Long-term outcomes

Given the lack of knowledge regarding the long-term effects of 3D-printed medical devices, additional research is required to evaluate their safety, efficacy, potential risks, and durability compared to conventional devices [103]. Studies conducted over a long period should identify any potential problems and problems related to their use [105].

To meet requirements and standards, 3D-printed medical devices must undergo quality control. The printing procedure, checking, and testing for mechanical characteristics, biocompatibility, and other factors must be closely monitored. For the development of a safe and successful product, a solid and trustworthy process is required [106]. The adoption of 3D printing is constrained in medical facilities with limited resources due to the need for specialized training and knowledge of the hardware and software. However, more training and educational resources are becoming accessible as technology becomes more pervasive [109].

Uncertainty exists regarding the long-term efficacy and safety of 3D-printed medical implants and devices. To ensure consistent and dependable products, additional research is required to assess their results and address quality control measures [108].

### 8.5 Material compatibility

Material properties must be assessed for 3D-printed medical devices to guarantee long-term safety and efficacy. Further study and testing are required because mechanical and biological characteristics may differ from those of conventional materials. For the health of patients and the avoidance of potential complications, it is essential to comprehend how materials interact with the human body [107]. The safety and efficacy of 3D printing materials in implants and medical devices must be examined. The use of some materials in medical applications may be constrained because they may not be biocompatible or cause adverse reactions [108]. As an illustration, there is no discernible difference in the rate of bone fusion between PEEK, titanium, and tantalum materials in lumbar interbody fusion, regardless of the cage material used in 3D printing. Bone fusion success can be increased using ideal biological agents with osteoinductive, osteoconductive, and osteogenic properties [105].

Materials for 3D printing must be safe and compatible with the human body, necessitating using materials that can withstand normal stresses and strains. This presents a problem because not all materials are suitable for human use [104]. The range of materials ideal for medical applications is constrained by 3D printing's mechanical requirements, which also require biocompatible materials. For 3D printing, reliable and safe materials must be carefully chosen [103]. Choosing the right materials for 3D printing medical devices is essential for biocompatibility, mechanical strength, and durability. These substances ought to be safe and unreactive. Their mechanical characteristics ought to be appropriate for the intended use and be strong enough to withstand the stresses and strains placed on the body [106].

Material compatibility is crucial in producing surgical tools for preclinical surgeries, as the steam sterilization process requires non-toxic materials that won't harm animals. 3D printing technology allows for various materials, but not all are suitable for preclinical surgeries. Careful material selection is essential to ensure the safe use of animals [49].

### 8.6 Clinical validation

Due to its limited use in diagnostics, 3D printing has yet to be widely adopted in the medical field. There are still areas of medicine where its application has yet to be investigated, even though it has shown promising results in orthopedics and cardiology [104]. Clinical validation is required for the safety and efficacy of 3D-printed medical devices. This process involves thorough testing and evaluation, including animal studies and clinical trials. It is essential to ensure humane use of these devices, despite being time-consuming and expensive [103].

Production of surgical equipment for preclinical procedures must take clinical validation into account as well. The local ethics committee for animal research approved the tests, as is required to ensure that they are carried out ethically and responsibly. A technology called fluoroscopic control, which employs X-rays to offer real-time views of the surgical site, can also confirm that drilling and sawing are done correctly. Doing so makes it possible to guarantee that the surgical equipment is in good working order and that the surgical procedures are being carried out correctly [49].

Quality variation may impact clinical validation, necessitating quality control measures [108]. The inability to compare and reproduce 3D printing processes and materials results in variations in medical device quality and performance [106]. For example, the previous study examines the rabbit model's clinical validation of a 3D-printed auxetic intervertebral disc implant [104].

Next, the lack of regulation and standardization in 3D printing for medical applications results in inconsistent quality, safety, and regulatory approval. To create guidelines and rules, efforts are being made. More investigation and validation are required to ensure the safety and effectiveness of 3D-printed medical devices and implants. This comprises clinical trials to evaluate their efficacy in treating medical conditions and long-term studies to evaluate their durability and biocompatibility [109].

## 9 CONCLUSIONS

Technology based on 3D printing has changed how medical imaging is used to reconstruct a physical model. Various printing techniques are used depending on the material, surgery site, and type of guide. Machine learning has made anatomical segmentation easier. 3D-printed guide templates have become an essential supplemental tool in surgical procedures by minimizing waste and conserving resources. Collaborating with experts in several domains, such as image processing, biotechnology, and biomaterials, better software interfaces and automated algorithms are being created. 3D printed changes in function, shape, and performance over time, reducing the need for additional surgery.

In therapeutic settings, artificial intelligence boosts output and saves resources. For instance, 3D-printed guidance will increasingly be used in orthopedics. Applications for 3D printing can be characterized as condition-specific or patient-specific depending on how the technology alters biomechanical or geometry properties. Several studies have reported promising clinical outcomes. As 3D printing technology advances, printing resolution will rise.

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