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From digital design to patient care: Additive Manufacturing for personalized biomedical implants and devices

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Abstract - Additive manufacturing (AM) has emerged as a transformative technology in biomedical engineering, enabling the fabrication of patient-specific implants and devices with high precision and complex geometries. By integrating advanced imaging, computer-aided design (CAD), and layer-by-layer fabrication, AM allows for tailored solutions that replicate anatomical structures while optimizing mechanical strength, porosity, and biological functionality. This mini review highlights the digital workflow, materials, and fabrication technologies used in personalized implants, including metals, polymers, ceramics, and hybrid composites. Clinical applications in orthopedics, dentistry, craniofacial reconstruction, and cardiovascular medicine are discussed, emphasizing improvements in fitness, function, and postoperative outcomes. Current challenges such as vascularization, mechanical limitations, regulatory barriers, and cost are examined. Finally, future perspectives focus on smart materials, multi-material printing, bioactive constructs, and AI-assisted design, which are poised to expand AM's role in personalized medicine and regenerative therapies. This review underscores the potential of AM to advance patient-centered care through tailored, functional, and clinically relevant biomedical implants.

Keywords - Additive manufacturing, personalized implants, biomedical devices, patient-specific design, tissue engineering

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1. Introduction

Additive manufacturing (AM), commonly known as 3D printing, has emerged as a transformative technology in biomedical engineering, enabling the fabrication of patient-specific implants and devices with unprecedented precision [1]. Unlike conventional subtractive manufacturing methods, which often require extensive machining and produce significant material waste, AM builds complex structures layer by layer directly from digital models [2]. This capability allows for the production of implants that precisely match a patient's anatomy, improving fitness, function, and clinical outcomes [3]. The increasing availability of high-resolution imaging modalities such as computed tomography (CT) and magnetic resonance imaging (MRI), combined with advanced computer-aided design (CAD) tools, has accelerated the development of personalized biomedical solutions, bridging the gap between digital planning and clinical application [4, 5].

Personalized implants and devices address a range of clinical challenges across orthopedic, dental, craniofacial, and cardiovascular applications [6, 7]. Traditional "off-the-shelf" implants often fail to fully conform to individual patient anatomy, leading to suboptimal load distribution, impaired healing, and higher complication rates [8, 9]. By contrast, AM enables the design and fabrication of patient-specific constructs that not only replicate anatomical geometry but also allow optimization of internal porosity, mechanical strength, and surface characteristics to enhance osseointegration, vascularization, and tissue regeneration [9, 10]. Moreover, AM facilitates rapid prototyping, iterative testing, and even production of complex lattice structures or hybrid devices that are difficult or impossible to manufacture using conventional methods [11].

The success of AM-based personalized implants relies on the integration of digital design, material selection, and fabrication strategies. Materials used in AM range from metals and ceramics to polymers and composites, each chosen according to the mechanical, biological, and functional requirements of the intended implant [5]. Surface modifications and functionalization can further enhance biocompatibility, antimicrobial properties, or drug delivery capabilities, making these implants highly versatile for diverse clinical applications [12, 13]. In addition, emerging technologies such as multi-material printing, smart biomaterials, and AI-assisted design are expanding the possibilities for customized, functional, and adaptive implants that respond to dynamic physiological environments [14, 15].

Despite these advancements, challenges remain in translating AM-based implants from the laboratory to clinical practice [16, 17]. Issues such as post-processing, sterilization, regulatory approval, cost-effectiveness, and long-term performance must be addressed to ensure safe and reproducible patient outcomes [18]. Nevertheless, ongoing innovations in imaging, materials science, computational design, and printing technologies continue to push the boundaries of what is possible in personalized medicine [9, 19]. This mini-review aims to provide a concise overview of additive manufacturing for patient-specific biomedical implants and devices, highlighting the digital workflow, materials, fabrication technologies, clinical applications, current challenges, and future perspectives [20]. By emphasizing the integration of digital design and patient-centered solutions, this review underscores the growing impact of AM on precision medicine and personalized healthcare [21].

2. Digital workflow for Personalized Implants

The digital workflow forms the backbone of additive manufacturing for personalized biomedical implants, enabling the translation of patient-specific anatomical data into functional, tailored devices [8, 22]. This workflow integrates imaging, computer-aided design, and printing preparation, ensuring that implants not only match the patient’s geometry but also meet mechanical and functional requirements [23]. The precision of each step directly affects the quality, fit, and clinical success of the final implant [18]. By leveraging advanced imaging and computational tools, clinicians and engineers can design implants that optimize both biological performance and structural integrity, paving the way for highly personalized therapeutic solutions [14, 24].

2.1. Imaging and Data Acquisition

The process begins with high-resolution imaging techniques such as computed tomography (CT), magnetic resonance imaging (MRI), and 3D scanning, which capture detailed anatomical information of the target tissue or defect site [8, 25]. CT scans are commonly used for bone-related applications due to their high spatial resolution and ability to accurately quantify bone density, while MRI is preferred for soft tissue imaging because of its superior contrast resolution [10, 26]. These imaging datasets are processed to generate volumetric models of the patient’s anatomy, which serve as the foundation for implant design. Accurate imaging is essential to ensure that the resulting digital model reflects the true geometry of the tissue, allowing the implant to achieve optimal fit, load distribution, and functional integration with surrounding structures [27, 28].

2.2. Computer-Aided Design (CAD)

Once the imaging data is acquired, it is imported into computer-aided design (CAD) software to create a patient-specific digital model[29]. CAD tools enable precise manipulation of anatomical structures, modification of implant geometry, and simulation of mechanical performance under physiological loads [30]. Features such as lattice structures, porosity gradients, and surface textures can be incorporated to enhance osseointegration, reduce weight, and improve vascularization [5, 31]. Advanced CAD software also allows finite element analysis (FEA) to predict stress distribution, deformation, and fatigue resistance, ensuring that the implant can withstand in vivo conditions [32]. The combination of anatomical accuracy and mechanical optimization is critical for producing implants that are both biologically compatible and functionally robust [5, 10].

2.3. Slicing and Printing Preparation

After the CAD model is finalized, it undergoes slicing, where the three-dimensional geometry is divided into thin layers to guide the additive manufacturing process [33]. Slicing software generates the toolpath for the printer, specifying parameters such as layer thickness, deposition speed, infill pattern, and support structures [34, 35]. Printing preparation also involves material selection and optimization, taking into account the mechanical, thermal, and biocompatible properties required for the intended application [9, 21]. For multi-material or hybrid implants, additional considerations include nozzle assignment, deposition sequence, and crosslinking or curing strategies. Careful preparation ensures that the printed implant faithfully reproduces the digital design while maintaining structural integrity and biological functionality, ultimately bridging the gap between digital planning and clinical implementation [36].

3. Additive Manufacturing Technologies for Biomedical Devices

Additive manufacturing (AM) encompasses a variety of technologies that enable layer-by-layer fabrication of patient-specific biomedical implants and devices [37, 38]. The choice of AM technique depends on the material, desired resolution, mechanical requirements, and intended clinical application [14, 33]. Advances in AM have expanded its applicability across metals, polymers, and ceramics, allowing the production of complex geometries, internal lattice structures, and multi-material constructs that are difficult or impossible to fabricate with conventional methods [39, 40]. These technologies provide flexibility in implant design, rapid prototyping, and the ability to produce personalized solutions tailored to individual anatomical and functional requirements [41].

Stereolithography (SLA) is a high-resolution AM technique that uses a UV laser to selectively cure photopolymer resins [42]. SLA is widely used for dental, craniofacial, and surgical guide applications due to its precision and smooth surface finish. Selective Laser Sintering (SLS) and Electron Beam Melting (EBM) employ laser or electron beams to fuse powdered materials, primarily metals or ceramics, enabling the production of load-bearing implants such as orthopedic and cranial plates

[10, 43]. These powder-based methods allow control over porosity and internal architecture, which is crucial for osseointegration and tissue ingrowth [44]. Fused Deposition Modeling (FDM) is another widely used method for polymer-based devices, offering cost-effectiveness and versatility in fabricating biodegradable scaffolds and anatomical models, though its resolution is generally lower than SLA or SLS [10, 45].

Bioprinting techniques have emerged as a specialized branch of AM, enabling the deposition of cell-laden bioinks and hydrogel matrices for tissue engineering applications [9, 46]. Extrusion-based, inkjet, and laser-assisted bioprinting allow for spatial placement of living cells, growth factors, and biomaterials to create constructs with biological functionality [44]. Multi-material printing capabilities enable the combination of structural polymers with bioactive hydrogels, producing hybrid devices that mimic native tissue complexity [47, 48]. Such approaches have been applied to fabricate vascularized tissue constructs, cartilage models, and soft tissue implants, demonstrating the potential of AM to move beyond structural devices toward functional regenerative solutions [10, 49].

The selection of AM technology also depends on post-processing requirements, scalability, and sterilization protocols [5, 50]. Techniques like SLA and SLS may require cleaning, curing, or sintering, while metallic implants often undergo heat treatment to achieve the desired mechanical properties [51]. Integration with computational tools such as finite element analysis (FEA) and topology optimization allows prediction of mechanical performance and iterative refinement of implant design [52]. By combining digital design, material science, and AM technologies, personalized biomedical devices can be produced with high precision, structural integrity, and clinical relevance, offering significant improvements over traditional manufacturing approaches [28, 53].

4. Materials for Personalized Biomedical Implants

The selection of materials is a critical factor in the success of personalized biomedical implants, as it directly influences mechanical performance, biocompatibility, and long-term functionality [54, 55]. Additive manufacturing allows the use of diverse materials, ranging from metals and polymers to ceramics and composites, each offering unique advantages for specific clinical applications [56]. The material choice is guided by factors such as load-bearing requirements, tissue compatibility, degradation behavior, and fabrication constraints [57, 58]. Optimizing these properties ensures that patient-specific implants provide structural support, promote tissue integration, and minimize complications [57].

4.1. Metals (Titanium, Co-Cr Alloys, Stainless Steel) – Mechanical Strength, Load Bearing

Metals such as titanium, cobalt-chromium (Co-Cr) alloys, and stainless steel are widely used in load-bearing applications due to their high strength, corrosion resistance, and fatigue durability [59]. Titanium and its alloys are particularly favored for orthopedic and craniofacial implants because of their biocompatibility, lightweight nature, and excellent osseointegration [9, 60]. Co-Cr alloys provide superior wear resistance, making them suitable for joint replacements and articulating surfaces. Stainless steel is often used for temporary fixation devices or plates and screws due to its cost-effectiveness and mechanical stability [10, 61]. Powder-based AM methods such as Selective Laser Sintering (SLS) and Electron Beam Melting (EBM) allow fabrication of complex metallic implants with controlled porosity to enhance bone ingrowth and reduce stiffness mismatch with native tissue [14, 62].

4.2. Polymers (PLA, PCL, PEKK, PEEK) – Lightweight, Bioresorbable Options

Polymers, including polylactic acid (PLA), polycaprolactone (PCL), polyether ketone (PEKK), and polyether ether ketone (PEEK), are increasingly used for lightweight and bioresorbable implants [8, 63]. These materials offer tunable mechanical properties, controlled degradation rates, and biocompatibility, making them suitable for temporary scaffolds or load-sharing implants [63]. PLA and PCL are biodegradable thermoplastics commonly used in bone and soft tissue scaffolds, while PEKK and PEEK provide high-strength, non-degradable options for cranial and orthopedic applications [64]. Polymers can be combined with bioactive fillers or fibers to enhance osteoconductive and mechanical performance [65]. Fused deposition modeling (FDM) and extrusion-based printing enable fabrication of polymeric implants with precise geometry and porosity tailored to patient-specific requirements [66].

4.3. Ceramics and Composites – Bone-Mimicking and Bioactive Scaffolds

Ceramics such as hydroxyapatite, tricalcium phosphate, and bioactive glasses are widely used for bone-mimicking implants due to their bioactivity, osteoconductive, and chemical similarity to native bone minerals [67]. However, their brittleness limits are used in load-bearing applications unless they are combined with polymers to form composites [68]. Composite materials, integrating ceramics with polymers or metallic matrices, provide mechanical reinforcement while maintaining biological functionality [8, 69]. For example, hydroxyapatite-PLA composites combine strength and osteoconductive, supporting bone regeneration while gradually degrading [70]. Additive manufacturing enables precise control over ceramic and composite scaffold architecture, allowing graded porosity, tailored mechanical strength, and enhanced tissue integration, which are essential for personalized orthopedic and craniofacial implants [71, 72].

5. Clinical Applications for Personalized AM Implants

In dentistry, AM has revolutionized the production of crowns, bridges, dental implants, and surgical guides, providing high precision and rapid turnaround [73]. Personalized implants and prosthetics improve occlusal alignment and esthetic outcomes while minimizing chair time [74, 75]. Craniofacial and maxillofacial reconstruction also benefit from AM, particularly in trauma or congenital defect repair. Patient-specific plates, mandibular reconstructions, and orbital implants can be fabricated using metals, polymers, or composites, with anatomical fidelity derived from CT or MRI scans [76]. The use of lattice and porous structures enhances integration with native tissue, supporting vascularization and bone in-growth [77]. Overall, AM enables custom-fit solutions that improve surgical planning, functional restoration, and cosmetic outcomes.

5.1. Cardiovascular Devices

Personalized AM implants are increasingly applied in cardiovascular medicine, where anatomical variability is critical [78]. Patient-specific vascular grafts, stents, and heart valve scaffolds can be fabricated to match vessel geometry and flow dynamics [14, 15]. Biocompatible polymers, sometimes reinforced with metals or biodegradable composites, are used to ensure mechanical integrity while supporting tissue remodeling. Incorporation of growth factors or endothelial cells into scaffolds can promote rapid endothelialization and reduce thrombogenicity [5, 79]. Computational fluid dynamics (CFD) simulations combined with CAD allow optimization of implant design to minimize turbulent flow and improve long-term function [80, 81]. Such customized cardiovascular devices offer promising solutions for congenital defects, aneurysms, and valve replacements, where standard devices may not fit effectively [82].

5.2. Emerging Applications and Hybrid Constructs

Beyond orthopedic, dental, and cardiovascular uses, AM enabling hybrid and multi-material implants for soft tissue regeneration, neurosurgery, and organ reconstruction [83]. Bioprinting allows deposition of cell-laden hydrogels and growth factors to create tissue-engineered constructs for cartilage, skin, and neural repair [84, 85]. Multi-material implants can combine load-bearing metals with bioactive polymer or ceramic layers to achieve both mechanical support and regenerative functionality [10, 86]. Patient-specific AM scaffolds are also being explored for drug delivery, controlled release of growth factors, and incorporation of sensors for monitoring tissue healing [87, 88]. These emerging applications highlight the versatility of AM in precision medicine, providing tailored solutions that integrate structural, functional, and biological requirements for optimal clinical outcomes [89, 90].

6. Challenges and Limitations

Despite the significant advancements in additive manufacturing for personalized biomedical implants, several challenges hinder widespread clinical adoption [91]. One major limitation is the mechanical and material constraints of commonly used biomaterials [78, 92]. Metals offer high strength but may suffer from stress shielding or limited bioactivity, whereas polymers and ceramics provide biocompatibility but often lack sufficient mechanical durability for load-bearing applications [93]. Achieving an optimal balance between structural integrity, degradation rate, and biological performance remains difficult. Additionally, reproducing complex anatomical geometries with high precision can be limited by printer resolution, material properties, and post-processing requirements, which may affect implant accuracy and clinical outcomes [10, 94].

Another critical challenge involves biological and functional considerations [95]. Ensuring long-term biocompatibility, proper tissue integration, and minimizing immune responses are essential for successful implantation [96]. Vascularization within larger constructs remains a major bottleneck, as insufficient blood supply can lead to cell death and impaired healing [13, 97]. Similarly, integrating bioactive components, such as growth factors or cell-laden scaffolds, requires careful optimization to maintain functionality during the printing process and in vivo [98]. Patient-specific implants must also account for variations in tissue properties, age, and disease state, which adds complexity to design and fabrication protocols [99]. Finally, regulatory, economic, and translation barriers pose additional hurdles. Standardization of AM processes, material certifications, sterilization protocols, and quality control is still evolving, complicating regulatory approval [100]. The cost of high-resolution printers, specialized materials, and post-processing procedures may limit accessibility, especially in resource-constrained settings. Furthermore, large-scale clinical validation is necessary to demonstrate safety, efficacy, and reproducibility, which can be time-consuming and expensive [9, 101]. Overcoming these challenges requires interdisciplinary collaboration among engineers, clinicians, material scientists, and regulatory bodies to develop robust, reliable, and clinically viable AM solutions for personalized patient care [5, 102].

7. Conclusion and Future Perspective

Additive manufacturing has revolutionized the development of personalized biomedical implants and devices by enabling precise, patient-specific solutions that improve fitness, functionality, and clinical outcomes. The integration of advanced imaging, computer-aided design, and layer-by-layer fabrication allows the creation of implants that replicate complex anatomical structures while optimizing mechanical and biological performance. Metals, polymers, ceramics, and hybrid composites provide diverse material options tailored to load-bearing, bioactive, or biodegradable applications. Clinical applications in orthopedics, dentistry, craniofacial reconstruction, and cardiovascular medicine demonstrate the significant impact of AM on precision medicine, offering enhanced implant integration and reduced surgical complications.

Looking forward, the future of personalized AM implants lies in the convergence of smart materials, multi-material printing, and bioactive constructs. Incorporating growth factors, living cells, or stimuli-responsive components can transform static implants into functional, regenerative systems capable of dynamic interactions with the host tissue. Computational tools, including artificial intelligence and finite element analysis, will further optimize design, predict mechanical performance, and enable patient-specific customization at unprecedented scales. In situ printing and hybrid approaches combining metals, polymers, and hydrogels promise to expand AM applications into soft tissue regeneration and complex organ repair, moving beyond structural implants toward multifunctional biomedical solutions. Despite its potential, widespread clinical translation requires overcoming challenges related to regulatory approval, material standardization, cost, and long-term performance. Collaborative efforts between engineers, clinicians, and material scientists are essential to ensure safety, reproducibility, and efficacy. As these barriers are addressed, additive manufacturing is poised to become a cornerstone of personalized medicine, offering tailor-made, clinically relevant implants that enhance patient care, accelerate recovery, and enable next-generation regenerative therapies.

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Conflict of Interest

The authors declare that there are no competing interests related to this work.

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