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Short Communication

Custom Implants and Beyond: The Biomedical Potential of Additive Manufacturing

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Abstract

Additive manufacturing, commonly known as 3D printing, is revolutionizing the field of biomedical engineering by enabling the creation of custom implants tailored to individual patient anatomy. This technology uses digital design files to layer-by-layer build structures from various materials, including biocompatible metals, polymers, and ceramics. In medical applications, this precision allows for the creation of implants that closely match the contours and geometries of a patient's unique anatomical features, offering improved fit, functionality, and comfort compared to traditional, mass-produced implants. The potential benefits extend beyond just enhanced patient outcomes. With additive manufacturing, healthcare providers can reduce surgical times by designing implants that require minimal intraoperative modification. Moreover, the flexibility of this technology facilitates rapid prototyping and iterative design, enabling healthcare professionals to collaborate with engineers in refining implant designs before they are used in surgery. This iterative approach is particularly useful in complex cases, such as craniofacial reconstruction, where conventional implants may not adequately address the intricacies of a patient's skeletal structure.

Introduction

Additive manufacturing (AM), commonly known as 3D printing, is revolutionizing the field of biomedical engineering [1]. AM has opened new possibilities for personalized medicine, especially in custom implants, by enabling the creation of complex, custom-designed structures. This summary report explores the diverse applications of additive manufacturing in creating custom implants and other biomedical devices, highlighting this technology's benefits, challenges, and prospects. AM is a process by which three-dimensional objects are created by layering material according to a digital design. This technology offers precise control over the final product's shape, structure, and material composition [1]. In biomedical applications, this capability translates into the production of customized implants, prosthetics, and surgical tools specifically tailored to individual patient needs. Traditionally, these implants were manufactured using methods like casting or high-precision machines such as Computer Numerical Control (CNC) [2]. While these traditional techniques can achieve high accuracy, they often lack the flexibility and efficiency that additive manufacturing provides in creating complex, patient-specific geometries with shorter lead times. As shown in Figure 1 [3], custom implants are one of the most impactful applications of additive manufacturing in the biomedical field. Traditional implants are often standardized, leading to potential complications due to patients' varying anatomical structures. With AM, implants can be designed to

Figure 1: A representation of manufacturing Custom implants [3].

fit the exact geometry of a patient's anatomy, reducing the risk of complications and improving surgical outcomes. Additive manufacturing has created customized orthopedic implants for joint replacements, spinal fusion, and bone reconstruction [4].

Beyond implants, additive manufacturing opens new frontiers in tissue engineering and regenerative medicine [5]. Researchers are experimenting with bioinks composed of living cells and biomaterials [6] to create tissue scaffolds supporting cell growth and tissue regeneration. This capability has profound implications for future treatments, allowing for the possibility of growing replacement tissues and organs tailored to individual patients, thereby reducing rejection risks and the need for immunosuppressive drugs. Overall, the versatility and precision of additive manufacturing are driving a new era of personalized medicine, with transformative possibilities in patient-specific implants, tissue engineering, and beyond [7].

The ability to produce complex lattice structures with varied porosity allows for improved osseointegration, where bone grows into the implant, enhancing stability and reducing recovery time. Craniofacial implants, used for reconstructive surgery after trauma or congenital defects, benefit significantly from custom designs. Additive manufacturing allows for the creation of intricate structures that conform to the unique contours of a patient's skull or face, leading to more natural and aesthetically pleasing results [4]. Researchers are exploring various new materials [8,9], including biocompatible metals, polymers, and composites, to develop implants that offer improved mechanical strength, durability, and tissue integration [10].

The topic was selected due to the growing importance of personalized medicine and the increasing demand for custom medical devices. Additive manufacturing offers transformative solutions, as it can produce implants tailored to individual patients while allowing for innovative designs in tissue engineering and regenerative medicine. The section will delve into the background and highlight the benefits, challenges, and prospects of additive manufacturing in biomedical engineering. This short report explores the diverse applications of additive manufacturing in creating custom implants and other biomedical devices. The technology's potential to revolutionize the medical field is underscored by its ability to produce highly complex geometries, resulting in more effective implants that conform to a patient's unique anatomy. This capacity significantly reduces surgical complications and enhances patient outcomes.

Method

To write this summary paper on additive manufacturing in biomedical engineering, started by conducting a comprehensive literature search across several scientific databases, including PubMed, Scopus, and Google Scholar. We used keywords such as "additive manufacturing," "3D printing," "custom implants," "biomedical engineering," and "tissue engineering" to identify relevant articles, studies, and scholarly works. The search was supplemented by examining references in critical articles to ensure a broad and thorough collection of sources. Then, inclusion and exclusion criteria were used to select studies published within the last decade, focused on biomedical applications of additive manufacturing, and provided empirical evidence or detailed analyses. Special attention was given to quality assurance, regulatory compliance, and safety considerations due to the critical nature of medical applications. This information was then organized to create a cohesive narrative, reflecting the current state of additive manufacturing in the biomedical field and its potential impact on personalized medicine.

Results and discussions

While custom implants are a significant focus, additive manufacturing has broader applications in the biomedical field. Figure 2 illustrates a diverse range of biomedical implants fabricated using additive manufacturing, also known as 3D printing [11]. Each example represents different medical implants designed to meet specific patient needs.

Prosthetics and orthotics

AM enables the production of customized prosthetic limbs and orthotic devices that fit the specific requirements of individual patients. This customization leads to improved comfort, functionality, and aesthetics for users. Additionally, additive manufacturing allows for rapid prototyping and iterative design, enabling healthcare providers to fine-tune prosthetics and orthotics to achieve an optimal fit and performance [12]. Lightweight polymers, carbon-fiber composites, and other innovative materials can be used

Figure 2: Various biomedical implants produced using 3D printing technology [39]. The image includes the following examples: Craniofacial plate implant [15], mandibular implants [16], spinal [17] and sternum implants [18], lumbar cage [19], hip [20] and knee implants [21].

to create durable yet flexible devices. These materials can improve the aesthetics and functionality of prosthetics, offering patients a more comprehensive range of motion and a more comfortable experience. Hence, custom implants in prosthetics and orthotics, made possible by additive manufacturing, represent a significant leap forward in personalized medical care, offering enhanced comfort, improved functionality, and a better quality of life for patients [13,14].

Surgical tools and guides

AM has significantly impacted the development of surgical tools and guides by enabling the creation of customized instruments tailored to specific surgical needs. These custom tools, such as scalpels, retractors, and forceps, are designed to fit the unique anatomical features of individual patients, allowing for greater precision and ergonomics in the operating room. The flexibility of additive manufacturing facilitates the production of complex geometries and intricate details, leading to highly functional and lightweight tools [22]. Similarly, surgical guides, used in procedures like orthopedic surgeries, dental implant placements, and craniofacial reconstructions, are designed to ensure precise surgical cuts and implant placements, reducing the risk of errors. These custom guides, created to fit individual patient anatomy, enhance surgical accuracy and can reduce surgical times. The rapid prototyping capabilities of additive manufacturing allow for iterative design and collaboration between surgeons and engineers, ensuring that surgical tools and guides are optimized for specific procedures before being used in surgery [23].

Bioprinting and tissue engineering

Bioprinting and tissue engineering represent a transformative approach to creating custom implants, using bio-inks that contain living cells and biodegradable materials to build structures layer by layer. This technique allows for precise control over cell placement, facilitating the development of tissue scaffolds that encourage cell growth, tissue regeneration, and integration with the surrounding environment [24]. In bone tissue engineering, for example, bioprinting enables the construction of scaffolds that support osteoblasts, promoting bone regeneration and healing. In softer tissue applications like cartilage or skin, bioprinting creates tailored grafts that meet specific patient needs. Beyond these applications, researchers are exploring multi-material bioprinting to replicate more complex tissues and organs, offering a path toward personalized regenerative medicine and potentially reducing the need for organ donors. This technology holds great promise for advancing custom implants and tissue engineering in ways that were once only imaginable [25].

Selection of material and applications

Figure 3 categorizes different types of biomedical materials

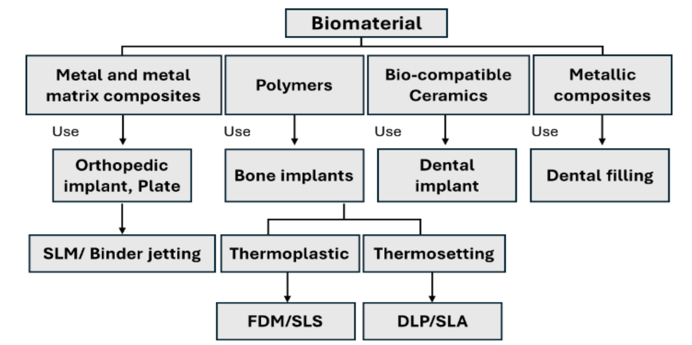

Figure 3: Overview of different biomaterials used in various applications that leverage additive manufacturing techniques [26].

and lists key attributes of an ideal biomaterial: ease of printing, biocompatibility, morphological similarity to living tissue, and non-toxicity. These characteristics are crucial for successful application in medical contexts. It also suggests that the choice of material for additive manufacturing in the medical field depends on specific requirements such as strength, durability, flexibility, and biodegradability [26].

Biomedical materials [27] used in custom-based implants vary widely, each offering unique advantages tailored to specific applications. The choice of material is crucial for ensuring implant effectiveness, biocompatibility, and durability. This discussion explores the use of metals, polymers, ceramics, and composites in creating customized implants, detailing the applications and highlighting the importance of each material type.

Metals and alloys: Metals and alloys are commonly used in biomedical implants due to their high strength, durability, and biocompatibility. Titanium (Ti) is a prominent example, prized for its strength-to-weight ratio, corrosion resistance, and ability to integrate with bone tissue (osseointegration) [7]. Titanium is frequently used for orthopedic implants, such as joint replacements because it provides robust structural support while promoting bone growth around the implant. Additionally, titanium's biocompatibility makes it suitable for spinal fusion devices and dental implants. Cobalt-chromium alloys (CoCr) are another group of metals favored for their exceptional strength and wear resistance. These alloys are typically employed in applications requiring high mechanical stress and fatigue resistance, such as hip and knee replacements. Stainless steel, particularly the 316L variant, is also used in biomedical applications due to its durability and cost-effectiveness. Stainless steel is often chosen for plates, screws, and pins used in orthopedic surgeries, offering a reliable and affordable option for internal fixation [28].

Polymers: Polymers are appreciated for their flexibility, biocompatibility, and ease of processing. Polylactic acid (PLA) is a biodegradable polymer in drug delivery systems [29] and bone implants. PLA's biodegradability makes it an excellent choice for applications where gradual resorption is desirable, such as drug-eluting stents and tissue scaffolds.

Polyether ether ketone (PEEK) is another significant polymer known for its high strength and compatibility with medical imaging techniques like MRI. PEEK is commonly used in spinal implants and orthopedic components due to its durability and radiolucency [30].

Ceramics: Ceramics are valued for their hardness, wear resistance, and bioactivity. Hydroxyapatite (HA), a calcium phosphate ceramic, closely resembles human bone, making it ideal for coatings on metal implants and as a bone graft substitute. This bioactivity encourages bone growth, enhancing implant stability. Alumina and zirconia are other ceramics used in biomedical applications, particularly in dental implants and joint replacements. Their hardness and smooth surfaces reduce friction and wear, contributing to the longevity of dental and orthopedic implants [31].

Composites: Composites combine the benefits of multiple materials to achieve a balance of properties. Carbon-fiber-reinforced polymers offer high strength with reduced weight, making them suitable for orthopedic implants and prosthetics where weight reduction is beneficial. Ceramic-polymer composites are used in dental fillings, combining the bioactivity of ceramics with the flexibility of polymers. This combination provides the necessary strength for dental applications while allowing for some degree of flexibility and resilience [32].

The choice of material for custom-based implants depends on the application's specific requirements, including strength, flexibility, biocompatibility, and biodegradability. Metals are ideal for plates, screws, and orthopedic implants due to their durability, while polymers find use in drug delivery and bone implants because of their versatility and biodegradability. Ceramics are favored in dental implants for their hardness and bioactivity, and composites offer a balanced approach for dental fillings, combining multiple advantageous properties.

Examples of current applications: There are a range of applications for additive manufacturing in the medical field, showcasing both prosthetic and stabilization devices. Buonamici, et al. [33] investigated the external stabilization devices designed and produced through additive manufacturing, technology creates supportive structures for medical treatment and rehabilitation. These devices are likely customized to fit individual patient anatomy, providing enhanced stability and support during recovery. focus shifts to upper-limb prosthetics, specifically highlighting the "Hero Arm," an advanced prosthetic device developed by Open Bionics [34]. This prosthesis, created through additive manufacturing, demonstrates the versatility and potential of 3D printing in producing complex, functional components that can improve the quality of life for amputees. The use of additive manufacturing allows for customization, enabling prostheses to be tailored to the unique needs of each user. Ku, et al. [35] demonstrated a bionic hand undergoing grasping and pinching evaluation. This application emphasizes the importance of functional testing in prosthetic development, where the bionic hand is evaluated for its ability to perform fine motor tasks. The use of additive manufacturing in creating these bionic hands allows for intricate designs and precise control of mechanical elements, contributing to improved dexterity and functionality in prosthetic devices.

Challenges and Considerations: Despite its promise, additive manufacturing in biomedical applications faces several challenges. Regulatory issues, quality assurance, and biocompatibility concerns are significant hurdles. Quality assurance in additive manufacturing is a critical concern due to the inherent variability in the process and the need for customized products. Unlike traditional manufacturing, which relies on standardized mass production, additive manufacturing often involves creating unique items tailored to individual patients, such as custom implants. This customization introduces material properties, layer-by-layer construction, and post-processing variability. Ensuring consistent quality across these custom products requires rigorous testing, validation, and equipment calibration. Manufacturers must implement robust quality control measures, including precise dimensional accuracy checks, material characterization, and mechanical testing, to ensure that each product meets safety and performance standards [36,37]. The lack of uniformity can lead to discrepancies in product quality, which, if not properly managed, can pose a risk to patient safety. As additive manufacturing becomes more widely adopted in biomedical applications, quality assurance must be a top priority to maintain the reliability and safety of medical devices [38].

Future trends and prospects: The future of AM in the field of biomedical engineering, particularly in custom implants, is characterized by rapid advancements in technology, materials science, and computational design. These trends point toward a transformative impact on personalized medicine, offering new possibilities for patient-specific implants and beyond [39].

The evolution of new materials is another significant trend shaping the future of additive manufacturing. New biocompatible metals, polymers, ceramics, and composites are being developed with improved mechanical properties and biological compatibility. For instance, titanium alloys with enhanced strength and reduced weight are gaining popularity in orthopedic applications, while bioactive ceramics are being used to promote bone regeneration. Polymers with varying degrees of flexibility and biodegradability are opening new avenues for tissue engineering and drug delivery systems. The ability to tailor these materials for specific medical applications is crucial for developing custom implants that meet each patient's unique needs. Digital technologies and artificial intelligence (AI) are playing an increasingly important role in designing and manufacturing custom implants. AIdriven design tools allow for optimizing implant geometries based on patient-specific data, such as medical imaging and 3D scanning. This level of customization improves implant fit and functionality, leading to better surgical outcomes. Machine learning algorithms can also be used to predict the performance and longevity of implants, providing valuable insights for further design refinement. Additionally, AI can streamline the quality assurance process, detecting defects and ensuring consistent production standards. While custom implants remain a focal point, the biomedical potential of additive manufacturing extends beyond these applications. Bioprinting is emerging as a promising avenue for tissue engineering, where living cells and biomaterials are printed to create tissue scaffolds that support cell growth and tissue regeneration. This technology can revolutionize regenerative medicine, creating patient-specific tissues and, eventually, whole organs. Furthermore, additive manufacturing enables the development of custom surgical tools and guides, enhances precision during surgical procedures, and reduces the risk of errors.

Conclusion

Additive manufacturing has transformed the biomedical engineering landscape, offering unprecedented customization and personalization. Custom implants, in particular, represent a significant advancement in patient-specific healthcare. As technology and materials evolve, the potential for additive manufacturing to improve medical outcomes and quality of life is immense. The continued development of regulatory frameworks and quality standards will be essential to ensure the safety and effectiveness of these groundbreaking biomedical applications.

Author contributions

A.K.G.: Initiated the study, methodology, writing, and reviewing, A.C.: Analyzing, writing, and reviewing; A.K.: writing and reviewing; A.G.: writing and reviewing.

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