Biomechanics and Design of Medical Implants

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ABSTRACT
The quality of life for people with orthopedic disabilities has significantly improved as a result of recent developments in orthopedic prosthetic design. However, there are still significant issues that must be resolved if orthopedic prostheses are to continue to work more effectively. The most urgent challenges are to improve biocompatibility to encourage greater integration with natural tissues, durability to endure daily use, and sensory feedback to improve movement control. Promising new technologies have been created to solve these issues, including 3D printing, regenerative medicine, artificial intelligence, and smart prostheses. The functionality of orthopedic prostheses could be significantly improved by this cutting-edge technology. Addressing a number of crucial issues is necessary in order for these next-generation orthopedic prostheses to reach their full potential. These include increasing investment in research and development, standardizing components to ensure quality and dependability, enhancing access to prosthetics, and interdisciplinary collaboration between professionals in orthopedics, materials science, biology, and engineering.
Significant advancements in the realms of bioengineering and medicine have been made possible by nanomaterials. In the current paper, a comprehensive analysis of several biocompatible nanocomposites is presented. It is also rigorously examined how well they work with cutting-edge fabrication techniques like additive manufacturing when designing effective medical implants. Regarding the requirements and future of the implantable medical device sectors, the significance of nanocomposites and processing techniques is also thoroughly anticipated.

Keywords: additive manufacturing; 3D printing; nanocomposites; medical implants; prosthetics; Orthopedic prosthesis design; Biocompatibility; Durability; Sensory feedback; 3D printing; Regenerative medicine; Artificial intelligence

INTRODUCTION
Moulds and other traditional manufacturing processes take a lot of time and money, rendering them unsuitable for applications in biomedical engineering that require complex geometries. Additive manufacturing, sometimes known as 3D printing, has become a practical and quick method for creating geometrically challenging objects. It was created in the 1980s and entails material layering in 3D space while being directed by a computer-generated model. This makes it possible to build intricate designs that would be difficult to make using traditional manufacturing methods.
The application of AM in healthcare is expanding, particularly in tissue engineering, implant design, and therapeutic delivery. A rapidly expanding use of AM is bioprinting, which enables in vitro drug screening, disease modeling, and the creation of implantable tissue. [2]
AM addresses critical points in porous implant materials, such as manufacturing feasibility and accuracy, bone elastic properties, and osseointegration pores sizes. This has inspired new geometrical lattice designs

for intervertebral fusion devices. These structures are fabricated and tested, and when integrated into medical devices, they could offer superior medical outcomes. [3]
AM holds great promise for personalised medical applications such as personalised implants, medical models, and saw guidance. AM is used on splints, orthodontic devices, dental models, and drill guides in dentistry. Additionally, it has been looked into for developing artificial tissues and organs. Reconstructing 3D models from patient anatomy is now possible thanks to medical imaging's digitalization. Using 3D scanning techniques, a workflow for personalised medical devices comprises imaging or recording patient geometry. The creation of patient-specific implants that can be produced additively using this data is possible. Before the device is ready for clinical use, post-processing, such as polishing, is frequently needed. [1]

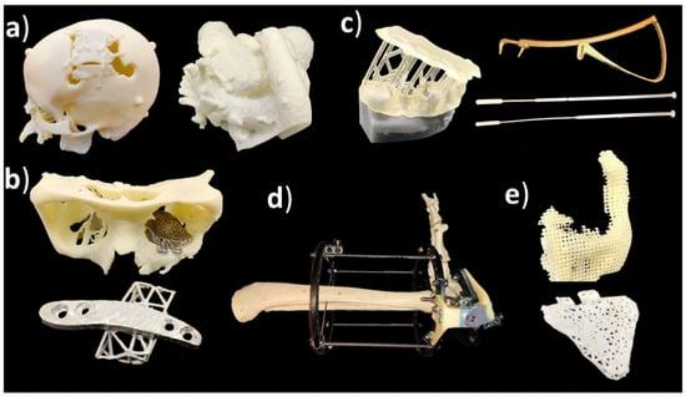

Figure1: Classification of medical applications of additive manufacturing:

1. Medical models;
2. Implants;
3. Tools, instruments and parts for medical devices;
4. Medical aids, supportive guides, splints and prostheses;
5. Biomanufacturing.

Owing to the physicochemical qualities of nanoparticles, nanotechnology has advanced in areas like agriculture and additive manufacturing (AM). A third industrial revolution may result from the possibility of creating elaborate, tiny, and sophisticated designs made possible by AM. [4]
Nanomaterials have been thoroughly investigated for a variety of engineering applications, including energy materials, biomedical applications, and microelectronics. They are recognised for their increased surface area, reactivity, and robustness. Given that they can save lives, they are particularly interested in developing cutting-edge implants and tissue engineering. A high strength-to-weight ratio, a large surface area, and biocompatibility are necessary for these implants. To encourage cell adhesion, proliferation, and differentiation, a favorable topography must be created.[5]

LITERATURE OF REVIEW

Materials (metals, ceramics, or polymers and their composites) must be carefully chosen and designed, depending on the end-use of the device, to combine biocompatibility with certain qualities such as density, elasticity, fracture, and wear resistance, etc. Due to their excellent strength and ductility, metals have traditionally been utilised as implants [6].
Because of their great corrosion resistance, Ti alloys, CoCr alloys, and stainless steel in particular are extensively utilized. To improve biocompatibility with organic tissues, further surface functionalization is frequently needed [7], for example, by covering implants with hydroxyapatite (Hap) for bone

compatibility. Due to their castability and ductility, noble metals like Au, Ag, and Pt make intriguing prospects for use in dentistry. [5]

Since the 1980s, diverse techniques for AM have been developed for layered printing of different materials. There are currently seven different established techniques for AM as outlined by the ISO/ASTM 52900 standard, and summarized comparisons of the techniques are outlined in Figure 2. Below, we briefly describe each process. [2]

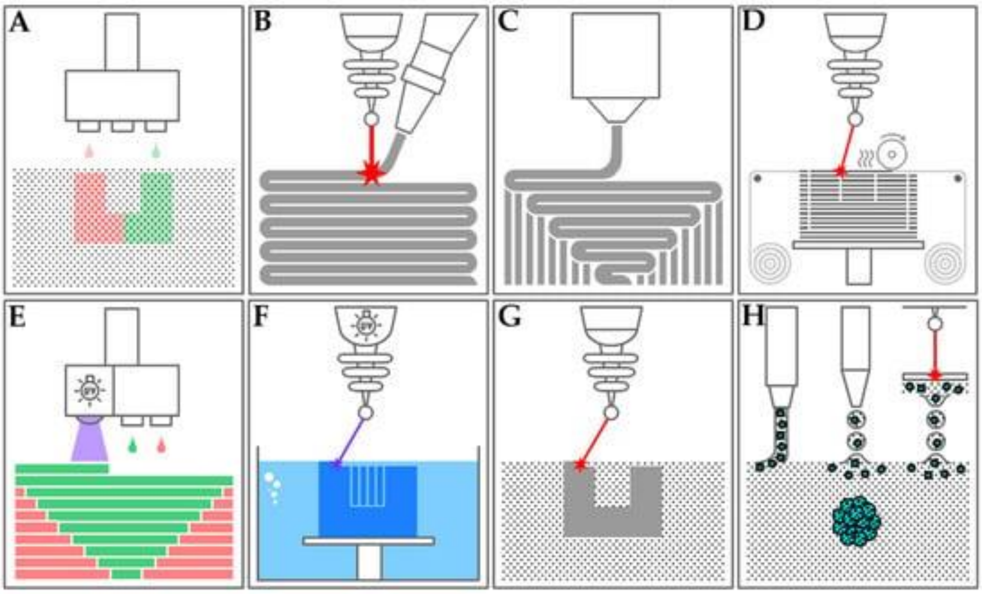

Figure 2. Types of additive manufacturing (AM). (**A**) Binder jetting—a liquid binder is jetted over a precise region of powder; additional powder is placed on top and the process repeats. (**B**) Directed energy deposition: a laser is used to melt metal as it is extruded from a nozzle. (**C**) Material extrusion—molten thermoplastics are dispensed through a nozzle and cooled quickly on the print bed. (**D**) Sheet lamination: a sheet of material is cut to size with a blade or laser, the next sheet with adhesive is then added, and heat is applied to adhere the layers before the second layer is cut to shape. (**E**) Material jetting (MJ)—a layer of liquid resin is sprayed and then cured (often with UV light) before proceeding to the next layer. (**F**) Stereolithography—the print bed is lowered by a one-layer distance into a vat of liquid resin, which is then UV-cured; the print bed continues to move through the resin one layer at a time. (**G**) Powder bed fusion: a layer of powder (often metal) is spread over the print bed before being molten using a laser and formed into a layer. The print bed moves down, the next layer of powder is spread over the solidified layer, and the process repeats. (**H**) Extrusion bioprinting (left)—similar to material extrusion, a bioink (mixture of cells and carrier material) is extruded from a nozzle or needle layer-by-layer before crosslinking or curing. Inkjet bioprinting (center)—picoliter-sized droplets of bioink are deposited onto the print bed and allowed to coalesce into fibers. Laser-assisted bioprinting (right): a laser pulse causes small droplets of bioink to be dropped from a surface into defined geometries.

*All figures are designed and created by the authors.

Recently, the FDA responded to a growing trend of 3D-bio-printed medical technologies and provided a more comprehensive regulatory pathway for technologies in this area with the issuing of new guidance advising on the technical aspects of manufacturing 3D-printed medical devices [8]. In 2016, FDA released a draft guidance document titled "Technical Considerations for Additive-Made Medical Devices to outline the technical considerations, testing, and characterization recommendations for 3D-printed devices. 3D-printing technologies also include direct-write methods such as inkjet printing with different biomaterials.

The metal 3D-printing technique enables the manufacturing of biomimicking implant devices with similar properties compared to natural bone. Figure 3 illustrates the various types of biomimicking implants fabricated using metal 3D printing. [9]

Fig. 3 3DP implants

Designing orthopedic prostheses entails creating medical tools that can be used to replace lost or broken bones and joints. According to Fig. 4, the objective of orthopedic prosthesis design is to produce devices that are inexpensive, accessible, and functional for a variety of applications while also being robust, functional, and adaptable. A synthetic hip, multi-component prosthesis, bionic foot, hybrid prosthesis, and bionic orthosis are just a few of the five cutting-edge orthopedic devices for lower limb replacement and augmentation that are described in Fig. 4 below. These devices are intended to increase mobility and improve patients' quality of life. To do this, orthopedic prosthesis designs must take into account a variety of variables, including the kind and location of the injury or ailment, the individual's age, and general health, as well as their physical capabilities and functional needs. Additionally, choosing materials and technologies that will offer the required strength and durability while still being biologically compatible with the body is part of the design process. [9,10]

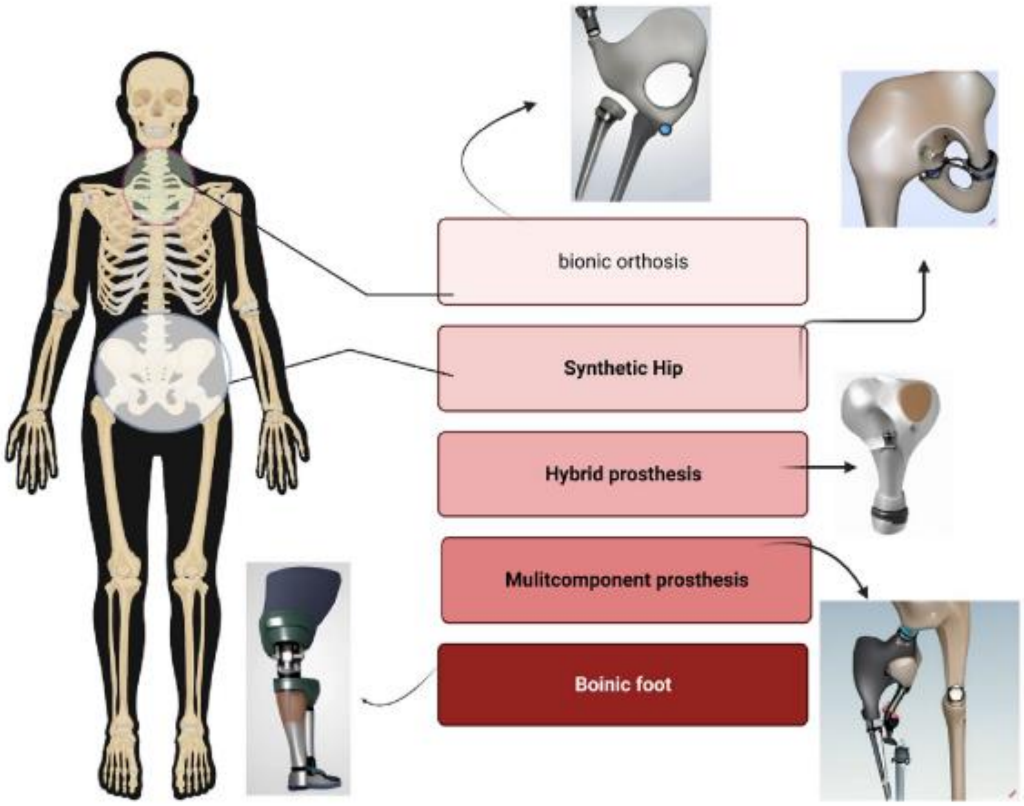

Fig. 4 Comparison of advanced orthopedic devices for lower limb replacement and augmentation The figure shows five different types of advanced orthopedic devices: (a) Synthetic Hip, a prosthetic device used for total hip replacement; (b) Multicomponent Prosthesis, a modular implant that allows for customizable surgical solutions; (c) Bionic Foot, an advanced prosthetic device that mimics the natural movements and functions of a human foot; (d) Hybrid Prosthesis, a combination of conventional and 3D-printed implant components for improved functionality and stability; and (e) Bionic Orthosis, a wearable device that utilizes advanced sensors and motors to augment human locomotion. These devices represent some of the latest advancements in orthopedics and are designed to improve mobility and enhance the quality of life for patients with lower limb-related conditions, whether through joint replacement or augmentation.

DISCUSSION AND FINDINGS

This review concentrated on the advantages additive manufacturing (AM) offers over traditional fabrication techniques in the field of biomedicine today. Not only may we anticipate lower hardware costs as AM technology develops, but we can also anticipate the emergence of novel materials that will enhance its biomedical and tissue engineering applications. The use of thermoplastics for low-cost 3D printing is now widespread and is seen in many hospitals and research facilities. Fast-growing production of new and translational materials may soon make clinical use in tissue-repair applications possible. The development of bioprinting as a method for building 3D models that resemble tissues and depict physiological systems for drug testing and disease modelling has proven to be quite successful. Organoids, which are tiny, functioning organ building blocks, have been successfully created using bioprinting. The ability to print an organ that can be transplanted into a patient is the biggest prospect for bioprinting, though. Since the patient's own cells can be used in the bioprinting process, there would be no need for waitlists or stringent histocompatibility testing. Before attempting to print an entire organ, bioprinting technology must address problems including micro vascularization and long-term bioink stability. It is nevertheless incredibly intriguing to see what the near future holds, given the present rate of progress.

CONCLUSION

Nanomaterials have been used in medical implants for a few decades already. However, it is still difficult to make them compatible with new AM technologies, especially for specialized medical applications. Researchers from a range of disciplines, including bioengineering and mechanical engineering, now have the chance to gain insight into the selection of the best materials for 3D printing based on the type of application. The quick commercialization of additive manufacturing (AM) technology for medical implant applications will be made possible by a thorough analysis of the physics of material selection, process optimization, and design/geometry requirements.

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