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A Three-Dimensional Printed Porous PLA Polymer Implant: A Critical Review

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Abstract

The idea is to use alternative materials related to materials with functional classification and porosity in the human body. For example, the need for a replacement for human bones should be lightweight, rigid, non-toxic, and have an internal porosity that differs from the external surface. People now live longer and more comfortably when they experience fractures, amputations, and vertebral replacements, bone implants, which were previously unavailable or were limited and very expensive. These advancements highlight the ongoing efforts to enhance materials used in medical contexts, emphasizing functionality, biocompatibility, and the ability to interact harmoniously with the human body. The present study provides a review of materials with functional classification and porosity in medical applications and methods of their manufacture, which can be successful substitutes in the human skeletal system. Recently, regarding biocompatibility, PLA is considered excellent, making it suitable for medical and biomedical applications. The use of 3D printing technologies in manufacturing porous structures from various materials such as PLA, ABS, and Titanium shows that these manufactured structures have excellent mechanical properties and good biocompatibility. Based on the results, it is possible to design customized structures that meet specific needs by changing the size, shape, and porous structure ratio.

Keywords: Additive Manufacturing; Biomedical; Functionally Graded Materials; Mechanical Properties; Porous Material

1. Introduction

Advanced technology in medicine is revolutionizing healthcare, helping diagnose diseases accurately and quickly, and providing patients with adequate treatment. It allows people to live longer, thanks to medical advances. This advanced medical technology includes modern instruments and devices that improve patients' quality of life, such as the contact area between living tissue and the implant, which is an essential challenge for engineers in this field. Bones are an important and multifunctional part of the human body, providing mechanical support, bearing muscles, ligaments, and tendons, and protecting vital organs. Bones also serve to store minerals and contribute to the production of blood through the bone marrow, which plays a crucial role in maintaining the overall health and well-being of the human body [1]. Bone fractures are one of the most common types of traumatic injuries worldwide, and their treatment is often a significant economic burden on society [2], [3]. Complications such as delayed healing of fractures or non-healing of fractures occur in about 10% of patients. High risks, e.g., those with osteoporosis, malnourished people, and postmenopausal women, as well as older people or those with impaired blood flow, are at increased risk of delaying the healing of fractures [4]. At the same time, people who have joint diseases such as degenerative arthritis and rheumatoid arthritis need surgeries such as hip or knee joint replacement. Devices and components can be used for specific periods to stabilize fractures or bone implants used in these cases [5]; one of the applications of the polymer used to help Knee Arthroplasty can be illustrated in Fig. 1. The key points regarding the use of PMMA (polymethyl methacrylate) in knee arthroplasty including the fact that the PMMA is widely used as a bone cement in joint arthroplasty, including total knee arthroplasty (TKA), to secure the implant to the host bone.

Furthermore, PMMA acts as a "grout" that mechanically locks the bone and implant together without chemical bonding. The polymerization of PMMA involves an exothermic reaction with three main steps: initiation, propagation, and termination. PMMA is the most commonly used bone cement in primary TKA and revision total knee arthroplasty (rTKA).

While PMMA is the standard material used, some associated concerns, such as complications like fracture, bone loss, and infection, can lead to the need for revision surgery.

In summary, PMMA is the widely accepted polymer-based bone cement used in knee arthroplasty procedures to secure the implant to the bone. However, its use is not without potential complications that may sometimes require revision surgery.

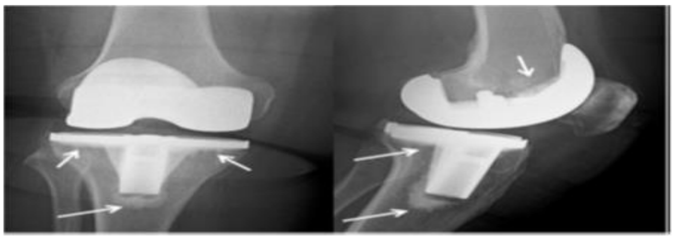

Figure 1. The knee arthroplasty uses a polymer-type PMMA [6].

Orthopedics uses biomaterials to restore or replace damaged skeletal structures [7]. Among the essential properties that must be present in every biomaterial are possessing the required and appropriate mechanical properties (such as weight and microelasticity), showing good chemical stability (resistance to hydrolysis, oxidation, and corrosion), ensuring biocompatibility, not showing adverse reactions (toxicity, immune rejection or infection) and showing high corrosion resistance [8]-[11]. The use of artificial models for knee replacement in the human body can be illustrated in Fig. 2.

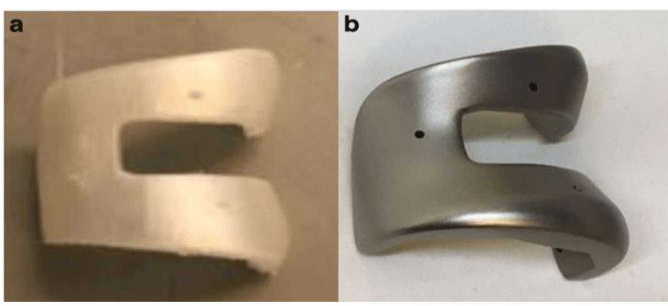

Figure 2. PLA and metal 3D printed [12].

The mechanical requirements of the implant are determined by the function, as well as other factors such as strength to withstand loads and flexibility to withstand shear stress. In the orthopedic field, the implant materials must withstand repeated loading and unloading cycles under various forces, such as bending and shear. In addition, implant devices are exposed to corrosive environments over long periods, potentially affecting their properties. Therefore, it is necessary to assess the mechanical properties of the materials used more accurately to reduce breakage and maintain optimal performance [13].

The assessment of the required mechanical properties includes examining the strain produced due to the force of the strain (tension). The evaluation of mechanical properties provides essential points about the ability of implanted materials to withstand and adapt to external forces, which makes the selection and design of implanted materials one of the mechanical requirements for their intended applications [14].

Since the development of biomedical technologies is of great importance, the urgent need for medical technologies today requires modern materials and methods with specific technologies to achieve the desired purposes. The success of medical devices largely depends on the materials used in their manufacture, where ceramic materials and composite materials are used [15], [16], especially polymers, metals, and their alloys. The designed implant is another factor of great importance, as the designed implants mimic the function of the natural organs of the body.

Medical devices need to meet some requirements such as biocompatibility, bone fusion, strength, wear and corrosion resistance, lack of rubber tensile strength, defective durability to fatigue, chemical similarity with vital tissues, and traditional designs may not meet these diverse requirements [17]-[19] for example, some devices can cause premature failure or failure after long-term use in the human body [20]; these problems stem from the fact that one or more basic mechanical or biological requirements are not fully met. The bone structure is constantly undergoing a process of remodeling, which allows it to react to its environment and stress factors in this regard.

Porous materials play a crucial role in bone and tissue replacement due to their relatively low rigidity and improved integration with bone through the growth of osteocytes [21], [22]. Increasing the coefficient of porous permeability and the spongy bone's area significantly reduces the critical bending strength. Thus, breaking bones becomes more accessible due to their reduced bending strength [23].

The bone implantation technique seeks to correct skeletal defects in load-exposed applications. Hard metals and alloys such as titanium and stainless steel have been successfully used in bone transplantation due to their excellent mechanical and biological properties [24]. However, these applications need help with stress scaling and impermeability [25]. A porous design resembling a natural skeleton should be considered to achieve the biomechanical requirements of Surgical Orthopedic platforms.

Porous biostructures often have angles of less than 90 degrees, which causes an accumulation of mechanical stresses, and this leads to successive cracks when a more significant accumulation of stresses occurs, and therefore, the failure of these biostructures [26].PLA is widely used in bone and dental applications, for example, fixation devices such as screws in reconstructive operations including those related to the jaw joint, fractures of the chest, shin bone, fingers, toes; and arthroscopic fixation [21].

Polylactic acid (PLA) is an aliphatic polyester produced from non-toxic renewable sources, such as corn and sugar cane, with properties of interest in the medical field [22], [23]. This polymer is characterized by its behavior upon contact with the biomaterial, where it gradually decomposes into harmless lactic acid or carbon dioxide and water and is metabolized inside the cell [24]. PLA also does not produce toxic or carcinogenic effects in surrounding tissues, is perfectly absorbed back, and its production is relatively cost-effective compared to conventional biodegradable biopolymers. Due to its biodegradable, disintegrating, and bio-absorbable properties, PLA has become one of the most widely used polymers in clinics with numerous applications involving medical models, fragile structures, suturing, cell carriers, drug delivery systems, and many other applications [25].

Recently, with the advent of molten deposition modeling (FDM) technology in the medical field, one of the most popular three-dimensional printing technologies, interest in PLA has risen significantly due to its thermally favorable properties. It can be heated to its melting point, cooled, and reheated without significant deterioration. With FDM technology, custom structures can be quickly manufactured, and pads can be made for various research and surgical practice applications, such as implants intended for the patient, surgical manuals (craniofacial surgery), and surgical instruments [26].

2. Functionally Graded Materials

Functionally graded materials (FGMs) are classified as modern high-tech materials, as they provide various vital functions and can also imitate gradient properties. One of the examples of such materials is natural bone, since the principle of functional gradation can be used in bone tissue transplantation. Materials with functionally graded composition have multiple properties, such as mechanical and biological design, graded composition, porous surfaces, and volume. It also improves bone integrity, wear resistance, and the effects of stress levels. [27]-[30].

The gradation directions of the components used in the models for industrial plants can be different, as in Fig. 3.

Fig. 3a shows that the gradient in mechanical properties is the most rigid on the outer surface. In contrast, in Fig. 3b, the gradient has the most significant characteristics of the inner part over the length of the sample. Fig. 3c is the gradient of the characteristics in the longitudinal direction of the sample.

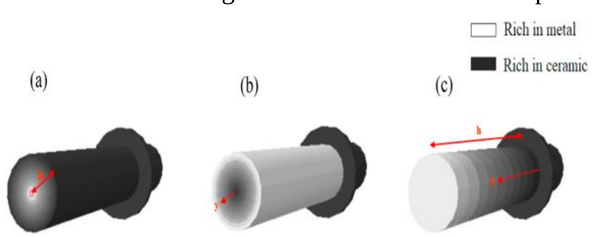

Figure 3. The modeled implant fixtures' various gradation directions: FGM-1 fixture (a), FGM-2 fixture (b), and FGM-3 fixture (c) [31].

The gradation directions of the components used in the industrial plant models can differ. This is evident from the search results, particularly from the criteria of "Functionally Graded Materials (FGMs)."

Many studies in the above literature mention that gradients within FGMs can be developed in one, two, or even three different directions, depending on the specific application and manufacturing process. This flexibility in gradation direction allows for creating materials with tailored properties that can be optimized for specific industrial applications, such as aerospace, biomedical implants, or sports facilities.

Integrating materials like thermoplastic substances, which possess unique properties such as flexibility, elasticity, and antibacterial surfaces, showcases the potential for creating tailored solutions for medical applications like urinary catheters and cartilage replacements.

There are simply three types based on which FGM can be classified [32], which can be illustrated in Fig. 4.

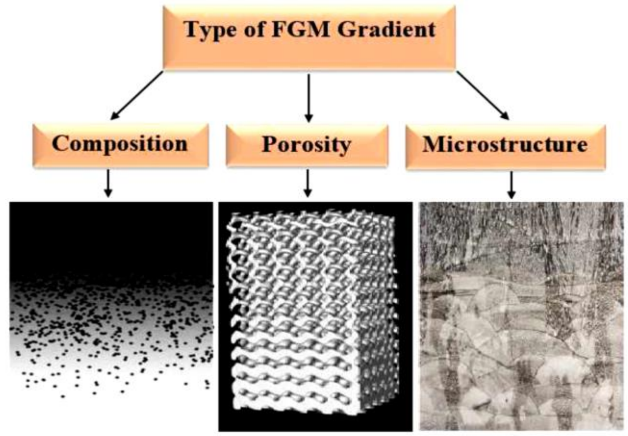

Figure 4. Classification of FGM based on the type of FGM gradients: Composition (a). Porosity (b). Microstructure (c) [33].

- Gradation in composition: This type of functionally graded material involves a gradual change at the chemical level. Research can change the composition from polymeric materials to other materials, such as metal.
- Gradation in microscopic structure: a gradual change in the properties of a substance by a change in microscopic structure. In this type of functionally graded material, the material's properties can be improved by changing the size, direction, or distribution of microscopic properties.
- Porous gradient of FGM: In this type of functionally graded material, the pores inside the material change. Porosity is changed in a controlled manner to improve the required properties.

2.1. Porous Functionally Graded Materials

At the stages of the development of FGM, the idea took off to eliminate some inappropriate properties in conventional composite materials. These problems were solved by gradually changing the composition to obtain better properties without compromising other properties or changing the porosity depending on the application [34]-[37]. Fig. 5 shows five types (different gradations) of porosity used in modern applications.

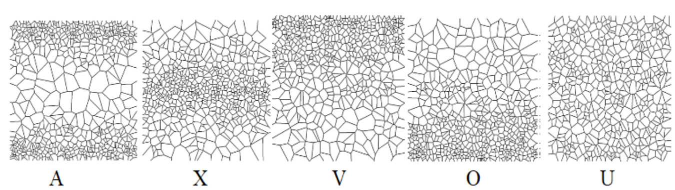

Figure 5. Distributions of cavities (porosity) [38].

In the cases of A and V, the porosity can be expressed as a function of the spatial position in the material's interior. The U pattern represents an even (uniform) distribution of pores in the porous structure. Patterns X and O represent a symmetrical gradient in which the porous gradient X decreases from the central plane down to the surface. In contrast, the cavity in pattern O continuously increases to the center [38].

2.2. PFGM in Medical Applications

Since ancient times, biomaterials have been used in the treatment of human diseases; for example, in 2000 BC, ivory was used by the Egyptians to replace missing teeth [39], [40], while they used wood to replace missing bones such as bones of legs and fingers [41]. They used braces and splints to support and protect broken bones after surgeries in those periods. While copper has been used to replace missing bone fragments, these implants have failed due to the toxic effects of copper ions. In the ancient Indian historical text of the Vedas period (1800-1500 BC), the use of an artificial leg, teeth, and eyes is mentioned.

The best bone and implant fixation potential for porous interconnected structures is defined by the characteristics of lower rigidity and larger surface area compared to structures with a large quantity. It also has a porosity gradient that allows large pores to grow at the tip of the implant and a denser core to maintain the required mechanical properties.

Shahar et al. [42] found that the uniform porous distribution affects the mechanical properties, leading to a stable evolution of the Modulus of elasticity. The value of the Modulus of elasticity changes smoothly and evenly with the change in the density of pores.

PFGMs show great potential in bone transplantation [43], [44] and in porous structures, and their development with a lighter weight than the previous generation. Porous materials play a crucial role in bone and tissue replacement due to their relatively low rigidity and improved integration with bone through the growth of osteocytes [21], [22]. Functionalized materials with a porous gradient make it possible to control biocompatibility and cellular interactions in bone implants. Thanks to their properties and constant technological improvements, PFGM provides an innovative and effective solution in medical applications. By offering products with high performance and improved biocompatibility, these materials can contribute to developing new technologies for treating diseases and injuries and improving human life. The porosity and gradual structure of the human bone can be seen in Fig. 6.

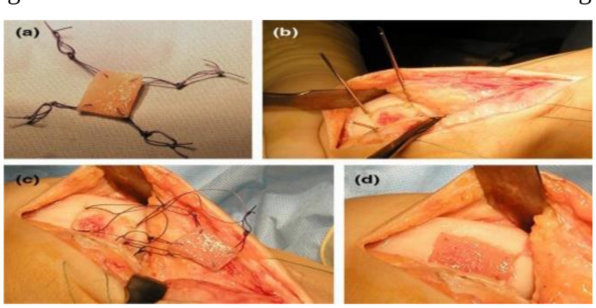

Figure 6. Bone transplantation in 3-D fibrin with a PGA/PLA [45]

Since the development of technology for biomedical technologies is of great importance in people's lives, the urgent need for medical technologies today requires modern materials and methods with ultra-precise technologies to achieve the necessary purposes. The success of medical devices largely depends on the materials used in their manufacture, where ceramic materials and composite materials are used [15], [16], especially polymers, metals, and alloys. The designed implant is another factor of great importance, as the designed implants mimic the function of the natural organs of the body. The bone implantation technique seeks to correct skeletal defects in load-exposed applications. Hard metals and alloys such as titanium and stainless steel have been successfully used in bone transplantation due to their excellent mechanical and biological properties [24]. However, these applications need help with stress scaling and impermeability [25]. A porous design resembling a natural skeleton should be considered to achieve the biomechanical requirements of Surgical Orthopedic platforms. The concept revolves around utilizing alternative materials with specific functional classifications and porosity for applications within the human body. These materials aim to address the need for innovative solutions in medical procedures, particularly in implants and prostheses. By exploring novel biomaterials that interact effectively with the body, promote healing, and exhibit biocompatibility, researchers are advancing the field of regenerative medicine and tissue repair.

2.3. 3D Printer Technology in the Manufacture of Medical Materials for FGM

Changes in the spatial position of the material depend on the porosity of the material itself, which can be achieved using such materials using additive manufacturing techniques (3D printer). These techniques are essential in medicine, including integrating implants with bone tissue or replacing natural materials. The pore size helps wound healing and improves implant density, thus reducing stress concentration [27].

In medical applications, 3D printer technology allows printing implants or precision parts, such as prostheses, blood vessels, and bones. Fig. 7 shows the 3D printer and its role in manufacturing samples from PLA material. In this type of printing, various materials, such as polymers, fiberglass, etc., are used to produce multilayer products that have properties similar to living tissues. Additionally, developing materials with 3-D ordered pores allows for targeted drug delivery and localized treatment, reducing the need for systemic medication and minimizing side effects.

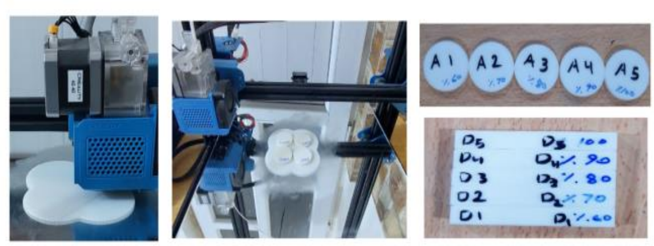

Figure 7. The 3D printer was fabricating Prose Functionally Gradient Materials (PFGM).

Additive manufacturing is a technology that allows products to be built layer by layer using materials such as polymers or ceramics. As shown in Fig. 7 above, it uses artificial polymers as bone implants. This technique can produce hermetically designed porous structures with complex curves, allowing us to control the bone sublimation rate accurately. Porous structures can achieve porosity and optimal overlap of bone growth around the implant in the healing period. This helps to enhance the stability and bone integrity of the implant, thereby improving the chances of implant success and its function in the long term. Using porous structures and colloids as the outer layer of implants is a promising future technology for improving bone integrity and implant stability. It allows us to manufacture implants of various shapes with controllable porosity to promote bone growth [3]. Research in polymeric materials and 3D printing has contributed to rapid advances in tissue engineering and regenerative medicine, which envision the possible future of organ transplantation [46], [47]. Table 1 illustrates some of the brief benefits of 3D printer technologies in medical uses.

Table 1. Some brief benefits of 3D printing manufacturing technology in the specialty of the medical and dental fields

Area	Findings
Orthopedic [48]	Cost and time-saving
Transplants [49]	Personalization
Surgery [50]	Time savings
	Improved medical outcome
	Decreased radiation exposure
Implants [51]	Incorporation of antibiotics
Dental [52]	Personalization, cost savings
Dental [53]	Cost and time savings
	Personalization
	Digital storage
Pharmacy [54]	Personalization
Pharmacy [55]	Personalization
	On-demand manufacturing
Orthopedics [56]	Accuracy
	Cost and time savings
	Personalization
	Fully automated and digitized manufacturing
Implants [57]	Supply chain possibilities
Medical [58]	Ability to use different materials
Dental implants [59]	Rough and porous surface
	Better Stabilization
	Osseointegration
Medical devices [60]	Design iterations
	Supply chain possibilities
	Complex Geometries
Surgery [61]	Improved understanding of anatomy and the accuracy of surgery

2.4. Biocompatibility

One of the main factors affecting porous structural properties is permeability. Still, pore size also plays an important role, and adjusting pore size and porosity has great potential to improve structural properties [62].

Regarding biocompatibility, most of the minerals used as biomaterials have a relatively low potential for bone formation and bone immunogenicity, especially when compared to polymers. However, they can be produced consistently high in quality and purity and molded into various shapes with the desired properties and surfaces.

Biocompatibility with living tissues in the human body and bone integration are significant biological factors in medical operations such as organ transplantation or human orthopedic surgery. The implanted materials or artificial objects must be well compatible with living tissues and the human body to achieve success in the operation and avoid any complications leading to implant failure.

Fig. 8 shows the mechanical properties of bone implants, including mechanical resistance, surface roughness, wear resistance, and resistance to shock or compression.

Orthopedics uses biomaterials to restore or replace damaged skeletal structures [7]. Every biomaterial must possess the required and appropriate mechanical properties (such as weight and micro elasticity), show good chemical stability (resistance to hydrolysis, oxidation, and corrosion), ensure biocompatibility, not show adverse reactions (toxicity, immune rejection, or infection), and show high corrosion resistance [8]-[11].

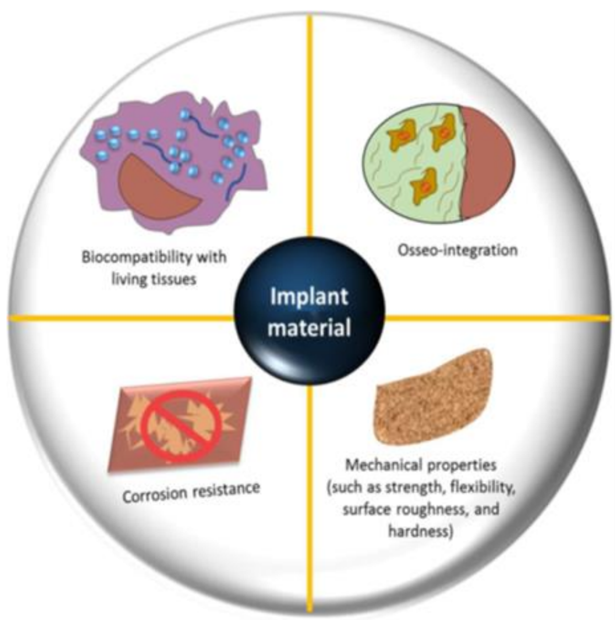

Figure 8. The key used in designing a dental implant [11].

Other factors include strength to withstand loads and flexibility to withstand shear stress. In the orthopedic field, the implant materials must withstand repeated loading and unloading cycles under various forces, such as bending and shear. In addition, implant devices are exposed to corrosive environments over long periods, potentially affecting their properties. Therefore, it is necessary to assess the mechanical properties of the materials used more accurately to reduce breakage and maintain optimal performance [63]. The assessment of the required mechanical properties includes the examination of the strain produced due to the force of the strain (tension). The evaluation of mechanical properties provides essential points about the ability of implanted materials to withstand and adapt to external forces, which makes the selection and design of implanted materials one of the mechanical requirements for their intended applications [64].

2.5. Polymer Orthopedic Implants

3D printing technologies are used to manufacture metal structures from titanium alloys for applications in the field of orthopedic implants and the design of prostheses. These studies deal with research into these structures' mechanical properties and biocompatibility, highlighting the effectiveness of 3D printing technologies in improving the quality and performance of these systems. In a study conducted by Hindy et al. [65], the biocompatibility of 3D metal models of titanium alloys of leg bone cells was studied by the 3D printer method (SLM). The results showed that the manufactured structures contain partially dissolved molecules on the surface. The samples printed by SLM with a porous gradient had an excellent similarity between the young and human bone units. Zhang et al. [66] discussed the mechanical properties of designs of trabecular structures manufactured from titanium alloy by 3D printer with EBM technology. He confirmed that the behavior of the structure network's gradual collapse and internal failure all depend on the porosity and size ratios of the structure used. He experimentally showed that the apparent elasticity value of the internal network of the cellular module ranges from 0.39 to 0.618 GPa, which is close to the normal bone value, and the tensile effect can be reduced. Thus, they are considered helpful in promoting the application of prostheses. In a study by Bahram Jafari et al. [67], the final bone arrangement was compared with two novel implants, including radial FGM-coated and Ti implants with hydroxyapatite coatings. The results show that the average results in the titanium, HA-coated, and FGM models were 2.68, 2.49, and 2.32 GPa. According to these values, cortical bone has strengths of 17.75, 16.86, and 17.20 GPa. Regarding bone density and remodeling stimulus, radial FGM implants exhibited the highest response. Based on the levels of surface stiffness (10, 20, 30, and 40 GPa), the implant surfaces were judged to be superior to those coated with HA. Clinical testing has shown that remodeling increases bone density around implants and reduces stress concentration in the cortical neck. The stress values were in the safe zone regarding overload-induced bone resorption. Similarly, in another study, Bittredge et al. [68] turned to solving the problem of stress roasting for total shoulder implants. To overcome this problem, using LPBF laser powder fusion technology to manufacture test samples of titanium Ti-6Al-4V experimentally, the results showed that a sustained strength of 200 MPA, an elastic modulus of 11.8 GPa, which are suitable properties for skeletons with a hardness close to the human bone, and the proposed structure can be applied more effectively in shoulder bone replacement operations. Finally, Emanuelli et al. [69] worked on improving the connection between the implant and the bone and reducing the lateral contractility of the prosthesis. Composite bone-implant systems have been manufactured using a new alloy called β-Ti21S, and this alloy has the advantage that it has a lower modulus of elasticity compared to other conventional types of titanium alloys, such as α + β. The pore size and thickness of the manufactured structures were reduced in both composite bone graft systems with a negative Poisson ratio. Crushing mechanics tests were performed to determine the stable elastic Modulus of about 4 GPa for both composite bone-implant systems.

2.6. Synthetic Polymer PLA by the 3D Printer in Orthopedic Implants

3D printing for orthopedic implants commonly uses the synthetic polymer PLA. Polylactic acid is one of the most effective materials for bone implants. It is biodegradable and can be readily absorbed by the body. The hardware supports newly formed tissue, resorbs over time, and transfers the load to newly formed tissue, eliminating the need for revision surgery. Screws, pins, plates, and rods are among the orthopedic applications for PLA since they can be molded into complex geometries. By utilizing 3D printing technology, PLA implants can be customized into different shapes and compositions with specific degradation rates to meet the needs of patients.

Niaza et al. [70] studied porous structures manufactured by 3D printing using the molten solid formation method. Long-term deformation tests and Charpy impact shock tests show that PLA/HA structures with a maximum force of destruction upon impact up to 119 N can operate under a load of up to 10 MPA without changing shape and losing mechanical properties.

Hu et al. [71] manufactured cell container structures in a 3D printer. Combining the excellent mechanical performance of Polylactic acid (PLA) and the biocompatibility and bio printability of the double-mesh hydrogel of gum yield - poly (ethylene glycol) acrylate (GG-PEGDA) to meet the requirements of the necessary intervertebral disc regeneration as having positive biocompatibility as well as suitable mechanical properties, this composite structure holds the potential to assist intervertebral disc regeneration. Anthony Xavior et al. [27] used three samples of variable density across their width and three other materials of constant density manufactured by the 3D printer. The material of acrylonitrile butadiene styrene (ABS) was selected. The tensile and compressive stress values were calculated while the bending and three-point bending test techniques were used. It was found that after reducing the weight by 38.9%, the tensile strength decreased by 13.875%, the bending strength decreased by 25.6%, and the compression strength decreased by 31.545%. This indicates that when using FMG in applications exposed to a large amount of bending and tensile loads, the decrease in strength is slight. Kumar et al. [72] adopted the study of structural (geometric) bone adaptation, using techniques such as the 3D printer technology to manufacture porous structures from ABS plus material, where the results showed that when changing the size ratio of the mesh structure from 20% to 40%, the elasticity and tensile strength as well as energy absorption increase by more than two times.

Similarly, in another study, Tang et al. [73] used PLA filaments to print two structures with Square and circular porous structures with a pore size ranging from 1 mm to 2 mm and a porosity ratio of up to 80% with FDM technology. The results indicated that the porous structure with a circular shape has better performance, unlike the porous structure with a circular shape, which produces a high concentrated tension; the reason for this is that it contains sharp edges, and therefore, the high tension leads to a decrease in the Modulus of elasticity. On the other hand, in a study conducted by Pop et al. [74], synthetic polymers ABS, PLA, and PLA/PHA Bamboo Fill, which were printed by a 3D printer, were used. Experimentally, it was shown that the printed material of PLA possesses the highest compressive strength, three-point bending, and impact resistance, while ABS offers the best performance of tensile strength. This means that if the part being used is somewhere and exposed to compression stress and high bending stress, it is recommended to use a PLA polymer. A study by Kholil et al. [75] used a 3D printer to fabricate functionally graded porous structures using FDM additive manufacturing technology. Experimentally, the result showed that the compressive strength of ABS and PLA materials changes with the change in the thickness of each layer and that printed samples of PLA material have the highest yield value compared to ABS materials. The highest compressive strength was found in a 0.15 mm thick layer of PLA material with a yield strength value of 66.78 MPA.

In a study by Mantecón et al. [76], PLA printed by a 3D printer using FFF technology was used to obtain substitutes for reproducible and effective full-size skulls. The results showed that 3D-printed skulls reasonably embody the behavior of human skulls. Finally, Chao et al. [77] proposed a method for designing a mesh-like porous structure (TLPS) with a variety of pores based on their study of the mechanical properties and permeability of natural bone; the results showed that the compressive strength was 270-580 MPA, and the elasticity was between 6.43 and 9.716 GPA; these results were better than the mechanical properties of natural bone. It was explained that the design method of the proposed reticular-like porous structure is suitable not only for ordinary bone models but also for complex and irregular models. Recently, PLA has been intensively studied in additive manufacturing applications, where the mechanical performance is superior to PLA compared to other polymeric materials [78]-[80].

In general, PLA is a 3D printable polymer characterized by biocompatibility and isotropic customization and has also been found to be used in medical applications such as orthopedic replacements [81, 82]. Regarding biocompatibility, PLA is excellent, making it suitable for medical and biomedical applications [83]-[85].

The most crucial result drawn from the research on a 3D printed porous PLA polymer implant is the need to enhance the osteogenic activity of synthetic polymers used in 3D printing to improve their effectiveness in tissue reconstruction. Specifically, the study emphasizes the importance of strengthening the interaction between synthetic polymers and human dental pulp stem cells to promote differentiation into osteoblasts, which is crucial for bone regeneration. This finding underscores the significance of optimizing the biological response of the implant material to enhance its performance in medical applications, particularly in tissue and bone reconstruction procedures. However, enhanced static and dynamic analysis of porous materials used in bone replacement will solve more complex systems in biological treatment [86]-[88].

3. Conclusions

The use of 3D printing technologies in manufacturing porous structures from various materials such as PLA, ABS, and titanium is considered a critical topic, attracting many researchers to use these materials in manufacturing multiple parts of the human body and increasing interest in biomedicine. The literature review from the provided sources highlights that manufactured structures exhibit excellent mechanical properties and good biocompatibility, making them well-suited for medical applications like tissue and bone reconstruction. These structures are designed to meet specific requirements in the medical field, ensuring they are durable, safe for biological interactions, and suitable for use in reconstructive procedures. The emphasis on mechanical properties and biocompatibility underscores the importance of these factors in developing advanced materials for medical applications, particularly in tissue and bone reconstruction.

For future research directions, it is essential to consider that designing customized structures that meet specific application requirements can be achieved by varying the sizes, shapes, and porous structures. Several studies emphasize the importance of developing advanced porous structures compatible with living tissues and indicate that advanced porous structures can be manufactured using these technologies for diverse medical and engineering applications requiring high performance and longevity.

Furthermore, it is necessary to test the behavior of the PLA polymer in a laboratory by selecting it as a replacement part in the human body, comparing the laboratory results with numerical results using auxiliary programs such as ANSYS, and highlighting more to understand its behavior under the influence of different loads and for critical medical applications, for example, replacing bone parts of the human skull, leg bone or human vertebra, lumbar vertebrae, which are more damaged.

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Conflict of interest

The authors declare that there are no conflicts of interest regarding the publication of this manuscript.

Author Contribution Statement

Ahmed H. Mohammad proposed the research problem.

Emad Kadum Njim completed the introduction section.

Muhsin J. Jweeg and Muhanna¬d Al-Waily reviewed the final manuscript.

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