Progress and Prospects of 3D Printing Human Skeletal Scaffold

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Abstract. In recent years, bone injury repair is still a difficult problem in the medical field. Traditional bone scaffolds are not effective in treating bone injuries in the short term. Based on the progress of 3D printing technology in the research and development of human bone scaffolds, this paper mainly explains the advantages of 3D printing scaffolds compared with traditional scaffolds and the various performance requirements of 3D printing scaffolds through the evolution of bone scaffolds. This paper mainly summarizes several main 3D printing bone scaffold technologies and methods and concludes that 3D printing scaffold is indeed more valuable, but each printing method has its advantages and disadvantages. 3D printing has a higher fixed capital and better performance and effectively shortens the recovery period. But there are still some problems with the performance of its materials Through the integration of the above data, this essay puts forward the problems that need to be solved in the future in this field and the direction of development.

Keywords: 3D printing, Skeletal scaffold, Medical rehabilitation.

1. Introduction

The repair of bone defects and cartilage injuries has always been a challenging issue in clinical medicine. Due to common issues such as long postoperative recovery time, high hospitalization costs, as well as various individual problems such as varying trauma areas, aging bone, and antibody rejection, the difficulty of bone repair work has greatly increased. It is urgent to seek a suitable scaffold material for repairing bones. Nowadays, 3D-printed bone repair scaffolds have brought new hope to clinical treatment work. This type of scaffold can not only adapt well to the composition and structural characteristics of human bone tissue, and eliminate bone stress problems, but also guide the growth of cells and blood vessels through the structure of pores, significantly strengthening the control of bone repair direction. In addition, the significance of 3D printing human bone scaffolds lies in improving surgical accuracy, shortening surgical time, and providing personalized treatment plans for patients. In terms of bone defect repair, 3D printing technology can "customize" bone defect implants according to the specific situation of patients, avoiding the limitations of traditional implant size and shape fixation, making surgery more personalized, and improving treatment effectiveness. The current research challenge in this field is how to further improve the performance of the printing material, to improve the characteristics of various aspects of the scaffold. This article mainly analyzes the evolution of bone scaffolds, the performance of scaffolds, and different scaffold printing technologies, and summarizes the advantages and disadvantages of different 3D printing technologies in the field of bone repair scaffolds.

2. Introduction to the Basics of Human Bone Scaffolds

2.1. Background of the Research Topic

Bones, as the main supporting structure of the human body, assist in movement and protect important organs. They are the hardest tissues in the human body. However, in recent years, an increasing number of people have developed bone defects due to bone tumors, strong impacts, contamination of damaged areas, and inadequate bone development [1]. The previous treatment for bone defects mainly involved bone grafting to repair the defects. Human bone scaffolds are among the commonly used materials for bone repair and transplantation. Human Bone scaffolds generally require good pore connectivity, but traditional manufacturing techniques for human bone scaffolds mainly include phase separation, solvent casting, particle leaching molding, and foaming technology [2]. These traditional manufacturing techniques are limited by the inability to effectively control the small pore structure and pore size in the scaffold, which affects the connectivity of the scaffold pores. With the development of 3D printing technology in the medical field, this emerging additive construction technology can be used to print human bones in bone treatment. Due to its controllable design and manufacturing technology, 3D printed human bone scaffolds can meet their mechanical properties through manufacturing methods, structural design, and different material selection (mechanical compression performance), biological performance (pore connectivity, biocompatibility e).

2.2. External Fixation of the Human Skeletal Framework

The human bone scaffold shown in Fig. 1 is a common external fixation bone scaffold, External fixation brackets are generally suitable for situations where the soft tissue condition of the injury site is compromised, such as extensive soft tissue damage. External fixation brackets are usually drilled through the skin into the bone, and then screws are screwed in to achieve fracture reduction and fixation through nonincision or small incision.

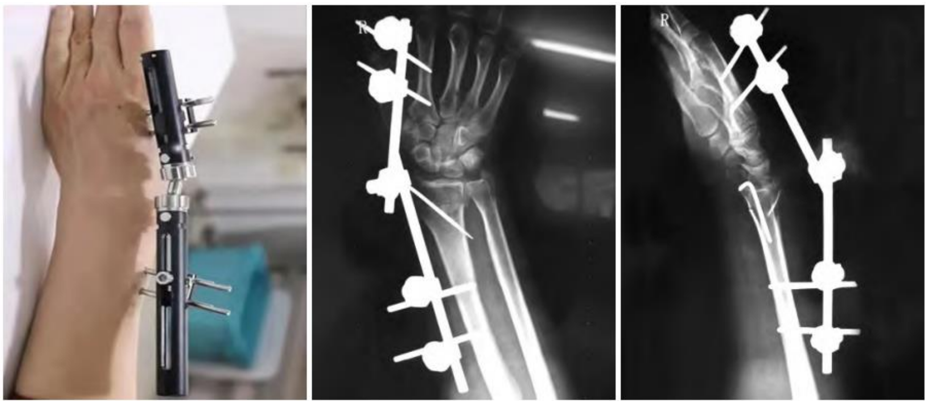

Figure 1. Schematic diagram of external fixation of human bone scaffold [3]

2.3. 3D printing of Tissue Engineering Skeleton

For the replacement of human bone defects, tissue engineering bone scaffolds are currently the most ideal type of replacement, which have significant economic value and practical significance for the clinical treatment of bone defect diseases. For human bone tissue regeneration, 3D printing is used to prepare bone tissue scaffolds, whose structure can simulate the multi-scale structure of human tissue in morphology [4]. In the research of tissue engineering bone tissue scaffolds, relevant scaffolds need to have appropriate shape, pore size, porosity, degradability, biocompatibility, mechanical properties, and ideal cellular response to induce bone regeneration [5].

3. Technical Requirements for 3D-printed Bone Scaffolds

The core requirement in conducting experiments on the configuration and exploration of bone scaffolds is to promote the regeneration of bone tissue, cells, and blood vessels. At present, the commonly used materials are titanium alloys, ceramics, composites, and hydrogels.

3.1. Porous structure

Due to the significantly higher elastic modulus of traditional solid titanium alloy implants compared to human bone, there is a substantial difference in mechanical properties between human bone tissue and the implanted material. The resulting stress shielding effect can also lead to bone resorption, ultimately suppressing the process of bone regeneration. However, 3D-printed porous scaffolds achieve a balance in elastic modulus [6]. This technology fuses metal powder melted and re-solidified by a high-intensity electron beam with other metals, gradually forming a three-dimensional structure. The porous structure scaffolds not only solve the problem of difficulty in clearly locating the small microstructures inside in the past but also interact with each other inside the scaffold. The appropriately distributed pore structure enables the scaffold to form a complete mechanical chain with human bone, thereby guiding and improving the direction and speed of bone tissue regeneration [7].

3.2. Degradability

Biodegradability refers to the ability of a scaffold material to be decomposed into harmless substances by microorganisms or physical processes under certain environmental conditions. Degradability is a necessary condition for the widespread application of bone scaffolds in the medical market, For example, Zhou et al. synthesized a triblock copolymer PLA polyethylene glycol PLA (PELA) using polyethylene glycol as the hydrophilic segment, The hydrophilicity and degradation rate of PLA have been improved, and the scaffold construction material obtained by physically mixing it with nano HA has greatly enhanced its degradability, without acute or long-term toxicity in vitro and in vivo [8].

3.3. Mechanical Property

The mechanical properties of the scaffold should be adjustable, and it should match the needs of cortical and cancellous bone in the human body when repairing load-bearing and no-load bone tissues, to provide sufficient support [4]. It may be difficult to ensure the ideal scaffold preparation material with good mechanical properties using a single material, but mixed materials can be obtained by mixing with other materials. For example, PLA/HA composite porous bone scaffolds, polylactic acid/nano silica/hydroxyapatite ternary composite materials, n-HA/PLA composite nanofiber materials, etc.

3.4. Individualization

The printing of bone scaffolds should meet different needs, whether macro or precision parts and can be achieved through a variety of processes. Because of the problems caused by different factors such as bone density and the location of bone trauma, 3D printing technology can provide personalized treatment plans according to the individual situation of patients. The problem of different bone densities can be solved by selecting materials of different densities. Printing the corresponding shape of the bone scaffold solves the problem of different locations of the bone trauma.

4. Printing technology methods

4.1. Selective Laser Melting Technology

Selective Laser Melting (SLM) technology was first conceptualized by the Fraunhofer Institute in Germany in 1995 and was successfully developed seven years later. With the aid of computer software, metal powder is effectively transformed into a three-dimensional solid model under the influence of high-energy laser beams, which not only does not require any external tools but also fully guarantees the precision of printed parts [9].

4.2. EBM-electron Beam Melting

Electron beam melting (EBM), refers to the melting of metal powder or metal wire by an electron beam with high energy and fast speed, thereby obtaining the corresponding entity. It has high accuracy because the electron beam is controlled by a set of electromagnetic coils, which can accurately guide the electron beam to the designated target area. In addition, the parts printed by EBM technology have high strength and density, because the characteristics of high-energy electron beams themselves create a vacuum environment effectively, without the need for a dedicated setup to isolate material powder from external air [10].

5. The process of 3D printing human bone scaffolds

5.1. 3D printing titanium alloy bone tissue scaffold

The rise of 3D printing technology provides a novel method to produce complex metal implants. This method can avoid the stress-shielding effect of physical implants, meet the personalized design needs of patients, and facilitate the inward growth of bone tissue. Among them, titanium alloy has become a commonly used material for 3D-printed bone scaffolds due to its excellent biocompatibility (degradability), corrosion resistance, and good mechanical properties. Although 3D printing technology can effectively control the macroscopic structure of porous implants, the surface morphology that determines tissue reactions is beyond its control range [11]. Therefore, in some cases, such as when applying implants to patients with osteoporosis or larger bone defects, specific surface treatments may be required to further enhance the bone integration ability of 3D-printed implants. The 3D printing technology of titanium alloy scaffolds mainly includes SLM and EBM. After printing, the surface of the 3D-printed porous titanium-based implant was modified through HF/HNO3 dual-acid treatment and micro-arc oxidation process to improve the biocompatibility of the implant surface [12].

5.2. 3D-printed bioceramic bone tissue scaffold

Bioceramic bone scaffold is an ideal artificial bone defect repair material after metal bone scaffold. Due to the diverse shapes of bone defects, the combination of additive manufacturing technology and bioceramics provides the possibility of personalized, customized, and complex-shaped bone scaffolds [13]. But ceramics all have a common disadvantage - high brittleness [14]. Resulting in high costs and difficulty in forming complex cavities in traditional processing techniques. Additive manufacturing is an emerging manufacturing technique that shapes materials based on three-dimensional models through layer-by-layer stacking. Its advantages include rapid prototyping, personalized production, and integrated fabrication of complex structures. The combination of additive manufacturing technology and bioceramics can meet the individualized treatment needs in the field of biomedicine. Three main types of additive manufacturing technologies can be used to prepare bioceramic materials, namely stereolithography forming technology (pull up/sink down), material extrusion technology, and adhesive spraying technology. The principle is shown in Fig. 2 [15].

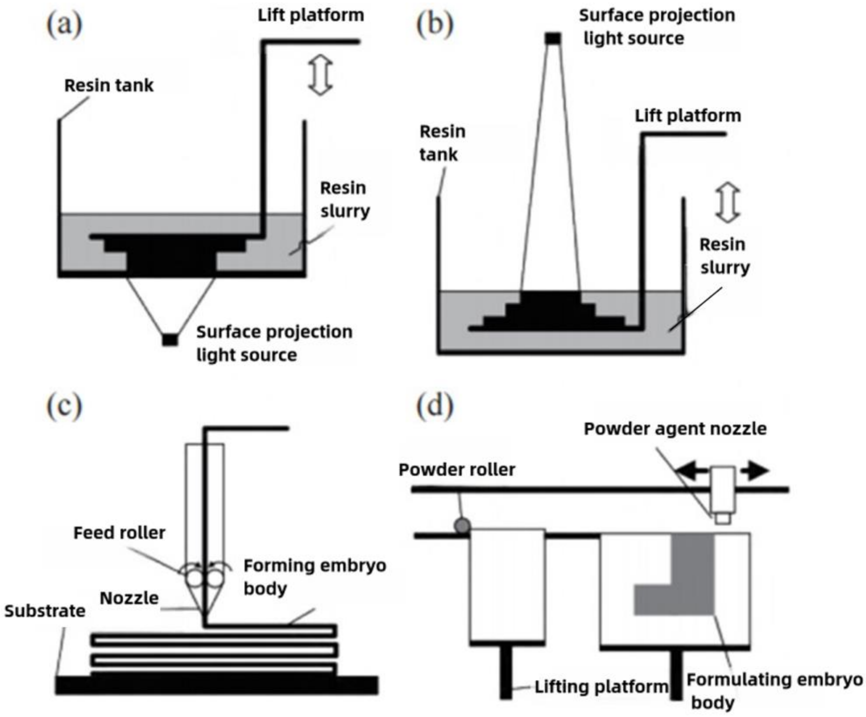

Figure 2. The Process and Technology of 3D Printing Bioceramic Bone Tissue Scaffold [16]

5.3. 3D printed composite material bone tissue scaffold

In practical applications in the medical field, various materials always have different advantages and disadvantages. Therefore, by integrating different types of materials, the shortcomings of individual materials are mitigrated, further meeting the needs of implants. Composite materials are usually composed of two or more materials that exhibit specific characteristics, and using one material compensates for the shortcomings of another material. As a breakthrough in the application of 3D printing materials, its combination forms are diverse, including the combination of ceramic and metal materials, ceramic and polymer materials, and other forms [17] For example, the combination of bioceramics and polylactic acid hydroxyacetic acid copolymers has been widely used in the preparation of artificial bone scaffolds due to the excellent compressive strength and good biocompatibility of bioceramics [18]. Among them, the application of β - tricalcium phosphate (β - TCP) is particularly extensive [19]. However, bioceramics have high brittleness, which limits their application and often requires mixing with other biomaterials to prepare composite scaffolds. Poly (lactic acid glycolic acid) copolymer (PLGA) is an FDA-approved biodegradable material for clinical use [20]. However, the mechanical performance of pure PLGA scaffolds is poor. Therefore, mixing PLGA with β - TCP to improve the performance of the scaffold is currently a research hotspot in the preparation of artificial bone scaffolds both domestically and internationally [21].

To confirm the effect of a 3D polycaprolactone hydroxyapatite scaffold on improving cell adhesion, proliferation, and cartilage differentiation, Yao et al. printed a bio dentin/polycaprolactone composite scaffold using an extrusion-based printing method, which was applied in orthopedics and dentistry. It has been proven that it can promote cell proliferation and differentiation [22].

5.4. 3D printing hydrogel bone tissue scaffold

Hydrogel is a natural polymer material. Its advantage for 3D printing bone tissue is that its composition is highly similar to that of articular cartilage, contains a lot of water, has good biocompatibility, greatly reduces the rejection reaction of the human body after surgery, and has cell adhesion sites, which is conducive to cell adhesion, thus strengthening the connection between bones. However, it also has some problems. Its mechanical properties are relatively poor, and it is easy to be damaged, and the accuracy of hydrogels as biomaterials in 3D printing is relatively low [23]. Fig. 3 shows the process of hydrogel 3D printing artificial cartilage.

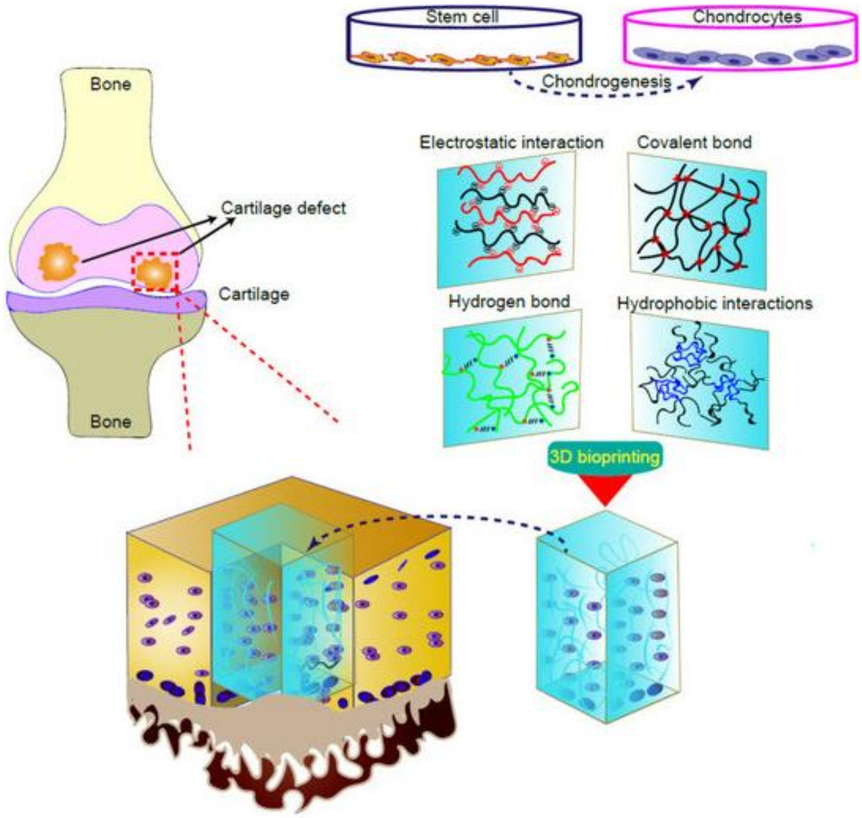

Figure 3. The process of creating artificial cartilage tissue with biological functions through 3D bioprinting [24]

The composition of the hydrogel can be adjusted to make it have different properties and cellular reactions. Yang and others have successfully produced a new type of nano conductive hydrogel, which can act as an electrical carrier in the organism, effectively stimulate the internal electricity of the organism, strengthen the absorption of calcium by local bones, and play an important role in the field of electrical excitation of bone tissue regeneration [5] Xu et al. combined N-acryloyl glycinamide (NAGA) with PNAGA hydrogel, improved the viscosity of PNAGA hydrogel, produced hydrogel with high strength and anti-swelling ability, and printed the artificial meniscus of self strengthening supramolecular poly N-acryloyl glycinamide (PNAGA) stent by 3D printing method based on extrusion, which greatly alleviated the wear of cartilage [21]. As the hydrogel will not solidify at room temperature at a specific ratio, the 3D printer Ultimaker uses extrusion-based printing methods to print it. It uses a stainless steel plate as a printing base, is in contact with dry ice, uses isopropanol as a thermal fluid, and leaves an outlet to remove carbon monoxide. Due to the high water content of the hydrogel, it will freeze immediately after contact with the stainless steel plate. The printing method is shown in Fig. 4.

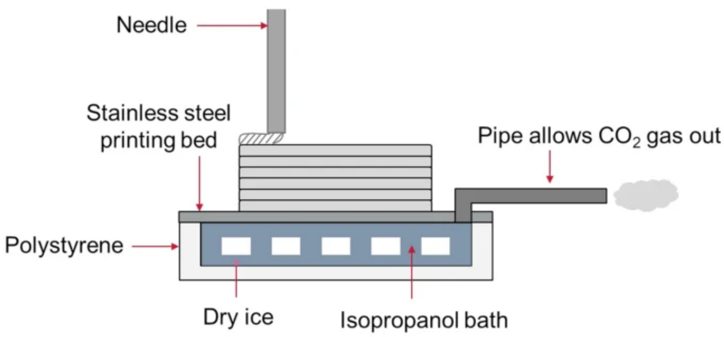

Figure 4. Schematic diagram of low-temperature 3D printing program and settings [25]

6. Conclusion

The advantages and future development potential of 3D printing technology in the field of printing human bones are huge. It gets rid of the singleness of traditional external fixation means, has higher precision and better performance, promotes the individuation and pertinence of patient treatment means, effectively shortens the recovery cycle, and slows down the pain of patients in the rehabilitation process. However, the current 3D printing technology in this neighborhood also has several difficult problems: first, the hardness of the material, many printing materials have brittle, poor mechanical properties, a long time will be damaged, greatly affecting the service life of the stent, so the future of the field is to seek and develop more suitable printing materials to improve the service life of the stent; Secondly, the wear of the support in the printing process, such as in the construction of complex structures, the print head may collide with the parts, affecting the molding of the support, which requires researchers to develop better printing algorithms and plan the printing order of each part; Finally, the performance of the scaffold material is the problem of how to make the regeneration rate of the bone more consistent with the degradation rate of the scaffold material, while ensuring that no harmful substances are produced. At present, composite 3D printing technology has great potential for development, because composite materials can learn from each other to fill the limitations of a single material. This printing method can effectively increase the development of better printing materials.

Authors Contribution

All the authors contributed equally and their names were listed in alphabetical order.

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