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Research and analysis on key issues of 3D printing human bones

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Abstract. Bone repair surgery is a highly challenging surgical procedure, requiring not only the technical skills of experienced surgeons, but also the suitability of bone materials for individual patients. Additionally, the patient's recovery process plays an important role in the success of the surgery. To address these challenges, various types of 3D printing technologies have been developed, with a focus on material selection and structural analysis. In this study, the authors analyse and summarize different materials and printing structures used in 3D printed bones, as well as the application of this technology in clinical medicine. They also identify key challenges that need to be addressed and provide a vision for the future development and prospects of 3D printed bone technology. With further advancements and refinements in 3D printing technology, we can expect this technique to play an increasingly important role in bone repair surgeries, ultimately leading to better patient outcomes and quality of life.

Keyword: 3D printing, human bones, polymer materials.

1. Introduction

Bone is an important component of the human body. It can support the human body. When maintaining an upright posture, the human body needs a skeleton structure composed of the cervical spine, lumbar spine, thoracic spine, sacrum, pelvis, and lower limb femur, tibia, and foot bones to maintain an upright posture [1]; Skeletons constitute various joints of the human body, such as the knee, ankle, and hip joints, used to achieve human movement and labor [2]; Bones are also the protective "armor" of human organs, such as the skull, which protects the brain, and the ribs, which protect the chest from damage. After a bone receives damage, it can repair and heal itself within a certain range [3]. It is well known that the main and most reliable method for treating bone defects is autologous bone transplantation [4]. However, autologous bone is taken from the patient's iliac bone and other parts. Not only is the amount of bone taken limited, but also the human body will suffer new trauma. When the bone defect is large, it is difficult to meet the clinical needs; Allogeneic bone can be treated to reduce its immunogenicity, but it can also cause a reduction in bone conduction and bone induction capabilities, damaging bone health [5]. In orthopedic clinical trials, personalization and precision are an important research direction in orthopedics. In the past, surgery only passed Medical imaging methods such as optical films, CT scanning images, and MRI imaging are used for surgical analysis [6]. However, image information can produce uncontrollable factors during photography, and it lacks accuracy and intuition in reflecting the location of the lesion, the extent of damage, and anatomical abnormalities. Simply relying on the experience of doctors and the condition seen during surgery, the deviation generated by judging the damaged site of the lesion may directly affect the effectiveness of surgery and the safety of the surgical process. In recent years, 3D printing technology has become increasingly mature and further developed into the medical field, opening a new journey in the manufacturing of bones. 3D printing mainly analyses the location and morphology of patients' lesions through the principle of layer upon layer stacking of materials, using computer tomography and other technologies, thereby quickly and accurately preparing bone tissue scaffolds with complex structures [7]. In addition, 3D technology can also simulate surgery by preparing a patient's bone model to achieve the goal of improving surgical power, These have extremely high application value for the treatment and diagnosis of orthopedic diseases bone reconstruction research based on reverse engineering and 3D printing technology. Currently, there are many examples of 3D printed bones on the market [8]. In terms of materials, the materials used to make bones can be titanium alloys, polymer materials, or biocompatible materials, each of which has different effects; In terms of structure, bones produced by different 3D printing technologies have their own advantages and disadvantages. Compared to other technologies, 3D printing technology can effectively reduce the treatment cost of bone repair, greatly improve the treatment success rate, and has far-reaching significance in leading the technological revolution in bone repair surgery and derived bone tissue culture technology Research and application of 3D printing bone repair technology based on biocompatible materials [9]. Currently, there are endless theories about 3D printed bones, but there is a lack of comprehensive analysis of the characteristics of various types of 3D printed bones. Based on 3D printing bone technology, this article analyses and summarizes different materials and structures [10]. Then the author analyses its application in the medical clinical field. Finally, the author pointed out the shortcomings of the current technology and looked forward to the future of this technology.

2. Material analysis

In 3D printing bone implants, the common materials include synthetic polymer materials, natural polymer materials, metal materials, and bio ceramics. Different types of materials have different advantages and disadvantages.

2.1. Synthetic polymer materials

Polyetheretherketone is a common synthetic polymer material at present. PEEK is a thermoplastic aromatic semi-crystalline synthetic polymer. It can be autoclaved for thousands of times under high temperature conditions, which can well meet the requirements of surgical equipment manufacturing. Moreover, PEEK has no toxicity, and its corrosion resistance, light weight and strong stability make it the closest material to human bones. Its characteristics of non-conductivity, non-heat conductivity and non-cold conductivity make the human body feel no discomfort after the bone is implanted into the human body [4]. This material has been used to repair many joint defects, such as jaw, skull, spine, lumbar spine and oral cavity. Moreover, compared with traditional metal materials implanted into human body such as stainless steel and titanium alloy. Moreover, its strength and fatigue life will be greatly improved. Therefore, in the future development, the composite of polyetheretherketone and inorganic non-metallic materials will be the mainstream trend.

Polyetheretherketone basically has no obvious shortcomings, and its most prominent problem is that the price of materials is relatively expensive. Compared with other bone materials, the price of polyetheretherketone materials is several times that of other materials. It will be a huge expense for families from ordinary families.

Reference [11] chose 7 healthy adults with fresh upper limbs. The specimens were scanned by CT and MRI in standard position, and Dicom data were collected and imported into Mimics 19.0 software for medical three-dimensional reconstruction. According to the reverse engineering data of radial head and anatomical parameters of proximal radial medullary cavity, the radial head prosthesis made of PEEK material was designed and printed in 3D. Through statistical sPSS19.0 software analysis, he concluded that the prosthesis made of radial head PEEK customized by 3D printing technology has a good anatomical shape and the accuracy is controlled within 1mm, which meets the design requirements of clinical individualized customized anatomical radial head replacement.

Poly lactic acid is a new type of biodegradable material. It can be extracted from regenerated plant resources. Starch in regenerated resources is used as raw material, which is saccharified into glucose, then bio-fermented to obtain lactic acid, and then obtained by chemical synthesis. Polylactic acid has very good degradability. It can be converted into carbon dioxide and water through degradation in nature and organisms, and is a new biodegradable material with real environmental protection. Up to now, the application of polylactic acid in 3D printed bones is also very effective. In terms of mechanical properties, polylactic acid has very good thermoplasticity, convenient processing and stable molding, and has been used to replace stainless steel in European and American countries. Polylactic acid also has good biocompatibility, glossiness and transparency, and very good heat resistance, which greatly meet the needs of manufacturing artificial bones. Reference [12] used polylactic acid and pea straw powder with different particle sizes as raw materials to prepare polylactic acid/pea straw powder composites by melt deposition molding process. It was found that the density of the composites added with light pea straw powder was smaller than that of pure polylactic acid, and the density value remained around 1.04 g/cm; The composite made of 120 mesh pea straw powder and polylactic acid has the best mechanical properties, and its tensile strength and tensile modulus are 86.95% and 90.70% of those of pure polylactic acid, respectively. Application and value of polymer materials in 3D printing of biological bones and scaffolds. Reference [13] used ethanol degreasing and hydrogen peroxide deproteinization to delipoprotein rabbit bone, ball milling, sieving and vacuum freeze-drying, The allogeneic bone powder with particle size less than 50um was prepared, and mixed with polylactic acid powder according to different mass fractions. The tubular bone tissue engineering scaffold structure was designed by computer aided design, and the STL format file which could be recognized by 3D printer was generated to print the bone tissue engineering scaffold. He used cross-line diffraction, universal material testing machine, Vickers hardness tester and gravimetry to test its performance. Then, through various experiments, it is shown that this scaffold has no obvious cytotoxicity and can be used in bone tissue engineering research.

Reference [14] drilled cancellous bone wounds with a depth of 4mm with drills with a diameter of 5mm on both sides of rabbits of the same kind, two on each side, with a distance of about 1520 cm. The left two wounds were filled with polylactic acid bone hemostatic glue (group A) and bone wax (group B) to stop bleeding. One wound on the right side was filled with PLA bone hemostatic glue (group A) to stop bleeding, The other wound without any treatment was taken as the blank control group (Group C) for comparative analysis. It was concluded that PLA bone hemostatic glue was rapid, effective, completely degraded and absorbed, and could be used as a good hemostatic glue for cancellous bone wounds. Further research could be expected to be a substitute for bone wax.

2.2. Natural polymer materials

Sodium alginate is a natural polymer material. Alginate is a natural macromolecular compound extracted from seaweed, which has very good bio adhesion, biocompatibility and biodegradability, so alginate has great advantages as a material for manufacturing bones [6]. Through the injection experiment of sodium alginate gel in goat knee, Reference [15] concluded that in meniscus, bone marrow mesenchymal thousand cells containing hIGF-1 gene and sodium alginate gel can be mixed injected to smelt furuncle to realize tissue reconstruction [16]. He also found biomedical grade, low viscosity and high mannose acid alginate cultured cells in vitro through in vitro culture experiments, and the survival rate of cells was the highest; The cells cultured with biomedical grade, low viscosity and high glycogen acid have the best survival state; The yield of proteoglycan was the highest in biomedical grade, medium viscosity and high mannose culture. Tissue-engineered cartilage constructed by suturing SIS membrane on the surface of chondrocytes-sodium alginate hydrogel-SIS complex can repair cartilage defect in situ and promote cartilage tissue regeneration.

2.3. Metallic material

Titanium alloy is one of the materials used earlier in 3D printing bones. First of all, compared with previous materials such as plexiglass, titanium alloy has better histocompatibility and can be better

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accepted by both donors and recipients. Secondly, titanium alloy material has the advantages of light texture and easy molding, which makes it better fit the bone shape required by patients and achieve more accurate details. But titanium alloy bones also have disadvantages. For example, it has the thermal conductivity of metal itself. Therefore, patients will be more sensitive to cold and hot temperature after operation. Compared with organic glass and other materials, titanium alloy has better histocompatibility, but compared with polyetheretherketone and other materials, its properties are relatively poor. If the patient does not heal well after operation, the titanium alloy may collapse, causing infection to the patient, and in severe cases, it may cause life danger. Hu Ruyin obtained that different types of 3D printed porous titanium alloy materials have good hip joint function by implanting them into animals, Enhancing the stability of acetabular prosthesis, good early bone growth and satisfactory short-term curative effect are better choices for hip replacement in patients with osteoporosis.

Reference [16] studied the mechanical properties of trabecular porous structure through mechanical experiments and finite element numerical simulation. They tested the tensile strength of titanium alloy trabecular bone structure by 3D printing of titanium alloy trabecular bone tensile specimens, analysed its failure mechanism, and analysed the influence of different printing positions on the tensile strength of titanium alloy trabecular bone. Finally, it is concluded that titanium alloy trabecular bone has high tensile strength.

2.4. Bioceramics

Bioceramic bone scaffold is an ideal material for repairing artificial bone defect after metal bone scaffold. The greatest advantage of bioceramics is its good biocompatibility. Bioceramic materials are mainly divided into bioinert ceramics, bioactive ceramics and biodegradable ceramics. Different bioceramics have different advantages. Among bio-inert ceramics, alumina has high hardness and zirconia has strong toughness. Tricalcium phosphate has strong degradability and does not pollute the environment. The chemical composition of hydroxyapatite is highly similar to that of inorganic parts of human bones [7]. However, as ceramics, the most obvious disadvantage is that they have a large brittleness coefficient and are not easy to process, so it is difficult to achieve higher precision in the details of manufacturing bones. Shao Huifeng made bio ceramic scaffold with excellent osteogenic performance through the idea of optimizing scaffold channel structure and TCP hybrid. Through observation, it is proved that the bone regeneration and repair ability of the scaffold can be improved by controlling the internal pore structure of the scaffold and adding appropriate amount of TCP.

3. Structural analysis

3.1. Introduction to 3D Printing Technology

3D printing technology is a new manufacturing technology and processing technology. The process of 3D printing is as follows: (1) Workers build and input the digital model needed to manufacture the article through computers; (2) The workers differentiate the digital model step by step through the computer and split it to obtain multi-layer cross sections; (3) the computer guides the printer, and the printer prints and accumulates the cross sections layer by layer with materials in sequence; (4) The final product was reinforced by bonding [2].

At present, the 3D Printing Technology used to print bones mainly include melt deposition molding technology, selective laser sintering technology, light curing molding technology and popular biological 3D printing technology in recent years.

3.2. Melt deposition molding technology

Melt deposition molding technology is also called melt accumulation printing technology. Its essence is to heat and melt linear materials through a heating pipe in a suitable temperature range, and then extrude materials through three-dimensional nozzle equipment. Under the nozzle, there will be a platform for building objects, and materials will flow to the platform to deposit and solidify. With the continuous outflow of materials, the objects on the printing platform solidify layer by layer. In this way, the finished product of the model is finally formed. Preparation and properties of 3D printed bone repair biomaterials and drug-loaded materials. Therefore, the materials for 3D printing in this way need to have good thermoplasticity. The advantage of melt deposition technology is that it is non-toxic and will not bring poisoning risk to human body. Moreover, the facilities required by this technology do not need a special site, and the molding speed is fast. Aiming at the problem of low surface smoothness of the model after being processed by segmented and equal layer thickness layering algorithm, Reference [17] proposed a smoothing processing algorithm applied to the boundary of different layer thicknesses; In order to ensure the forming quality of local feature areas of bone model, they also proposed an adaptive layer scanning speed algorithm based on perimeter and normal vector. Taking the tibia model as the experimental object, the research results show that their proposed algorithm improves the molding quality of the bone model and greatly improves the molding efficiency of the model. The most prominent disadvantage of melt deposition technology is that the precision of the articles it manufactures is not high enough, and the adhesion of each layer of materials is not strong enough, so the stability and mechanical properties of bones manufactured in this way are not particularly excellent, and the use of this type of bones in human body may be accompanied by certain risks. With the continuous development of technology and the needs of industry and scientific research, FDM 3D printers with double nozzles or even multiple nozzles and pneumatic FDM 3D printers have gradually appeared, which can not only print the types of materials at the same time, but also greatly improve the printing accuracy of FDM, and can realize mixed printing of various materials or ultra-high precision printing. Preparation and properties of 3D printed bone repair biomaterials and drug-loaded materials [6].

3.3. Selective laser sintering technology

Selective laser sintering technology is to heat the powder material on the surface of the machine by infrared laser, Promote the molecular diffusion between materials and complete the bonding between granular materials. Compared with melt deposition molding technology, selective laser sintering technology, Because it is controlled by laser, it has high precision and is suitable for printing porous biological scaffolds. However, this equipment needs a special laboratory environment, needs a certain amount of time for preheating and cooling, is inconvenient to operate, and has relatively high cost

3.4. UV-curing molding technology

The principle of light curing molding technology is that the computer will print the parts are sliced layer by layer, Light with specific wavelength and intensity irradiates the surface of photosensitive resin in the trough under the control of computer, The specific area on the surface of the photosensitive resin is cured. After one layer is cured, the next layer is cured by moving the lifting table, and the required sample is finally formed. Zhu Dongliang et al. passed the X-ray lumbar model of human body, With MSCT scanning-Mimics reconstruction-Magics system, UV-curing three-dimensional molding 30 printing mold body, Measure the data of the original motif and the 3D printed model separately, By analysing the two groups of inner diameter data, it is concluded that the 3D printing model of human skeleton by light-curing three-dimensional molding method has high accuracy, which can be used as a reliable solid restoration model and meet the medical applications such as teaching, hand wood planning, auxiliary device manufacturing, etc. [9]. Because materials get energy through light, this technology has the advantages of high precision and high speed. However, it may also cause unstable mechanical properties of articles.

3.5. Biological 3D printing technology

Biological 3D printing is a new product of the cross-integration of life science, materials science and manufacturing science. Tissues and organs with certain biological functions are constructed in vitro for the repair and replacement of damaged tissues and organs.

Rice University in the United States proposed to use high-precision lithography technology to construct complex vascularized network structure, which made it possible to construct complex tissues and organs. Carnegie Mellon University uses suspension glue as printing support to print high-precision complex structures such as heart valves and hearts, and the printed ventricles have the effect of synchronous contraction.

4. Application of 3D printing bone in medical clinical field

Up to now, the most prominent applications of 3D printing bone technology in the medical clinical field are mainly divided into the simulation and construction of patient defect bone solid models before surgery, the implantation of 3D printing bones on patients during surgery, and the printing of auxiliary materials required for patient recovery after surgery. Traditional preoperative preparation only involves medical imaging methods such as taking X-ray films, CT scanning images, and MRI imaging to perform preoperative analysis. These imaging information can only provide doctors with a general understanding of the patient's condition, lacking accuracy and intuition, and are not helpful in treating patients and preparing for surgery. 3D printing of patient defect bone models can solve these problems well. Firstly, this model can help doctors better formulate surgical plans. Doctors can perform simulation operations before performing surgery on patients, and perform surgical treatment on patients after making sufficient preparations. This can not only reduce the trauma to patients during surgery, improve treatment effectiveness, but also enable doctors to better implant prostheses in patients, improving the safety and accuracy of the surgical process. Moreover, doctors can anticipate possible problems during the surgery process in advance, which greatly reduces the risk of the surgery process [7].

Traditional surgical bone implantation involves doctors directly implanting different materials of prostheses into patients. However, this method is too simple to accurately match the injury site of the patient, and patients are prone to many sequelae and infections after surgery. This is not conducive to the improvement of the patient's condition. The implantation of 3D printed bones on patients perfectly solves this problem. 3D printed bones can be deployed and calibrated in various ways, and the medical conditions of different patients can be analysed separately and matched one-to-one, greatly improving the quality of surgery [2]. The 3D printing brace can be tailored to the patient's condition and play a good orthopedic role for the patient. Traditional fixed plaster has a heavy weight and is inconvenient to move. 3D printing supports not only can solve this problem, but also have the advantages of water resistance, allergy resistance, high breathability, and lightweight, which can greatly improve the comfort of patients.

5. Conclusion

This article reviews the materials, structures, and applications of 3D printed bones in the medical and clinical fields. Compared to other methods of making bones, 3D printed bones have the advantages of rapid molding, bone structure matching the human body, and personalized production. Moreover, 3D printing bone technology can create a model of human bone defects, allowing doctors to better understand the patient's condition, improving preoperative preparation, and helping to reduce surgical risks. After surgery, the 3D printing brace is designed to print specifically for the individual situation of the patient, and it can play a better correction role compared to previous braces. However, 3D printing also has some obvious disadvantages. For example, the materials and equipment for 3D printing bones are too expensive, and for some small hospitals, they do not have financial support, which affects the universality of 3D printing. Due to the machine printing, the technology of disinfection and sterilization bone bacteria is relatively weak compared with the traditional process, and patients are prone to infection or sequelae after use. Moreover, there are still certain shortcomings in the accuracy of 3D printing technology, and there is still great room for improvement in technology. Although there are many shortcomings in the current 3D printing bone technology, after step-by-step improvement by technical personnel, 3D printing bone must be the future of bone manufacturing. After weighing the advantages and disadvantages, the author believes that the future research direction of 3D printing bone technology should focus on the following points: (1) Research and discover new cheap materials to replace expensive materials, allowing 3D printing bone technology to have a broader market (2) Invent more advanced bacteria disinfection and sterilization system to improve the safety of human bones. (3) Strive for the development of 3D printing accuracy to the nanometre level.

In short, through the unremitting efforts of researchers, 3D printed bones will definitely excel in the field of medical equipment and play an increasingly important role in the field of orthopedic treatment in the future.

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