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Research Progress of 3D Printing Technology in Anterior Cruciate Ligament Reconstruction

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ABSTRACT

With the improvement of living standards, people are paying more and more attention to sports exercise. The incidence of anterior cruciate ligament (ACL) rupture has been increasing in recent years, and the age of onset is also becoming younger. The treatment effect is also increasingly concerned, which directly affects the quality of life of patients. At present, the main treatment method for ACL is arthroscopic reconstruction of the anterior cruciate ligament, and with the emergence of 3D printing technology, it has brought a new direction for the anterior cruciate ligament of the knee joint. To explore the latest research progress of 3D printing technology applied to the repair and reconstruction of the anterior cruciate ligament. 3D printing technology used for tunnel positioning in ACL reconstruction is superior to traditional tunnel positioning. 2). The preoperative simulation plan applied by 3D printing technology in ACL reconstruction can effectively reduce the time during surgery, thereby avoiding postoperative complications caused by repeated operations during surgery, and greatly improving the success rate of surgery for beginners. 3). 3D printing technology is currently more used in animal experiments in the field of tissue engineering research in ACL reconstruction, and there is less clinical application, lacking clinical data support. 4). At present, there are more reports on the short-term curative effect of 3D printing technology applied to the reconstruction of ACL rupture, and there is a lack of long-term curative effect follow-up results. 5). The application of 3D printing technology in the whole process of ACL reconstruction has great potential value.

KEYWORDS

3D printing; Anterior cruciate ligament reconstruction; 3D printed preoperative planning model; 3D printed intraoperative navigation template; Tunnel positioning,Tissue engineering

1 Introduction

The anterior cruciate ligament (ACL) is an important structure for maintaining the stability of the knee joint, which is prone to rupture due to improper exercise, leading to knee joint activity disorders, and can lead to complications such as osteoarthritis in severe cases. In recent years, with the progress of science and technology and the improvement of people's living standards, ACL injuries have gradually attracted the attention of clinical and scientific researchers. According to research reports: there are about 200,000 ACL injuries each year [1], and female athletes are more susceptible to ACL injuries, indicating the possibility of differences in anatomical structure and gender [2]. With the promotion of national sports, ACL injuries have become one of the most common sports injuries in China, and therefore, ACL reconstruction has gradually been valued by the public. At present, the traditional arthroscopic reconstruction of the anterior cruciate ligament is still the best choice for the treatment of ACL rupture, but the narrow field of view under arthroscopy, the individual anatomical structure of patients, and the proficiency of operators make it difficult to locate the tunnel, thus affecting the success rate of the surgery. With the emergence and development of 3D printing technology, it has gradually been applied to medicine. Its essence is to analyze the human skeleton and muscles in detail under the current medical imaging technology, and then combine the foundation of computers. 3D printing is used to make individualized models according to the patient's own anatomical characteristics. With the widespread application of 3D printing, ACL reconstruction combined with 3D printing has gradually come into the public eye. ACL reconstruction includes preoperative planning, precise tunnel positioning during surgery, and individualized treatment. Through the model, preoperative simulation of surgical operations can be performed to reduce the mistakes and time of beginners during surgery, avoid intraoperative bleeding and soft tissue damage, and at the same time, it has the advantages of increasing the accuracy and safety of tunnel positioning, shortening the time of intraoperative operation and radiation exposure, and reducing postoperative complications. Therefore, this article discusses the latest research progress of 3D printing technology in ACL reconstruction. 3D Printing Technology: The commonly used 3D printing technologies at home and abroad are: ① Selective Laser Melting ② Fused Deposition Modeling Technology ③ Chemical Vapor Deposition Method.

2 Application of 3D Printing in Preoperative Models

3D printed models are created through the analysis and storage of imaging data, combined with computer-assisted virtual technology, to establish models that are identical in size to the patient's bones at a 1:1 scale. Surgeons can use these models to plan complex surgeries preoperatively and practice repeatedly on the models. Compared with traditional imaging-based preoperative planning, this can improve the accuracy, safety of femoral tunnel positioning, and shorten the total surgical time required [3]. Ni et al. [4] conducted CT scans on 20 human cadavers, established 1:1 original knee joint models, and preoperatively designed and marked the positions and directions of the femoral and tibial bone tunnels, creating personalized 3D guides.

They concluded that the deviation between the preoperatively planned tunnel positions and the intraoperatively drilled tunnel positions was less than 0.6 millimeters, indicating a high precision of tunnel placement, thereby improving surgical efficiency and success rate. However, their navigation system required an increased number of intraoperative fluoroscopies, increasing radiation exposure, which limits its clinical application. Galvez et al. [5] studied seven different types of orthopedic diseases, and compared the effects of surgeries performed with preoperative 3D printed templates to those performed without templates. The results showed that the use of 3D printed anatomical models improved surgical planning, especially for patients for whom traditional techniques were insufficient to establish an appropriate strategy, leading to better intervention strategies and reducing surgical risks, surgical time, and recovery time.

It has been found that 3D printing technology can create the most realistic models preoperatively, thereby formulating the best preoperative plans. Compared with traditional imaging-based preoperative planning, it improves the precision of surgery and shortens the surgical time [6].

In summary, for beginners, preoperative simulation can reduce intraoperative errors and avoid complications such as soft tissue damage around the operation. For experienced surgeons, it avoids over-reliance on experience and neglecting individual differences, which can lead to surgical failure, and also shortens the surgical time.

3 Research on 3D Printed Guides in Bone Tunnels

The earliest concept of surgical navigation can be traced back to the skull stereotactic surgery described by Horly and Clarke et al. [7] in 1908, where a model was attached to another model, based on a coordinate system to treat skull lesions. With the application of 3D printing technology in ACL reconstruction, tunnel positioning is one of the key points of ACL reconstruction. Traditional positioning methods commonly used include the "clock face [8]" positioning method, the "resident's ridge landmark [9]" positioning method, etc., each with its own defects. For example, the clock face positioning method is highly dependent on the arthroscopy field of view and knee joint position, and the resident's ridge landmark positioning method may be unclear in some patients, leading to difficulties in positioning. With the application of 3D printed guides in bone tunnels, this problem has been better solved. Currently, there are many reports on 3D printed guides in bone tunnels, divided into femoral tunnel positioning [10] and tibial tunnel positioning [11].

3.1 Femoral Tunnel Positioning

Traditionally, femoral tunnel positioning is divided into four types: transtibial technique (TT) [12], anteromedial technique (AM) [13], outside-in (OI) [14], and modified transtibial technique (mTT) [15]. Studies have shown that the above four positioning methods each have their advantages and disadvantages, and there is no significant difference in clinical outcomes. However, accurate positioning of the femoral tunnel is crucial in anatomic ACL reconstruction [16]. Zee et al. [17] found that to improve the accuracy and consistency of femoral tunnel positioning in ACL reconstruction, the use of 3D printed surgical guides is a feasible option for further exploration. Rankin et al. [18] identified the anatomical location of the individualized femoral footprint of the uninjured contralateral knee of the subjects through MRI, and used 3D printing technology to print individualized ACL femoral tunnel guides to assist in ACL reconstruction. The results found that there was no statistical difference in the size and position of the tunnel positioning in the center of the MRI anterior cruciate ligament femoral footprint guide, thus verifying the accuracy of 3D printed guides in femoral tunnel positioning. Chen et al. [19] studied the feasibility and accuracy of using 3D printed femoral tunnel templates to guide the optimal positioning of the internal anatomical stop and low-tension maintenance (IDEAL) bone tunnel. The study results showed that using 3D printed technology to design femoral anchors in ACL reconstruction can achieve individualization and precise positioning of the bone tunnel in anterior cruciate reconstruction, supporting the goal of individualized and precise reconstruction. In clinical practice, the use of 3D printing technology in femoral tunnel positioning has been widely used, greatly improving the accuracy and success rate of tunnel positioning. This brings the reconstruction closer to the anatomic reconstruction of the anterior cruciate ligament, allowing the knee joint function to be restored to the greatest extent. Wang et al. [20] found through clinical research that 3D printed guide-assisted individualized ACL reconstruction can greatly improve the accuracy and safety of femoral tunnel positioning, while reducing intraoperative time and positioning times, and achieving higher knee stability. Lan et al. [21] found through clinical research on 80 patients with complete ACL rupture undergoing arthroscopic ACL reconstruction that the 3D personalized guide positioning method is more effective than traditional positioning methods for femoral tunnel positioning in knee ACL reconstruction, and can greatly reduce positioning time.

3.2 Tibial Tunnel Positioning

Accurate tibial tunnel positioning can effectively avoid complications such as anterior knee pain, limited knee extension, instability, and graft impingement. Traditional ACL single-bundle reconstruction often uses the method of drilling the femoral tunnel through the tibia. In recent years, this method has gradually been replaced by the technique of directly drilling the femoral tunnel through the anteromedial portal. Mauch F et al. [22] performed anterior cruciate ligament reconstruction surgery on 53 athletes under arthroscopy. The first group (Group N) of 24 athletes underwent reconstruction with the assistance of a navigation system, and the second group (Group M) of 29 athletes underwent reconstruction under traditional arthroscopy. X-rays were performed on the fourth day after surgery to determine the exact position of the tibial tunnel, and the center of the tibial tunnel (relative to the maximum anteroposterior diameter of the tibia, expressed as a percentage) was measured. The center of the tibial tunnel was compared with the "optimal" position pointed out in previous studies. The results showed that when the center of the tibial tunnel was compared with the best 44% found in previous studies, the value of Group M (37.6%) changed significantly, while Group N (40.5%) did not, indicating that 3D printed navigation templates are beneficial to the accuracy of tunnel positioning, improving the success rate of reconstruction surgery.However, Desaid et al. [23] found in clinical studies that ACL reconstruction with hamstring autografts still has a high failure rate.

In summary, with the rapid development of technology, computer navigation systems have also attracted much attention in this field, especially in the positioning of femoral and tibial tunnels. As the understanding and development of tunnel positioning, the femoral tunnel positioning through the tibia is gradually being eliminated. This technology is currently mainly used for the positioning of the femoral tunnel, effectively saving surgical time, avoiding complications caused by improper operations during surgery, improving the accuracy of tunnel placement, and improving early clinical outcomes after surgery. However, there is less research on the long-term effects, and in addition, this technology can help beginners increase the success rate of ACL reconstruction surgery in the clinic, and can also avoid skilled people's over-reliance on experience and neglect of individual anatomical differences leading to surgical failure.

3.3 Progress of 3D Printing in Tissue Engineering

Tissue engineering is a multidisciplinary field that integrates principles of biochemistry, engineering, and materials science. With the development of tissue engineering, it has become increasingly popular in ligament reconstruction. Among them, ACL reconstruction is one of the current research hotspots. After the rupture of the anterior cruciate ligament, its synovium is damaged, leading to the inability to form local hematoma, which affects the healing of the ligament and leads to a decrease in knee joint stability. 3D bioprinting can create complex tissue scaffolds containing cells, extracellular matrix components, and growth factors, enabling engineered tissues to mimic the structure and function of natural tissues for better healing. The tissue scaffold is a carrier for cell growth, proliferation, and differentiation, and after combining with the corresponding stem cells, cell differentiation and division promote tissue healing, playing an important role in tissue engineering. The ideal scaffold for reconstructing the anterior cruciate ligament is a three-dimensional structure with biocompatibility, mechanical properties, and can withstand the forces experienced by the original structure. 3D printing technology can also construct more individualized three-dimensional biological scaffolds based on the patient's condition while having good biological characteristics, promoting better ligament healing. Zhang et al. [25] used 3D printing technology to prepare ligament-bone composite scaffolds and implanted them into the position of the anterior cruciate ligament rupture in the left knee joint of 10 healthy pigs aged 4 months. After 3 months, biomechanical testing and histological observation of the regenerated ligament and ligament-bone interface were conducted, with the right knee joint retaining the anterior cruciate ligament as a control. The study found that 3D printing technology successfully prepared ligament-bone composite scaffolds and preliminarily achieved ligament-bone interface regeneration in pigs. Park et al. [26] used 3D printing technology on a rabbit rotator cuff repair model to construct a 3D printed composite polylactic-glycolic acid (PLGA) scaffold, using the scaffold as a carrier, combined with bone marrow mesenchymal stem cells (BM-MSCs). The study found that the PLGA scaffold had good biocompatibility and biodegradability, and the BM-MSCs-loaded PLGA scaffold was implanted at the injury site of the rabbit supraspinatus tendon-bone junction, and the study found that it greatly promoted tendon-bone healing, while the three-dimensional bioprinted scaffold sheath constructed with bone marrow mesenchymal stem cells also brought better healing effects in the bone integration between tendon and tunnel bone. Goradia et al. [27] conducted experiments on rabbits, placing mesenchymal stem cells on 3D printed scaffolds for use in the tendon-bone junction of anterior cruciate ligament reconstruction, and found that it could accelerate tendon-bone healing. Kajave et al. [28] used a combination of methylpropene-acrylated collagen (CMA) and bioglass (BG) with different components as composite inks for 3D printing, using a collagen matrix carrying human mesenchymal stem cells (hMSCs) (BioGIM) to create different BG gradients, and manufactured a scaffold similar to the ACL bone-ligament interface. The study found that through the carrying of the 3D scaffold, BioGIM can be integrated into the end of the synthetic ACL graft, and has the potential to provide guidance for tissue-specific cell differentiation, enhance functional matrix recombination, promote better graft integration, and achieve the basic biochemical clues for the complete reconstruction of the damaged ACL. Cao et al. [29] used 3D printed multiphase scaffolds and a layered cell seeding method with methacrylated gelatin (GelMA); (encapsulating fibroblasts, bone marrow-derived mesenchymal stem cells, and osteoblasts in GelMA) to prepare a biomimetic tendon-to-bone interface. Through in vitro and animal experiments, the study found that the layered preparation method of the 3D printed multiphase scaffold is an effective strategy for tendon-bone interface engineering, including efficient cell seeding, chondrogenic potential, and different matrix deposition at different stages. The application of 3D printing technology in tissue engineering is mainly reflected in the production of personalized scaffolds, using the scaffold as a carrier, carrying stem cells, growth factors, etc., to produce composite scaffolds that promote tissue healing. However, most domestic and foreign literature currently indicates that 3D printed biological scaffolds are still in the animal experiment stage, lacking clinical data support. Some scholars have also proposed [30] that tissue engineering and additive manufacturing provide new possibilities for exploring 3D scaffolds as substitutes for anterior cruciate ligament grafts.

3.4 3D Printing of Customized Internal Fixation Devices

In recent years, some studies have confirmed [31] that the healing level of transplant fixation devices is related to the porous structure of the transplant fixation devices. However, traditional methods find it difficult to control the pore size of the transplant fixation devices, but 3D printing technology can better control the pore size. Interconnected micropores (50-100μm) can increase the transport of blood vessels and nutrients during bone reconstruction [32], and in addition, large pores (200-400 μm) enhance the migration of various bone cells to the scaffold, promoting bone formation and mineralization [33], thereby accelerating the healing of the fixation site. The three-dimensional porous structure is one of the key factors in promoting bone growth. 3D printing can customize individualized three-dimensional porous spiral nail scaffolds according to their own needs, combined with mesenchymal stem cells, which can greatly promote healing and reduce the occurrence of complications. In the past, the graft in the bone tunnel was often fixed with interference screws during ACL reconstruction; however, postoperative complications such as biodegradable screw breakage, inflammation or foreign body reaction, tunnel enlargement, and delayed graft healing may occur. With the application of 3D printing technology in the production of individualized internal fixation devices, a fixation device that conforms more to the original anatomical relationship can be constructed, thereby promoting healing to the greatest extent. Huang et al. [34] used D3DP to construct screws in a rabbit ACL reconstruction model, combined with a bioactive coating to fix tendon grafts, greatly promoting the healing and stability of tendon grafts in the bone tunnel. Wang et al. [35] used 3D printing technology to manufacture personalized poly-L-lactic acid (PLLA) porous screws for use in ACL reconstruction, and the study found that it can not only fix the transplanted tendon but also increase bone induction, promote bone growth in the bone tunnel, and promote tendon-bone interface bone fusion.

In summary, 3D printing technology applied to internal fixation has greater advantages compared to traditional internal fixation, which can manufacture specific internal fixation devices with pore sizes and more conforming to the original anatomical relationship, promoting the transport of nutrients and carrying growth factors and stem cells, etc., thereby promoting the healing of bones and tendons.

In the field of ACL reconstruction, the clinically common treatment method is arthroscopic anterior cruciate ligament reconstruction. There is a wealth of literature on arthroscopic anterior cruciate ligament reconstruction, which is comprehensive and reports various benefits such as improving knee joint mobility, alleviating pain, and reducing the likelihood of complications. However, there are some limitations, such as poor visibility during surgery leading to operational difficulties, and the outcome is highly dependent on the surgeon's experience. Different operators may yield significantly different clinical results postoperatively. With the increasing maturity of 3D printing technology in orthopedics, it is now integrated throughout the entire process of ACL reconstruction. Preoperatively, 3D printing technology, combined with imaging, can produce 1:1 models with personalized bone dimensions, facilitating preoperative simulation of surgical methods and reducing intraoperative time. For complex cases, strategies can be adjusted in a timely manner. However, there is still a certain deviation between the model and the actual entity. The advent of 3D printed guides has made tunnel positioning more accurate, reducing both surgical time and soft tissue injury, as well as complications. However, there is currently no standardized specification for the guides in clinical practice.

3D printing technology is also one of the hot topics in research in the field of tissue engineering and implant fixation. 3D printing of special structures of absorbable fixation devices, using a scaffold as a carrier, combined with some mesenchymal stem cells that have the ability to differentiate and proliferate, can be implanted to fix the bone-muscle tendon area, accelerating bony healing and recovery, and achieving better surgical outcomes. However, there is a lack of long-term efficacy assessment.

4 Limitations of the Review

Currently, the application of 3D printing in anterior cruciate ligament (ACL) reconstruction lacks a substantial amount of clinical data for evaluation. Even with the maturation of 3D printing technology, it is challenging to print models that are identical to the original structures. Additionally, during the tunnel positioning process, the influence of soft tissues attached to the positioning points on 3D guides cannot be entirely ruled out. There is also a relative scarcity of literature on the combination of 3D printing technology with finite element analysis in ACL reconstruction, which is a direction for future efforts. There is no extensive clinical data to confirm the long-term postoperative efficacy of 3D printing technology in ACL reconstruction. Future researchers should conduct further follow-ups at 5, 10, and 20 years post-surgery to validate the outcomes.

5 Significance of the Review

With the improvement of living standards, an increasing number of people are beginning to value physical exercise. However, the number of individuals engaging in sports without proper guidance is also growing, leading to a rising incidence of ACL ruptures. This results in decreased knee stability, limited mobility, and ultimately severe complications such as osteoarthritis. The most common treatment plan currently is arthroscopic ACL reconstruction, but many aspects still fail to achieve the biological characteristics of the native ACL, leading to the need for secondary revisions. 3D printing technology can help establish models and perform simulated surgeries in ACL reconstruction, allowing for better formulation of individualized preoperative plans, avoiding some surgical risks, and increasing the success rate of surgical operations for beginners. With specific 3D printed personalized navigation templates, the positioning of tunnels during ACL reconstruction can be accurately determined, reducing intraoperative time and avoiding intraoperative complications, thereby increasing the success rate of the surgery. In the field of tissue engineering research, 3D printing can be used to create personalized implants and scaffolds combined with stem cells, greatly promoting the healing process and shortening postoperative recovery time.

6 Bold Outlook

In the future, with breakthroughs in 3D bioprinting and artificial ACL materials, 3D printing technology may be able to print artificial ACLs that are more personalized and better suited to human biomechanics. Utilizing 3D printing technology to create artificial ACL tissues that comply with human biomechanics could be the ultimate solution for the reconstruction of ACL ruptures.

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