Journal of Biosciences and Medicines, 2024, 12, 463-483
https://www.scirp.org/journal/jbm
ISSN Online: 2327-509X
ISSN Print: 2327-5081

Research Progress of Anterior Cruciate Ligament Reconstruction under Arthroscopy

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How to cite this paper: Yang, W.J., Chen, L.C. and Wei, J.H. (2024) Research Progress of Anterior Cruciate Ligament Reconstruction under Arthroscopy. *Journal of Biosciences and Medicines*, **12**, 463-483.
https://doi.org/10.4236/jbm.2024.1211037

Received: October 17, 2024
Accepted: November 24, 2024
Published: November 27, 2024

Abstract

As an important means to treat anterior cruciate ligament (ACL) injury, the reconstruction technology under arthroscopy has made remarkable progress in recent years, evolving gradually from the early traditional open surgery to the minimally invasive surgery under full arthroscopy. At present, it is widely used. Different graft choices (such as autologous hamstring, peroneus longus, artificial tendon, and allogeneic tendon, etc.) and fixation methods (such as metal suspension fixation, interference screw, etc.) have their own characteristics. However, this technology still faces some challenges, such as postoperative complications and the long-term stability of the graft. In terms of future trends, it will develop in a more accurate and personalized direction. New materials and technologies are expected to emerge continuously to improve the surgical effect and the rehabilitation quality of patients, providing stronger support for clinical application and research. This article will conduct a comprehensive review from aspects such as surgical methods, graft selection, fixation methods, ligamentization of the graft, challenges faced, and future trends in ACL reconstruction surgery.

Keywords

Arthroscopy, Anterior Cruciate Ligament Injury, Reconstruction, Application Status, Development History, ACL

1. Introduction

ACL injury is a common type of knee joint injury, occurring frequently especially in sports activities and accidents. With the changes in people's lifestyles and the increase in sports participation, the incidence of ACL injury is on the rise. The ACL plays a crucial role in maintaining the stability and normal movement function of the knee joint. Once damaged, it will seriously affect the patient's quality of life and athletic ability. The emergence of ACL reconstruction technology under arthroscopy has brought revolutionary changes to the treatment of anterior cruciate ligament injuries. Compared with traditional open surgery, arthroscopy has significant advantages such as less trauma, faster recovery, and fewer postoperative complications, and has become the mainstream method for treating ACL injuries.

The development of ACL reconstruction technology under arthroscopy has gone through multiple stages. In the early days, the surgical methods were relatively crude, causing greater damage to the knee joint. With the continuous progress of technology, the introduction of arthroscopy has made the surgery more minimally invasive and precise. From the initially simple single-bundle reconstruction to the in-depth research on anatomical structures and biomechanics later, double-bundle reconstruction and even more complex reconstruction methods have been developed. The improvement of surgical tools and equipment has also provided strong support for the development of this technology. In current clinical practice, ACL reconstruction technology under arthroscopy has been widely applied. In terms of graft selection, doctors will choose the appropriate graft according to the specific situation of the patient. Autologous grafts such as hamstring tendons are often given priority due to their good compatibility and biomechanical properties, while allogeneic tendons are used in specific circumstances [1]. There are various fixation methods, including screw fixation, suspension fixation, etc., and each method has its applicable range, advantages, and disadvantages [2]. Meanwhile, rehabilitation treatment also plays a crucial role in postoperative recovery. Although this technology has achieved remarkable accomplishments, it still faces some challenges. For example, complications such as postoperative infections and re-rupture of the graft occur from time to time, causing pain and additional treatment burdens to patients. In addition, the long-term stability of the graft still needs to be improved, as some patients may experience a decline in knee joint function years after the surgery. How to accurately assess the prognosis of patients and optimize the surgical plan to reduce the occurrence of adverse events are important issues that need to be addressed currently. In the future, ACL reconstruction technology under arthroscopy will develop in a more precise and personalized direction. Meanwhile, with the help of advanced imaging technologies and biomechanical analysis, more accurate preoperative planning and more refined intraoperative operations will be achieved. Moreover, new biomaterials and tissue engineering technologies are expected to be applied to the improvement of the graft, enhancing its performance and durability. Furthermore, the integration of multiple disciplines will provide patients with more comprehensive and efficient rehabilitation programs, further improving the surgical effect and the quality of life of patients [3].

The purpose of this paper is to conduct a comprehensive and in-depth discussion on the latest research progress of ACL reconstruction technology under arthroscopy. By analyzing the development trends of this technology in terms of graft selection, improvement of surgical methods, postoperative rehabilitation strategies, etc., it aims to provide richer theoretical basis and practical guidance for clinicians, so as to improve the surgical effect, reduce the occurrence of complications, promote patients to recover the knee joint function faster and better, and return to normal life and sports. Meanwhile, it also provides references for the further innovation and optimization of this technology in the future.

2. Anatomy and Physiological Functions of ACL

2.1. Anatomical Structure of ACL

The anterior cruciate ligament (ACL) originates from the anterior medial part of the intercondylar eminence of the tibia, fuses with the anterior horn of the lateral meniscus, and extends obliquely backward, upward, and laterally. Its fibers are attached to the medial border of the lateral femoral condyle in a fan-shaped pattern. The femoral insertion point of the ACL is located at the posterior part of the medial surface of the lateral femoral condyle, presenting an oval concave surface. The ACL is a fibrous tissue about 3 cm long, approximately the size of an adult's little finger, white, smooth, and surrounded by synovial tissue on the surface. When the knee is flexed at 90˚, the angle between the long axis of the ligament and the long axis of the femur is 26 ± 4˚. Its internal structure is compact, with fibers arranged in parallel. It is the narrowest in the middle, with a width of about 11.49 ± 1.59 mm and a thickness of 4.33 ± 0.49 mm. It does not exist as a single bundle but spreads out in a fan-shaped form as a collection of fiber bundles, with its two ends attached to the broad and flat bone surfaces of the femur and tibia. Traditionally, it is believed that the ACL is composed of the anteromedial bundle (AMB) and the posterolateral bundle (PLB). The force and movement conditions of these two bundles are different under different knee joint movement states, which has inspired many scholars to consider the choice of surgical procedures in ACL reconstruction technology [4] [5]. Additionally, some scholars believe that it is composed of three fiber bundles, but there is relatively little research on this theory, and thus it will not be explored in depth here.

2.2. Physiological Functions of ACL

The ACL plays a crucial role in restricting excessive flexion and extension of the knee joint. Zhang Sujie *et al.* [6] found in a study on the biomechanical characteristics and injury mechanisms of the ACL under different movement states of the knee joint that the variable stress on the ACL changes with the flexion and extension angles of the knee joint. The variable stress on the ACL is the largest when the knee is flexed at 30˚, and there is not much change at other angles, indicating that the variable stress on the ACL is mainly concentrated at the femoral attachment point. When the knee joint is overextended, the ACL can prevent the tibia from excessive anterior displacement, thereby avoiding joint injury. When the knee joint is flexed, it can also restrict the excessive posterior displacement of the tibia, ensuring that the joint movement is within a safe range. Liang Feng *et al*. [7] studied the correlation between the posterior tibial slope (PTS) and ACL injury and found that an excessive PTS is a risk factor for ACL injury. The reason may be related to the different variable stresses on the ACL. In addition, the ACL maintains the stability of the knee joint through the synergistic action with other ligaments and joint structures. It can restrict the internal rotation, varus and valgus, and hyperextension of the knee joint, effectively controlling the position and force distribution of the knee joint under different movement states, reducing the instability and potential injury risks of the joint. Meanwhile, the mechanoreceptors on the surface of the ACL regulate the muscles around the joint through the neural negative feedback mechanism, further enhancing the stability of the knee joint [8].

3. Development History of Anterior Cruciate Ligament Reconstruction Technology under Arthroscopy

3.1. Early Technologies and Methods

In the early stage, the operation process of anterior cruciate ligament reconstruction surgery under arthroscopy was relatively straightforward. Doctors usually conducted explorations through the limited visual field of the arthroscopy to determine the location and extent of the anterior cruciate ligament injury. Then, bone tunnels were drilled in the tibia and femur to introduce the grafts. However, due to the limitations of technology and equipment, the surgical operations were not precise enough, causing relatively large damage to the surrounding tissues. The main types of grafts commonly used in the early stage included autologous patellar tendon and fascia lata. The autologous patellar tendon had a relatively strong tensile strength, but the process of obtaining it would cause certain damage to the patellar tendon, which might lead to complications such as anterior knee pain after surgery [9]. The fascia lata, on the other hand, had problems such as relatively weak strength and a longer healing time [10] [11].

3.2. Improvements and Innovations in Technology

In recent years, the process of anterior cruciate ligament reconstruction surgery has been significantly optimized. In terms of preoperative assessment, with the help of advanced imaging technologies such as three-dimensional reconstructed CT and magnetic resonance imaging (MRI), the anatomical structure and injury situation of the knee joint can be understood more precisely, providing an accurate basis for the formulation of surgical plans [12] [13]. During the surgical process, the resolution and clarity of the arthroscopy have been continuously improved, enabling doctors to observe the internal details of the joint more clearly, thus drilling bone tunnels more precisely to ensure that the position and angle of the grafts are more in line with physiological requirements. In addition, the continuous update of minimally invasive surgical instruments has reduced the damage to the surrounding tissues and decreased the incidence of postoperative complications. New types of graftsn such as artificial ligaments have gradually been applied. Artificial ligaments have the characteristics of high strength and fast recovery, being able to quickly provide stability to the knee joint. However, artificial ligaments are usually expensive, and many patients do not prefer them as the first choice. Generally, they are jointly applied when the autologous tendon material is insufficient, or are more commonly seen in patients who need to recover the knee joint function in a short period, such as athletes and soldiers [14] [15]. Meanwhile, certain progress has also been made in the research of tissue-engineered ligaments. Constructed through biomaterials and cell culture technologies, they have better biocompatibility and adaptability, and are expected to become an ideal choice for anterior cruciate ligament reconstruction in the future [16]. In addition, the processing technology of autologous tendons has also been continuously improved. For example, through special weaving and pretreatment methods, the strength and durability of the grafts have been enhanced.

4. Current Application Status of Anterior Cruciate Ligament Reconstruction Technology under Arthroscopy

4.1. Application of Grafts

4.1.1. Autologous Grafts

Autologous grafts are widely used in anterior cruciate ligament reconstruction under arthroscopy. Among them, autologous hamstring tendons, peroneus longus tendons, and bone-patellar tendon-bone are the most common choices [17]. Among these, the hamstring tendon is the most frequently used. Autologous hamstring tendons possess good biocompatibility and adaptability, being able to integrate well with the recipient tissues, and the postoperative recovery effect is relatively ideal. Their advantages lie in the fact that they come from the patient's own body, with a low risk of rejection reaction, and their strength can meet the requirements of reconstruction. However, the harvesting of hamstring tendons will cause certain damage to the donor area, which may lead to pain and functional limitations in the short term after surgery. Chen Guomin *et al.* [18] conducted a comparative study on the efficacy of 81 patients undergoing anterior cruciate ligament reconstruction surgery and found that compared with harvesting hamstring tendons, harvesting the ipsilateral peroneus longus tendon had advantages such as faster early postoperative recovery, fewer donor area complications, and convenient tendon harvesting. Currently, there is basically a consensus in the medical field regarding arthroscopic ACL reconstruction surgery, but there is still controversy regarding the choice of grafts, and long-term research and discussion are still needed.

4.1.2. Allogeneic Grafts

Allogeneic grafts will also be used in specific circumstances, such as when the patient's own tissue conditions are not suitable or when multiple ligament repairs need to be carried out simultaneously. Currently, the application of allogeneic tendons is gradually increasing, but there are some problems. On the one hand, allogeneic grafts may trigger an immune rejection reaction. Although they have been strictly processed by modern technologies, there is still a certain risk. On the other hand, their sources are limited, it is difficult to fully guarantee their quality, and their price is relatively high, exerting great economic pressure on patients [19].

4.1.3. Ligamentization Process of Grafts

After anterior cruciate ligament reconstruction surgery, ligamentization is a complex process. In the early postoperative period, a hematoma will form around the graft, and inflammatory cells will gather to initiate the repair process. As time passes, fibroblasts will gradually proliferate, synthesize collagen, and begin to form immature fibrous tissues. Approximately several weeks later, the remodeling stage is entered, and the strength of the graft will gradually increase. Blood vessels will gradually grow into the graft to provide nutrition. Meanwhile, the cellular components will be continuously adjusted, and the arrangement of collagen fibers will be more orderly. This stage lasts for several months or even longer. Eventually, the graft will gradually approach the structure and function of a normal ligament and complete the ligamentization process [20]-[24]. Throughout this process, patients need to cooperate with rehabilitation training to promote blood circulation and tissue repair and accelerate the ligamentization process [25].

4.2. Application of Fixation Devices

Fixation devices can be classified into direct and indirect ones. Direct fixation devices include interference screws (made of metal materials such as titanium alloys, absorbable polymeric materials, and Polyetheretherketone (PEEK) materials), cortical suspension fixation, U-shaped nails, washers, and cross pins, etc. [26]-[28]. Among them, the interference screw is the most widely used. Titanium alloy screws possess relatively high strength and stability, being able to provide reliable fixation effects. However, they may cause some reactions such as the release of local metal ions, which may lead to problems such as local tissue inflammation. Absorbable polymeric materials are made of homopolymers or copolymers of absorbable polyesters such as polylactide, polycaprolactone, and polyglycolide, and components such as hydroxyapatite or bioceramics can be selectively added. These materials can gradually degrade after fulfilling their fixation functions in the body without the need for a second surgical removal. However, their mechanical strength is relatively low, and during the degradation process, complications such as aseptic inflammation reactions, screw loosening, and widening of the bone tunnel may occur. Polyetheretherketone (PEEK) materials have good mechanical properties, biocompatibility, and corrosion resistance. They are characterized by high strength, light weight, and can improve their osteoinductive and antibacterial capabilities through structural changes and surface functionalization. Cortical suspension fixation using loop plates has the advantages of being relatively firm, being able to provide reliable stability, being beneficial to the healing of the graft and the bone, having relatively simple surgical operations, reducing the surgical time and complexity. However, the "bungee effect" and "wiper effect" it produces are relatively obvious, and the probability of postoperative bone tunnel enlargement is relatively high, which to some extent increases the risk of surgical failure [29]. U-shaped nails, washers, and cross pins can also play roles in specific circumstances, but their applicable ranges are relatively narrow, and their clinical applications are not extensive, so they are not introduced here. Indirect fixation devices such as polyester-titanium button plates and staples have the characteristics of relatively simple operations and less damage to tissues. The polyester-titanium button plate is suitable for situations where the requirement for fixation strength is not high and tissue trauma needs to be reduced. Staples are often used in some small ligament reconstruction surgeries or as an auxiliary fixation means. However, the fixation strength of indirect fixation devices may not be as good as that of direct fixation devices, and careful selection should be made according to specific situations.

4.2.1. Drilling of Bone Tunnels

I) Preparation of Femoral Tunnels

Clinically, the commonly-used methods for locating the femoral-end tunnel are as follows:

1) Over-The-Top (OTT) Location Method: It was once widely used and was proposed by Macintosh *et al*. [30] in 1974. Its locating point is at the intersection of the lateral wall of the intercondylar fossa of the femur and the posterior part of the top of the intercondylar fossa. Its advantage lies in the use of bony landmarks to ensure the accuracy of location, which helps to restore the normal function of the anterior cruciate ligament and joint stability. At the same time, it reduces the surgical difficulty and the use of various equipment, thereby reducing the economic cost. However, its disadvantages are also quite obvious. That is, since the position of the over-located graft is not in the anatomical position, it can lead to an increase in the tension of the graft and ultimately lead to the failure of the graft. In addition, the anatomical differences of the femur in some patients are also important factors affecting the location.

2) Bony Landmark Location Method: This method can be divided into: a. The Resident's Ridge and the Bifurcation Ridge. The former is located at the middle and posterior 1/3 of the line connecting the top of the intercondylar fossa and the posterior lower edge of the lateral wall of the intercondylar fossa, adjacent to the femoral footprint area of the ACL. Because it has a high probability of occurrence in surgical cases, it is relatively easy for inexperienced junior doctors to find and locate, so it is widely used in clinical practice. The bifurcation ridge is the bony eminence between the two-bundle femoral-end insertions of the ACL. It also has the advantage of being easy to find, and the center of the two insertions of the ACL can be used as the locating point for the double-bundle reconstruction of the ACL. Generally speaking, their advantages are similar. Many studies have shown the reliability of using them as locating points [31] [32]. However, the anatomical differences of the femur in some patients often lead to inaccurate location. Some scholars' research on 318 femoral specimens found that about 50% of the

specimens did not have a bifurcation ridge, and there were also certain differences between men and women [33]. b. The Apex of the Deep Cartilage (ADC), that is, the vertex of the posterior cartilage margin of the lateral femoral condyle of the knee joint, is the vertex of the boundary between the bone and cartilage of the lateral femoral condyle of the knee joint. It must exist in the normal anatomical structure. Therefore, some studies believe that compared with the Resident's Ridge and the Bifurcation Ridge, the ADC locating point is more accurate and concise [34].

3) Computer-Navigation-Assisted Location: It utilizes computer technology and a navigation system to accurately locate the position of the bone tunnel during surgery. A three-dimensional model is constructed through preoperative medical image data, and the position information of the probe is fed back in real-time during the operation to help doctors accurately find the anatomical footprint area. Compared with traditional location methods relying on experience and bony landmarks, this technology improves the accuracy and repeatability of location and reduces adverse surgical conditions caused by inaccurate tunnel-angle location. With its advantages such as high precision, being beneficial to teaching, reducing surgical risk, and having great potential for remote surgery, it is gradually valued by scholars. However, it also has its disadvantages, such as increasing the surgical cost, prolonging the surgical time, requiring a certain amount of time and energy to learn, and the possibility of terminating the operation in case of equipment failure [35] [36].

4) 3D-Printing—Assisted Location: Pre-operatively, the patient's knee joint is scanned by CT or MRI to obtain detailed three-dimensional image data. Then, 3D-printing technology is used to produce a physical model that completely matches the patient's knee joint. Doctors can directly understand the anatomical structure of the knee joint through the model, including the morphology of the femur and tibia and the injury situation of the anterior cross-ligament. During the operation, doctors can refer to the model to more accurately determine the tunnel positions of the femur and tibia to ensure that the reconstructed ligament is in the optimal mechanical position. This assisted-location method improves the accuracy of the operation, reduces the operation time and blood loss, and reduces the incidence of postoperative complications. At the same time, it also provides better guarantees for the patient's postoperative rehabilitation. However, the economic cost and the precision error of the machine should also be considered by clinicians [37] [38].

II) Drilling of Tibial Tunnels

Generally speaking, the locating point of the tibial tunnel is located at the center of the tibial-insertion footprint area of the ACL. In recent years, the application of various new-type auxiliary devices has greatly accelerated the development of tibial-tunnel—preparation technology [39]. Individualized design has a huge impact on the success rate of surgery. For example, for patients of different body shapes and ages, the drilling points may be different. For patients with taller stature and larger bone structures, the drilling points may need to be adjusted appropriately to adapt to their larger joint space. For adolescent patients, because their bones are still in the growth and development stage, the selection of the drilling point should be more cautious to avoid affecting the growth plate. When determining the drilling point, the length and angle of the reconstructed ligament also need to be considered. If the drilling point is too close to the joint surface, it may lead to insufficient length of the reconstructed ligament and affect the range of motion of the knee joint. If the drilling point is too far away, the angle of the ligament may be inappropriate, reducing its effect of stabilizing the joint [40]. In addition, with the help of modern technology, the patient's knee joint can be evaluated in detail before and during the operation, providing a more accurate basis for determining the drilling point of the tibial tunnel [35] [41] [42]. During the surgical process, the real-time observation of the arthroscopy is also very important. Doctors can clearly see the internal structure of the joint through the arthroscopy to further accurately adjust the drilling point and ensure the accuracy and safety of the operation.

4.2.2. Single-Bundle vs. Double-Bundle Reconstruction

Single-bundle reconstruction technology involves selecting an appropriate graft and then weaving it into a single bundle to simulate the ACL, mainly restoring the function of the anteromedial bundle of the anterior cruciate ligament. The focus is on restricting the excessive anterior displacement of the tibia. After reconstruction, it can restore the anteroposterior stability of the knee joint to a certain extent. Its advantages include less bone destruction, relatively simple surgery, shorter operation time, more mature technology, and wide clinical application, etc. [43].

Double-bundle reconstruction, on the other hand, weaves the graft into two bundles, creates two tunnels on the femur and tibia respectively, implants the two tendons into the corresponding tunnel positions, and finally performs fixation. This method is closer to the normal anatomical structure and biomechanical characteristics of the anterior cruciate ligament. The anteromedial bundle is taut during flexion and is mainly responsible for the anteroposterior stability of the knee joint. The posterolateral bundle is taut in the extended position and is mainly responsible for the rotational stability of the knee joint. Therefore, double-bundle reconstruction can better restore the rotational stability of the knee joint while restoring the anteroposterior stability of the knee joint. However, it also has disadvantages such as a large amount of bone destruction, high surgical difficulty, long operation time, and a small range of promotion [44] [45].

Regarding the choice of reconstruction method, there is still controversy. A large number of studies have found that there is no significant difference in the self-perception of postoperative patients and objective indicators such as VAS score, IKDC score, and Lyscholm score between single-bundle and double-bundle reconstruction [46]-[49]. Clinically, it is necessary to comprehensively consider the specific situation of the patient, such as age, sports needs, and the degree of knee joint injury, and the doctor should make a comprehensive judgment to select an appropriate reconstruction method.

4.2.3. Reserving vs. Non-Reserving Stumps

In ACL reconstruction surgery, the treatment of the ruptured ACL stumps can be divided into reservation and removal. With in-depth research in recent years, people have gradually realized that there are significant differences between the two.

1) Post-Operative Healing:

Reserving Stumps: In the early stage of reconstruction, stump-preserving reconstruction is beneficial to the revascularization of the graft. A study on ACL stump-preserving reconstruction in New Zealand rabbits found that at 6 weeks after surgery, the percentages of vascular endothelial growth factor-positive cells, hypoxia-inducible factor -1α-positive cells, and microvascular density in the stump-preserving reconstruction group were significantly higher than those in the non-stump—preserving group. This means that reserving stumps can promote blood vessels to grow into the graft more quickly, provide better nutritional supply for the graft, and accelerate the healing process. However, at 12 weeks after surgery, the differences between the two groups in these indicators gradually decreased [50].

Non-reserving Stumps: In the case of non-reserving stumps, the reconstructed anterior cruciate ligament is completely exposed in the joint, which is not conducive to the growth of vascular and nerve fibers into the transplanted tendon. To a certain extent, it will affect the revascularization process and the establishment of blood supply to the reconstructed ligament and may lead to a relatively slow healing speed.

2) Bone Tunnel Changes:

Reserving Stumps: It has a certain inhibitory effect on bone tunnel enlargement in the early postoperative period. At 6 weeks after surgery, the degree of bone tunnel enlargement in the stump-preserving reconstruction group was significantly lower than that in the non-stump—preserving group. This is of positive significance for maintaining the stability of the bone tunnel and ensuring the fixation effect of the graft, reducing problems such as graft loosening that may be caused by bone tunnel enlargement.

Non-reserving Stumps: The bone tunnel enlargement in the non-stump—preserving group is relatively more obvious in the early postoperative period, which may affect the fixation strength of the graft and the stability of the knee joint and requires a longer rehabilitation and recovery period [50].

3) Proprioceptive Recovery:

Reserving Stumps: The research of Sha Lin *et al.* [51] found that there are proprioceptors in the anterior cruciate ligament stump. Reserving stumps is helpful for proprioceptive recovery. Proprioception plays an important role in knee joint motion control and posture adjustment. Reserving stumps can enable patients to adapt to the movement of the knee joint more quickly after surgery and improve the joint's control ability and stability [52] [53].

Non-reserving Stumps: Losing the proprioceptors in the stumps, the proprioceptive recovery is relatively slow, and patients may still feel that the movement coordination and stability of the knee joint are poor for a long time after surgery.

4) Surgical Difficulty:

Reserving Stumps: The surgical operation is relatively complex. It is necessary to implant and fix the graft while reserving the stumps. It requires higher technical skills from the doctor. The stumps need to be carefully handled to avoid excessive traction or damage to the stump tissues to ensure the effect of reserving stumps.

Non-reserving Stumps: The surgical operation is relatively simple. The stumps are directly removed and then the graft is implanted and fixed. The operation time may be relatively short, but this method may ignore the potential positive effects of the stumps.

4.2.4. Isometric vs. Anatomical Reconstruction

1) Isometric Reconstruction: It refers to the reconstruction of the cruciate ligament at a position where the length of the ligament remains constant during knee flexion and extension activities. Its purpose is to ensure that during knee joint movement, the length change of the reconstructed ligament is as small as possible to maintain the stability of the knee joint. As early as 2000, Li Chang *et al*. [54] found in an anatomical study of 30 cadavers that there were "isometric fibers" in the knee joint ACL, and the "isometric points" at the attachment sites were the positioning points for ACL reconstruction. This reconstruction method focuses more on the length stability of the ligament at different knee joint angles and has higher requirements for the fixation position of the graft. It is necessary to find the precise points that can achieve the isometric effect. Precise measurement and positioning are required during surgery to determine the appropriate positions of the femoral and tibial tunnels so that the length of the graft remains relatively stable during knee flexion and extension. This requires a higher level of technical skills and experience from the doctor, who needs to be familiar with the anatomical structure and biomechanical characteristics of the knee joint, and the operation process may be relatively complex [55]. It has certain advantages in maintaining knee joint stability in the early postoperative period. Especially during knee flexion and extension, because the length change of the ligament is small, it can better restrict the excessive anterior displacement and rotation of the tibia, which is beneficial for resuming sports in the near future [56].

2) Anatomical Reconstruction: It refers to the reconstruction at the anatomical position before ligament injury, that is, to restore the original origin and insertion positions, ligament thickness, and running direction and other anatomical structures of the anterior cruciate ligament as much as possible. This method emphasizes the similarity of the reconstructed ligament to the original ligament in terms of anatomical structure to maximize the restoration of the normal biomechanical function of the knee joint. Identifying the insertion points of the ACL on the femur and tibia is a crucial step. The femoral insertion point is generally located on the medial side of the lateral femoral condyle and has a specific footprint area. The boundaries and shapes of this area need to be accurately identified. The tibial insertion point is located on the anteromedial part of the tibial plateau. Under

arthroscopy, some small bony eminences and other landmarks can be seen to assist in positioning. In addition to bony landmarks, attention also needs to be paid to the surrounding soft-tissue landmarks. For example, the meniscus—ligament complex and synovial plica around the ACL can provide references for determining the running direction of the ligament [57] [58]. A follow-up study lasting 10 - 20 years showed that [59] anatomical reconstruction is more in line with the physiological structure of the knee joint. In the long term, it may be more beneficial for restoring the normal movement function and biomechanical characteristics of the knee joint. However, there may be a certain degree of instability in the early postoperative period. After a period of rehabilitation training, the recovery of movement function in the later stage may be more ideal. Compared with isometric reconstruction, patients can better perform higher-intensity sports and more complex knee joint movements [60].

4.2.5. Selection of Surgical Timing

The selection of the timing for ACL reconstruction surgery requires comprehensive consideration of multiple factors. Generally speaking, in the case of a simple anterior cruciate ligament rupture, the surgery can be performed after the acute phase has passed, when the joint has basically subsided in swelling and the range of motion is basically normal. Usually, it is about 2 weeks after the injury. At this time, the swelling has decreased, and the postoperative swelling and pain are relatively mild, which is conducive to early functional exercise and shortening the rehabilitation process [61]. If there is concurrent meniscus injury that can be sutured, the surgery should be performed as soon as possible after the acute phase has passed, preferably within 3 months, in order to seize the opportunity for meniscus repair [62]. In the case of acute ACL rupture combined with collateral ligament injury, it is recommended to postpone the surgical time. After knee joint immobilization for 3 to 6 weeks, functional exercise should be carried out. When the function is good without bearing weight and the swelling has subsided, then the ACL reconstruction surgery can be performed [63]. For special cases such as avulsion fractures of the ACL tibial plateau insertion point, the surgery should be performed as soon as possible. ACL reconstruction in adolescents should also be carried out as early as possible to reduce problems such as joint cartilage degeneration [64]. Doctors should determine the most appropriate surgical timing according to the specific situation of patients to achieve the best treatment effect.

4.2.6. Application of Tourniquet

During ACL reconstruction surgery, the tourniquet is usually placed at the upper 1/3 of the affected thigh. Before placement, the limb is wrapped with a liner or a sterile towel for protection. When using it, the lower limb is first elevated at a 45-degree angle for 1 to 2 minutes. Then, the exsanguination band is wrapped from the distal end to the proximal end, and then air is slowly pumped in. The pressure is determined by the disappearance of the dorsal pedis artery and posterior tibial artery pulsation or 100 mmHg higher than the systolic blood pressure. For the first use of the tourniquet on a single limb, it generally should not exceed 90 minutes. If the operation time is long and exceeds 90 minutes, the tourniquet should be loosened for 10 minutes. After the limb resumes blood supply, it can be inflated again, but the second use should not exceed 60 minutes. During the operation, attention should be paid to observing the patient's condition changes. After the operation, the air is slowly released, and at the same time, the area of the tourniquet is gently massaged to relax the leg and promote blood return.

The mainstream view is that the use of a tourniquet can reduce surgical wound bleeding, provide a clear field of vision, facilitate the doctor's operation, and also reduce the need for intraoperative blood preparation and transfusion. However, a Meta-analysis found that there was no statistically significant difference in the operation time, reduction in hemoglobin, postoperative morphine dosage, knee joint pain VAS score, and quadriceps muscle strength between the groups with and without the use of a tourniquet during ACL reconstruction. The conclusion was that there was no significant difference in postoperative efficacy between the use and non-use of a tourniquet during ACL reconstruction [65]-[67]. There is even a view that the application of a tourniquet will bring certain disadvantages. In terms of nerve damage, the tourniquet will block the limb's blood supply, leading to ischemic nerve damage. For example, the metabolism of the lower-limb nerves such as the sciatic nerve is affected, the endoneurial microvascular perfusion is insufficient, resulting in hypoxia, nerve fiber degeneration, and a slow conduction speed. At the same time, it may also cause mechanical nerve damage. The pressure of the tourniquet will directly compress the nerve. When the position is improper or the pressure is uneven, the nerve may be squeezed between the tourniquet and the bone, and its edge may also cause local contusion or indentation on the nerve, affecting nerve function [68] [69]. In terms of muscle damage, the long-term compression of the tourniquet will directly lead to muscle pain [70]. At the cellular and molecular level, it will cause muscle ischemia-reperfusion injury. During ischemia, anaerobic metabolism increases, leading to lactic acid accumulation. Reperfusion produces a large number of oxygen-free radicals that attack muscle cells, resulting in muscle pain, swelling, and dysfunction. It may also trigger muscle contracture, reducing the elasticity and extensibility of muscle fibers and affecting postoperative rehabilitation [71]. In terms of vascular damage, the pressure of the tourniquet can lead to intimal vascular damage, exposing the subendothelial collagen fibers, triggering platelet adhesion and aggregation to form a thrombus, and also causing an inflammatory reaction of the vascular wall, destroying the normal structure of the blood vessels [72]. At the same time, it also increases the risk of venous thrombosis. Because the tourniquet causes venous blood stasis, the blood stays in the vein for too long and is prone to form a thrombus. After the tourniquet is released, the hypercoagulable blood may enter the circulatory system, increasing the risk of serious complications such as pulmonary embolism [73].

5. Challenges Faced by Arthroscopic ACL Reconstruction

5.1. Technical Operation Difficulties

5.1.1. Accuracy of Bone Tunnel Location

The accuracy of bone tunnel location is of utmost importance in arthroscopic ACL reconstruction. If the location is inaccurate, it may lead to abnormal stress distribution of the graft, affecting the stability of the knee joint and functional recovery. For example, if the bone tunnel position is too anterior or posterior, the graft may be subjected to excessive tension or pressure during knee joint movement, increasing the risk of re-injury to the graft. In addition, inaccurate bone tunnel location may also lead to abnormal postoperative knee joint movement trajectories, causing pain and discomfort. To improve the accuracy of bone tunnel location, new technologies such as electromagnetic navigation systems and 3D-printed guides are gradually being applied, but there are still certain errors and technical limitations.

5.1.2. Stability of Graft Fixation

The stability of graft fixation is one of the keys to the success of the operation. Unstable fixation may lead to loosening or displacement of the graft in the early postoperative period, affecting the healing process. This will not only prolong the rehabilitation time but may also lead to surgical failure. There are many factors that affect the stability of graft fixation, such as the choice of fixation method, the quality and performance of the fixation device, and the shape and size of the bone tunnel. At present, although there are a variety of fixation methods available, each method has its limitations and requires comprehensive consideration and precise operation according to the specific situation of the patient.

5.2. Post-Operative Complications

5.2.1. Infection and Inflammation

Infection and inflammation are among the common post-operative complications. The occurrence mechanism is usually related to factors such as bacterial contamination during the surgical process, the patient's own immune status, and improper post-operative care. The surgical incision, bone tunnel, and the area around the graft can all become sites for bacterial growth, leading to local or systemic infections. The inflammatory response may be the body's immune response to surgical trauma and infection. To prevent infection and inflammation, strict skin disinfection and patient preparation are required before surgery. During surgery, the principle of aseptic operation should be followed. After surgery, antibiotics should be used rationally, and incision care and observation should be strengthened.

5.2.2. Graft Rejection and Failure

Graft rejection and failure are relatively serious post-operative complications. Graft rejection may be caused by the patient's own immune response, especially when using allogeneic grafts. Immune cells recognize allogeneic tissues as foreign bodies and launch an attack, resulting in damage to the structure and function of the graft. The reasons for failure are more complex and may be related to the quality of the graft, fixation method, improper post-operative rehabilitation, and individual differences of patients. Dealing with graft rejection and failure requires comprehensive consideration. For rejection reactions, immunosuppressants may be needed for regulation. For failed grafts, secondary surgical repair or replacement may be required.

6. Conclusions and Prospects

6.1. Summary of Research Conclusions

This paper comprehensively and in-depth explored the arthroscopic ACL reconstruction technology, covering the anatomy and physiological functions of ACL, the development history of the technology, the current application status, effects, challenges faced, and future development trends. Research shows that this technology has made remarkable progress in the treatment of ACL injuries and can effectively restore the stability of the knee joint and the patient's function. However, there are still some difficulties in technical operations and postoperative complications.

6.2. Prospects for Future Research Directions

Future research can focus on the following directions. Firstly, in terms of grafts, further exploration of new biomaterials and tissue-engineering technologies is needed to optimize the performance and durability of grafts. At the same time, in-depth research on the interaction mechanism between grafts and recipient tissues to improve the fusion effect of grafts. Secondly, for surgical techniques, methods of bone-tunnel-positioning and graft-fixation should be continuously improved to enhance the accuracy and stability of operations. In addition, with the help of emerging intelligent technologies, such as robot-assisted surgery, to improve the quality and effectiveness of surgery. Thirdly, the research on postoperative rehabilitation programs should be strengthened, and personalized and scientific rehabilitation plans should be formulated to promote patients' faster and better recovery. Finally, multi-center, large-sample long-term follow-up studies should be carried out to deeply understand the long-term efficacy and potential risks of this technology and provide more reliable basis for clinical decision-making. In conclusion, the arthroscopic anterior cruciate ligament reconstruction technology still has broad research space, and future research will continuously promote the improvement and development of this technology, bringing better treatment effects for patients.

Funding

National Natural Science Foundation of China (82260887); Innovation Project of Guangxi Graduate Education (YCSW2024536).

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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