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Contents

Thrice Monthly Volume 11 Number 35 December 16, 2023

EDITORIAL

MINIREVIEWS

ORIGINAL ARTICLE

Retrospective Study

World Journal of Clinical Cases

Thrice Monthly Volume 11 Number 35 December 16, 2023

Contents

LETTER TO THE EDITOR

World Journal of Clinical Cases

Thrice Monthly Volume 11 Number 35 December 16, 2023

Contents

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MINIREVIEWS

Research progress on preparation of lateral femoral tunnel and graft fixation in anterior cruciate ligament reconstruction

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Abstract

Anterior cruciate ligament (ACL) injury is one of the most common types of sports injuries. People's need to participate in sports and desire for a high quality of life promotes the continuous development of ACL reconstruction technology. Arthroscopic ACL reconstruction has been recognized as an effective method for the treatment of ACL injuries. This review analyses and summarizes the advantages and limitations of each surgical procedure for arthroscopic ACL reconstruction reported in the relevant literature so as to promote the future development of more relevant techniques.

Key Words: Arthroscopy; Anterior cruciate ligament; Anterior cruciate ligament reconstruction; Femoral tunnel; Anatomical reconstruction

Core Tip: In the past 50 years, with the improvement of the understanding of knee anatomy and its injury mechanism, anterior cruciate ligament reconstruction surgery has developed rapidly. The fixation methods are reviewed in order to provide reference for the treatment of preclinical cruciate ligament injuries.

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INTRODUCTION

The anterior cruciate ligament (ACL) is one of the main anatomical structures of the knee joint and is commonly subjected to sports injury. More than 120000 ACL reconstructions are performed annually in the United States, and the relative risk of ACL rupture in female athletes is 2-9 times higher than that in male athletes[1]. In the past 50 years, improved understanding of the knee anatomy and its proneness to specific types of injury has led to the rapid development of ACL reconstruction surgery. The fixation methods are reviewed to provide a reference for the treatment of preclinical cruciate ligament injuries.

ACL ANATOMY

The tibial insertion of the ACL originates from the outer surface of the medial intercondylar ridge, assuming a fan-shaped configuration. On the other hand, the femoral insertion is attached to the intercondylar notch located behind the inner surface of the lateral femoral condyle and exhibits an oval shape with an extended fiber bundle[2]. It is widely accepted that the ACL consists of two fundamental functional bundles, namely, the anteromedial (AM) bundle and posterolateral (PL) bundle, which play a crucial role in maintaining both anteroposterior and rotational stability of the knee joint[3]. Giuliani *et al*[4] conducted anatomical studies on cadavers and discovered that ACL width ranged from 7-17 mm with an average measurement of 11 mm. Additionally, he found that AM bundle had an average length of 33 mm while PL bundle averaged at 18 mm[5,6]. The blood supply of the ACL is derived from the middle genicular artery, as well as the medial and lateral arteries below the knee. Mechanoreceptors, including Ruffini bodies, ring bodies, Golgi bodies, and free nerve endings, are also present in the ACL. These sensory endings indicate a proprioceptive function within the ACL that plays a crucial role in maintaining knee joint stability[7]. ACL injury is one of the most common sports injuries, with non-contact injuries accounting for 70% of cases. It occurs more frequently during activities involving sudden changes in direction such as deceleration, jumping or knee bending. This instability leads to secondary complications like meniscus and cartilage wear, increased joint effusion and reduced exercise capacity[8]. Furthermore, when combined with other structural injuries such as meniscal tears or collateral ligament damage (medial or lateral), it further exacerbates knee joint instability and increases the risk of secondary injuries[9].

TIMING OF ACL RECONSTRUCTION SURGERY

Reijman *et al*[10] compared patients who underwent early ACL reconstruction *vs* those who had elective reconstruction after rehabilitation over a 2-year follow-up period. The results demonstrated significant improvements in symptom perception, knee joint function and exercise capacity among patients who underwent early reconstruction compared to those in the latter group. Herbst's prospective comparative study revealed that patients who received early ACL reconstruction surgery had significantly lower rates of extension limitation between 3°-5° at 12 mo post-surgery. Therefore it is recommended for individuals with high activity demands or athletes to undergo ACL reconstruction within 48 h to prevent articular cartilage damage[11]. In cases where there is acute hematoma or limited knee motion due to early immobilization, it is advisable to perform elective ACL reconstruction once hematoma resolution and adhesion subsidence have occurred.

SURGICAL TECHNIQUE (PREPARATION TECHNIQUE OF ACLR LATERAL FEMORAL TUNNEL)

Transtibial technique

The transtibial drilling technique involves establishing a femoral tunnel through the tibial tunnel, initially utilized for isometric reconstruction of the ACL under arthroscopy with the knee joint flexed at 90° during surgery. This approach simplifies femoral tunnel placement, reduces operation time, and ensures graft isometry. However, the success of the femoral approach heavily relies on the direction of the tibial tunnel, primarily determined by the origin of the external tibial ostium. Kopf *et al*[12] employed a 3D computed tomography model to visualize and quantify femoral and tibial tunnel positions in patients after ACL reconstruction using 32 transtibial techniques (TTs). When compared to anatomical reference data for tunnel positioning, results indicated that while the tibial tunnel was located medially in an anatomically PL position, both AM and PL tunnels had their respective femoral tunnels positioned anteriorly from their anatomical locations. Conventional tibial tunnels typically reach a maximum height of only 4 mm above the center of femoral insertion, resulting in a mere 50% to 60% overlap with respect to femoral footprint[13]. As this non-anatomically positioned femoral tunnel passes through the tibia, its internal opening becomes excessively high and deep while also causing an overly vertical graft angle ultimately leading to inadequate recovery of rotational stability within the knee joint[14]. Long-term studies have additionally revealed that non-anatomic reconstructions can contribute to earlier postoperative cartilage degeneration in knees[15]. Furthermore, when flexed, instead of rotating around a fixed center point within itself as intended; it has been observed that movement occurs between the tibia plateau and femur during knee joint motion resulting in relatively equal graft length achievement only. Modified TT techniques have demonstrated comparable effectiveness to other approaches for ACL reconstruction. Bhatia *et al*[16] positioned the modified tibial tunnel at the proximal entry point with a minimum tunnel size of 9 mm to ensure achieving anatomical positioning of the

femur using a 7 mm femoral offset guide. The guide pin was placed at the natural insertion point on the condyle wall, while alternative placements included distal and anterior or posterior positions relative to the natural insertion on the condylar wall. Sim *et al*[17] employed a robotic testing system for ACL reconstruction, demonstrating that both the modified TT technique, AM technique, and outside-in (OI) technique were viable in restoring normal knee motion biomechanics.

AM approach

The AM technique is an arthroscopic AM approach that focuses on anatomical reconstruction, aiming to restore the normal function of the knee joint to its maximum extent and prevent excessive tension of the graft by reconstructing the anatomical insertion point of the ACL femur at a flexion angle of 120°[18,19]. Unlike the TT method, which has limitations based on the position of the tibial tunnel, AM allows for independent preparation of the femoral tunnel, providing more flexibility and easier positioning within the anatomical footprint area. A meta-analysis revealed that compared to AM, TT resulted in a significantly more vertical femoral tunnel orientation and obvious anterior displacement of tibia relative to femur, leading to poor postoperative joint stability[20]. In contrast, AM offers a deeper and lower placement with more precise positioning. This enables faster recovery and improved rotational stability in reconstructed knees[21-23]. Studies demonstrated that as inclination increases in AM-prepared femoral tunnels, their length decreases[24,25], which was also supported by experimental results from Osti *et al*[22]. Consequently, there was a higher proportion of femoral tunnels shorter than 25 mm in length within the AM group. While this may affect graft healing and increase risk for bursting through posterior femoral cortex, it also reduces postoperative "wiper effect" caused by traction loop swinging[26]. However, no statistically significant difference was observed in Koos scores between TT and AM groups; all patients reported successful return to sports activities and work following both procedures[27].

OI

The OI technique is based on anatomical reconstruction, employing an ACL locator inserted into the AM femoral entrance to precisely locate the internal opening of the femoral tunnel. Simultaneously, an arthroscope is introduced through the anterolateral entrance to adjust the position of the femoral tunnel. This unique drilling technique offers considerable variability without necessitating knee joint flexion for intra-articular tissue protection. In cases where patients have a narrow intercondylar notch space, combined operations such as disability protection can be considered, reducing reliance on femoral drilling. Moreover, compared to the AM method[22,28], cortical fracture risk is less restrictive in this approach. Osti *et al*[22] confirmed that both AM and OI surgical techniques surpass TT technique in terms of ACL femoral tunnel positioning and reproduction of anatomical insertion while exhibiting comparable prognostic outcomes.

Over-the-top technology

The study reported an over-the-top (OTT) technique in which the graft was secured above the lateral femoral condyle [29]. Girgis *et al*[30] proposed that the overtop area is an arc-shaped region located at the junction of the posterior aspect of the femoral shaft and the most proximal part of the lateral femoral condyle, with its innermost side representing the location of OTT. During knee motion, soft tissue loading rather than bone tunnel loading occurs on the graft, significantly reducing wear at the opening of the femoral tunnel[31]. Two studies have continuously refined OTT by creating a groove on the lateral femoral condyle to enhance graft fixation and maintain optimal balance between graft isometricity and anatomical alignment[32,33]. Due to its avoidance of femoral tunnel preparation and protection of femoral epiphysis, OTT is applicable for revision patients with excessive or improperly positioned tunnels as well as adolescent patients with growth potential. Furthermore, combining OTT with retaining graft stump technique can better preserve ACL proprioceptors and integrity[34,35]. The advantages and disadvantages of the above techniques are summarized in Table 1. The OTT technology diagram is shown in Figure 1.

Oval tunnel

Śmigielski *et al*[36] proposed the ribbon-like theory in the article, the anatomical structure of the ACL is a flat, ribbon-like structure with a bundle, and the reason why the ACL is double-bundled is that it is twisted. A number of anatomical studies on the ACL have shown that the femoral attachment point is oval or semicircular and the tibial attachment point is oval or "C"-shaped. Therefore, Noh *et al*[37] suggested creating an oval bone tunnel to better reproduce the anatomical attachment point[2]. Some studies have shown that compared to the circular tunnel group, the Tegner score, pivot shift test and early graft maturity were better in the oval tunnel group than in the circular group[38,39]. The oval tunnel, which resembles the natural ACL footprint, is closer to the shape of the physiologic attachment point, wear of the graft and bone tunnel increases the contact area, prolongs graft life, increases nutrient exchange between the synovial fluid, and promotes healing of the tendon on the bone[40]. The oval tunnel not only maintains the tensile strength of double-bundle reconstruction, but also has the advantage of reducing bone loss in single-bundle reconstruction, which is a promising reconstruction technique.

ACL RECONSTRUCTION

Double-bundle reconstruction

In 1836, the Weber[41] described the division of the ACL into two functional bundles, and a cadaver study[42] found that

Table 1 Advantages and disadvantages of anterior cruciate ligament reconstruction techniques

Technique	Advantages	Disadvantages
Transtibial	Less surgical trauma; few complications[17]	Poor rotational stability of the knee joint; cartilage degeneration occurred earlier after surgery[14]
Anteromedial	The femoral tunnel was accurately positioned; better rotational stability[18,19]	The femoral tunnel is short; breaking the femoral cortex; a risk of injury to the common peroneal nerve[24,25]
Outside-in	Larger tendon-bone interface contact area[22]	Add auxiliary incision
Over-the-top	Reduce femoral inlet graft wear	Need to practice the technique[32,33]

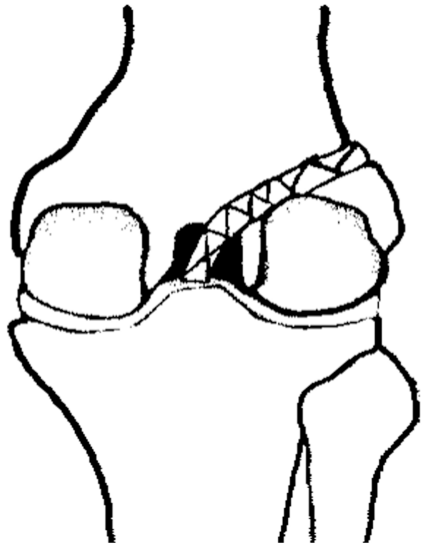

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Figure 1 Schematic diagram of over-the-top technology.

the in situ force of the AM was significantly higher than that of the PL at full extension of the knee, whereas the in situ forces are highest in the PL bundle and decrease with increasing flexion. The single-bundle ACL reconstruction technique mainly restores the function of the AM bundle, which limits but does not maintain well the anterior translation of the tibia during knee flexion. Rotational stability of the knee joint[43]. Kyung *et al*[44] believe that reconstruction with one bundle can restore the footprint of the original ACL more accurately, but it cannot restore the inclination angle of the original ACL in the coronal plane, while reconstruction with two bundles can restore the normal inclination of the two ACL bundles. The normal kinematics of the original ACL is better restored. The literature reports that, compared to reconstruction with one bundle, the incidence of graft fractures and osteoarthritis is significantly lower after reconstruction with two bundles, the anatomical structure of the ligaments can be better restored, the contact surface of the bone tract is large and the initial strength is high. A biomechanical *in-vitro* study has shown that stabilization of the knee with two bundles is superior to reconstruction with one bundle[45-47]. However, the technical requirements are higher than for reconstruction with one bundle and the operation time is longer, which increases the risk of the operation. Compared to reconstruction with one bundle, reconstruction with two bundles requires a larger space for the patient's intercondylar notch. If the intercondylar notch is less than 12 mm wide, the graft is very likely to impinge, and the preparation of four bone tunnels results in a large loss of bone mass, and the indications are limited. Studies have shown no difference in clinical scores, knee stability, and magnetic resonance imaging (MRI) appearance between patients who underwent single-bundle reconstruction and those who underwent double-bundle reconstruction, but patients who underwent double-bundle reconstruction had a longer recovery time. Two studies found that anterior tibial displacement was closer to the intact knee joint in double-bundle reconstruction compared with single-bundle reconstruction, and the incidence of cartilage degeneration and meniscal injury to the knee was lower[48,49]. However, they pointed out that anatomical double-bundle reconstruction is not significantly better than single-bundle reconstruction when using individualized ACL reconstruction techniques.

Single bundle reconstruction

With the confirmation of the ligament theory and the many problems that the reconstruction of double bundles has revealed, the reconstruction of single bundles has come into people's focus. The most important aspect of single-bundle reconstruction is the selection of the femoral insertion point. Pearle *et al*[50] proposed the IDEAL theory to place the tunnel in the femoral footprint area, *i.e.*, isometric, direct insertion, eccentrically located, anatomic, and low tension. The

main surgical options for single-bundle reconstruction are the traditional anatomic single-bundle reconstruction and the total internal technique. The conventional total tibial tunnel technique uses a hanging cortical fixation on the femoral side and interfering screws on the tibial side. In all-inside reconstruction (all-inside), the cortical bone is suspended, retrogradely drilled and a bone socket is prepared instead of a tunnel to reserve bone for later revision surgery. Some studies suggest that the all-inside technique may also reduce tunnel expansion by preventing the flow of synovial fluid into the socket. In addition, the all-inside technique reduces damage to the cortex and periosteum and reduces postoperative pain[51].

Three-beam reconstruction

In 1979, Norwood and Cross[52] described that the ACL is divided into three bundles - AM, intermediate and PL. Otsubo *et al*[53] identified the attachment areas of the three ACL bundles, while Fujie *et al*[54] and Kato *et al*[55] explained the biomechanical function of each bundle in detail. Dissecting three-bundle ACL reconstruction with two double-ring grafts performed with two femoral tunnels and one tibial tunnel to simulate three bundles within the native ACL[56-58], ATB viewed through secondary arthroscopy. The grafts show a fan-shaped tibial insertion, that better mimics the original triangular tibial footprint[56]. Compared with double-bundle or single-bundle ACL reconstruction, ATB ACL reconstruction requires only lower initial graft tension to maintain anterolateral stability[59]. Uchida *et al*[58] indicated that after reconstruction of the triple-bundled ACL with a hamstring autograft, the patient achieved satisfactory results in terms of objective stability of the knee joint after surgery. This technique still has many limitations. First, there are currently no studies showing that the triple-bundle reconstruction technique can reduce the graft failure rate. Secondly, the area of the femoral tunnel hole in triple-bundle ACL reconstruction is more than twice that of the single-bundle technique, while the area of the tibial tunnel hole is three times that of the single-bundle technique. Excessive bone loss leads to an increased risk of secondary revision[60]. In addition, three-bundle reconstruction surgery is more complicated, and the long operation time increases the risk of intraoperative and postoperative complications, and the cost of surgical treatment is higher.

FEMORAL GRAFT FIXATION

Aperture fixation

Depending on their material, interface screws can be divided into metal screws and screws made of bioresorbable material[61]. Metal screws can provide greater strength to the graft in the initial phase, but there is graft incision and postoperative pain, and the metal material interferes with postoperative MRI and other imaging studies, which hinders the assessment of postoperative graft healing[62]. Screws made of bioabsorbable material have better tissue compatibility and can be degraded and resorbed. They are excellent at controlling tendon gliding and the degree of incision of the grafted tendons is easier than with metal screws. The disadvantages are high cost, incomplete control of the degradation rate of the screw, some immune reactions and greater expansion of the bone tunnel. In addition, clinical complications such as local osteolysis and cysts may occur[63-66]. A meta-analysis concluded that resorbable screws have the same clinical effect compared to metal screws and that they do not need to be removed by a second surgical procedure, which is convenient for assessing the effect of postoperative graft healing, but the incidence of knee joint effusions is higher[67].

Cortical suspension fixation

Cortical suspension fixation utilizes an Endo-button with loops, which is designed in the form of a button plate. Currently, in clinical practice, two types of loops are commonly utilized: Fixed-length loops and adjustable-length loops. The aforementioned products exhibit user-friendly characteristics and possess a notable level of initial fixation strength. The fixation point is located at a considerable distance from the anatomical insertion point, resulting in a gap between the graft and the fixation device. This gap leads to relative movement, thereby increasing the likelihood of postoperative complications such as the bungee effect and wiper effect. Additionally, the graft is unable to completely conform to the bone tunnel, significantly impacting the healing process of both the tendon and bone. Speed can also result in the enlargement of the bone tunnel, thereby increasing the likelihood of revision[68,69]. Although the utilization of adjustable-length loops has been proposed as a potential solution to decrease the gap and minimize complications, Bressy *et al*[70] discovered that the tibial graft's stability is not optimal when relying solely on the button plate with adjustable-length loops for fixation.

Transverse nail fixation

Currently, the Rigidfix fixation system is the most commonly employed transverse nail in clinical practice. The utilization of transverse nail fixation offers several advantages. Firstly, it enhances the stability of the graft within the bone tunnel. Additionally, it increases the contact area between the tendon and bone, thereby promoting the healing process of the graft. The utilization of degradable absorbing material simplifies and expedites the operation process. Additionally, it allows for the distribution of resistance at the interface between the fixation material and the bone, thereby reducing the likelihood of posterior femoral cortical fracture. The drawback of this approach is the potential for breakage of absorbable transversal nails, which can result in the dissociation of fragments within the joint cavity. This can cause damage to the articular surface cartilage and meniscus, ultimately necessitating secondary surgery[9,71]. The advantages and disadvantages of several fixed methods are summarized in Table 2.

Table 2 Advantages and disadvantages of femoral graft fixation

Technique	Advantages	Disadvantages
Aperture fixation	High fixation strength[67]	Meta obstructing postoperative evaluation; the degradation rate of absorbable materials is not completely controllable[63-66]
Cortical suspension fixation	Adjustable length is easy to use	The probability of complications such as bungee jumping effect and wiper effect increased; bone tunnel enlargement[68,69]
Transverse nail fixation	More tendon-bone contact area; uniform resistance distribution[9,71]	Risk of nail breakage

Other fixation methods (OTT)

The femoral end fixation of the ACL in OTT reconstruction is unique. One suture rivet is positioned at the interface between the lateral epicondyle of the femur and the posterior femoral cortex. Two non-absorbable sutures are affixed to the distal end of the rivet. Two strands were inserted into the coil created by the traction wire at the femoral end of the grafted tendon and secured with a single knot. The two strands of suture were passed through the grafted tendon, folded, and subsequently tied individually to achieve the fixation of the femoral end. No matter the type of fixation device employed, it is imperative to select a fixation method that can offer adequate strength based on the patient's specific circumstances in order to minimize the rate of ACL revision.

CONCLUSION

Arthroscopic ACL reconstruction has become the primary surgery for ACL reconstruction. A large amount of clinical experience and data have been accumulated. Surgical concepts are constantly being updated. However, methods to better reconstruct the isometric, anatomical and proprioceptive properties of the graft and restore the function of the knee joint have yet to be discovered. In addition to the abovementioned introductions to surgical methods and graft selection, there are also a large number of biological experiments on the promotion of the ACL tendon-bone healing process, explaining ACL reconstruction at the molecular level. With the development of sports medicine and an in-depth understanding of the ACL reconstruction process, microscopic joint ACL reconstruction will develop more rapidly, and patients will have a better prognosis.

FOOTNOTES

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