RESEARCH PAPER

ANTERIOR CRUCIATE LIGAMENT (ACL) INJURIES: CURRENT CONCEPTS IN SURGICAL RECONSTRUCTION

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ABSTRACT

Anterior cruciate ligament (ACL) injuries represent one of the most frequently encountered knee injuries in athletes and physically active populations, particularly among young individuals participating in pivoting and high-demand sports. Over the past several years, substantial developments in reconstruction procedures, graft selection, fixation technology, and postoperative rehabilitation have contributed to improved knee stability, enhanced functional recovery, and higher rates of return to sporting activities. This narrative review highlights contemporary perspectives in ACL reconstruction, with special focus on graft options, operative techniques, and rehabilitation approaches.

Various grafts are currently utilized in ACL reconstruction, including bone–patellar tendon–bone (BPTB) autografts, hamstring tendon autografts, quadriceps tendon autografts, and allografts. Each graft type demonstrates unique benefits and disadvantages related to biomechanical strength, donor-site complications, graft incorporation, postoperative pain, and recovery timeline. Modern surgical management increasingly emphasizes anatomic restoration of the native ACL footprint through single-bundle or double-bundle reconstruction techniques, precise tunnel positioning, and selective preservation of residual ligament tissue to improve rotational stability and knee biomechanics. Emerging concepts such as internal brace augmentation, lateral extra-articular procedures, and biologic augmentation techniques have also shown promising clinical potential.

Rehabilitation following ACL reconstruction has progressively shifted from conservative immobilization-based programs toward accelerated, milestone-driven protocols. Current rehabilitation strategies prioritize early range-of-motion exercises, progressive muscle strengthening, neuromuscular re-education, proprioceptive training, and sport-specific conditioning. Increasing attention is also being directed toward psychological preparedness and objective functional assessment before return to sports participation.

Although clinical outcomes after ACL reconstruction have improved considerably, persistent concerns such as graft rupture, secondary injury, persistent instability, and development of post-traumatic osteoarthritis continue to influence long-term prognosis. Present evidence favors a patient-specific treatment approach that considers factors such as age, activity profile, associated meniscal or chondral injuries, and occupational or athletic requirements. Future research is expected to focus on biologic graft optimization, individualized rehabilitation models, enhanced surgical precision, and preventive strategies aimed at improving long-term joint preservation and functional outcomes after ACL reconstruction.

Keywords: Anterior cruciate ligament, ACL reconstruction, graft choices, hamstring graft, patellar tendon graft, rehabilitation, arthroscopic surgery, sports injuries.

How to cite this article: Singla J, Kansal A, Jain H, Kumar M. Anterior Cruciate Ligament (ACL) Injuries: Current Concepts in Surgical Reconstruction. Int J Drug Deliv Technol. 2026;16(54s): 188-207. DOI: 10.25258/ijddt.16.54s.15
Source of support: Nil.
Conflict of interest: None.

INTRODUCTION

Anterior cruciate ligament (ACL) injury is one of the most frequently encountered and clinically important ligament injuries involving the knee joint, especially among young athletes and physically active individuals participating in high-intensity sports such as football, basketball, skiing, volleyball, and handball. Over recent decades, the number of ACL injuries has risen considerably, largely because of increased participation in competitive sports, greater physical activity among younger populations, and enhanced diagnostic capabilities. The ACL functions as a major stabilizing structure of the knee by restricting anterior translation of the tibia relative to the femur while also maintaining rotational stability during complex movements. Injury to this ligament often leads to pain, joint swelling, instability, reduced athletic ability, and long-term impairment in knee function. Untreated ACL deficiency may further result in recurrent instability, meniscal tears, progressive cartilage damage, and early degenerative osteoarthritis of the knee joint [1,2].

Most ACL injuries occur through non-contact mechanisms and are commonly associated with sudden deceleration, rapid changes in direction, pivoting, twisting, or improper landing from a jump. Biomechanical investigations have shown that excessive valgus loading, rotational stress, poor neuromuscular control, and muscular imbalance contribute significantly to the pathogenesis of these injuries. Female athletes are considered particularly vulnerable to ACL rupture because of a combination of anatomical, hormonal, and neuromuscular influences [3]. Diagnosis is usually based on clinical history, physical examination findings, and radiological assessment. Among imaging modalities, magnetic resonance imaging (MRI) is regarded as the gold standard for evaluating ACL integrity as well as identifying associated meniscal, chondral, and other intra-articular injuries [4].

The management of ACL injuries has undergone major transformation over the years. While non-operative treatment consisting of physiotherapy, muscle strengthening, and activity modification may be appropriate for sedentary individuals or patients with low functional demands, surgical reconstruction remains the preferred option for active patients seeking return to sports or physically demanding activities. The major objectives of ACL reconstruction are restoration of joint stability, prevention of secondary intra-articular damage, and recovery of optimal knee function[5]. Advancements in arthroscopic techniques and improved understanding of native ACL anatomy have shifted surgical approaches from simple stabilization procedures toward more anatomic reconstruction methods aimed at reproducing the original insertion sites and biomechanical characteristics of the ligament[6].

Several graft options are currently available for ACL reconstruction, including bone–patellar tendon–bone (BPTB) autografts, hamstring tendon autografts, quadriceps tendon autografts, and allografts. Each graft possesses distinct advantages and disadvantages concerning graft strength, donor-site morbidity, fixation stability, incorporation time, and rehabilitation profile[7]. In addition, innovations in fixation systems, tunnel positioning methods, computer-

assisted surgical navigation, and biologic augmentation techniques have further enhanced surgical precision and postoperative outcomes. Despite these developments, ongoing debates continue regarding the ideal graft choice, single-bundle versus double-bundle reconstruction techniques, optimal timing of surgery, graft healing, and strategies for minimizing graft failure[8].

Postoperative rehabilitation is equally essential for achieving successful functional recovery after ACL reconstruction. Modern rehabilitation protocols focus on early restoration of range of motion, progressive muscle strengthening, neuromuscular re-education, proprioceptive training, and structured criteria-based return-to-sport programs. However, reinjury and graft rupture remain significant concerns, particularly in young athletes who resume high-risk sporting activities prematurely[9]. Current research is increasingly directed toward individualized rehabilitation approaches, biologic graft enhancement, internal bracing systems, and tissue-preserving surgical techniques with the goal of improving long-term functional outcomes and reducing postoperative complications[10].

Methodology

This narrative review was conducted through comprehensive literature searches using electronic databases including PubMed, Scopus, Web of Science, and Google Scholar. Relevant articles published between 2010 and 2026 were reviewed. Priority was given to randomized controlled trials, systematic reviews, meta-analyses, consensus guidelines, and landmark studies focusing on ACL reconstruction.

Search keywords included “ACL injury,” “ACL reconstruction,” “graft choices,” “hamstring autograft,” “bone patellar tendon bone graft,” “quadriceps tendon graft,” “double-bundle reconstruction,” “rehabilitation protocols,” and “return to sports.” Articles addressing surgical outcomes, biomechanical studies, graft healing, rehabilitation strategies, and recent technological advances were included. Non-English articles and studies with inadequate methodological quality were excluded.

Anatomy and Biomechanics of the ACL

The anterior cruciate ligament (ACL) is one of the primary stabilizing ligaments of the knee joint and plays a crucial role in preserving both static and dynamic stability of the knee. Anatomically, the ACL arises from the posteromedial surface of the lateral femoral condyle within the intercondylar notch and extends downward, forward, and medially to attach to the anterior intercondylar region of the tibial plateau. The ligament is functionally divided into two distinct bundles: the anteromedial (AM) bundle and the posterolateral (PL) bundle. These bundles function synergistically throughout knee movement, with the AM bundle remaining relatively tight during flexion and the PL bundle becoming more taut during extension, thereby providing continuous stabilization across varying degrees of motion.[11]

From a biomechanical perspective, the ACL primarily prevents excessive anterior displacement of the tibia in relation to the femur and also contributes to controlling rotational and valgus stresses at the knee joint. In addition to its mechanical role, the ligament contains mechanoreceptors that contribute to proprioception and neuromuscular coordination, helping maintain dynamic joint stability during movement.[12] Activities involving sudden stopping, pivoting, cutting maneuvers, or landing from jumps generate considerable rotational and shear forces across the knee, placing the ACL at significant risk of injury, particularly among athletes. The majority of ACL injuries occur through non-contact mechanisms that involve rapid

directional changes combined with valgus stress and internal rotation of the tibia.[13]

Loss of ACL integrity results in altered knee biomechanics and instability, often experienced clinically as recurrent episodes of the knee "giving way" during physical activity. Continued instability can produce abnormal stress distribution across the tibiofemoral compartment, predisposing the patient to secondary meniscal injury and progressive cartilage deterioration.[14] Long-standing ACL deficiency has also been linked to the early development of osteoarthritis due to repetitive microtrauma, chronic instability, and disturbed joint mechanics. Contemporary biomechanical evidence suggests that accurate restoration of native ACL anatomy during reconstruction is critical for achieving optimal rotational control, knee stability, and near-normal joint function following surgery.[15]

Epidemiology and Mechanism of Injury

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Clinical Evaluation and Diagnosis

Clinical diagnosis of anterior cruciate ligament (ACL) injury is based on a careful combination of patient history, physical examination findings, and radiological assessment. Patients typically report acute knee pain following a twisting or pivoting injury, often associated with a sudden "pop" sensation heard or felt at the moment of trauma. Rapid onset swelling commonly develops within a few hours due to hemarthrosis resulting from intra-

articular bleeding after ligament rupture.[20] Many patients subsequently experience sensations of instability or repeated episodes of the knee "giving way," especially during activities involving turning, pivoting, or stair descent. In the acute stage, difficulty in weight-bearing, reduced range of motion, and quadriceps muscle inhibition are also frequently observed.

Comprehensive physical examination remains essential for establishing the diagnosis. Among clinical tests, the Lachman test is considered the most sensitive and reliable maneuver for evaluating ACL integrity. This test assesses anterior translation of the tibia relative to the femur with the knee positioned at approximately 20–30 degrees of flexion. The anterior drawer test is also commonly performed, although its diagnostic sensitivity may decrease in acute injuries because of pain and hamstring muscle spasm. The pivot shift test is highly specific for ACL insufficiency and is particularly useful for assessing rotational instability of the knee.[21] Increased anterior tibial displacement or a clearly positive pivot shift test strongly indicates ACL rupture. Clinical evaluation should additionally include assessment for associated injuries such as meniscal tears, collateral ligament damage, osteochondral lesions, and possible neurovascular compromise.

Magnetic resonance imaging (MRI) is widely accepted as the gold standard imaging modality for confirming ACL injury and identifying associated intra-articular abnormalities. MRI allows excellent visualization of ligament disruption, edema, bone contusions, meniscal injuries, cartilage defects, and other soft tissue abnormalities, thereby playing an important role in both diagnosis and preoperative planning.[22] Timely and accurate diagnosis is critical to reduce the risk of recurrent instability, secondary meniscal injury, progressive cartilage degeneration, and long-term functional impairment of the knee joint.

Indications for ACL Reconstruction

Anterior cruciate ligament (ACL) reconstruction is commonly indicated in patients who develop symptomatic knee instability and functional limitation following ACL rupture. Young, physically active individuals, particularly athletes involved in pivoting, cutting, or contact sports, are considered ideal candidates for surgical reconstruction because they often aim to return to their previous level of athletic participation.[23] Surgery is also recommended for patients experiencing recurrent episodes of instability during daily activities, those with associated meniscal injuries requiring repair, combined ligamentous injuries, or individuals who fail to achieve satisfactory functional stability after comprehensive conservative treatment.

The major goals of ACL reconstruction are restoration of normal knee stability, prevention of secondary meniscal and cartilage damage, improvement in functional performance, and facilitation of safe return to sports and occupational activities. The timing of surgery is individualized and depends on multiple factors including patient age, activity level, associated injuries, degree of instability, and restoration of preoperative range of motion. Modern treatment strategies increasingly focus on patient-specific management based on functional demands and long-term expectations. In contrast, nonoperative treatment may remain appropriate for elderly individuals, sedentary patients, or those with low functional requirements who can compensate adequately through rehabilitation, muscle strengthening, and neuromuscular training.[24]

Graft Choices in ACL Reconstruction

Bone–Patellar Tendon–Bone (BPTB) Autograft

Bone–patellar tendon–bone (BPTB) autograft has long been regarded as one of the standard graft options for ACL reconstruction because of its excellent biomechanical strength and reliable fixation properties. This graft is obtained by harvesting the central third of the patellar tendon along with attached bone blocks from the patella and tibial tubercle, allowing direct bone-to-bone healing within the femoral and tibial tunnels.[25] The technique provides strong initial fixation, rapid biological incorporation, and excellent long-term joint stability, making it especially suitable for elite athletes and highly active patients who require dependable knee function and early return to sport.

Numerous long-term clinical studies have demonstrated favorable graft survival rates and successful functional outcomes following BPTB reconstruction. Because bone-to-bone healing occurs more rapidly than soft tissue integration, early graft stability is often superior, which may support more confident rehabilitation progression. However, the procedure is associated with certain disadvantages including anterior knee pain, discomfort during kneeling, patellar tendinitis, donor-site morbidity, extension loss, and, in rare cases, patellar fracture or patellar tendon rupture. Despite these potential complications, the strong biomechanical characteristics and consistently durable outcomes of BPTB autografts continue to make them a widely preferred option in modern ACL reconstruction surgery.

Hamstring Tendon Autograft

Hamstring tendon autografts are currently among the most frequently used grafts for ACL reconstruction. These grafts are generally created using the semitendinosus tendon either alone or combined with the gracilis tendon to form a multi-stranded construct with high tensile strength and adequate durability.[26] Over the past several years, hamstring grafts have gained substantial popularity because they provide good functional outcomes while producing less postoperative discomfort and fewer anterior knee complications compared with BPTB autografts. Biomechanical evidence has shown that quadrupled hamstring grafts possess tensile strength comparable to or greater than that of the native ACL, making them suitable for both recreational and competitive athletes.[27]

One of the major advantages of hamstring autografts is the relatively less invasive harvesting technique, which involves a smaller surgical incision and improved cosmetic appearance. Patients undergoing hamstring graft reconstruction usually report lower rates of anterior knee pain and kneeling discomfort than those treated with BPTB grafts.[28] Reduced donor-site morbidity and fewer extensor mechanism complications have significantly contributed to the widespread acceptance of this graft choice. Additionally, preservation of the patellar tendon and extensor apparatus often allows a more comfortable early rehabilitation period.

Despite these advantages, hamstring tendon autografts also have certain limitations. Soft tissue graft incorporation into bone tunnels occurs more slowly than the bone-to-bone healing seen with BPTB grafts, which may prolong biological integration. Harvesting the semitendinosus and gracilis tendons can lead to temporary or persistent hamstring weakness, especially during deep knee flexion and internal rotation movements.[29] Concerns have also been raised regarding graft stretching and residual laxity, particularly when fixation methods are inadequate or rehabilitation progresses too aggressively in the early postoperative phase. Nevertheless, long-term clinical outcomes, knee stability, and patient satisfaction remain highly favorable, and hamstring autografts continue to represent one of the most popular graft choices for ACL reconstruction worldwide.[30]

Quadriceps Tendon Autograft

Quadriceps tendon autografts have gained increasing popularity as an alternative graft option for ACL reconstruction because of their favorable biomechanical characteristics and relatively lower donor-site morbidity. The graft is usually harvested from the central portion of the quadriceps tendon, either with or without an attached patellar bone block, resulting in a thick graft with a large cross-sectional area and adequate diameter.[31] Improvements in surgical instrumentation and harvesting techniques have simplified graft procurement and fixation, leading to broader clinical acceptance in both primary and revision ACL reconstruction procedures.

One of the primary advantages of the quadriceps tendon autograft is the availability of a strong and substantial graft, which is especially advantageous in larger individuals and revision surgeries where graft size is an important consideration. In comparison with bone–patellar tendon–bone (BPTB) autografts, quadriceps tendon grafts are associated with lower incidences of anterior knee pain, less discomfort during kneeling, and reduced risk of patellar fractures or patellar tendon-related complications.[32] Donor-site morbidity is generally lower, while the graft itself demonstrates biomechanical strength comparable to that of the native ACL. Several comparative investigations have reported functional outcomes, postoperative stability, and return-to-sport rates similar to those observed with BPTB and hamstring tendon autografts.

Despite these advantages, certain limitations remain associated with quadriceps tendon grafts. Long-term follow-up data are still relatively limited compared with the extensively studied BPTB and hamstring grafts. Potential complications include postoperative quadriceps weakness, extensor mechanism discomfort, and difficulty during early rehabilitation because of quadriceps muscle inhibition.[33] In addition, surgeon experience and technical familiarity may influence graft selection, as quadriceps tendon harvesting requires careful surgical execution to minimize tendon injury and unnecessary soft tissue trauma. Nevertheless, current evidence increasingly supports quadriceps tendon autografts as a dependable and versatile option for both primary and revision ACL reconstruction, with outcomes comparable to traditional graft choices.[34]

Allografts

Allografts are biologic grafts obtained from cadaveric donor tissues and may include patellar tendon, Achilles tendon, tibialis anterior tendon, or hamstring tendon grafts. Their use in ACL reconstruction has increased over recent years because they eliminate the need for autograft harvesting and therefore avoid donor-site morbidity.[35] Allografts provide several practical advantages, including reduced operative time, smaller surgical incisions, decreased postoperative pain, and improved comfort during the early rehabilitation period. Since graft harvesting is unnecessary, surgical trauma is minimized and cosmetic outcomes are often superior.

These grafts are particularly beneficial in revision ACL reconstruction, multiligament knee injuries, and older or less physically demanding patients in whom minimizing surgical morbidity is desirable. Allografts also preserve the patient's native tissues, which can be advantageous in cases involving previous graft harvest or insufficient autologous tissue availability. However, several limitations restrict their routine use in young and highly active athletic populations. Biological incorporation and graft remodeling occur more slowly in allografts than in autografts, potentially leading to delayed healing and temporary reduction in graft strength during the early

postoperative period. Clinical studies have demonstrated higher rates of graft failure and rerupture among young competitive athletes treated with allografts compared with autograft reconstruction.[35]

Additional concerns include the theoretical possibility of disease transmission, immune-related graft reactions, weakening of graft tissue due to sterilization procedures, and increased overall cost. Sterilization methods such as irradiation and chemical processing may negatively influence collagen structure and biomechanical integrity of the graft. Consequently, many surgeons prefer to reserve allografts for revision surgeries, older individuals with lower activity demands, or patients in whom autograft harvesting is not feasible. Appropriate patient selection and individualized surgical planning remain essential for achieving optimal outcomes with allograft ACL reconstruction.

Surgical Techniques in ACL Reconstruction

Arthroscopic Single-Bundle Reconstruction

Arthroscopic single-bundle anterior cruciate ligament (ACL) reconstruction remains the most commonly performed surgical procedure for ACL-deficient knees worldwide. This technique primarily reconstructs the anteromedial (AM) bundle of the native ACL, which functions as the principal restraint against anterior tibial translation.[36] Technological advancements in arthroscopic visualization and instrumentation have enabled minimally invasive reconstruction associated with reduced postoperative morbidity, smaller incisions, and faster rehabilitation. Compared with more technically demanding procedures, single-bundle reconstruction is relatively simpler to perform, requires shorter operative time, and consistently demonstrates favorable long-term clinical outcomes.

Contemporary surgical concepts strongly emphasize anatomic tunnel placement within the native femoral and tibial ACL footprints in order to restore near-normal knee biomechanics and improve rotational stability.[37] Precise tunnel positioning is considered one of the most critical determinants of successful graft function and long-term surgical outcome. Incorrect or nonanatomic tunnel placement may lead to persistent instability, graft impingement, abnormal knee kinematics, and eventual reconstruction failure. Modern arthroscopic techniques therefore focus on individualized tunnel positioning and accurate restoration of native ACL anatomy to optimize postoperative stability and functional recovery.

Double-Bundle Reconstruction

Double-bundle ACL reconstruction was introduced with the objective of more accurately reproducing the native anatomy and biomechanical function of the anterior cruciate ligament by reconstructing both the anteromedial (AM) and posterolateral (PL) bundles. The underlying principle of this technique is that restoration of both functional bundles may provide improved rotational control and more physiological knee kinematics during dynamic movements.[38] Biomechanical investigations have demonstrated that double-bundle reconstruction can offer superior rotational stability compared with conventional single-bundle procedures, particularly during pivoting activities and high-demand athletic maneuvers.

Despite these potential biomechanical advantages, double-bundle reconstruction is technically more complex and requires advanced surgical expertise. The procedure is associated with longer operative duration, increased surgical complexity, additional fixation implants, and higher overall treatment costs. Other concerns include tunnel convergence, hardware-related complications, and greater technical difficulty during revision surgery.

Moreover, existing clinical evidence has not consistently shown significant superiority of double-bundle reconstruction over well-performed anatomic single-bundle reconstruction in terms of patient-reported outcomes, knee function, or return-to-sport rates.[39] As a result, the routine application of double-bundle techniques remains controversial, and many surgeons reserve this approach for carefully selected patients with high functional demands, severe rotational instability, or participation in elite-level sports activities.

Anatomic ACL Reconstruction

Anatomic ACL reconstruction is based on the principle of restoring the native insertion sites, orientation, and biomechanical characteristics of the original ligament as accurately as possible. Precise placement of femoral and tibial tunnels within the natural ACL footprints is considered essential for optimal graft function and restoration of normal knee mechanics.[40] Contemporary anatomic reconstruction techniques aim to reproduce both anterior and rotational stability while minimizing graft impingement, abnormal joint loading, and postoperative instability. Research has demonstrated that anatomically positioned grafts more effectively restore physiological knee kinematics and may contribute to reducing long-term degenerative changes within the joint.

Advances in surgical technology, including three-dimensional imaging, computer-assisted navigation, fluoroscopic assistance, and patient-specific instrumentation, have significantly improved tunnel placement accuracy and surgical reproducibility. These innovations enable surgeons to identify native anatomical landmarks more precisely and optimize graft positioning during reconstruction. Enhanced biomechanical restoration achieved through anatomic ACL reconstruction has been associated with improved functional outcomes, greater knee stability, and higher patient satisfaction following surgery.[41]

Remnant Preservation Techniques

Remnant-preserving ACL reconstruction techniques are designed to retain viable residual fibers of the native anterior cruciate ligament during surgical reconstruction whenever feasible. Preservation of these remaining fibers may provide important biological advantages by maintaining synovial tissue coverage, vascular supply, and mechanoreceptors that contribute to proprioceptive function.[42] The preserved remnant tissue may additionally act as a biological scaffold that supports graft revascularization, cellular proliferation, and graft incorporation during the healing process. Several clinical and experimental studies have suggested that remnant preservation may improve postoperative proprioception, enhance graft maturation, and potentially facilitate earlier functional recovery.

Despite these potential benefits, remnant-preserving procedures also present certain technical challenges. Excessive residual tissue may obstruct arthroscopic visualization, complicate accurate tunnel positioning, and increase the likelihood of cyclops lesion formation, which can subsequently result in extension loss. Careful intraoperative assessment and meticulous surgical technique are therefore essential to maximize the biological advantages of remnant preservation while minimizing postoperative complications and technical errors.

Extra-Articular Augmentation Procedures

Extra-articular augmentation procedures, including lateral extra-articular tenodesis (LET) and anterolateral ligament (ALL) reconstruction, have regained considerable interest in recent years, especially among patients considered at high risk for graft failure. These procedures are commonly

performed in combination with intra-articular ACL reconstruction to improve rotational control and reduce persistent pivot shift instability.[43] Common indications for augmentation procedures include high-grade pivot shift, generalized ligamentous laxity, chronic ACL insufficiency, revision ACL reconstruction, and participation in high-risk pivoting sports among young competitive athletes.

Biomechanical and clinical evidence suggests that LET and ALL reconstruction may significantly reduce rotational laxity and lower graft failure rates, particularly in high-demand athletic populations. By limiting excessive internal rotation of the tibia and controlling anterolateral instability, these procedures may help protect the reconstructed graft during the critical early healing phase and during return-to-sport activities. However, concerns remain regarding the possibility of excessive lateral compartment constraint and the long-term influence of these procedures on normal knee biomechanics and joint loading patterns.

Graft Fixation Methods

Secure graft fixation is a critical determinant of successful ACL reconstruction because it allows early mobilization, facilitates biological incorporation, and maintains graft stability during rehabilitation. Commonly used fixation methods include interference screws, cortical suspensory fixation devices, cross pins, and hybrid fixation systems.[44] Interference screws are widely utilized because they provide direct compression of the graft within the bone tunnel and are suitable for both soft tissue grafts and bone plug fixation. Cortical suspensory fixation devices have become increasingly popular, particularly in hamstring tendon graft reconstruction, because they provide strong fixation strength along with adjustable tensioning capabilities.

Modern fixation technologies offer excellent initial mechanical stability, thereby supporting accelerated rehabilitation protocols and earlier restoration of knee function. Advances in biomaterials, implant design, and fixation systems have also contributed to reduced tunnel widening, improved graft integration, and lower rates of hardware-related complications. Selection of the appropriate fixation method generally depends on several factors including graft type, bone quality, surgeon preference, surgical technique, and individual patient characteristics.

Rehabilitation Protocols After ACL Reconstruction

Early Rehabilitation Phase

The early postoperative phase of rehabilitation following ACL reconstruction primarily aims to control pain and swelling, restore full knee extension, activate quadriceps function, and initiate protected weight-bearing activities.[45] Modern rehabilitation protocols strongly advocate early mobilization and immediate range-of-motion exercises in order to minimize the risk of arthrofibrosis, joint stiffness, and muscle wasting. Achieving full extension during the initial postoperative period is considered particularly important for optimal long-term functional recovery.

Various supportive modalities such as cryotherapy, compression therapy, neuromuscular electrical stimulation, and gradual assisted ambulation are commonly incorporated during this phase to facilitate recovery and improve joint function. Early quadriceps activation exercises, patellar mobilization, and gait training are also emphasized to restore muscle control and prevent abnormal movement patterns. Rehabilitation progression during this stage is carefully monitored to protect the healing graft while promoting safe restoration of knee mobility and functional independence.

Intermediate Phase

The intermediate stage of rehabilitation focuses on progressive strengthening of the lower limb musculature, improvement of proprioception, enhancement of neuromuscular control, and normalization of gait mechanics. During this period, rehabilitation programs commonly emphasize closed-chain strengthening exercises because they reduce anterior tibial shear forces while promoting functional joint stability and muscular coordination. Progressive strengthening of the quadriceps, hamstrings, gluteal muscles, and core musculature is essential for restoring dynamic knee stability.

Balance training, coordination exercises, and proprioceptive retraining are important components of this phase, as they help re-establish neuromuscular control and reduce the likelihood of reinjury during functional activities. Rehabilitation intensity is gradually increased according to patient tolerance, muscular recovery, and functional progression. Careful supervision remains important to avoid excessive loading or premature return to high-impact activities during graft healing.

Advanced Rehabilitation

Advanced rehabilitation programs are designed to prepare the patient for safe return to sports and high-level functional activities. This phase typically includes plyometric exercises, agility drills, advanced neuromuscular training, sport-specific functional exercises, and progressive conditioning programs. Modern rehabilitation approaches increasingly recognize that successful return to sport depends not only on physical recovery but also on restoration of neuromuscular performance and psychological confidence.

Assessment of psychological readiness, fear of reinjury, movement quality, and athletic confidence has therefore become an integral component of advanced rehabilitation. Rehabilitation programs are individualized according to the patient's sporting demands, functional goals, and neuromuscular performance. Current evidence supports a criterion-based progression model rather than relying solely on postoperative timelines, thereby helping reduce reinjury risk and ensuring adequate recovery before return to competitive activities.

Return-to-Sport Criteria

Return-to-sport clearance following ACL reconstruction is based on multiple clinical, functional, and psychological parameters. Common criteria include restoration of full and painless knee range of motion, absence of joint effusion, symmetrical lower limb muscle strength, satisfactory performance on functional hop tests, and adequate psychological preparedness for athletic participation. Functional assessment batteries evaluating limb symmetry, balance, agility, and dynamic movement control are frequently utilized before athletes are permitted to resume sports activities.

Although many athletes return to sports approximately 9–12 months after surgery, the timing of return should be individualized according to graft healing, neuromuscular recovery, functional performance, and sport-specific demands. Premature return to high-risk activities may substantially increase the risk of graft rupture or secondary injury. Consequently, modern rehabilitation protocols emphasize comprehensive functional assessment and gradual progression to ensure safe and successful return to competition.

Complications of ACL Reconstruction

Although anterior cruciate ligament (ACL) reconstruction generally produces favorable functional outcomes and allows a high proportion of patients to return to sports, several postoperative complications may negatively influence recovery and long-term knee function. One of the most important complications is graft failure, which may result from traumatic reinjury,

improper tunnel positioning, inadequate biological graft incorporation, fixation failure, or premature return to high-demand athletic activities. Graft rupture is particularly concerning among young athletes involved in pivoting sports and frequently requires revision reconstruction. Persistent postoperative instability may also occur because of technical errors such as nonanatomic tunnel placement, inadequate graft tensioning, or failure to recognize associated ligamentous injuries, ultimately leading to compromised knee biomechanics and reduced functional performance.

Postoperative infection, although relatively rare, remains a serious complication that can result in cartilage damage, graft compromise, prolonged rehabilitation, and unsatisfactory clinical outcomes. Early identification and timely treatment with intravenous antibiotics and arthroscopic debridement are essential to preserve graft integrity and maintain joint function. Arthrofibrosis is another important postoperative complication characterized by excessive intra-articular scar tissue formation, leading to pain, stiffness, restricted range of motion, and inability to achieve full extension. Factors contributing to arthrofibrosis include delayed rehabilitation, prolonged immobilization, excessive surgical trauma, and postoperative inflammation. Cyclops lesions, which consist of localized fibrous nodules located anterior to the graft, may similarly produce extension block and mechanical symptoms that occasionally require arthroscopic excision.

Tunnel malposition continues to represent one of the most common technical causes of failed ACL reconstruction. Incorrect positioning of the femoral or tibial tunnels may lead to graft impingement, abnormal graft tension, persistent laxity, restricted knee movement, and eventual graft failure. Contemporary anatomic reconstruction techniques combined with improved intraoperative visualization and imaging guidance have substantially reduced the incidence of these technical complications. Deep vein thrombosis (DVT) may also occur after surgery as a consequence of temporary immobilization and impaired venous circulation, although its incidence is relatively low in arthroscopic procedures. Preventive strategies such as early mobilization, mechanical compression devices, and thromboprophylaxis in selected high-risk patients are important for minimizing this complication.

Long-term complications following ACL reconstruction include the development of post-traumatic osteoarthritis, which may occur even after technically successful surgery. Chronic instability, associated meniscal injury, cartilage degeneration, recurrent inflammation, altered joint loading, and abnormal biomechanics all contribute to progressive degenerative changes within the knee joint over time. Therefore, meticulous surgical technique, individualized graft selection, accurate tunnel placement, structured rehabilitation, and carefully supervised return-to-sport protocols are essential for minimizing complications and optimizing long-term functional and clinical outcomes after ACL reconstruction.

Recent Advances in ACL Reconstruction

Internal Brace Augmentation

Internal brace augmentation has emerged as a significant advancement in contemporary anterior cruciate ligament (ACL) reconstruction. This technique involves the use of high-strength suture tape positioned alongside the reconstructed graft to provide additional mechanical reinforcement during the early stages of biological healing. The internal brace functions as a protective support structure that shares load with the graft, thereby reducing excessive stress during rehabilitation and early return-to-activity

phases. The technique has gained considerable interest because graft ligamentization and maturation are prolonged biological processes during which the reconstructed ligament remains susceptible to elongation or failure. By strengthening the graft construct, internal brace augmentation may enhance initial stability and potentially decrease reinjury rates, particularly among young athletes and high-risk individuals.

Biomechanical investigations have demonstrated that suture tape augmentation can improve graft strength and reduce cyclic elongation without significantly limiting normal knee motion. Clinically, this approach may support accelerated rehabilitation protocols, earlier mobilization, and increased patient confidence during recovery. Internal bracing has also shown promising applications in ACL repair procedures where preservation of native ligament tissue is achievable. However, concerns persist regarding possible overconstraint of the knee joint, stress shielding of the graft, and potential long-term effects on graft remodeling and maturation. Although early clinical outcomes appear encouraging, additional long-term studies are required to determine definitive benefits, ideal patient selection, and optimal surgical indications for internal brace augmentation.

iological Enhancement

Biological enhancement strategies represent one of the most rapidly developing areas in ACL reconstruction research. Traditional ACL reconstruction techniques primarily restore mechanical stability, whereas biological graft incorporation and healing remain relatively slow processes. To accelerate graft maturation and improve tissue regeneration, several biologic augmentation methods have been investigated, including platelet-rich plasma (PRP), stem cell therapy, growth factor delivery, and collagen-based scaffolds.

Platelet-rich plasma contains concentrated platelets enriched with biologically active growth factors such as platelet-derived growth factor, transforming growth factor-beta, and vascular endothelial growth factor, which may stimulate angiogenesis, collagen production, and cellular proliferation. PRP has been applied to graft harvest sites, bone tunnels, and reconstructed ligaments in an attempt to enhance tendon-to-bone healing and reduce postoperative inflammation. While some studies have demonstrated improved graft maturation and decreased postoperative pain, current clinical evidence remains inconsistent regarding its overall effectiveness.

Stem cell therapy has also generated significant interest because mesenchymal stem cells possess regenerative and immunomodulatory properties that may facilitate tissue repair and accelerate graft incorporation. These stem cells may be derived from bone marrow, adipose tissue, or synovial tissue and have the potential to improve collagen organization and ligament remodeling. Growth factor supplementation and collagen scaffold technologies are similarly being explored to create biologically favorable environments for graft healing. Collagen matrices may function as structural frameworks that support cellular migration, vascularization, and tissue regeneration during the healing process.

Despite promising experimental and early clinical findings, many biological enhancement techniques remain investigational, and standardized treatment protocols have not yet been universally established. Variability in preparation techniques, dosage, timing, and methods of application continues to limit definitive conclusions regarding long-term clinical efficacy and reproducibility.

Computer-Assisted and Robotic Surgery

Technological advancements in computer-assisted and robotic surgery have

substantially improved the precision and reproducibility of ACL reconstruction procedures. Accurate tunnel placement is considered one of the most critical determinants of successful ACL reconstruction because malpositioned tunnels may result in graft impingement, persistent instability, restricted motion, and eventual graft failure. Computer-assisted navigation systems provide real-time intraoperative guidance, enabling surgeons to identify anatomic landmarks more accurately and optimize graft orientation during reconstruction.

Three-dimensional imaging technologies, fluoroscopic assistance, and virtual surgical planning have further enhanced the ability to reproduce native ACL anatomy with greater precision. Robotic-assisted surgical systems offer additional benefits by reducing human error and improving consistency during tunnel drilling and graft positioning. These technologies may be particularly useful in revision surgeries, patients with complex anatomy, and cases requiring highly individualized reconstruction strategies.

In addition to improving surgical accuracy, computer-assisted systems may facilitate objective intraoperative assessment of knee kinematics, graft positioning, and tensioning characteristics. Such innovations have the potential to standardize surgical procedures and reduce variability among surgeons. Nevertheless, widespread adoption remains limited by high equipment costs, increased operative setup time, and the requirement for specialized technical training. As technology continues to evolve, robotic and navigation-assisted ACL reconstruction may become increasingly integrated into routine orthopedic surgical practice.

Personalized Rehabilitation

Postoperative rehabilitation following anterior cruciate ligament (ACL) reconstruction has evolved considerably from traditional time-based protocols toward highly individualized and criterion-based recovery strategies. Personalized rehabilitation programs are designed according to patient-specific characteristics such as age, activity demands, graft type, biomechanical deficits, neuromuscular function, and psychological readiness for return to activity. This individualized approach aims to optimize recovery, reduce reinjury risk, and improve long-term functional outcomes.

Wearable sensor technologies have become increasingly important in modern rehabilitation because they allow continuous monitoring of gait mechanics, limb-loading symmetry, joint movement, and muscle activity throughout the recovery process. These devices provide objective real-time feedback that helps clinicians evaluate functional progression and identify abnormal movement patterns that may increase the risk of reinjury. Advanced biomechanical motion analysis systems also assist in assessing landing mechanics, balance, agility, and dynamic knee stability during sport-specific activities and functional testing.

Artificial intelligence (AI) and machine learning technologies are beginning to play an expanding role in rehabilitation planning and postoperative monitoring. AI-driven systems may analyze extensive patient data to predict recovery patterns, detect high-risk biomechanical movements, and guide individualized rehabilitation progression. In addition, mobile applications and tele-rehabilitation platforms facilitate continuous remote supervision, improve patient adherence to exercise programs, and enhance communication between clinicians and patients during recovery.

Psychological assessment has also become a crucial component of personalized rehabilitation programs. Fear of reinjury, lack of confidence, anxiety, and

psychological distress can negatively influence return-to-sport outcomes even after adequate physical recovery has been achieved. Consequently, modern rehabilitation protocols increasingly incorporate psychological readiness evaluations alongside objective physical performance assessments before clearance for return to athletic participation.

Future Directions

Future advances in ACL reconstruction are expected to focus increasingly on biologic restoration, personalized medicine, and injury prevention strategies. Tissue-engineered grafts designed to replicate the structure and biomechanical properties of the native ligament represent one of the most promising areas of ongoing research. Developments in biomaterials, scaffold engineering, and regenerative medicine may eventually enable the creation of synthetic-biologic hybrid grafts capable of superior integration, improved healing, and enhanced long-term durability.

Gene therapy approaches are also being investigated as potential methods for enhancing ligament healing and cellular regeneration through modulation of growth factor activity and collagen synthesis. Such strategies may improve graft incorporation, accelerate tissue healing, and reduce the risk of graft failure or post-traumatic joint degeneration. Additional biologic enhancement techniques involving stem cells, bioactive scaffolds, molecular therapies, and regenerative biologics may further transform postoperative recovery and ligament regeneration in the future.

Improvement of injury prevention programs remains critically important because prevention of primary ACL injury is considerably more effective than treatment after ligament rupture has occurred. Neuromuscular training programs focusing on landing mechanics, movement control, core stability, strength conditioning, and balance training have already demonstrated substantial reductions in ACL injury risk, particularly among female athletes and high-risk sporting populations.

Patient-specific surgical planning using advanced imaging technologies, three-dimensional modeling, and artificial intelligence may allow highly individualized reconstruction strategies tailored to each patient's anatomy, biomechanics, and functional demands. AI-assisted rehabilitation monitoring and predictive analytics may further enhance return-to-sport decision-making while reducing reinjury rates and improving long-term functional outcomes.

Despite major progress in surgical reconstruction and rehabilitation science, prevention of post-traumatic osteoarthritis following ACL injury continues to represent a major research priority. Future treatment strategies will likely focus not only on restoring mechanical stability of the knee but also on preserving cartilage health, maintaining long-term joint function, and protecting overall knee integrity throughout the patient's lifetime.

Discussion

Anterior cruciate ligament (ACL) reconstruction has undergone substantial evolution over the past few decades, progressing from conventional open procedures to advanced arthroscopic and anatomic reconstruction techniques. Current evidence suggests that optimal clinical outcomes depend on a comprehensive and multifactorial treatment approach involving appropriate patient selection, individualized graft choice, precise surgical technique, and structured postoperative rehabilitation.[46] Improved understanding of ACL anatomy, biomechanics, and neuromuscular function has significantly enhanced the ability to restore knee stability, improve functional performance, and facilitate successful return to sports. However, despite these advancements, several controversies and

long-term concerns continue to influence treatment strategies and patient outcomes.

Graft selection remains one of the most widely debated aspects of ACL reconstruction. Bone–patellar tendon–bone (BPTB) autografts continue to provide excellent fixation strength, dependable bone-to-bone healing, and superior mechanical stability, particularly among elite athletes and individuals involved in pivoting sports. Nevertheless, complications such as anterior knee pain, kneeling discomfort, and donor-site morbidity have contributed to increasing preference for hamstring and quadriceps tendon autografts. Current literature indicates that hamstring and quadriceps tendon grafts can provide functional outcomes and patient satisfaction comparable to BPTB grafts while reducing extensor mechanism complications and postoperative discomfort in appropriately selected individuals.[47] Consequently, modern graft selection has become increasingly patient-specific and is influenced by factors such as age, activity level, occupational demands, anatomical considerations, and surgeon experience.

The transition toward anatomic ACL reconstruction has further improved restoration of native knee biomechanics and rotational stability. Accurate tunnel placement within the natural femoral and tibial ACL footprints is now considered a fundamental principle because nonanatomic graft positioning is strongly associated with persistent instability, abnormal knee kinematics, and graft failure. In addition, extra-articular augmentation procedures such as lateral extra-articular tenodesis (LET) and anterolateral ligament (ALL) reconstruction have gained increasing popularity among high-risk patients, including young athletes, revision reconstruction cases, and individuals with generalized ligamentous laxity. Emerging evidence suggests that these adjunctive procedures may improve rotational control and decrease graft rerupture rates without significantly impairing knee function.[48]

Postoperative rehabilitation has also evolved considerably from prolonged immobilization-based protocols to accelerated, criterion-based rehabilitation programs emphasizing early mobilization, neuromuscular retraining, proprioceptive recovery, and psychological readiness assessment. Contemporary rehabilitation strategies increasingly acknowledge that restoration of muscle strength alone is insufficient for safe return to sports. Persistent deficits in movement symmetry, neuromuscular control, dynamic balance, and psychological confidence have been identified as important contributors to reinjury risk following ACL reconstruction.[49] Young athletes who return prematurely to high-level sporting activities continue to demonstrate relatively high graft rerupture rates, emphasizing the importance of individualized return-to-sport criteria and comprehensive functional testing before clearance for competitive participation.

Despite major advances in surgical techniques and rehabilitation protocols, post-traumatic osteoarthritis following ACL injury continues to represent a significant long-term clinical challenge. Even after technically successful reconstruction, altered joint biomechanics, associated meniscal damage, cartilage degeneration, and recurrent inflammatory processes may contribute to progressive degenerative changes within the knee joint. Therefore, current research efforts increasingly focus not only on restoring mechanical stability but also on preserving long-term joint health and minimizing osteoarthritis progression. Emerging biologic therapies including platelet-rich plasma, stem cell augmentation, scaffold-based regenerative technologies, and personalized rehabilitation approaches may further improve graft incorporation,

tissue healing, and long-term functional recovery in the future.[50] Continued high-quality prospective studies and long-term clinical investigations remain essential for refining surgical techniques, improving biologic healing, reducing reinjury rates, and enhancing overall quality of life in patients undergoing ACL reconstruction.

Conclusion

Anterior cruciate ligament (ACL) injuries continue to represent a major cause of knee instability and functional limitation among physically active individuals. Surgical reconstruction techniques have advanced significantly with improvements in graft selection, anatomic reconstruction methods, fixation technologies, and rehabilitation protocols. Current evidence supports individualized treatment approaches based on patient characteristics, functional demands, activity level, and associated intra-articular injuries. Successful outcomes depend on meticulous surgical execution, appropriate graft selection, and comprehensive rehabilitation programs emphasizing muscle strengthening, neuromuscular recovery, proprioceptive training, and safe return-to-sport assessment. Emerging biologic augmentation methods and personalized rehabilitation strategies demonstrate promising potential for enhancing graft healing and reducing reinjury risk. Long-term preservation of joint health, prevention of post-traumatic osteoarthritis, and optimization of return-to-sport outcomes remain important future objectives in the management of ACL injuries.

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