Anterior Cruciate Ligament Injuries: Anatomy, Physiology, Biomechanics, and Management

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OBJECTIVE: Anterior cruciate ligament (ACL) injuries are the most common ligament injury in the United States. These injuries can be career ending for athletes and severely disabling for all individuals. Our objectives are to review the epidemiology of these injuries, as well as ACL biomechanics, anatomy, and nonsurgical and surgical management so that generalists as well as sports medicine physicians, orthopedists, and others will have a better understanding of this serious injury as well as choices in its management.

DATA SOURCES: PubMed was used to identify relevant articles. These articles were then used to identify other sources.

MAIN RESULTS: Anterior cruciate ligament injuries occur more commonly in women than in men due to a variety of anatomical factors. The ACL consists of 2 major bundles, the posterolateral and the anteromedial bundles. Forces transmitted through these bundles vary with knee-joint position. Some patients with ACL injuries may not be candidates for surgery because of serious comorbid medical conditions. However, without surgical repair, the knee generally remains unstable and prone to further injury. There are a variety of surgical decisions that can influence outcomes. Single-bundle versus double-bundle repair, whether to leave the ruptured ACL remnant in the knee, the selection of the graft tissue, graft placement, and whether to use the transtibial, far anteromedial portal, or tibial tunnel-independent technique are choices that must be made.

CONCLUSIONS: With a sound knowledge of the anatomy and kinetics of the knee, newer improved surgical techniques have been developed that can restore proper knee function and have allowed many athletes to resume their careers. These new techniques have also limited the disability in nonathletes.

KEY WORDS: anterior cruciate ligament, anterior cruciate ligament reconstruction, posterolateral bundle, anteromedial bundle, hamstring tendon graft, patellar tendon graft, quadriceps tendon graft


INTRODUCTION

In the United States, anterior cruciate ligament (ACL) injuries total between 100 000 and 200 000 yearly, making this the most common ligament injury.1–4 This number continues to increase in both the general population and in individuals who play sports. Football players sustain the greatest number of ACL injuries (53% of the total) with skiers and gymnasts also at high risk.5,6 This is a focused review based on a search of PubMed using the topic headings below that will be of interest to clinicians who take care of patients with ACL injuries. Articles identified through PubMed articles were then used to identify additional sources. A comprehensive review of each area is beyond the scope of this article, and the reader is referred to discussions of specific areas in the references.

FACTORS THAT CONTRIBUTE TO ANTERIOR CRUCIATE LIGAMENT INJURIES

Anterior cruciate ligament injury rates tend to be higher for women than for men.7–9 At the United States Naval academy, in intercollegiate soccer, basketball, and rugby, women had a relative risk of 3.96 of ACL injury compared with men. The National Collegiate Athletic Association Injury Surveillance System (1990-2002) found that the rate of ACL injury, regardless of the mechanism, was significantly higher for female collegiate athletes than for male collegiate athletes in both soccer and basketball.10 The stronger the quadriceps muscles, the larger and hence stronger the ACL, although it is unclear that in any one individual that an increase in quadriceps size and strength results in an increase in ACL size.7 Quadriceps muscles, even after adjustments for differences in weight and lean body mass, are larger in male athletes than in female athletes.

There are neuromuscular and biomechanical risk factors associated with ACL injury.11 Compared with running, there is a significant increase in ACL load during sidestepping and crossover cutting maneuvers.12 This is the result of a large increase in varus/valgus and internal/external rotation movements. These increased stresses during cutting put the ACL at risk, especially when the knee is at flexion angles between 0 and 40 degrees. Appropriate muscle activation strategies may counter these movements. A project aimed at implementing neuromuscular training for soccer and handball players resulted in increased electromyography activity for the medial hamstring muscles, thereby decreasing the risk of dynamic valgus.13

Notch stenosis may contribute to an increase in rates of ACL injury.14–17 The notch width index (NWI) has been used as...
a measure of notch stenosis. The NWI is the ratio of the width of the intercondylar notch to the width of the distal femur at the level of the popliteal groove. In a study, the mean NWI for normal knees was 0.2338; for acute ACL injured knees, it was 0.2248; and for those with bilateral ACL injuries, it was 0.1961. Notch stenosis is not felt to be a factor in gender differences in ACL injury. In a study of 895 US Military Academy cadets who were followed up for more than 4 years, small femoral notch width was found to be a significant risk factor for ACL injuries in men and women and body mass index was a risk factor in women. The NWI did not differ significantly between male and female athletes. Notch width has also been found to correlate with ACL and posterior cruciate ligament (PCL) width, and it has been argued that it is the ACL size rather than notch size that is the important risk factor for ACL injury.

ANTERIOR CRUCIATE LIGAMENT ANATOMY

The ACL controls anterior movement of the tibia and inhibits extreme ranges of tibial rotation. The majority of authorities believe that the ACL consists of 2 major bundles, the posterolateral bundle (PL) and the anteromedial bundle (AM). The component ACL bundles are named based on their tibial insertion. Both bundles originate on the posteromedial side of the lateral femoral condyle and insert on a region just anterior to the intercondylar tibial eminence (Figure 1). The broad ACL tibial insertion point occurs so that there is no physiological impingement on the intercondylar notch in full extension. Placement of the ACL graft insertion into the tibia during reconstructive surgery must adhere to this principle. Mean length of the AM bundle is 33 mm and is 18 mm for the PL bundle. The overall width of the ACL in cadavers ranged from 7 to 17 mm, with the average being 11 mm. Average ACL cross-sectional area is 36 and 47 mm² for women and men, respectively. The ACL is composed of type I collagen fibers. Dissection by Giuliani et al found that the primary blood supply to the ligament comes from the middle genicular artery, with additional supply coming from the inferomedial and inferolateral genicular arteries. There are also several types of mechanoreceptors found within the ACL: Ruffini corpuscles, pacinian corpuscles, Golgi-like organs, and free nerve ends.

ANTERIOR CRUCIATE LIGAMENT BIOMECHANICS

Forces transmitted through ACL bundles vary with knee-joint position. To replicate the in situ strain associated with the ACL, Gabriel et al tested an anterior tibial load and a combined rotatory load applied to the medial side of the knee stressing the valgus angle and an internal tibial torque to test the allocation of forces between the PL and AM bundles using a robotic testing system in 10 cadaveric knees. The greatest forces transmitted through the AM bundle were at 60 and 90 degrees of flexion. The force was greatest for the PL bundle at full extension. At 15 degrees of flexion, there was no statistical difference in stress between the 2 bundles. At greater flexion angles, the AM bundles had a significantly higher in situ force than the PL bundle. Another study using cadaveric knees found that the PL bundle handled more force overall than the AM bundle in response to anterior tibial loads, whereas the in situ forces in the AM bundle remained relatively constant and unaffected by the changes in flexion angle and anterior tibial load force.

In situ forces in the PL bundle correlate to that of the entire ACL at different angles of flexion. This suggests that reconstruction during surgery of the PL bundle as closely as possible to that of the intact knee might be of more importance than that of the AM bundle. Because most injuries to the ACL occur when the knee is at full extension, the PL bundle is considered more important for the overall biomechanical stability of the knee because the in situ force is greatest in the PL bundle at full extension.

Based on the above, it seems that the AM and PL bundles have unique contributions to load transfer across the knee joint. Surgical ACL reconstruction tends to restore the limit of anterior tibial translation closer to that of an intact knee. However, more complex rotatory motions, such as internal tibial and valgus rotation, are less successfully addressed by standard ACL reconstructions. It would thus seem that...
reconstructions that predominately replicate the AM bundle and its function may not restore full knee function and stability. Because the PL bundle carries the majority of load when the knee is at full extension or at 15% of flexion, especially in response to rotatory loads, and the AM bundle carries the majority of load with the knee flexed past 30%, surgical techniques should address the function of both bundles.

**DIAGNOSING ANTERIOR CRUCIATE LIGAMENT INJURIES**

The most common history of an ACL injury may be of a noncontact deceleration, jumping, or cutting action, frequently involving changing direction. This frequently involves rotational maneuvers or lateral bending of the knee into a valgus position with the knee extended and the tibia rotated. If the ACL injury results from direct contact, present in about one-third of patients, there is often a history of hyperextension or valgus stress on the knee. A pop is frequently heard and/or felt. Postinjury swelling of the knee frequently occurs at about 4 hours and aspiration usually reveals hemarthrosis.

Physical examination frequently establishes a diagnosis of ACL injury, especially if the examination is done soon after the injury before swelling, pain, and muscle guarding occurs. Anterior stability of the knee is usually assessed with the Lachman test. The Lachman test is usually performed In 1% to 9.8% of reconstructions that predominately replicate the AM bundle and its function may not restore full knee function and stability. Because the PL bundle carries the majority of load when the knee is at full extension or at 15% of flexion, especially in response to rotatory loads, and the AM bundle carries the majority of load with the knee flexed past 30%, surgical techniques should address the function of both bundles.

**TREATMENT OF ANTERIOR CRUCIATE LIGAMENT INJURIES**

Regardless of whether surgical or nonsurgical treatment is ultimately pursued, patients should be advised to ice, compress, elevate, and limit the use of the injured knee immediately after the injury. If the injury to the ACL also affects the associated structures within the knee, including the menisci, PCL, medial collateral ligament, or lateral collateral ligament, surgical reconstruction is needed.

**Nonsurgical (Conservative) Management of Anterior Cruciate Ligament Injuries**

Some patients with ACL injuries may not be candidates for surgery because of serious comorbid medical conditions including serious cardiac, renal, or hepatic disease or because they no longer wish to participate in strenuous physical activities. For individuals who opt for conservative treatment, physical therapy with an experienced physical therapist or athletic trainer aimed at strengthening the muscles around the knee, especially the quadriceps femoris and hamstring muscles, is pursued. However, without surgical repair, the knee generally remains unstable and prone to further injury.

Long-term studies have shown that there is a significant increase in rates of damage to menisci and articular cartilage associated with delayed reconstruction. The rate of healing for meniscal tears is faster when done at the same time as ACL reconstruction as opposed to being performed alone.

Generally, about one-third of patients who are selected as suitable for conservative treatment are able to complete the therapy regimen without the need for surgical intervention. However, patients with high level of sports activity show poor results after conservative treatment of ACL ruptures.

**Surgical Management of Anterior Cruciate Ligament Injuries**

Because of the frequent failure of nonsurgical approaches to ACL injuries, surgery remains the treatment of choice in almost all athletes who want to remain active. Unfortunately, surgery is not universally successful. Some problems that have resulted in failed ACL reconstruction are graft impingement on the intercondylar roof, graft tension, nonanatomic femoral and tibial tunnel placement (not reproducing the histological and biomechanical characteristics of the native ligament), and incomplete replication of an intact ACL, in particular omitting reconstruction of the PL bundle. Despite these efforts, 15% to 25% of patients who undergo ACL reconstruction continue to suffer pain and instability in their injured knee.

Often, when reconstruction is performed, there is a piece of the ruptured ACL remaining that can be either removed or left in the knee. If the ligament piece is left in place, it can impact visualization during surgery and possibly impact the quality of the reconstruction. In 1% to 9.8% of reconstructions, impingement or a Ciclop lesion (focal nodule[s] of fibrous tissue sitting in the intercondylar notch anterior to the reconstructed ACL) may occur when parts of the ACL are left.

When the ruptured ACL is left in place, mechanoreceptors may help with reinnervation. Sensory neurons involved in kinesthesia may also be preserved in the ruptured ACL. It has been suggested that the ACL functions as a sensory organ, not only providing proprioceptive feedback but...
also initiating protective and stabilizing muscular reflexes. In a study, patients who had undergone surgery 3 months to 3.5 years after the ACL injury had the remainder of the ruptured ACL “adapted to the posterior cruciate ligament ... and sometimes with scar tissue connected to the femur,” whereas the second group had “[free floating] ... ACL remnants.”

In the first group, mechanoreceptors of Ruffini, pacchinian, and, in 1 patient’s specimen, Golgi-like organs were present (Figure 2). In the second group, no significant numbers of mechanoreceptors were found. If reinnervation of the ACL causes restoration of kinesthesia and if ACL remnants can be left without risking impingement in the postreconstruction knee biomechanics, it seems to be of benefit.

Graft Selection

The 2 most commonly used grafts in ACL reconstruction are the patellar tendon (PT) and the 4-strand hamstring (HS) tendon made of gracilis and semitendinosus tendons. Both PT and HS autografts result in a functionally stable knee in more than 95% of surgeries with a 3% absolute difference in graft failure: 1.9% with PT and 4.9% with HS tendon grafts. Benefits of PT grafts include that they are readily accessible, have good structural fixation properties, and have the potential for tendon-to-bone healing. Detriments include anterior knee pain, loss of sensation, patellar fracture, and inferior patellar contracture, although patellar knee pain has been associated with less aggressive rehabilitation methods and use of open kinetic chain extension exercises. The use of PT grafts has also been associated with postreconstruction extensor quadriceps weakness.

The HS tendon graft with all 4 strands equally tensioned can withstand much greater tension strains than a 10-mm PT graft. Some researchers have found that harvesting HS grafts can severely reduce HS strength and endurance up to 9 months after the surgery. Hamstring grafts can also be difficult to harvest because graft diameter and lengths are variable. A review of patients determined that HS graft diameter was related to height but not to body mass index. When height decreases below 147 cm and graft diameter decreases below 7 mm, there is an association between graft strength and its cross-sectional diameter.

In a meta-analysis, PT autografts were compared with HS tendon autografts. Using KT-1000 arthrometer testing, statistically significant differences between these graft types were found: the PT group had a 79% side-to-side difference of <3 mm compared with 73.8% for the HS group, leading the authors to conclude that PT autografts led to more stable reconstructed knees than HS tendon grafts. No significant differences between PT and HS grafts were found between the proportion of patients requiring postoperative meniscal surgery, and no statistically significant differences were seen between PT autografts and HS autografts infection rates.

Quadriceps tendon grafts used for ACL reconstruction have been associated with significantly less anterior knee pain and graft-site morbidity compared with PT grafts. These grafts are taken from the central third of the quadriceps tendon and are composed of the vastus medialis, vastus intermedius, and rectus femoris, yielding a bilaminar graft. The mean cross-sectional area for a 10-mm-wide quadriceps tendon graft is 64 mm², larger than 37 mm² for the PT; hence, quadriceps tendon grafts produce a broader anatomic insertion of the reconstructed ACL to the tibia. This can decrease physiologic impingement on the intercondylar notch in full extension of the knee. Quadriceps muscle power is not compromised, despite sacrificing a part of the tendon. Overall, quadriceps tendon grafts have the advantage of ease of excision and are comparable with respect to graft size and strength with both PT and HS grafts.

The main advantage of allografts versus autografts is avoidance of donor-site morbidity. Other advantages include savings in operative time of graft harvest, availability of larger grafts, superior cosmesis, and the possibility for multiple ligament reconstructions. Potential disadvantages include delayed graft incorporation, disease transmission, potential immune reactions, altered mechanical properties caused by sterilization, and cost of the allograft. Of primary concern is whether allografts are less stable than autografts. A recent meta-analysis found that allografts failed 3 times more frequently than autografts. However, a recent study found that autografts and nonirradiated (vs radiated or chemically processed) allografts had similar side-to-side differences of <3 mm according to the KT-2000 arthrometer.

Single-Bundle Versus Double-Bundle Reconstruction

Between 10% and 30% of patients reported persistent instability in their reconstructed knee after single-bundle surgery. This resulted in a return-to-sport rate of only 60% to 70% for single-bundle restorations. Single-bundle reconstruction can restore anterior-posterior knee stability but produces knees that are unable to resist combined rotatory loads and do not have normal rotational kinematics. Double-bundle restored knees are better at resisting extrinsic forces placed on the knee. Although the double-bundle technique is better at restoring normal knee kinematics, there are some disadvantages. It is more difficult to perform surgically and could be the cause of reconstruction failures due to the improper positioning of bone tunnels.

FIGURE 2. Mechanoreceptors, Ruffini (black arrow) and pacchinnian (white arrow), in a torn anterior cruciate ligament (ACL) specimen adapted to the PCL. Taken from Georgoulis et al with permission.
Graft Placement

Placement of grafts can have a major impact on the clinical outcome of ACL reconstruction. Failure to regain full flexion postoperatively can be caused by high graft tension during extension of the knee, which in turn may cause the graft to stretch. This may occur when the ACL graft is placed vertically at the apex of the notch, with the tibial tunnel being in a vertical orientation at an angle >70 degrees from the medial joint line of the tibia and the femoral tunnel and then drilled through that tibial tunnel. Prevention of PCL impingement can be achieved by 3 different techniques: widen the notch so that the space between the PCL and lateral femoral condyle exceeds the diameter of the graft by 1 mm, construct the tibial tunnel at an angle of 60 to 65 degrees with respect to the medial joint line of the tibia, which moves the femoral tunnel farther down the sidewall and decreases the risk of PCL impingement, and making certain that the lateral edge of the tibial tunnel is placed through the tip of the lateral tibial spine. There is no consensus on the amount of ligament tensioning or the optimal knee flexion angle. Some surgeons prefer to set the tension of the AM bundle in moderate flexion and the PL bundle near full extension. The preference for tensioning angles mirrors the position of the bundles to provide the greatest strength when at the most tension in intact knees.

Femoral Tunnel Drilling Techniques

There are different techniques for creating the femoral tunnel. The transtibial technique (drilling through the tibial tunnel) and the far anteromedial portal technique (drilling through the far anteromedial tunnel) are frequently used in ACL surgeries to create a femoral bone tunnel for the AM and PL graft in double-bundle reconstructions (Figure 3). Although both are commonly used, the far anteromedial portal approach makes it easier to access the femoral footprint of the AM and PL bundles. This is because unlike in the transtibial technique, the placement of the femoral tunnel is not limited by the site or angulation of the tibial tunnel. For the far anteromedial portal procedure, the PL bundle tunnel should be drilled at a knee position of 110 degrees of extension to avoid damage to the subchondral bone, cartilage of the lateral femoral condyle, and peroneal nerve. For the transtibial technique, the knee should be flexed at 90 degrees for drilling of the femoral bone tunnel. For the transtibial technique, the graft bending angle of the AM and PL bundles are considerably larger than that of the far anteromedial portal technique at low flexion angles when the graft is fully stretched. Nishimoto et al believe that the far anteromedial portal technique can produce a more obtuse bending angle at the femoral tunnel in comparison to the transtibial technique and that the former approach might reduce the abrasive stress at this position in anatomic double-bundle ACL reconstructions.

Recently, investigators from Duke have emphasized the importance of placing the ACL graft within the ACL footprint on the femur to restore normal joint kinematics. In the tibial tunnel-independent technique, the graft is placed closer to the center of the native ACL attachment compared with the transtibial technique. Using MRI of 8 patients in each group, the transtibial technique placed the tunnel center an average of 9 mm from the center of the ACL attachment, compared with 3 mm for the tibial tunnel-independent technique. In another study, the same group used MRI and biplanar fluoroscopy to compare 12 patients where the graft was placed near the anteroproximal border of the ACL and 10 patients where the graft was placed near the center of the ACL. Grafts placed anteroproximally on the femur were longer and more vertical than the native ACL, whereas anatomically placed grafts more closely mimicked ACL motion and length in the contralateral knee.

**POSTOPERATIVE REHABILITATION**

Goals of postoperative rehabilitation are to restore normal joint motion and strength to the reconstructed knee while protecting the graft. As a consequence of improvements in surgical techniques, graft selection, and fixation methods, rehabilitation programs have changed in recent years to permit immediate weight bearing, early range of motion (within 1-2 weeks after the surgery), and earlier return to sports (usually not before 6 months or until there is return of at least 80% of thigh strength and the ability to do sport-specific agility drills). However, too early return to sports activities may result in graft failure and decisions regarding when to return to sports activities should be based on the functional assessment rather than on time from ACL reconstruction. Generally, early in the rehabilitation program, closed kinematic chain exercises to strengthen the hamstring and quadriceps are started. Closed kinematic chain exercises are those in which the foot is in contact with a solid surface such as with squats and leg presses. Open kinematic chain exercises, in which the foot is not in contact with a solid surface, such as those using leg extension, are considered less safe in the postoperative period and should be added no
sooner than 6 weeks after the surgery. Postoperative rehabilitation should also include exercises to enhance core strength, balance, and proprioception.55

FUTURE DIRECTIONS

Future directions in ACL injury research will seek to improve all aspects of care of the patient with an ACL injury. Research in interface tissue engineering aims to improve the regeneration of tissue interfaces to improve the fixation of soft tissue grafts by devising a new generation of integrative fixation devices for soft tissue repair.56 Freeze-dried allografts offer potential advantages including limited immunogenicity, ease of graft storage, and the potential for improved biologic function.57 Platelet-rich plasma has the potential to speed recovery after ACL reconstruction by improving autograft maturation, donor-site morbidity, pain control, and allograft incorporation.58 Other future developments in ACL reconstruction may include repair of the injured ACL and newer synthetic replacement grafts.59 Whether the potential benefits currently ascribed to each of the above areas will be borne out remains to be determined.

CONCLUSIONS

Anterior cruciate ligament injuries may result in the premature end of athletic careers and serious disability in nonathletes. With a sound knowledge of the anatomy and kinetics of the knee, newer improved surgical techniques have been developed that can restore proper knee function, allowing many athletes to resume their careers, and have also limited disability in nonathletes.

When reconstruction is advised as the correct management of an ACL injury, there are a variety of options. Which type of graft, deciding on a single-bundle versus double-bundle reconstruction, choosing the placement of grafts, and whether to use the transtibial, far anteromedial portal, or tibial bundle reconstruction, choosing the placement of grafts, and fixation of soft tissue grafts by devising a new generation of integrative fixation devices for soft tissue repair.56 Freeze-dried allografts offer potential advantages including limited immunogenicity, ease of graft storage, and the potential for improved biologic function.57 Platelet-rich plasma has the potential to speed recovery after ACL reconstruction by improving autograft maturation, donor-site morbidity, pain control, and allograft incorporation.58 Other future developments in ACL reconstruction may include repair of the injured ACL and newer synthetic replacement grafts.59 Whether the potential benefits currently ascribed to each of the above areas will be borne out remains to be determined.

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