Operative Treatment of Primary Anterior Cruciate Ligament Rupture in Adults

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Operative management of an acute anterior cruciate ligament (ACL) rupture may be required in young and active patients to stabilize the knee and return patients to desired daily activities.

ACL reconstruction should be performed anatomically.

The majority of studies show no differences between anatomic single-bundle and double-bundle ACL reconstruction with respect to patient-reported outcome scores. Double-bundle reconstruction may provide superior knee joint laxity measurements compared with the single-bundle technique.

Following ACL reconstruction, the age and activity level of a patient are predictive of his or her time of return to sports and reinjury.

Concomitant meniscal and/or cartilage damage at the time of surgery, in addition to a persistent knee motion deficit, are associated with the development of osteoarthritis after ACL reconstruction.

Anterior cruciate ligament (ACL) rupture is a common injury worldwide. Estimates suggest an annual incidence for ACL rupture of thirty-five per 100,000 people of all ages, with an approximately two to eight-times higher risk in female athletes than in male athletes. These injuries often result in instability of the knee, increased joint laxity, and reduced activity and participation, as well as an increased risk of knee osteoarthritis in the long term. Surgical reconstruction of the ACL is often recommended, particularly in young and active patients, to facilitate a return to the desired daily activities, including sports.

As the estimated annual health-care cost of ACL surgery is $3 billion in the United States alone, providing patients with the best potential for a successful outcome after ACL reconstruction remains a topic of intense interest among clinicians and researchers. In this review, a critical assessment of the evidence for operative treatment of primary ACL rupture in adults (eighteen years of age or older) is provided, including principles for decision making, clinical outcomes, and guidelines for return to sports.

Anatomy and Function

The ACL is composed of two functional bundles, the anteromedial and posterolateral bundles, which are named for the location of their respective insertion sites on the tibia. The tibial insertion site of the ACL reveals a characteristic fan-shaped footprint, whereas the femoral insertion site demonstrates a smaller, oval-shaped appearance. The femoral insertion site is identifiable
using the position of two osseous ridges on the medial wall of the lateral femoral condyle. The lateral intercondylar ridge, or so-called resident’s ridge, denotes the anterior border of the femoral insertion site. The lateral bifurcate ridge runs perpendicular to the lateral intercondylar ridge, between the femoral insertion sites of the anteromedial and posterolateral bundles.

Functionally, the anteromedial and the posterolateral bundles behave synergistically with knee flexion, whereby both anterior-posterior and rotational stability of the knee are provided. Individually, the anteromedial bundle length remains constant throughout the knee flexion-extension, attaining peak tension between 45° and 60° of flexion. In comparison, the posterolateral bundle is tight in extension and loosens with flexion, thereby allowing axial rotation of the knee to occur. Varying mechanical behaviors of the functional bundles of the ACL have been reported.

A thorough understanding of the anatomy and function of the native ACL is fundamental for the treatment of ACL injuries. This understanding ultimately aids the surgeon in determining the most appropriate treatment strategy for a partial or complete rupture of the ACL.

Treatment of ACL Injuries
ACL injuries can be managed with nonoperative or operative treatment. The decision to recommend operative treatment for an acute ACL rupture is multifactorial and must be individualized to each patient on the basis of his or her age, desired activity level, and presence of potential concomitant injuries. In general, younger and more active patients are more likely to require surgery to return to functionally demanding activities. In the remainder of this review article, we focus on operative treatment of ACL injuries. While rehabilitation after ACL reconstruction is an important aspect of the ultimate success after ACL reconstruction, it is not a focus of this review.

Operative Treatment
Once the decision to proceed with operative treatment of an ACL rupture is made, timing of the procedure becomes an important variable to consider. Preoperative range of motion, swelling, and quadriceps strength have been investigated as factors that can affect the ultimate success of ACL reconstruction. Preoperative swelling and limited range of motion have been related to the development of arthrofibrosis after surgery.

Preoperative quadriceps strength deficits of >20% have been shown to significantly affect the two-year functional outcome of ACL reconstruction with bone-patellar tendon-bone autograft. Moreover, it has been reported that preoperative quadriceps strength of >90% of that of the noninjured leg significantly increased postoperative strength two years after surgery compared with those with <75% of preoperative quadriceps strength. Rehabilitation prior to surgery should focus on regaining range of motion, reducing swelling, and strengthening the quadriceps.

Intraoperatively, the rupture pattern of the ACL should be confirmed, and if a partial one-bundle rupture is evident, augmentation surgery should be considered. Partial ACL ruptures have been reported to occur in approximately 5% to 35% of patients. Performing a one-bundle augmentation surgery carries the theoretical advantages of maintaining proprioceptive fibers, biomechanical strength, and biological healing potential. Careful dissection and preservation of the native insertion sites can facilitate determination of the appropriate tunnel location(s).

Presently, the majority of surgeons who perform ACL reconstructions do so using a single-bundle technique. The double-bundle technique is more commonly utilized in Europe and Asia than it is in the United States. Regardless, it is important to understand the double-bundle anatomy of the ACL so that surgeons can perform an anatomic single-bundle or double-bundle ACL reconstruction. In the event that a surgeon has experience performing double-bundle ACL reconstruction and considers this as part of the preoperative planning process, the decision to perform anatomic single-bundle or double-bundle ACL reconstruction is based on several criteria. A comprehensive flowchart to assist surgeons in this decision has been previously described.

The variation in size of the tibial insertion site is one element to consider (Fig. 1). A tibial insertion site size of <14 mm, measured arthroscopically, makes it difficult to perform a double-bundle reconstruction. Furthermore, arthritic changes, multiligament injury, severe bone bruising, open physees, and a narrow notch width are considered indications to perform single-bundle reconstruction. Variation in the shape of the notch can also influence whether two femoral tunnels can be drilled safely for double-bundle reconstruction.

Typical graft options for ACL reconstruction include bone-patellar tendon-bone autograft, hamstring tendon autograft, quadriceps tendon autograft, and allograft. Of these options,
bone-patellar tendon-bone graft is not suitable for double-bundle reconstruction. For the purposes of preoperative planning, the sagittal thickness of the patellar and quadriceps tendons can be measured on magnetic resonance imaging (MRI) scans to provide the surgeon with an idea as to potential graft size. Studies have also evaluated the use of MRI in predicting hamstring graft size and have found that, while cross-sectional area measurements on MRI scans correlate positively with intraoperative graft size, measurements of graft diameter do not. Magnussen et al. found that a hamstring autograft size of $\leq 8$ mm in diameter was associated with a higher rate of early revision than were those of $>8$ mm. In patients having primary surgery, allograft may be used when there are concerns of donor site morbidity or cosmesis. Fresh-frozen allografts are typically preferred over irradiated, chemically processed, or preserved grafts and provide results equal to those of autografts. Recent studies have, however, indicated higher rates of graft failure following ACL reconstruction with varying types of allograft, particularly in younger active individuals desiring an early return to sport.

Ultimately, daily activities and patient lifestyle influence graft choice for an individual undergoing ACL reconstruction. For example, in a patient with daily activities that include kneeling (e.g., wrestling or religious practices), the use of a bone-patellar tendon-bone autograft may be contraindicated because it is associated with a higher prevalence of anterior knee pain.

Proper tunnel placement is critical in anatomic ACL reconstruction. Nonanatomic tunnel placement has been previously shown to decrease knee motion and to produce abnormal rotational knee kinematics during dynamic loading. A recent study has evaluated the ACL tunnel positions used by twelve surgeons and found a lack of agreement in the ideal position for single-bundle ACL tunnels. Several intraoperative and postoperative methods have been described to evaluate tunnel placement. Postoperatively, anteroposterior and lateral radiographs

<p>| TABLE I Advantages and Disadvantages of Available Graft Choices for ACL Reconstruction |</p>
<table>
<thead>
<tr>
<th>Graft Choice</th>
<th>Advantages</th>
<th>Disadvantages</th>
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<tr>
<td>Bone-patellar tendon-bone</td>
<td>Bone-to-bone healing in both tunnels</td>
<td>Not suitable for double-bundle reconstruction</td>
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<tr>
<td></td>
<td>Comparable stiffness to native ACL</td>
<td>Risk of anterior kneeling pain</td>
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<td>Invasive, large incision</td>
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<td>Risk of patellar fracture</td>
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<td>Fixed length</td>
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<td>Weaker than native ACL</td>
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<td>Hamstring</td>
<td>Ease of harvest</td>
<td>Soft-tissue healing</td>
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<td></td>
<td>Cosmesis</td>
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<td></td>
<td>Minimal donor site morbidity</td>
<td>graft size can be unpredictable</td>
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<td></td>
<td>Comparable strength to native ACL</td>
<td>Not suitable for certain athletes who rely heavily on their hamstring muscles</td>
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<tr>
<td>Quadriceps tendon</td>
<td>Large graft</td>
<td>less stiffness than native ACL</td>
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<td></td>
<td>Can be used for single or double-bundle reconstruction</td>
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<td></td>
<td>Option of a one-sided bone block</td>
<td>Invasive, large incision</td>
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<td>Risk of patellar fracture</td>
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<td>Allograft</td>
<td>No donor site morbidity</td>
<td>Theoretical risk of disease transmission</td>
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<td></td>
<td>Available in various types and sizes</td>
<td>Longer healing time</td>
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<td></td>
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<td>Increased risk of rerupture, especially in younger patients and irradiated grafts</td>
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Fig. 2 A standard 45° flexion weight-bearing posteroanterior (PA) radiograph, made one year after single-bundle ACL reconstruction, demonstrating a 45° femoral tunnel angle relative to the long axis of the femur, suggestive of anatomic tunnel placement.
can be used to evaluate tunnel angle and implant position. Illingworth et al. described a femoral tunnel angle measurement based on the long axis of the femur on an anteroposterior radiograph, whereby an angle of <32.7° is likely to be nonanatomic (Fig. 2). Postoperative MRI measurements of the insertion site, inclination angle, and length of the ACL can also be compared with those made preoperatively (Fig. 3). A three-dimensional computed tomography (CT) scan is presently considered the gold standard for evaluation of tunnel placement (Figs. 4 and 5). Meuffels et al. demonstrated that three-dimensional measurements provided the highest reliability in the evaluation of femoral and tibial tunnel placement. Moreover, a three-dimensional CT scan can be particularly useful in planning for knees in which revision surgery may eventually be required.

Clinical Outcomes After ACL Reconstruction

A Level-I clinical trial by Frobell et al. randomized 121 physically active adults to a structured rehabilitation program with early ACL reconstruction or to a rehabilitation program alone with the option of delayed ACL reconstruction. At the two-year follow-up, the difference using a subscale of the Knee Injury and Osteoarthritis Outcome Score (KOOS) was a mean of 39.2 for the early ACL reconstruction group and a mean of 39.4 points for the rehabilitation and optional delayed reconstruction group (p = 0.96). The rehabilitation and optional delayed reconstruction group had a higher rate of meniscal surgery than the early reconstruction group. Similar results were also found with recently reported five-year results of this trial. In total, thirty patients (51%) in the delayed reconstruction group ultimately had ACL surgery. Therefore, nonoperative management may be feasible in a well-defined cohort of patients with an acute ACL tear who have been counseled accordingly.

The outcomes of single-bundle and double-bundle reconstruction have been reported previously (Figs. 6 and 7). A recent Cochrane review by Tiamklang et al. evaluated the effects of single-bundle compared with double-bundle reconstructions in adult patients in seventeen randomized and quasi-randomized controlled trials. The authors reported no detectable differences between single-bundle and double-bundle reconstructions in patient-reported outcomes up to five years after surgery. The two to five-year follow-up evaluation demonstrated improvements in the International Knee Documentation Committee (IKDC) knee examination, pivot-shift test, and knee laxity measurements on the KT-1000 arthrometer with double-bundle reconstruction. Single-bundle reconstructions had a higher rate of new meniscal injury. Importantly, methodological deficiencies were prevalent in all trials included in the review and should be considered when evaluating the results of this study.

In a recent Level-I randomized controlled trial by Hussein et al., anatomic double-bundle ACL reconstruction was compared with anatomic single-bundle and conventional single-bundle ACL reconstructions with hamstring autograft. Two hundred and eighty-one patients were prospectively followed for a mean of 51.15 months after surgery. The patients in the anatomic double-bundle group had improved anteroposterior laxity (measured with the KT-1000 arthrometer) and rotational laxity (pivot-shift test) compared with the anatomic single-bundle group; the anatomic single-bundle group had improved anteroposterior and rotational laxities compared with conventional...
The only significant difference in patient-reported outcome was a higher Lysholm score in the anatomic double-bundle group in comparison with the conventional single-bundle group. There were no significant differences in patient-reported outcome scores in the comparison of anatomic double-bundle with anatomic single-bundle reconstruction. In a second prospective comparative study (Level II), anatomic single-bundle reconstructions were compared with anatomic double-bundle reconstructions with hamstring autograft, with the procedures individualized on the basis of intraoperative measurements of the native ACL tibial insertion site size. At a mean follow-up of thirty months after surgery, no differences between the groups were detected with respect to the Lysholm and IKDC Subjective Knee Form scores or the results of the KT-1000 measurements and pivot-shift tests.

The majority of published studies have shown no differences between anatomic single-bundle and double-bundle ACL reconstruction in terms of patient-reported outcomes. Differences may exist with regard to knee joint laxity measurements, favoring double-bundle reconstruction. There is also some evidence to suggest that individualized surgery may facilitate similar outcomes with respect to knee joint laxity, regardless of whether single or double-bundle reconstruction is performed. Further investigation is needed to confirm or dispute these findings.

The outcomes after one-bundle augmentation reconstruction for partial rupture of the ACL have been reported in several series. Sonnery-Cottet et al. reported that reconstruction of the anteromedial bundle with preservation of the posterolateral bundle significantly decreased anteroposterior laxity (Telos stress radiography), while significantly increasing the IKDC Subjective Knee Form and Lysholm scores at a mean follow-up of twenty-six months. Adachi et al. compared ACL augmentation surgery in partial ACL tears and complete ACL reconstruction with complete ACL tears at a mean follow-up of 2.6 years. The authors reported augmentation surgery to be superior for joint stability and position sense. A recent systematic review found that...
the available evidence to support augmentation was weak but encouraging.

**In Vivo Biomechanics After ACL Reconstruction**

In vivo kinematic studies evaluate knee biomechanics without the “time-zero” limitation of in vitro studies. They also enable serial assessment of the effects of healing on knee function after ACL reconstruction and can involve realistic weight-bearing activities, such as running, jumping, and stair-climbing.

Georgoulis et al. compared ACL-reconstructed and contralateral, normal knees using conventional video-motion analysis with surface markers. While no differences were evident during walking, greater internal tibial rotation in the reconstructed knee was observed during more demanding pivoting tasks. Tashman et al. used dynamic stereoradiography to assess knee kinematics during the stance phase of downhill running, and found greater external rotation and adduction in ACL-reconstructed knees compared with the contralateral, uninjured limbs. The surgical technique used for that study incorporated nonanatomic placement of the graft, demonstrating that nonanatomic ACL reconstruction fails to restore preinjury knee function under functional loading conditions. Abebe et al. utilized biplanar fluoroscopy and MRI to evaluate knee function during a series of static joint positions and reported that single-bundle reconstruction with anatomic femoral tunnel placement resulted in knee joint kinematics that were more closely restored relative to the intact knee compared with nonanatomic tunnel placement.

In a separate study, tibiofemoral rotations and translations in knees that had anatomic double-bundle ACL reconstruction were compared with those in the contralateral, normal knees using a biplane radiographic system during the early to midstance phase of running. A model-based tracking method was also utilized to evaluate tibiofemoral kinematics. No significant or clinically important differences were found between the ACL-reconstructed and contralateral limbs with regard to kinematic variables after anatomic double-bundle reconstruction.
These results suggest that anatomic double-bundle reconstruction may be effective for restoring knee function compared with the uninjured side. It is not, however, known whether anatomic single-bundle reconstruction may produce results similar to anatomic double-bundle reconstruction compared with the contralateral knee.

**Return to Sports After ACL Reconstruction**

The timing of return to sports after ACL reconstruction is multifactorial. Graft choice is an important consideration with regard to whether there is bone-to-bone healing (bone-patellar tendon-bone graft) or soft tissue-to-bone healing. In a systematic review and meta-analysis, Ardern et al. assessed forty-eight studies with a total of 5770 patients at a mean follow-up of 41.5 months after ACL reconstruction. In total, while 82% of the patients reported returning to some level of sporting activity, 63% of the patients returned to sports participation at the preinjury level, and only 44% returned to competitive sports. The leading reason given for not returning to sporting activity was fear of reinjury.

Brophy et al. evaluated the return to sports among soccer athletes and found that younger or male athletes were more likely to return to play than were older or female athletes. Smith et al., who separately evaluated the return to the preinjury activity level among seventy-seven competitive athletes with a mean age of twenty-one years (range, fifteen to thirty years), found that 71% (fifty-five) returned to preinjury activity levels by twelve months after surgery. Further research on return to sports should evaluate the rate of return to the preinjury activity in terms of the type, frequency, intensity, and duration of participation.

**Graft Failure After ACL Reconstruction**

Graft failure in the ipsilateral knee after ACL reconstruction and native ACL rupture in the contralateral knee have been investigated. A recent study from the Danish Knee Ligament Reconstruction Register compared anteromedial with transtibial femoral tunnel drilling during ACL reconstruction. Anteromedial drilling had a higher overall rate of revision surgery (5.16%) than transtibial drilling (3.20%), with a relative risk of 2.04 (95% confidence interval, 1.39 to 2.99). Surgeons should use caution when evaluating these results, given the tendency of the transtibial technique to place the graft in a nonanatomic position. Individuals undergoing anatomic ACL reconstruction may be at higher risk for graft failure, particularly with early return to activity, given the higher, closer to normal, in situ forces on an anatomically placed graft.

A recent study by Bourke et al. of patients undergoing ACL reconstruction with either bone-patellar tendon-bone or hamstring autograft found graft failure to be 11%, while concomitant ACL rupture was 13%. Graft choice did not affect failure rate. Other authors have also reported a higher risk of failure in the contralateral ACL compared with the ipsilateral graft. Shelbourne et al. followed 1415 patients for a minimum of five years after ACL reconstruction with bone-patellar tendon-bone autograft and found a lower patient age and higher activity level to be associated with increased injury to either knee. Returning to activity before six months postoperatively did not appear to increase the risk for injury. In this particular study, the group with an age of less than eighteen years returned at a mean 4.6 months after surgery. In a prospective analysis of failure in anatomic ACL reconstruction with allograft, van Eck et al. found that 48% (thirteen) of twenty-seven reruptures occurred within nine months after surgery, before the patients had received clearance to return to sports. Further investigation is required to determine factors affecting ACL graft failure, including consideration for graft healing. On the basis of the available evidence, a lower patient age and higher activity level, but not time to return to sport, appear to be predictive of reinjury.

**Osteoarthritis After ACL Reconstruction**

The development of osteoarthritis after ACL reconstruction is a concern. Li et al. retrospectively investigated the predictors of radiographic knee osteoarthritis after nonanatomic single-bundle ACL reconstruction. Radiographic osteoarthritis, defined as Kellgren and Lawrence grade-2 changes in at least one compartment or grade-1 changes in at least two compartments, were demonstrated by 39% (ninety-six) of 249 patients at a mean 7.86 years follow-up. The most optimal set of predictors for osteoarthritis were body mass index, length of follow-up, prior medial meniscectomy, and medial chondrosis of grade 2 or greater. Separately, Roe et al. investigated differences in osteoarthritis rates in a consecutive cohort of nonrandomized patients who underwent ACL reconstruction with hamstring or bone-patellar tendon-bone autograft. At seven years of follow-up, 45% (twenty-four) of fifty-three patients in the bone-patellar tendon-bone group and 14% (seven) of fifty-one in the hamstring group showed signs of radiographic osteoarthritis (p = 0.002).

Several studies with longer-term follow-up have also been performed. Oiestad et al. prospectively evaluated knee function and the prevalence of osteoarthritis in patients ten to fifteen years after isolated ACL reconstruction and in patients who had concomitant meniscal and/or cartilage pathology. Radiographic assessment using the Kellgren and Lawrence classification system revealed that 80% of the patients in the concomitant pathology group had joint space narrowing of grade 2 or greater compared with 62% in the isolated group (p = 0.008). However, differences were not detectable between groups with respect to symptomatic osteoarthritis. In a separate study of the same cohort, Oiestad et al. reported that the prevalence of patellofemoral osteoarthritis was 26.5% (forty-eight of 181 patients twelve years after reconstruction) and was associated with older age, increased symptoms, and greater tibiofemoral osteoarthritis, as well as reduced knee function. Salmon et al. also reported an association between degenerative joint changes and meniscectomy, increased knee joint laxity, and loss of knee motion thirteen years after ACL reconstruction with bone-patellar tendon-bone autograft. Similarly, Shelbourne et al. evaluated 780 patients undergoing ACL reconstruction with bone-patellar tendon-bone autograft and, at a minimum of five years of follow-up, found that the loss of normal knee flexion and extension was associated with an increased rate of radiographic osteoarthritis. In two separate studies of patients in whom concomitant knee pathology was absent at the time of surgery, Shelbourne and Gray and Lebel et al. reported...
that the rate of osteoarthritis was 2% and 8%, respectively, beyond the mean follow-up time of ten years.

It is the general consensus of the available evidence that meniscal and/or cartilage damage and knee motion deficits after surgery are associated with the development and/or progression of osteoarthritis after ACL reconstruction. Furthermore, patients without concomitant joint pathology at the time of ACL surgery appear to have a low rate of osteoarthritis, even at relatively long-term follow-up. Continued investigation into the cause and development of osteoarthritis after ACL reconstruction, including early recognition via advanced imaging modalities or identification of relevant biomarkers, will be important.

In conclusion, operative management of acute ACL rupture is common in young and active patients and can achieve predictable outcomes (Table II). The use of double-bundle reconstruction appears to provide no difference compared with single-bundle reconstruction in patient-reported outcomes. The age and activity level of the patient are predictive of the return to sports and of reinjury. On the basis of the currently available data, the time to return to sports may not be predictive of reinjury to the reconstructed ACL. Meniscal and/or cartilage pathology noted at the time of ACL reconstruction, as well as a knee motion deficit postoperatively, are associated with the development and/or progression of osteoarthritis. Future studies investigating operative methods for the treatment of ACL injuries are warranted. It is imperative that these studies be adequately powered and use patient-relevant and sensitive outcome measures.

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