

Graft Selection for Anterior Cruciate Ligament Reconstruction

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Abstract

More than 100,000 anterior cruciate ligament reconstructions are done in the United States each year. With improvements in technology and surgical ability, the number of variables that must be considered has increased dramatically. The choice of autograft or allograft, which is one of the most important variables, has largely become a decision to be made by the surgeon and the patient. It is critical to understand the advantages and disadvantages of each type of graft to make informed and intelligent decisions.

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Anterior cruciate ligament (ACL) reconstruction is the sixth most common orthopaedic procedure in the United States; more than 100,000 are done each year.¹ ACL reconstruction is rapidly evolving, and it is essential to keep up to date on surgical techniques. Approximately 85% of surgeons doing ACL surgery perform fewer than 10 such procedures each year. Success rates among experts are no better than 85% to 90%, and they are lower if the determining factor is a return to sport at the preinjury level.¹

As efforts continue to improve

function and return to sport, ACL reconstruction has become more complex. The choice of graft, graft size, single- or double-bundle reconstruction, tunnel placement, fixation method, preoperative and postoperative rehabilitation, and time to return to sport are important factors and have significant variability.

Autografts and Allografts

The selection of graft is controversial. Each type of graft has unique properties as well as advantages and disadvantages. The ideal graft would reproduce the native anatomy and normal

biomechanics; allow strong initial fixation and rapid incorporation; have a low rate of donor site morbidity; have a low risk of disease transmission; have sufficient length, diameter, and flexibility to accomplish the desired purpose; and be cost-effective.² The three broad categories of grafts are autografts, allografts, and synthetic grafts. In the autograft category, the three primary types are bone–patellar tendon–bone (BPTB); hamstring, which is composed of the gracilis and semitendinosus tendons; and the quadriceps tendon. Among allografts, the choices are anterior and posterior tibial, semitendinosus, gracilis, Achilles, and quadriceps tendons as well as BPTB. The available synthetic graft types are Dacron, silk, and ligament assistive device. (DVD 34.1)

Biomechanical Properties

The native ACL has an ultimate tensile load of 2,160 N and a stiffness of 242 N/mm.³⁻⁵ No graft choice is superior to any other from a mechanical standpoint because all are stron-

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ger than the native ACL. Among 10-mm autografts (mean cross-sectional area = 32.3 mm²), BPTB has an ultimate tensile load of 2,977 N and a stiffness of 620 N/mm, quadrupled hamstring (mean cross-sectional area = 52.9 mm²) has an ultimate tensile load of 4,090 N and a stiffness of 776 N/mm, and quadriceps tendon (mean cross-sectional area = 64.6 mm²) has an ultimate tensile load of 2,174 N and a stiffness of 463 N/mm.⁶⁻⁹ Among allografts, the ultimate tensile loads of doubled anterior (mean cross-sectional area = 48.2 mm²) and posterior (mean cross-sectional area = 41.9 mm²) tibial tendon are 4,122 N and 3,594 N, respectively, with a stiffness of 460 N/mm and 379 N/mm, respectively;^{10,11} Achilles tendon (mean cross-sectional area = 67 mm²) has an ultimate tensile load of 4,617 N and a stiffness of 685 N/mm.^{12,13}

Freezing and storage have a minimal effect on the ultimate tensile strength and load deformation mechanics of donor ligaments.^{14,15} The effect of donor age on the biomechanical properties of donor ligaments also is minimal.¹¹

Graft Incorporation

Grafts differ in the time required for incorporation, and this factor can affect the time to return to sport. ACL incorporation proceeds through three different phases: inflammation and graft necrosis, revascularization and cell repopulation, and graft remodeling. Inflammation and graft necrosis begin almost immediately after surgery and can continue for as long as 2 months. The donor fibroblasts undergo cell death, and the remaining collagenous tissue becomes a scaffold for later remodeling.^{16,17} With revascularization and the migration of host fibroblasts into the

graft tissue, the graft itself undergoes mechanical changes. The graft can be as weak as 11% of normal strength, and this phase can last as long as 6 months after surgery.¹⁸ Eventually, the graft is incorporated and matures. The cellular population and collagen fiber orientation appear nearly normal within 12 to 18 months after surgery.¹⁹⁻²³

Time to incorporation varies among the types of graft material. In general, autografts are incorporated more quickly than allografts. Autograft BPTB is incorporated within 6 weeks, autograft hamstring within 12 weeks, and autograft quadriceps tendon in 6 to 12 weeks.⁶⁻⁸ BPTB, hamstring, anterior and posterior tibial, and Achilles tendon allografts are incorporated as late as 6 months.^{6,7,11,13}

Graft Harvesting

The potential for donor site morbidity must be considered with an autograft. Each type of autograft presents its own challenges, and the harvesting procedure is highly dependent on the surgeon. For example, harvesting a BPTB autograft requires bony cuts into both the tibia and the patella, with a risk of stress fracture and articular cartilage damage to the patella. Quadriceps tendon harvesting is difficult because of the denser cortical bone in the proximal patella, the curved patellar surface, and the adherent suprapatellar pouch. Hamstring harvesting requires identifying and reflecting the sartorial fascia and then identifying the gracilis and semitendinosus tendons to protect other structures in the vicinity, such as the medial collateral ligament. It is important to harvest the tendon carefully to avoid premature amputation of the graft.²

Anterior knee pain is common after ACL reconstruction. Several

studies found a tendency toward increased anterior knee pain after a BPTB autograft harvest.²⁴⁻²⁹ However, anterior knee pain is equally common after BPTB autograft and allograft ACL reconstructions and therefore probably is not specifically caused by donor site morbidity.¹⁹ Anterior knee pain may be caused by loss of motion, quadriceps weakness, and inadequate rehabilitation. An accelerated rehabilitation protocol with faster return of range of motion could decrease symptom severity.^{20,21}

Donor site complications are infrequent but serious. The complications related to BPTB autograft include patellar fracture, patellar tendon rupture, tendinitis, local tenderness, and numbness.^{22,23} The complications associated with hamstring autograft include injury to the superficial branch of the saphenous nerve, premature truncation of the hamstring tendon graft, and residual muscle weakness with deep flexion.^{24,25}

Disease Transmission

There is a small but significant risk of disease transmission when allografts are used. Multiple safeguards are in place, and the filtering process is evolving. The American Association of Tissue Banks (AATB) continually updates its policies and now requires a detailed sexual, medical, and social history for every potential cadaver donor. Donor tissue is tested for human immunodeficiency virus (HIV) -1 and -2, hepatitis B and C, syphilis, human T-cell lymphotropic virus, and aerobic and anaerobic bacteria. The US Centers for Disease Control and Prevention (CDC) has reported the occurrence of 26 allograft-associated bacterial infections after 1 million procedures.^{26,27}

Cost-Effectiveness

The popular belief that the cost of using allografts is higher than that of using autografts is a misconception. Variables related to individual surgical techniques affect the cost of the procedure, including the ease of autograft harvest, the number of allografts used (single- or double-bundle), the recovery room time, and the possible need for an overnight patient stay after autograft surgery because of harvest-related pain. A prospective, nonrandomized study compared the cost of isolated ACL reconstruction using allograft or autograft. Operating room costs were higher for autograft procedures because of the greater operating time associated with graft harvest, but this factor did not offset the cost of the allograft tissue itself. The cost of autograft procedures was related to the increased likelihood of an overnight patient hospital stay, although this factor was the result of surgeon preference. The authors concluded that allograft Achilles tendon ACL was less expensive than autograft BPTB because of shorter surgical time and a lower rate of overnight admission for pain control.²⁸

Clinical Outcomes

No Level I prospective, randomized studies have compared the clinical outcomes of using autograft or allograft tissue in ACL reconstruction. In all intermediate- and long-term studies comparing the use of autograft and allograft tissues in ACL reconstruction, 85% to 90% of all patients had a good or excellent result, as measured by both subjective and objective instruments.²⁹⁻³⁷

Using Multiple Grafts

The preferred choice of ACL grafts for the senior author (FF) and those

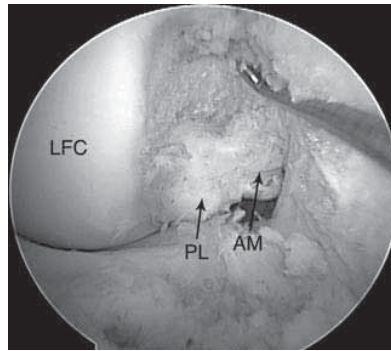


Figure 1 The arthroscope in the anteromedial portal allows an excellent view of the femoral insertions of the AM and PL bundles. In 90° of knee flexion, the femoral insertion sites of the AM and PL bundles are horizontally aligned. Ample room is available on the lateral wall of the notch to drill the tunnel nonanatomically. LFC = lateral femoral condyle.

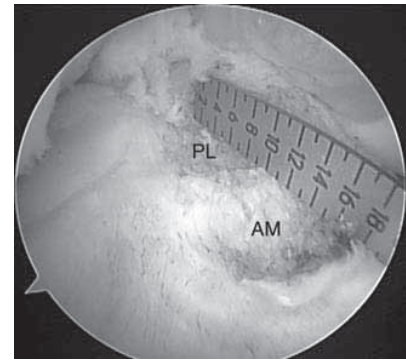


Figure 2 The footprints of the AM and PL bundles (tibial side) are marked with a thermal device, and their length and width are measured.

at his academic institution (University of Pittsburgh Medical Center, Pittsburgh, PA) has evolved with research findings as well as experience in performing 50 to 300 ACL surgeries per year since 1982. Originally, BPTB autografts were used; in the mid 1980s BPTB and Achilles tendon allografts were preferred; in the early 1990s, soft-tissue autografts; and in the late 1990s, anterior tibial allografts. Since 2002, double-bundle reconstruction using allograft tissue has been the predominant choice for ACL reconstruction.

Factors to consider regarding graft selection include the patient's preference, lifestyle, age, sports participation, and comorbidities, such as an earlier trauma or hamstring injury, a patellofemoral condition, or Osgood-Schlatter disease. Allograft soft tissue, particularly anterior tibial tendon tissue, is generally preferred. Long-term studies have found no definitive advantage to using autograft tissue. With allograft tissue,

there is no need to consider donor site morbidity, and the risk of disease transmission is exceedingly small. In addition, allograft soft tissue allows sufficient flexibility for double-bundle ACL surgery. The ACL is reconstructed in an anatomic fashion with respect to tunnel location and graft size. After measuring the insertion site size of both the anteromedial (AM) and posterolateral (PL) bundles in the femur and tibia, the graft can be tailored to a specific size.

Several intraoperative steps are key to providing the most anatomic reconstruction possible. The injury pattern of the torn ACL is first identified. A thermal device is used to isolate and measure the insertion sites of the tibia and femur (Figures 1 and 2). The minimal insertion site size is 12 mm; anatomic double-bundle reconstruction proceeds if the anatomic insertion sites are large enough to accommodate tunnels in both the femur and the tibia (Figure 3). In the senior author's practice, approximately 20% of patients have an entire ACL insertion site length of less than 12 mm or an open physis, severe arthritic changes, or multiple ligament inju-

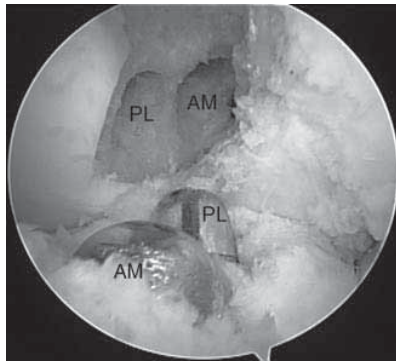


Figure 3 The final appearance of the anatomically placed femoral and tibial tunnels before graft passage, with dilators protruding from the tibial tunnels.

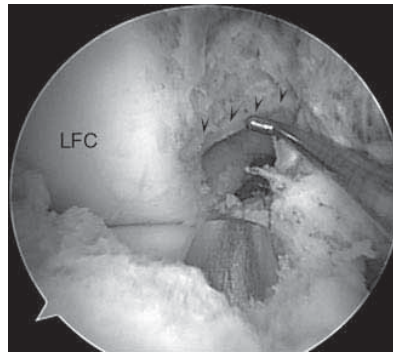


Figure 4 Anatomic single-bundle ACL surgery is done by placing the single tibial and femoral tunnels between the anatomic AM and PL insertion sites on both the tibia and femur. The arrows point to the intercondylar ridge. LFC = lateral femoral condyle.

ries. These patients are treated with an anatomic single-bundle reconstruction with tunnel placement between the anatomic insertion sites of the AM and PL bundles (Figure 4). Suspensory fixation on the femoral side and interference fixation on the tibial side are preferred. In an attempt to reproduce the native tensioning patterns, the PL bundle is fixed in full extension; the AM bundle then is fixed at 45° of flexion.³⁸

The patient uses crutches and a brace during the first 4 weeks, undergoes 3 months of supervised physical therapy and range-of-motion exercises, and returns to sports activities between 6 and 9 months after surgery. In the first 100 consecutive procedures over a 2-year period, allograft was used in 83 and hamstring autograft in 17. The clinical outcomes were evaluated more than 2 years after surgery. The average side-to-side difference in range of motion was 2° in extension and 2° in flexion. As measured with the KT-2000 Arthrometer (Medmetric, San Diego, CA), the average side-to-side difference in anterior-posterior translation was 1 mm. Ninety-four percent of the

patients had a normal pivot-shift test, and 6% had an almost normal test. None of the patients reported pain, swelling, or instability during activities of daily living, and 72% reported no problems during strenuous or very strenuous sports activities performed on a regular basis.³⁹

Using Hamstring Autografts

An ACL study group survey found that BPTB autograft was the most commonly used graft for ACL reconstruction, and hamstring autograft was the second most commonly used (J Campbell, MD, Hawaii, unpublished data, 2006). The use of hamstring autograft is increasing because the functional results are similar to those of BPTB graft but morbidity rates are lower.

Surgical Technique for Hamstring Harvesting

The knee joint is flexed at 90°, and the skin incision is made using a 3-cm vertical, transverse, or oblique incision 4 cm medial and just distal to the tibial tubercle. The pes anserinus often is easier to feel than to see.

Two bumps that identify the tendons are felt when a finger is passed over the insertion from proximal to distal; the higher bump is the gracilis tendon, and the lower one is the semitendinosus tendon. The gracilis is round and palpable deep to the aponeurosis of the sartorius; the semitendinosus is flatter and inferiorly located. An incision along the superior border of this aponeurosis exposes the two tendons. The tendons become more distinct medially and proximally, where they can be isolated and picked up with a right angle clamp or a tendon hook. A Penrose drain is placed around each tendon for easier manipulation.

The tendons, especially the semitendinosus, usually have some adhesions, and there may be some anatomic variation. Any surrounding tissues must be separated with scissors from the tendons, with the knee flexed at 90° and a finger around the tendon. A hard pull on the semitendinosus may be required to be sure of cutting the proximal accessory tendon, which is 8 to 10 cm from the tibial insertion.

The tendon stripper does not meet strong resistance while advancing. If jamming occurs, the stripper must be removed retrograde, and the tendon is further released before proceeding. The tendon insertion is left intact while an open tendon stripper is used. A small open-section corkscrew tendon stripper is slipped onto the tendon and gently advanced. It is important to maintain tension on the tendon and avoid rotating or changing the orientation of the tendon stripper while harvesting. This procedure is done for both tendons. To provide an additional length of approximately 2 cm for the graft, the tendons should be detached as distally as possible by separating the aponeurosis from each side of the distal tendon insertions

and detaching them with part of the periosteum.

When using a closed stripper, tendons must be transected as distally as possible. A No. 2 suture is whipstitched at the end of the tendon to apply tension to the tendon during stripping. In general, a closed tendon stripper can harvest a longer tendon graft with more muscular tissue than an open stripper, and it is easier to use. A closed stripper allows the tendon length to be selected before cutting. In both open and closed tendon stripping, any muscle fiber remnants should be stripped from the tendon to avoid an unnecessary increase in graft diameter (Figure 5).

Complications Related to Hamstring Harvesting

Nerve Injury

The reported incidence of injury to the infrapatellar or main branch of the saphenous nerve during harvesting of the hamstring autograft is as high as 55%.^{40,41} This injury decreases anterolateral or distal skin sensation and can cause sensory loss or hyperalgia; pain with ambulation; and neuropathic pain in the medial knee, calf, and ankle. Severe nerve pain is treated with neurolysis or neurectomy. The likelihood of injury to the infrapatellar branch can be decreased with blunt dissection and an oblique or horizontal skin incision.^{40,42,43} The main saphenous branch is less likely to be injured if the knee is bent and the hip is externally rotated while harvesting the gracilis tendon to decrease tension on the nerve as it crosses the tendon.

Donor Site Pain

There is a risk of pain with kneeling after a hamstring autograft harvest, although the frequency is lower than

after a BPTB autograft (6% and 30%, respectively, at 2-year follow-up).⁴⁴ After 10 years, the risk of anterior knee and kneeling pain is lower after hamstring harvest than after BPTB harvest.⁴⁵ Harvest site morbidity was found to be higher in women (M Kurosaka, MD, San Diego, CA, unpublished data presented at the American Academy of Orthopaedic Surgeons annual meeting, 2007); activity-related soreness at the donor site among both men and women was resolved by 3 months.³¹

Medial Collateral Ligament Injury

In the experience of one of the authors (PC), the superficial medial collateral ligament is at risk of being damaged with the scalpel during incision into the sartorius fascia, although this injury is rare. This complication has not yet been reported in the literature.

Premature Graft Amputation

If the tendons are not sufficiently freed from all fascial bands and accessory insertions before stripping, the stripper can be misdirected and produce a short, truncated graft. An accessory semitendinosus insertion diverges from the main tendon to attach to the medial head of the gastrocnemius-soleus complex, approximately 5 to 10 cm proximal to the distal insertion. This band must be cut prior to harvest.

Prodromos and associates³² suggested using a posterior mini-incision in the medial part of the popliteal flexion crease for viewing and cutting the proximal accessory semitendinosus tendon. The length of the anterior incision can be decreased to improve cosmesis. This method may be useful in revision surgery, where the tissue layers stick together in the vicinity of an earlier tibial tunnel. (DVD 34.2)

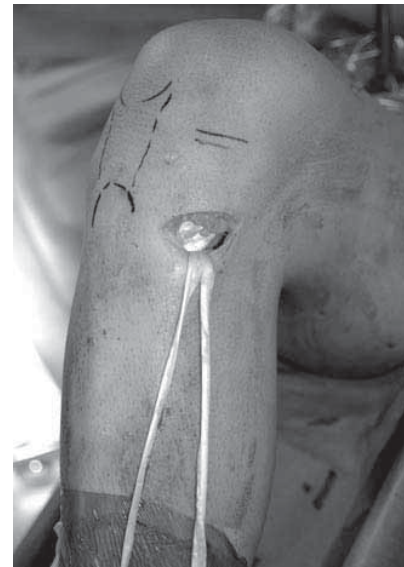


Figure 5 The semitendinosus and gracilis tendon have been harvested with an open stripper through a horizontal skin incision. The tibial tubercle and medial joint line landmarks are marked.

Hamstring Strength Deficit

The deficit in hamstring strength is minimal and temporary, and strength returns to normal after a short period of rehabilitation.^{31,33-35,41} Regeneration of the tendons and semimembranosus can be seen on CT and MRI studies.^{34,36,37,46-48}

Graft Characteristics and Fixation

Four-Strand Hamstring Grafts

A four-strand hamstring graft has a broader footprint than a single-strand graft, but its complex structure requires uniform tensioning and fixation of all strands.⁷ Soft-tissue grafts have a slower rate of tunnel incorporation because tendon-to-bone healing takes longer (12 weeks) than bone-to-bone healing (6 weeks).⁴⁹ Hamstring grafts have a collagen mass 65% greater than that of BPTB graft and have larger collagen fibers. The ultimate tensile strength of the

hamstring graft is as high as 4,500 N with uniform tensioning, and the average cross-sectional area is 52.9 mm² compared with an average cross-sectional area of 32.3 mm² for a 10-mm BPTB graft.

The strength and stiffness of the fixation construct primarily depend on the bone properties and fixation type. To optimize hamstring fixation, the graft implant complex should be preconditioned before femoral and tibial fixation. Aperture fixation offers no stability advantage.⁵⁰ On the femoral side, hybrid fixation is the strongest type of fixation for four-strand hamstring grafts, followed in descending order of strength by onlay grafting, crossed pins, and interference screws.⁵¹⁻⁵³ The tibial fixation is the weak link of the construct; it is strongest when expandable devices are used, followed by hybrid fixation, interference screws, and onlay grafting.^{52,53}

Outcomes of Single-Bundle Hamstring and BPTB Grafts

No significant differences in activity level, subjective assessment, or range of motion have been identified between single-bundle hamstring and BPTB grafts at short-, mid-, or long-term follow-up.⁴⁵ Gait analysis studies have shown that neither single-bundle soft-tissue grafts nor BPTB grafts control internal rotation.^{54,55} The residual pivot-shift rate (for example, moderate or severe glide) is 9% to 64% after BPTB reconstruction and 35% to 50% after a four-strand single-bundle hamstring reconstruction.⁵⁶⁻⁶³ KT-1000 measurements revealed more residual laxity after hamstring grafts than after BPTB grafts, but these results were based on first-generation fixation methods (interference screws, in-

line staples with graft slippage) and included two-strand grafts.^{44,57,64,65}

A meta-analysis by Prodromos and associates⁵⁰ compared BPTB and four-strand hamstring grafts fixed with second-generation methods (buttons, hybrid tibial fixation) and found that four-strand hamstring grafts had an overall higher stability than BPTB grafts. Stability after four-strand hamstring grafting was found to be fixation dependent. The rate of stability after four-strand hamstring grafts with button femoral fixation and second-generation tibial fixation was higher than that of any other graft-and-fixation combination.

No discernible radiographic differences between hamstring and BPTB grafts were found at 5-year follow-up (M Kurosaka, MD, San Diego, CA, unpublished data presented at the American Academy of Orthopaedic Surgeons annual meeting, 2007). At 10-year follow-up, Pinczewski and associates⁴⁵ reported less moderate-grade osteoarthritis with four-strand hamstring grafts than with BPTB grafts. Early re-rupture rates were higher after hamstring grafts than after BPTB grafts, but late re-rupture rates were identical. Instrumented laxity of more than 2 mm was associated with contralateral ACL rupture at 2-year follow-up.

Anatomic ACL Reconstruction With Double-Bundle Hamstring Grafts

Anatomic ACL reconstruction designed to replicate the AM and PL bundles is based on the hypothesis that a reconstructed AM bundle controls anterior tibial translation and a reconstructed PL bundle controls tibial rotation. Numerous studies have supported the use of this method to reproduce normal

knee kinematics.^{56,62,66-71} Improving knowledge of ACL footprint anatomy has led to greater standardization of surgical technique. The procedure has become popular in Japan, Europe, and, more recently, the United States.⁷²

Graft Preparation

A double-stranded semitendinosus graft with a diameter between 6 and 9 mm is used for reconstructing the AM bundle. A double-stranded gracilis tendon graft is used for the PL bundle (Figure 6). If the diameter of the double-stranded gracilis graft is less than 5 mm, the tendon graft can be tripled or quadrupled.

Surgical Technique

An anatomic reconstruction is based on drilling four tunnels in the center of the anatomic insertion sites of the AM and PL bundles on both the femur and the tibia (Figure 7). Using an accessory AM skin portal helps in positioning the tunnels in the lateral femoral condyle. Because of length variations, the AM bundle is tensioned and fixed at 45° to 60° of knee flexion. The PL bundle is tensioned and fixed with the knee close to full extension (Figure 8). Graft fixation is achieved with a button device at the femoral site and a hybrid interference screw and screw-post system at the tibial site.

Outcomes of Single-Bundle and Double-Bundle Hamstring Reconstruction

Robotic and navigation studies found that reconstruction of both bundles leads to a pattern of stability almost identical to the kinematics of a normal knee.^{70,73,74} Gait analysis showed that although BPTB and single-bundle four-strand hamstring reconstruction does not control tibial internal rotation,^{54,55} an

anatomic two-bundle reconstruction does (AD Georgoulis, MD, Ioannina, Greece, personal communication, 2007).

Several studies that compared four-strand hamstring single-bundle reconstruction with anatomic double-bundle reconstruction reported no differences in function or subjective outcomes.⁵⁸⁻⁶³ Few differences have been found in the results of instrumented anterior stability tests, although significantly less positive control of rotational stability (pivot shift) was present after anatomic double-bundle ACL reconstruction (Table 1). However, reconstruction with the double-bundle technique was shown to improve the pivot shift, using clinical or instrumented measures.⁵⁸⁻⁶³

Compared with BPTB grafts, using hamstring autografts for ACL reconstruction leads to less morbidity and provides identical, if not superior, anterior stability and functional results. However, hamstring graft harvesting is more demanding.

Using BPTB Autografts

BPTB autograft has long been considered the gold standard for ACL reconstruction.⁷⁵⁻⁸⁰ Although the increasing popularity of hamstring autograft has lowered the status of BPTB autograft, it remains the best graft choice in a variety of circumstances.

Autograft Versus Allograft

Autografts have several advantages over allografts, and well-publicized difficulties with the use of allografts have had the effect of supporting the use of autografts. Proponents of allografts have suggested that athletes can return to play sooner because of the lack of donor site morbidity. However, allografts have been shown in the animal model to have a

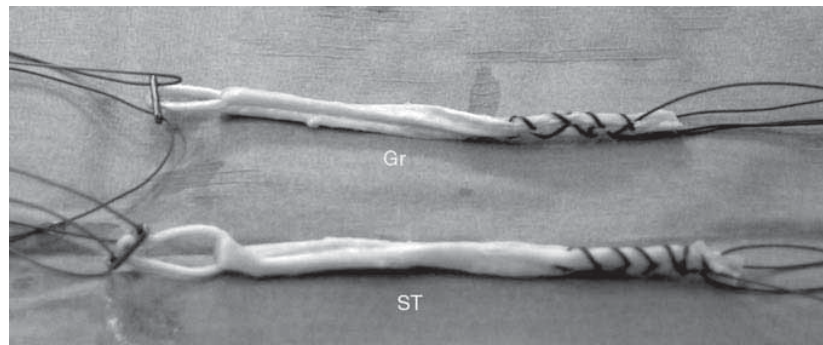


Figure 6 Each tendon has been fashioned by passing a tendon loop through a button (20 mm for the semitendinosus and 15 mm for the gracilis). The free ends of the tendons are stitched together on a 35-mm length with a continuous baseball stitch. The semitendinosus is used for reconstructing the AM bundle, and the gracilis is used for the PL bundle. Gr = gracilis tendon, ST = semitendinosus.

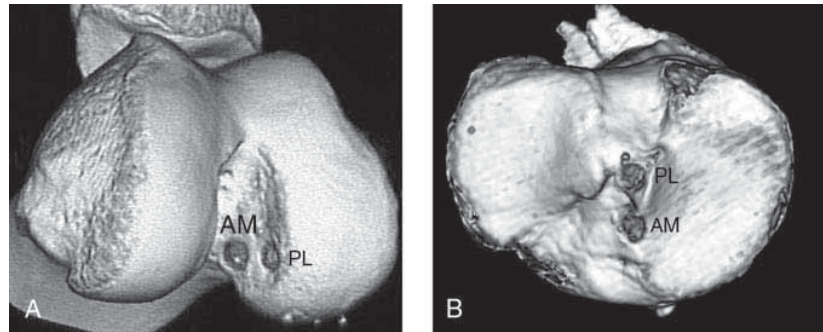


Figure 7 **A**, A three-dimensional CT scan of the AM and PL femoral tunnels. The average diameter of the AM tunnel is 7 mm, and the PL tunnel is 6 mm. The distance between the centers of the tunnels is 8 to 9 mm. Both femoral tunnels are located behind the resident's ridge (also called lateral intercondylar ridge) when the notch is viewed from the AM portal. **B**, CT scan showing the tibial tunnels; the PL tibial tunnel is posterior and slightly lateral to the AM tunnel.

longer incorporation time.⁸¹ Therefore an allograft is at greater risk of rupture than an autograft with early return to play. The clinical results of allografts used in ACL reconstruction approach those of autografts. However, several studies have shown increased laxity over time with allograft use.⁸²⁻⁸⁵

The risk of viral or bacterial contamination of allograft tissue can be devastating, as was revealed by highly publicized infections from allografts obtained under suspicious circumstances. The risk of infection prob-

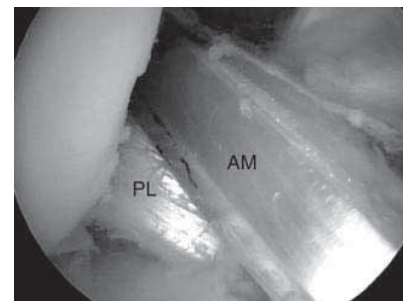


Figure 8 Endoscopic view of a two-bundle ACL reconstruction. The PL bundle crosses the AM bundle from behind. The AM bundle is primarily sagittally oriented. The PL bundle has a more transverse orientation to control tibial rotation.

Table 1
Studies of Instrumented Anterior Stability Tests

Study	Surgical Techniques	KT-1000 Measured Side-to-Side Difference (mm)	% of Patients With a Pivot Shift
Yagi et al ⁶⁰	Single-bundle AM	1.9	25
	Single-bundle PL	1.7	20
	Anatomic double bundle	1.3	15
Aglietti et al ⁵⁸	Single bundle	2.4	42
	Double-bundle transtibial	1.6	24
	Anatomic double bundle (outside in)	1.4	16
Yasuda et al ⁵⁹	Single bundle	2.8	50
	Anatomic double bundle	1.1	12.5
Jarvela ⁶¹	Single bundle	1.8	36
	Anatomic double bundle	1.4	3.33
Muneta et al ⁶²	Single bundle	2.4	41.2
	Anatomic double bundle	1.4	14.7
Asagumo et al ⁶³	Single bundle	1.9	19.2
	Anatomic double bundle	1.7	12.7
Mean values (all studies)	Single bundle	2.12	34.8
	Anatomic double bundle	1.18	10.6

ably is underreported because there is no official monitoring system. Two infections involving *Clostridium sordellii* were reported to the CDC in 2001. The incident came to public attention when one of the patients died from sepsis. A subsequent CDC investigation into allografts used for musculoskeletal procedures identified 14 patients with allograft-associated *Clostridium* infections. All of the infected allografts were obtained from a single tissue bank.⁸⁶ Although recommendations were made to improve screening and allograft preparation procedures, these and similar incidents continue to concern orthopaedic surgeons. A recent study of all ACL allografts used by a single surgeon found that 4.8% were positive on routine cultures, although no clinical infections resulted.⁸⁷

This study heightened concern about the potential for catastrophic infection in patients receiving allograft tissue.

The host immunologic response also is of some concern when using intra-articular allografts, but it does not have a significant effect on clinical outcomes. Immunogenicity decreases with washing and freezing; however, there is an increased risk of rejection with fresh osteochondral allografts.⁸⁸

Autograft also has the advantages of availability and cost. The increasing popularity of allografts, particularly BPTB allografts, has led to a shortage during the past several years. The cost of allografts varies with the individual supplier. To some extent, the cost of obtaining allograft tissue is offset by the costs

of autograft harvesting.

The Advantages of BPTB Autografts

The biomechanical properties of BPTB grafts are similar to those of the native ACL. Cooper and associates⁶ found that the biomechanical strength of a BPTB autograft is even greater than previously reported. A 10-mm BPTB graft was found to have a higher ultimate tensile load (2,977 N) and greater stiffness (455 N/mm) than native ACL (2,160 N and 243 N/mm, respectively). The use of interference screws allows for secure bony fixation of the BPTB graft on both ends.^{78,89} Bony fixation also allows more rapid graft incorporation, which has direct implications for postoperative rehabilitation and return to sport.^{49,90}

Because the tendinous portion of the BPTB graft does not occupy the entire cross section of the construct, less notchplasty or roofplasty is required, and there is less graft impingement than with soft-tissue grafts. BPTB graft also has been shown to be better suited for patients with excessive ligamentous laxity, young men involved in highly competitive sports, and patients requiring an early aggressive rehabilitation program.^{2,37,65,91,92} It also is well suited for revision procedures after primary grafting of hamstring autograft or allograft. Shelbourne and Urch⁹³ and Rubenstein and associates⁹⁴ found that contralateral BPTB grafts can be used for revision.

Both BPTB and hamstring grafts were successful in numerous clinical studies; however, several studies found better results when BPTB grafts were used. In many comparisons of BPTB and hamstring autografts, the results of KT-1000 testing were significantly better in

patients who received a BPTB graft.^{44,64,65,91,95} A meta-analysis by Freedman and associates⁵⁷ reported that the failure rate for BPTB grafts was less than 50% of the rate reported for hamstring grafts. Williams and associates⁹⁶ and Adam and associates⁹¹ also reported better clinical results with BPTB grafts. Less tunnel widening was found with BPTB grafts; this factor has important implications for revision ACL reconstruction.^{65,97,98}

BPTB grafting is well suited for athletes such as hurdlers, who require strength in deep knee flexion. Hamstring harvesting was found to cause persistent weakness at high flexion angles.^{99,100}

Although BPTB grafts are widely believed to be associated with an increased incidence of anterior knee pain and pain with squatting, the risk is minimal, especially if the patellar defect is filled with bone graft before closure.^{44,65,101-103}

Graft Positioning

The ideal femoral tunnel positioning in ACL reconstruction is controversial, and both double-bundle and single-bundle techniques have been promoted. Although double-bundle reconstruction has some biomechanical advantages, the clinical advantages are less clear; allografts usually must be used.^{60,104-107} As an alternative, the senior author has recently explored the use of quadriceps tendon and hamstring tendon autograft sources for double-bundle ACL reconstruction. Placement of the posterolateral graft component results in a short tunnel that can jeopardize important posterolateral corner structures.¹⁰⁸

Single-bundle reconstruction with a more horizontal placement was shown to have better results than more vertical placement on the

International Knee Documentation Committee Subjective Knee Evaluation.¹⁰⁹ In a recent prospective randomized study, the clinical results of single-bundle ACL reconstruction with more horizontal graft placement were found to be comparable to those of double-bundle reconstruction.¹¹⁰

Surgical Technique

The graft is harvested after the diagnosis of ACL deficiency is confirmed by a preoperative work-up and examination under anesthesia. Harvesting at the beginning of the procedure allows the graft to be prepared while the surgery proceeds and the harvest incision to be used for arthroscopic portals.

Harvesting the patellar portion of the graft requires extreme care. A saw can be used at an angle or horizontally to soften the corners; it should not penetrate beyond the cortex. The osteotome should not be levered from the sides of the graft when harvesting. The bone graft is harvested at a sharper angle on the patellar side than on the tibial side, using a smaller saw blade. Predrilling the corners of the graft can reduce the risk of patellar fracture. The harvested graft is taken to a table for final preparation and pretensioning (Figure 9).

The tibial tunnel landmarks have been well described, and the posterior aspect of the anterior horn of the lateral meniscus has been shown to be important.¹¹¹⁻¹¹³ If a transtibial technique is used for femoral tunnel placement, the exterior starting point should be far medial¹⁰⁸ (Figure 10). Medial collateral ligament fibers can be subperiosteally reflected before the tibial tunnel is overdrilled. A fully threaded drill bit with a sleeve can be used to capture the bone graft for later placement in the

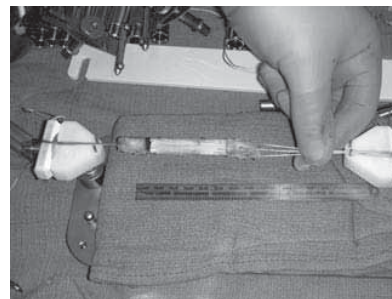


Figure 9 Harvested BPTB autograft after preparation and during pretensioning. The leading edge (harvested from the tibia) is bulletted, and a suture is passed near the end of the bone. The suture is placed perpendicular in the patellar bone block (for the tibial tunnel) to reduce interference screw cutting.

patellar defect.

An over-the-top guide should be used for femoral guide pin placement. Accurate placement of this guide requires clearing the back of the notch, then rotating the guide to place the pin as horizontally as possible. The femoral tunnel is overdrilled using a terminally threaded (carrot-top) drill bit. If transtibial drilling is planned, the drill bit should be introduced into the notch by pushing or oscillating it through the tibial tunnel to reduce tibial tunnel expansion.

The graft is passed from the tibia into the femur, with the bone blocks facing anterior. With final passage of the graft, the interference screw guide pin can be placed on the most anterior portion of the femoral bone plug, as far as possible from the tendinous portion of the graft. The knee is hyperflexed; during screw placement, the screwdriver handle is pushed toward the tibia to avoid divergence. The guidewire for the tibial tunnel screw should pass freely along the anterior bone block before tibial fixation. Screw guidewires should be removed before final

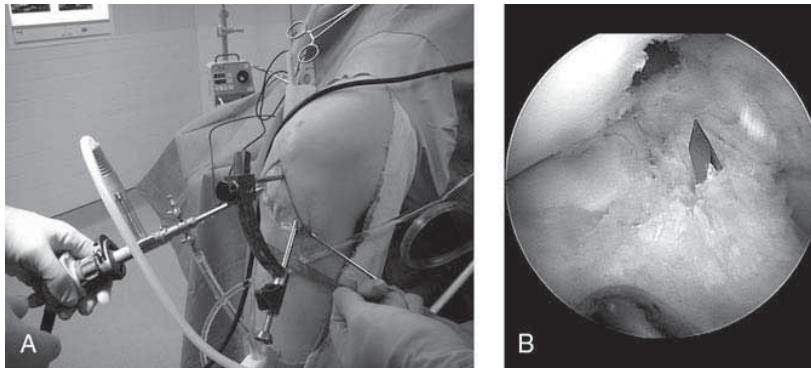


Figure 10 **A**, For exterior tibial tunnel placement, the guide is placed far medial to allow more horizontal femoral tunnel placement. **B**, Arthroscopic view of intra-articular tibial guidewire placement.



Figure 11 Arthroscopic view of the final graft placement and fixation.

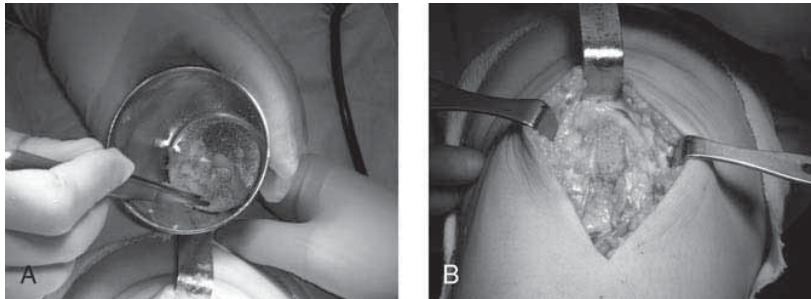


Figure 12 Bone graft harvested from tibial tunnel drilling (**A**) is packed into the patellar defect (**B**).

screw tightening to avoid breakage. The final graft position and fixation are carefully inspected before closure (Figure 11).

Bone graft saved from tibial tunnel drilling should be packed into the patellar defect; bone graft from the initial BPTB graft preparation also can be used (Figure 12). The paratenon is closed over the defect to allow room for the defect to heal with collagenous tissue, as has been shown in an animal model.¹¹⁴ Prolonged postoperative bracing is not advantageous.¹¹⁵

BPTB autograft has multiple advantages over soft-tissue allograft, including lower infection rates, earlier incorporation, and less laxity. BPTB grafts can be fixed with inter-

ference screws on each end to provide the strongest possible fixation. BPTB grafts were found to be clinically superior to soft-tissue grafts in several studies, especially in patients who have ligamentous laxity or require deep flexion strength. Horizontal graft placement, which can easily be achieved with a BPTB graft, may avoid the need for a double-bundle construct. The surgical technique for ACL reconstruction using BPTB autograft is reproducible and successful.

Using Allograft Tissue

The use of musculoskeletal allograft tissue in primary and revision ACL surgery is expanding. Although comprehensive data are not readily

available on the number of ACL allograft reconstructions done in the United States, cumulative tissue bank data indicate that the number has increased during the past 5 to 10 years. Achilles tendon and anterior tibial tendon allograft tissue currently must be back ordered. The increase has primarily occurred because the use of allografts eliminates donor site morbidity and decreases surgical time.

The spread of disease and infection from donor to host is a risk of allograft use, although more groups are becoming involved in ensuring the safety of musculoskeletal allografts used in knee surgery. The US Food and Drug Administration (FDA) and the AATB are the most important agencies regulating the quality and safety of allograft tissues. The AATB frequently updates its *Standards for Tissue Banking*.¹¹⁶ Orthopaedic surgeons using allograft tissues should be familiar with the AATB guidelines, use allograft tissues only from an AATB-accredited tissue bank, and understand the individual tissue bank's processing techniques. Although tissue bank accreditation by the AATB is voluntary, the surgeon should consider a lack of AATB accreditation as a red

flag. The American Academy of Orthopaedic Surgeons established the Tissue Banking Project Team in February 2002 to work with the FDA and the CDC to develop guidelines for the safe use of musculoskeletal allograft tissues.⁸⁸ Final regulations establishing requirements and standards for tissue banks became effective in May 2005.

The Musculoskeletal Transplant Foundation (MTF) is a not-for-profit organization founded in 1987 by academic orthopaedic surgeons to provide musculoskeletal allografts of the highest quality and safety.¹¹⁷ It is one of the largest providers of allograft tissue in the world. In 2002, the MTF recovered harvested tissue from 4,431 donors and distributed almost 300,000 units of allograft tissue. No confirmed infection has been associated with any of the more than 2 million MTF-provided units of transplanted tissue. The MTF's high standards for screening and selecting donors as well as for all other processes could be used as a template for the industry.¹¹⁷

Procurement, Sterilization, and Storage

Understanding the allograft process from donor selection to tissue transplantation is equivalent to understanding the AATB *Standards for Tissue Banking*. The suitability of each donor is determined by a physician using a standardized questionnaire, physical assessment, and a review of medical records and the autopsy report, if any. Musculoskeletal tissue donation is precluded if the donor had a history of autoimmune disease, ingestion or exposure to toxic substances, rheumatoid arthritis, systemic lupus erythematosus, polyarteritis nodosa, sarcoidosis, or clinically significant bone disease. Blood screening for infectious disease in-

cludes tests for antibodies to HIV, hepatitis C virus (HCV), human T-lymphotropic virus, and syphilis, as well as hepatitis B surface and core antigens. Nucleic acid testing of blood for HIV-1 and HCV, which markedly decreases the time needed for virus detection, was added in 2005.¹¹⁸

Tissue excision must begin within 24 hours of asystole if the body was cooled, and it must begin within 15 hours if the body was not cooled. Aseptic technique is used to retrieve all tissues. All musculoskeletal tissues are processed in a bacteriologically and climate-controlled environment. Tissues are cultured after harvest and before processing.¹¹⁶

An ideal secondary sterilization method would eliminate all possibility of infection while maintaining all of the tissue's biologic and mechanical properties. None of the currently available techniques fulfills these requirements. Ethylene oxide formerly was popular for sterilization, but most tissue banks have discontinued its use because of associated graft failure and chronic synovitis.^{117,119} The AATB requires banks that use ethylene oxide for secondary sterilization to subsequently lower the amount and breakdown products of ethylene oxide to a specified level.¹¹⁶ Gamma irradiation is popular for secondary sterilization at the currently recommended dose of 2.5 mrad, which is the highest that can be used without significantly altering the biomechanical properties of the graft. Although a 2.5-mrad dose effectively eliminates bacterial surface contamination, a dose higher than 3 mrad is required to kill viruses.^{88,119} Antibiotic soaking can be used to augment low-dose gamma irradiation, but its effectiveness is limited by incomplete penetrance.^{88,119} In addition,

controversy remains about the clinical effects of irradiation. Rappe and associates¹²⁰ found a 33% catastrophic failure rate after primary ACL reconstructions using irradiated Achilles tendon allograft, compared with a 2.4% failure rate after reconstruction using nonirradiated tissue.

Several new techniques are now available for sterilizing allograft tissue. The Allowash process (LifeNet, Virginia Beach, VA) uses irradiation, ultrasound, centrifugation, and negative pressure, in combination with reagents including biologic detergents, antibiotics, alcohols, and hydrogen peroxide, to improve solubility and remove lipids, bone marrow, and blood elements.¹²⁰ The BioCleanse technique (Regeneration Technologies, Gainesville, FL) uses a low-temperature chemical sterilization process with liquid sterilants that perfuse the inner matrix of the tissue before the tissue is irradiated.¹²¹ The FDA has approved the BioCleanse process as a means of killing implanted spores and viruses. More than 300,000 grafts have been implanted after this process was used, with no known infection.¹²² In the Clearant process (Clearant, Los Angeles, CA), the tissue is frozen, water is extracted, and dimethyl sulfoxide is added as a radioprotectant. The tissue is subsequently irradiated with 50 kGy, which is two to four times higher than the dose recommended for avoiding cell damage.¹²¹ None of these proprietary methods is supported by animal or other data to show its effect on biologic incorporation of allografts or eventual outcome.

Like the available sterilization methods, the options for storing allograft tissue are not perfect. The approaches to storage include the

use of fresh allografts, fresh freezing, cryopreservation, or lyophilization. Fresh grafts are implanted shortly after harvest; there is a risk of disease transmission in the absence of secondary sterilization and storage processing. Freezing fresh allografts at a temperature of -80° to -196° allows storage for 3 to 5 years, but the process kills the cells.^{119,122} In cryopreservation, the tissue undergoes controlled freezing while cellular water is extracted by glycerol and dimethyl sulfoxide; the graft has a shelf life of 10 years, and as many as 80% of cells remain viable.^{119,122} Lyophilization (freeze drying) results in a residual moisture level of less than 5%. This process allows the graft to be stored at room temperature for as long as 3 to 5 years.^{119,122}

Infection, especially with HIV or HCV, is the most important risk in using musculoskeletal allografts. The risk of contracting HIV from a musculoskeletal allograft is estimated at 1 in 1.6 million.^{88,119} In 2002, at least 6 of 38 patients tested positive for HCV after receiving allograft tissue from a donor with undetected virus.¹²³ Nucleic acid testing for HIV and HCV, which is now required by the AATB, detects the actual virus rather than its antibody.¹¹⁶ HIV is an RNA virus that infects white blood cell DNA, and this DNA is stable in cadaver blood as long as 48 hours. Polymerase chain reaction for HIV is quite effective in detecting infected white blood cell DNA; results are available within approximately 10 days.¹²² The HCV virus is continually cleared from the serum by immune system enzymes so that its half-life in cadaver blood can be a few hours. Polymerase chain reaction for HCV can produce a false-negative result if the serum is obtained from the do-

nor several hours after death.⁸ Nonetheless, the AATB requirement for HCV nucleic acid testing can increase the safety of musculoskeletal allografts.

There also is a risk of allograft-associated bacterial infection. The CDC called for reports of bacterial infections associated with musculoskeletal allograft after a postoperative death in 2001. Three days after a 23-year-old man received an osteochondral femoral condyle graft, he developed pain at the surgical site that rapidly progressed to shock, and he died the next day. Premortem blood cultures grew *C sordellii*. Another patient who received a fresh femoral condyle graft and a frozen meniscal allograft from the same donor developed septic arthritis; cultures for anaerobic bacteria were not obtained. The body of the donor had been refrigerated 19 hours after death, with tissue procurement 23.5 hours after death. *C sordellii* also was cultured from nonimplanted donor tissue. As of March 2002, the CDC had identified 26 musculoskeletal allograft-associated bacterial infections.¹²⁴ Thirteen of the 26 patients had infection with various species of *Clostridium*, of whom 11 had received tissues processed by the same tissue bank. All of these tissues had been processed aseptically, but none were terminally sterilized. Of the remaining 13 patients, 11 were infected with gram-negative bacilli (5 of whom had a polymicrobial infection) and 2 had a culture-negative infection. Evidence implicated the allograft in 8 of the 13 patients. Three patients had received grafts that reportedly had undergone gamma irradiation, but 8 patients received allografts that were not terminally sterilized.¹²⁴ The CDC investigation determined that spore-forming bacteria are potential

pathogens, and a sporicidal method must be used for aseptically processed tissue to be considered sterile. Health care providers should be aware of the risk of bacterial infection.^{124,125}

The only absolute indication for the use of allograft tissue in primary or revision ACL reconstruction is the unavailability of autogenous tissue. Most patients have a favorable outcome regardless of whether allograft or autograft is used. Surgeons who prefer autogenous tissue cite the risk of infection, the potential for an immune response, and possibly a greater risk of failure in an athletically active patient with the use of allografts. Surgeons who prefer allograft tissue cite comparable knee stability, the absence of donor site morbidity, and less postoperative pain, as well as smaller incisions and a shorter surgical procedure.

The difficulty in reaching a consensus is primarily the result of a lack of long-term data comparing the outcomes of Achilles or BPTB autograft with those of exactly the same allograft tissue, when used in primary ACL reconstruction with the same surgical technique and rehabilitation protocol in a uniform patient population. The outcome of a BPTB allograft in a collegiate football player cannot be compared with that of a soft-tissue allograft in a 50-year-old tennis player. Surgeons currently must rely on animal studies and the few available clinical outcome data, which are difficult to interpret because of differences in patient populations. Allograft studies cannot be considered together because of differences in surgical and rehabilitation techniques, tissue processing, patient populations, and outcome measurement tools. Many different types of allograft tissues are used, including BPTB, Achilles ten-

don, and the currently popular soft-tissue-only graft. Singhal and associates¹²⁶ recently reported a failure and reoperation rate of more than 50% in patients younger than 25 years after endoscopic ACL reconstruction using an anterior tibial allograft fixed with interference screws, followed by an accelerated rehabilitation program. Luper and associates¹²⁷ reported a failure rate higher than 20% in patients younger than 40 years after reconstruction with a BPTB allograft; the allograft material, a prolonged incorporation time, high Tegner scores, and minimal postoperative pain may constitute a formula for early failure.

Animal studies evaluated the histologic incorporation and biomechanical properties of allograft and autograft ligament at different stages of healing, finding similar revascularization and incorporation.¹²⁸⁻¹³¹ The biomechanical differences between allograft and autograft ACL reconstruction were studied in goat and dog models. Allograft ligaments probably are weaker than autograft ligaments during graft incorporation, but this factor has not been shown to lead to a clinically significant increase in graft failure. Allografts can require 1.5 times as long as autografts for incorporation, but completely incorporated allograft ligament tissue appears to be histologically and functionally similar to autograft tissue.

The comparative studies are few and of poor design, and they have not shown consistent differences in objective or subjective outcomes.^{19,30} Concern remains as to the long-term functioning of allografts, particularly soft-tissue allografts in young, athletically active patients. Nonetheless, no significant clinical differences in patient outcomes or satisfaction were found 3

to 5 years after allograft or autograft reconstruction.

Allograft tissue is particularly useful in revision ACL reconstruction.^{26,122} If autograft tissues were used for the index surgery, the autograft options for additional surgery are limited. Because revision ACL reconstruction frequently involves existing hardware and tunnel lysis, the ability to order a patient-specific allograft type and size is attractive. The greater tensile strength of a larger soft-tissue graft may be optimal for a salvage operation. BPTB, Achilles tendon, or anterior or posterior tibial tendon allograft tissue can be used in revision ACL reconstruction.

The advantages of allografts over autografts include availability, a shorter procedure, and the elimination of donor site morbidity. Disease transmission remains a concern, although allograft safety has improved dramatically during the past 15 years. It is mandatory that tissue from an AATB-accredited tissue bank be used. The surgeon must be familiar with the processes of the bank supplying the graft because banks use different procedures for donor screening, tissue harvesting, tissue processing, safety purification, and secondary sterilization. Implantation of allograft tissue can cause infection with significant morbidity and mortality.

Summary

No one type of graft can be considered the gold standard in ACL surgery. The challenge for the orthopaedic surgeon is to select the best graft for an individual patient, with an understanding of the rationale for each option and the variables that affect postoperative management, such as the shorter incorporation time of BPTB autografts and the increased flexibility of allograft in double-

bundle surgery. Any graft tissue has a higher ultimate tensile strength than the native ACL ligament.

References

1. Griffin LY, Agel J, Albohm M, et al: Noncontact anterior cruciate ligament injuries: Risk factors and prevention strategies. *J Am Acad Orthop Surg* 2000;8:141-150.
2. West RV, Harner CD: Graft selection in anterior cruciate ligament reconstruction. *J Am Acad Orthop Surg* 2005; 13:197-207.
3. Woo SL, Hollis JM, Adams DJ, Lyon RM, Takai S: Tensile properties of the human femur anterior cruciate ligament tibia complex: The effects of specimen age and orientation. *Am J Sports Med* 1991;19:217-225.
4. Noyes FR, Butler DL, Grood ES, Zernicke RF, Hefzy MS: Biomechanical analysis of human ligament grafts used in knee ligament repairs and reconstructions. *J Bone Joint Surg Am* 1984;66:344-352.
5. Frank CB, Jackson DW: The science of reconstruction of the anterior cruciate ligament. *J Bone Joint Surg Am* 1997;79:1556-1576.
6. Cooper DE, Deng XH, Burstein AL, Warren RF: The strength of central third patellar tendon graft: A biomechanical study. *Am J Sports Med* 1993; 21:818-823.
7. Hamner DL, Brown CH Jr, Steiner ME, Hecker AT, Hayes WC: Hamstring tendon grafts for reconstruction of the anterior cruciate ligament: Biomechanical evaluation of the use of multiple strands and tensioning techniques. *J Bone Joint Surg Am* 1999;81:549-557.
8. Staubli HU, Schatzmann L, Brunner P, Rincon L, Nolte LP: Mechanical tensile properties of the quadriceps tendon and patellar ligament in young adults. *Am J Sports Med* 1999; 27:27-34.
9. Harris NL, Smith DA, Lamoreaux L, Purnell M: Central quadriceps tendon for anterior cruciate ligament re-

- construction: Part 1. Morphometric and biomechanical evaluation. *Am J Sports Med* 1997;25:23-28.
10. Haut Donahue TL, Howell SM, Hull ML, Gregersen C: A biomechanical evaluation of anterior and posterior tibialis tendons as suitable single loop anterior cruciate ligament grafts. *Arthroscopy* 2002;18:589-597.
 11. Pearsall AW, Hollis JM, Russell GV Jr, Scheer Z: A biomechanical comparison of three lower extremity tendons for ligamentous reconstruction about the knee. *Arthroscopy* 2003;19:1091-1096.
 12. Lewis G, Shaw KM: Tensile properties of human tendo Achilles: Effect of donor age and strain rate. *J Foot Ankle Surg* 1997;36:435-445.
 13. Wren TA, Yerby SA, Beaupre GS, Carter DR: Mechanical properties of the human Achilles tendon. *Clin Biomech (Bristol, Avon)* 2001;16:245-251.
 14. Woo SL, Orlando CA, Camp JF, Akeson WH: Effects of post mortem storage by freezing on ligament tensile behavior. *J Biomech* 1986;19:399-404.
 15. Smith CW, Young IS, Kearney JN: Mechanical properties of tendons: Changes with sterilization and preservation. *J Biomech Eng* 1996;118:56-61.
 16. Clancy WG Jr, Narechania RG, Rosenberg TD, Gmeiner JG, Wisniewski DD, Lange TA: Anterior and posterior cruciate ligament reconstruction in rhesus monkeys. *J Bone Joint Surg Am* 1981;63:1270-1284.
 17. Arnoczky SP, Tarvin GB, Marshall JL: Anterior cruciate ligament replacement using patellar tendon: An evaluation of graft revascularization in the dog. *J Bone Joint Surg Am* 1982;64:217-224.
 18. Beynonn BD Jr: Anterior cruciate ligament injury rehabilitation in athletes: Biomechanical considerations. *Sports Med* 1996;22:54-64.
 19. Shelton WR, Papendick L, Dukes AD: Autograft versus allograft anterior cruciate ligament reconstruction. *Arthroscopy* 1997;13:446-449.
 20. Sachs RA, Daniel DM, Stone ML, Garfein RF: Patellofemoral problems after anterior cruciate ligament reconstruction. *Am J Sports Med* 1989;17:760-765.
 21. Shelbourne KD, Nitz P: Accelerated rehabilitation after anterior cruciate ligament reconstruction. *Am J Sports Med* 1990;18:292-299.
 22. Viola R, Vianello R: Three cases of patella fracture in 1,320 anterior cruciate ligament reconstructions with bone-patellar tendon-bone autograft. *Arthroscopy* 1999;15:93-97.
 23. Marumoto JM, Mitsunaga MM, Richardson AB, Medoff RJ, Mayfield GW: Late patellar tendon ruptures after removal of the central third for anterior cruciate ligament reconstruction: A report of two cases. *Am J Sports Med* 1996;24:698-701.
 24. Miller SL, Gladstone JN: Graft selection in anterior cruciate ligament reconstruction. *Orthop Clin North Am* 2002;33:675-683.
 25. Nakamura N, Horibe S, Sasaki S, et al: Evaluation of active knee flexion and hamstring strength after anterior cruciate ligament reconstruction using hamstring tendons. *Arthroscopy* 2002;18:598-602.
 26. Shelton WR, Treacy SH, Dukes AD, Bombay AL: Use of allografts in knee reconstruction: I. Basic science aspects and current status. *J Am Acad Orthop Surg* 1998;6:165-168.
 27. Simonds RJ, Holmberg SD, Hurwitz RL, et al: Transmission of human immunodeficiency virus type 1 from a seronegative organ and tissue donor. *N Engl J Med* 1992;326:726-732.
 28. Cole DW, Ginn TA, Chen GJ, et al: Cost comparison of anterior cruciate ligament reconstruction: Autograft versus allograft. *Arthroscopy* 2005;21:786-790.
 29. Stringham DR, Pelmas CJ, Burks RT, Newman AP, Marcus RL: Comparison of anterior cruciate ligament reconstructions using patellar tendon autograft or allograft. *Arthroscopy* 1996;12:414-421.
 30. Harner CD, Olson E, Irrgang JJ, Silverstein S, Fu FH, Silbey M: Allograft versus autograft anterior cruciate ligament reconstruction: 3 to 5 year outcome. *Clin Orthop Relat Res* 1996;324:134-144.
 31. Yasuda K, Kondo E, Ichiyama H, et al: Anatomic reconstruction of the anteromedial and posterolateral bundles of the anterior cruciate ligament using hamstring tendon grafts. *Arthroscopy* 2004;20:1015-1025.
 32. Prodromos CC, Han YS, Keller BL, Bolyard RJ: Posterior mini-incision technique for hamstring anterior cruciate ligament reconstruction graft harvest. *Arthroscopy* 2005;21:130-137.
 33. Lipscomb AB, Johnston RK, Snyder RB, et al: Evaluation of hamstring strength following use of semitendinosus and gracilis tendons to reconstruct the anterior cruciate ligament. *Am J Sports Med* 1982;10:340-342.
 34. Simonian PT, Harrison SD, Cooley VJ, Escabedo EM, Deneka DA, Larson RV: Assessment of morbidity of semitendinosus and gracilis tendon harvest for ACL reconstruction. *Am J Knee Surg* 1997;10:54-59.
 35. Marder RA, Raskind JR, Carroll M: Prospective evaluation of arthroscopically assisted anterior cruciate ligament reconstruction: Patellar tendon versus semitendinosus and gracilis tendons. *Am J Sports Med* 1991;19:478-484.
 36. Eriksson K, Kindblom LG, Hamberg P, Larsson H, Wredmark T: The semitendinosus tendon regenerates after resection: A morphologic and MRI analysis in 6 patients after resection for anterior cruciate ligament reconstruction. *Acta Orthop Scand* 2001;72:379-384.
 37. Cross MJ, Roger G, Kujawa P, Anderson IF: Regeneration of the semitendinosus and gracilis tendons following their transection for repair of the anterior cruciate ligament. *Am J Sports Med* 1992;20:221-223.
 38. Gabriel MT, Wong EK, Woo SL, Yagi M, Debski RE: Distribution of in situ forces in the anterior cruciate

- ligament in response to rotatory loads. *J Orthop Res* 2004;22:85-89.
39. Fu FH, Shen W, Starman JS, Okeke N, Irrgang JJ: Primary anatomic double-bundle anterior cruciate ligament reconstruction: A preliminary 2-year prospective study. *Am J Sports Med* 2008;36:1263-1274.
 40. Mochizuki T, Muneta T, Yagishita K, et al: Skin sensory change after arthroscopically-assisted anterior cruciate ligament reconstruction using medial hamstring tendons with a vertical incision. *Knee Surg Sports Traumatol Arthrosc* 2004;12:198-202.
 41. Soon M, Neo CP, Mitra AK, Tay BK: Morbidity following anterior cruciate ligament reconstruction using hamstring autograft. *Ann Acad Med Singapore* 2004;33:214-219.
 42. Papastergiou SG, Voulgaropoulos H, Mikalef P, Ziogas E, Pappis G, Gianakopoulos I: Injuries to the infrapatellar branch(es) of the saphenous nerve in anterior cruciate ligament reconstruction with four-strand hamstring tendon autograft: Vertical versus horizontal incision for harvest. *Knee Surg Sports Traumatol Arthrosc* 2006;14:789-793.
 43. Portland GH, Martin D, Keene G, et al: Injury to the infrapatellar branch of the saphenous nerve in anterior cruciate ligament reconstruction: Comparison of horizontal versus vertical harvest site incisions. *Arthroscopy* 2005;21:281-285.
 44. Corry IS, Webb JM, Clingeffer AJ, et al: Arthroscopic reconstruction of the anterior cruciate ligament: A comparison of patellar tendon autograft and four-strand hamstring tendon autograft. *Am J Sports Med* 1999;27:444-454.
 45. Pinczewski LA, Lyman J, Salmon LJ, et al: A 10-year comparison of anterior cruciate ligament reconstructions with hamstring tendon and patellar tendon autograft: A controlled, prospective trial. *Am J Sports Med* 2007;35:564-574.
 46. Nakamae A, Deie M, Yasumoto M, et al: Three-dimensional computed tomography imaging evidence of regeneration of the semitendinosus tendon harvested for anterior cruciate ligament reconstruction: A comparison with hamstring muscle strength. *J Comput Assist Tomogr* 2005;29:241-245.
 47. Okahashi K, Sugimoto K, Iwai M, et al: Regeneration of the hamstring tendons after harvesting for arthroscopic anterior cruciate ligament reconstruction: A histological study in 11 patients. *Knee Surg Sports Traumatol Arthrosc* 2006;14:542-545.
 48. Rispoli DM, Sanders TG, Miller MD, et al: Magnetic resonance imaging at different time periods following hamstring harvest for anterior cruciate ligament reconstruction. *Arthroscopy* 2001;17:2-8.
 49. Yoshiya S, Nagano M, Kurosaka M, et al: Graft healing in the bone tunnel in anterior cruciate ligament reconstruction. *Clin Orthop Relat Res* 2000;376:278-286.
 50. Prodromos CC, Joyce BT, Shi K, et al: A meta-analysis of stability after anterior cruciate ligament reconstruction as a function of hamstring versus patellar tendon graft and fixation type. *Arthroscopy* 2005;21:1202.
 51. Hammond GW, Armstrong KL, McGarry MH, et al: Hybrid fixation improves structural properties of a free tendon anterior cruciate ligament reconstruction. *Arthroscopy* 2006;22:781-786.
 52. Kousa P, Jarvinen TL, Vihavainen M, Kannus P, Jarvinen P: The fixation strength of six hamstring tendon graft fixation devices in anterior cruciate ligament reconstruction: Part I. Femoral site. *Am J Sports Med* 2003;31:174-181.
 53. Kousa P, Jarvinen TL, Vihavainen M, Kannus P, Jarvinen P: The fixation strength of six hamstring tendon graft fixation devices in anterior cruciate ligament reconstruction: Part II. Tibial site. *Am J Sports Med* 2003;31:182-188.
 54. Chouliaras V, Ristanis S, Moraiti C, et al: Effectiveness of reconstruction of the anterior cruciate ligament with quadrupled hamstrings and bone-patellar tendon-bone autografts: An in vivo study comparing tibial internal-external rotation. *Am J Sports Med* 2007;35:189-196.
 55. Ristanis S, Giakas G, Papageorgiou CD, et al: The effects of anterior cruciate ligament reconstruction on tibial rotation during pivoting after descending stairs. *Knee Surg Sports Traumatol Arthrosc* 2003;11:360-365.
 56. Nedeff DD, Bach BR Jr: Arthroscopic anterior cruciate ligament reconstruction using patellar tendon autografts: A comprehensive review of contemporary literature. *Am J Knee Surg* 2001;14:243-258.
 57. Freedman KB, D'Amato MJ, Nedeff DD, et al: Arthroscopic anterior cruciate ligament reconstruction: A metaanalysis comparing patellar tendon and hamstring tendon autografts. *Am J Sports Med* 2003;31:2-11.
 58. Aglietti P, Giron F, Cuomo P, et al: Single- and double-incision double-bundle ACL reconstruction. *Clin Orthop Relat Res* 2007;454:108-113.
 59. Yasuda K, Kondo E, Ichiyama H, Tanabe Y, Tohyama H: Clinical evaluation of anatomic double-bundle anterior cruciate ligament reconstruction procedure using hamstring tendon grafts: Comparisons among 3 different procedures. *Arthroscopy* 2006;22:240-251.
 60. Yagi M, Kuroda R, Nagamune K, et al: Double-bundle ACL reconstruction can improve rotational stability. *Clin Orthop Relat Res* 2007;454:100-107.
 61. Jarvela T: Double-bundle versus single-bundle anterior cruciate ligament reconstruction: A prospective, randomized clinical study. *Knee Surg Sports Traumatol Arthrosc* 2007;15:500-507.
 62. Muneta T, Koga H, Mochizuki T, et al: A prospective randomized study of 4-strand semitendinosus tendon anterior cruciate ligament reconstruction comparing single-bundle and

- double-bundle techniques. *Arthroscopy* 2007;23:618-628.
63. Asagumo H, Kimura M, Kobayashi Y, et al: Anatomic reconstruction of the anterior cruciate ligament using double-bundle hamstring tendons: Surgical techniques, clinical outcomes, and complications. *Arthroscopy* 2007;23:602-609.
 64. Anderson AF, Snyder RB, Lipscomb AB Jr : Anterior cruciate ligament reconstruction: A prospective randomized study of three surgical methods. *Am J Sports Med* 2001;29:272-279.
 65. Feller JA, Webster KE: A randomized comparison of patellar tendon and hamstring tendon anterior cruciate ligament reconstruction. *Am J Sports Med* 2003;31:564-573.
 66. Bellier G, Christel P, Colombet P, et al: Double-stranded hamstring graft for anterior cruciate ligament reconstruction. *Arthroscopy* 2004;20:890-894.
 67. Franceschi JP, Sbihi A, Champsaur P: Arthroscopic reconstruction of the anterior cruciate ligament using double anteromedial and posterolateral bundles. *Rev Chir Orthop Reparatrice Appar Mot* 2002;88:691-697.
 68. Hamada M, Shino K, Horibe S, et al: Single- versus bi-socket anterior cruciate ligament reconstruction using autogenous multiple-stranded hamstring tendons with EndoButton femoral fixation: A prospective study. *Arthroscopy* 2001;17:801-807.
 69. Hara K, Kubo T, Suginoshita T, Shimizu C, Hirasawa Y: Reconstruction of the anterior cruciate ligament using a double bundle. *Arthroscopy* 2000;16:860-864.
 70. Mae T, Shino K, Miyama T, et al: Single- versus two-femoral socket anterior cruciate ligament reconstruction technique: Biomechanical analysis using a robotic simulator. *Arthroscopy* 2001;17:708-716.
 71. Pederzini L, Adriani E, Botticella C, et al: Technical note: Double tibial tunnel using quadriceps tendon in anterior cruciate ligament reconstruction. *Arthroscopy* 2000;16:E9.
 72. Buoncristiani AM, Tjoumakaris FP, Starman JS, et al: Anatomic double-bundle anterior cruciate ligament reconstruction. *Arthroscopy* 2006;22:1000-1006.
 73. Yagi M, Wong EK, Kanamori A, et al: Biomechanical analysis of an anatomic anterior cruciate ligament reconstruction. *Am J Sports Med* 2002;30:660-666.
 74. Colombet P, Robinson J, Christel P, et al: Using navigation to measure rotation kinematics during ACL reconstruction. *Clin Orthop Relat Res* 2007;454:59-65.
 75. Aglietti P, Buzzi R, D'Andria S, et al: Arthroscopic anterior cruciate ligament reconstruction with patellar tendon. *Arthroscopy* 1992;8:510-516.
 76. Aglietti P, Buzzi R, Zaccherotti G, et al: Patellar tendon versus doubled semitendinosus and gracilis tendons for anterior cruciate ligament reconstruction. *Am J Sports Med* 1994;22:211-217.
 77. Aglietti P, Buzzi R, Giron F, et al: Arthroscopic-assisted anterior cruciate ligament reconstruction with the central third patellar tendon: A 5-8-year follow-up. *Knee Surg Sports Traumatol Arthrosc* 1997;5:138-144.
 78. Bach BR Jr, Tradonsky S, Bojchuk J, et al: Arthroscopically assisted anterior cruciate ligament reconstruction using patellar tendon autograft: Five- to nine-year follow-up evaluation. *Am J Sports Med* 1998;26:20-29.
 79. Otto D, Pinczewski LA, Clingelefer A, et al: Five-year results of single-incision arthroscopic anterior cruciate ligament reconstruction with patellar tendon autograft. *Am J Sports Med* 1998;26:181-188.
 80. Patel JV, Church JS, Hall AJ: Central third bone-patellar tendon-bone anterior cruciate ligament reconstruction: A 5-year follow-up. *Arthroscopy* 2000;16:67-70.
 81. Jackson DW, Grood ES, Goldstein JD, et al: A comparison of patellar tendon autograft and allograft used for anterior cruciate ligament reconstruction in the goat model. *Am J Sports Med* 1993;21:176-185.
 82. Barrett G, Stokes D, White M: Anterior cruciate ligament reconstruction in patients older than 40 years: Allograft versus autograft patellar tendon. *Am J Sports Med* 2005;33:1505-1512.
 83. Grossman MG, ElAttrache NS, Shields CL, Glousman RE: Revision anterior cruciate ligament reconstruction: Three- to nine-year follow-up. *Arthroscopy* 2005;21:418-423.
 84. Uribe JW, Hechtman KS, Zvijac JE, et al: Revision anterior cruciate ligament surgery: Experience from Miami. *Clin Orthop Relat Res* 1996;325:91-99.
 85. Victor J, Bellemans J, Witvrouw E, et al: Graft selection in anterior cruciate ligament reconstruction: Prospective analysis of patellar tendon autografts compared with allografts. *Int Orthop* 1997;21:93-97.
 86. Kainer MA, Linden JV, Whaley DN, et al: Clostridium infections associated with musculoskeletal-tissue allografts. *N Engl J Med* 2004;350:2564-2571.
 87. Centeno JM, Woolf S, Reid JB III, et al: Do anterior cruciate ligament allograft culture results correlate with clinical infections? *Arthroscopy* 2007;23:1100-1103.
 88. Rihn JA, Harner CD: The use of musculoskeletal allograft tissue in knee surgery. *Arthroscopy* 2003;19(suppl 1):51-66.
 89. Steiner ME, Hecker AT, Brown CH Jr, et al: Anterior cruciate ligament graft fixation: Comparison of hamstring and patellar tendon grafts. *Am J Sports Med* 1994;22:240-246.
 90. Arnoczky SP: Biology of ACL reconstructions: What happens to the graft? *Instr Course Lect* 1996;45:229-233.
 91. Adam F, Pape D, Schiel K, et al: Biomechanical properties of patellar and hamstring graft tibial fixation techniques in anterior cruciate ligament reconstruction: Experimental study with roentgen stereometric analysis. *Am J Sports Med* 2004;32:71-78.

92. Yunes M, Richmond JC, Engels EA, et al: Patellar versus hamstring tendons in anterior cruciate ligament reconstruction: A meta-analysis. *Arthroscopy* 2001;17:248-257.
93. Shelbourne KD, Urch SE: Primary anterior cruciate ligament reconstruction using the contralateral autogenous patellar tendon. *Am J Sports Med* 2000;28:651-658.
94. Rubinstein RA Jr, Shelbourne KD, VanMeter CD, et al: Isolated autogenous bone-patellar tendon-bone graft site morbidity. *Am J Sports Med* 1994;22:324-327.
95. Otero AL, Hutcheson L: A comparison of the doubled semitendinosus/gracilis and central third of the patellar tendon autografts in arthroscopic anterior cruciate ligament reconstruction. *Arthroscopy* 1993;9:143-148.
96. Williams RJ III, Hyman J, Petrigliano F, et al: Anterior cruciate ligament reconstruction with a four-strand hamstring tendon autograft. *J Bone Joint Surg Am* 2004;86:225-232.
97. Hersekli MA, Akpınar S, Ozalay M, et al: Tunnel enlargement after arthroscopic anterior cruciate ligament reconstruction: Comparison of bone-patellar tendon-bone and hamstring autografts. *Adv Ther* 2004;21:123-131.
98. Clatworthy MG, Annear P, Bulow JU, et al: Tunnel widening in anterior cruciate ligament reconstruction: A prospective evaluation of hamstring and patella tendon grafts. *Knee Surg Sports Traumatol Arthrosc* 1999;7:138-145.
99. Hiemstra LA, Webber S, MacDonald PB, et al: Hamstring and quadriceps strength balance in normal and hamstring anterior cruciate ligament-reconstructed subjects. *Clin J Sport Med* 2004;14:274-280.
100. Adachi N, Ochi M, Uchio Y, et al: Harvesting hamstring tendons for ACL reconstruction influences postoperative hamstring muscle performance. *Arch Orthop Trauma Surg* 2003;123:460-465.
101. Buss DD, Warren RF, Wickiewicz TL, et al: Arthroscopically assisted reconstruction of the anterior cruciate ligament with use of autogenous patellar-ligament grafts: Results after twenty-four to forty-two months. *J Bone Joint Surg Am* 1993;75:1346-1355.
102. Tsuda E, Okamura Y, Ishibashi Y, et al: Techniques for reducing anterior knee symptoms after anterior cruciate ligament reconstruction using a bone-patellar tendon-bone autograft. *Am J Sports Med* 2001;29:450-456.
103. Ferrari JD, Bach BR Jr: Bone graft procurement for patellar defect grafting in anterior cruciate ligament reconstruction. *Arthroscopy* 1998;14:543-545.
104. Petersen W, Tretow H, Weimann A, et al: Biomechanical evaluation of two techniques for double-bundle anterior cruciate ligament reconstruction: One tibial tunnel versus two tibial tunnels. *Am J Sports Med* 2007;35:228-234.
105. Steckel H, Murtha PE, Costic RS, et al: Computer evaluation of kinematics of anterior cruciate ligament reconstructions. *Clin Orthop Relat Res* 2007;463:37-42.
106. Steckel H, Starman JS, Baums MH, et al: The double-bundle technique for anterior cruciate ligament reconstruction: A systematic overview. *Scand J Med Sci Sports* 2007;17:99-108.
107. Zelle BA, Vidal AF, Brucker PU, et al: Double-bundle reconstruction of the anterior cruciate ligament: Anatomic and biomechanical rationale. *J Am Acad Orthop Surg* 2007;15:87-96.
108. Golish SR, Baumfeld JA, Schoderbek RJ, et al: The effect of femoral tunnel starting position on tunnel length in anterior cruciate ligament reconstruction: A cadaveric study. *Arthroscopy* 2007;23:1187-1192.
109. Jepsen CF, Lundberg-Jensen AK, Faunoe P: Does the position of the femoral tunnel affect the laxity or clinical outcome of the anterior cruciate ligament-reconstructed knee? A clinical, prospective, randomized, double-blind study. *Arthroscopy* 2007;23:1326-1333.
110. Streich NA, Friedrich K, Gotterbarm T, Schmitt H: Reconstruction of the ACL with a semitendinosus tendon graft: A prospective randomized single blinded comparison of double-bundle versus single-bundle technique in male athletes. *Knee Surg Sports Traumatol Arthrosc* 2008;16:232-238.
111. Morgan CD, Kalman VR, Grawl DM: Definitive landmarks for reproducible tibial tunnel placement in anterior cruciate ligament reconstruction. *Arthroscopy* 1995;11:275-288.
112. Jackson DW, Gasser SI: Tibial tunnel placement in ACL reconstruction. *Arthroscopy* 1994;10:124-131.
113. Zantop T, Wellmann M, Fu FH, et al: Tunnel positioning of anteromedial and posterolateral bundles in anatomic anterior cruciate ligament reconstruction: Anatomic and radiographic findings. *Am J Sports Med* 2008;36:65-72.
114. Sanchis-Alfonso V, Subias-Lopez A, Monteagudo-Castro C, et al: Healing of the patellar tendon donor defect created after central-third patellar tendon autograft harvest: A long-term histological evaluation in the lamb model. *Knee Surg Sports Traumatol Arthrosc* 1999;7:340-348.
115. McDevitt ER, Taylor DC, Miller MD, et al: Functional bracing after anterior cruciate ligament reconstruction: A prospective, randomized, multicenter study. *Am J Sports Med* 2004;32:1887-1892.
116. American Association of Tissue Banks: *Standards for Tissue Banking*, ed 12. MacLean, VA, American Association of Tissue Banks, 2008.
117. Gocke DJ: Tissue donor selection and safety. *Clin Orthop Relat Res* 2005;435:17-21.
118. Rigney PR: AATB Bulletin: Implementation of nucleic acid testing (NAT). <http://www.aatb.org/files/2004bulletin42.pdf>. Published September 9, 2004. Accessed October 23, 2008.

119. Caldwell PE III, Shelton WR: Indications for allografts. *Orthop Clin North Am* 2005;36:459-467.
120. Rappe M, Horodyski M, Meister K, et al: Nonirradiated versus irradiated Achilles allograft: In vivo failure comparison. *Am J Sports Med* 2007;35:1653-1658.
121. Vangsness CT Jr, Wagner PP, Moore TM, et al: Overview of safety issues concerning the preparation and processing of soft-tissue allografts. *Arthroscopy* 2006;22:1351-1358.
122. Shelton WR: Arthroscopic allograft surgery of the knee and shoulder: Indications, techniques, and risks. *Arthroscopy* 2003;19:67-69.
123. Tugwell BD, Patel PR, Williams IT, et al: Hepatitis C virus (HCV) transmission to several organ and tissue recipients from an antibody-negative donor. *Ann Intern Med* 2005;143:648-654.
124. Centers for Disease Control and Prevention: Update: Allograft-associated bacterial infections. United States, 2002. *Morbidity and Mortality Weekly Report* 2002;51:207-210.
125. McAllister DR, Joyce MJ, Mann BJ, et al: Allograft update: The current status of tissue regulation, procurement, processing, and sterilization. *Am J Sports Med* 2007;35:2148-2158.
126. Singhal MC, Gardiner JR, Johnson DL: Failure of primary anterior cruciate ligament surgery using anterior tibialis allograft. *Arthroscopy* 2007;23:469-475.
127. Luper KT, Greene PY, Barrett GR: Allograft ACL reconstruction in the young active patient (Tegner activity level and failure rate). *Arthroscopy*, in press.
128. Jackson DW, Grood ES, Arnoczky SP, et al: Cruciate reconstruction using freeze dried anterior cruciate ligament allograft and a ligament augmentation device (LAD): An experimental study in a goat model. *Am J Sports Med* 1987;15:528-538.
129. Jackson DW, Grood ES, Arnoczky SP, et al: Freeze dried anterior cruciate ligament allografts: Preliminary studies in a goat model. *Am J Sports Med* 1987;15:295-303.
130. Arnoczky SP, Warren RF, Ashlock MA: Replacement of the anterior cruciate ligament using a patellar tendon allograft: An experimental study. *J Bone Joint Surg Am* 1986;68:376-385.
131. Shino K, Kawasaki T, Hirose H, et al: Replacement of the anterior cruciate ligament by an allogeneic tendon graft: An experimental study in the dog. *J Bone Joint Surg Br* 1984;66:672-681.