Graft Selection in Anterior Cruciate Ligament Reconstruction

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Abstract

The ideal graft for use in anterior cruciate ligament reconstruction should have structural and biomechanical properties similar to those of the native ligament, permit secure fixation and rapid biologic incorporation, and limit donor site morbidity. Many options have been clinically successful, but the ideal graft remains controversial. Graft choice depends on surgeon experience and preference, tissue availability, patient activity level, comorbidities, prior surgery, and patient preference. Patellar tendon autograft, the most widely used graft source, appears to be associated with an increased incidence of anterior knee pain compared with hamstring autograft. Use of hamstring autograft is increasing. Quadriceps tendon autograft is less popular but has shown excellent clinical results with low morbidity. Improved sterilization techniques have led to increased safety and availability of allograft, although allografts have a slower rate of incorporation than do most types of autograft. No graft has clearly been shown to provide a faster return to play. However, in general, patellar tendon autografts are preferable for high-performance athletes, and hamstring autografts and allografts have some relative advantages for lower-demand individuals. No current indications exist for synthetic ligaments.

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Advances in surgical technique and rehabilitation have resulted in marked improvement in the outcome of anterior cruciate ligament (ACL) reconstruction over the past 10 years. Most recent series approach a 90% success rate in terms of restoration of knee stability, patient satisfaction, and return to full athletic activity.[1] The optimal graft material remains controversial, regardless of the graft tissue selected. The graft should have structural properties similar to those of the native ACL; these properties should be present at the time of graft implantation and persist throughout the incorporation period. The ideal material also should allow secure fixation, permit rapid biologic incorporation, and limit donor site morbidity.

The graft options available include autograft and allograft tissue as well as synthetic ligaments. Autograft options include the patellar, hamstring, and quadriceps tendons (Fig. 1, A). Allograft choices consist of the quadriceps, patellar, Achilles, hamstring, and anterior and posterior tibialis tendons, as well as the fascia lata (Fig. 1, B). Patellar tendon autografts have been the most popular graft choice because of their strength characteristics, ease of harvest, rigid fixation, bone-to-bone healing, and favorable clinical outcomes. However, donor site morbidity of patellar tendon autografts has led to the investigation and use of alternative graft sources.

Synthetic ligaments are classified as scaffolds, stents, or prostheses. The prototype is the carbon fiber scaffold ligament. The scaffold stimulates fibrous tissue ingrowth and contributes to the ultimate strength of the new ligament. A stent, such as the Kennedy ligament augmentation device, supports and protects autograft tissues during the healing phase, when the autogenous tissue is weakest. Examples of prosthetic ligament substances include polyethylene and Gore-Tex (W. L. Gore, Flagstaff, AZ).[2]

In selecting a graft for ACL reconstruction, results of the preoperative examination, as well as patient age, activity level, and comorbidities, must be considered. Graft sources can be compared on the basis of many criteria, including biomechanical properties, biology of healing, ease of graft harvest, fixation strength, graft site morbidity, and return-to-play guidelines (Table 1).

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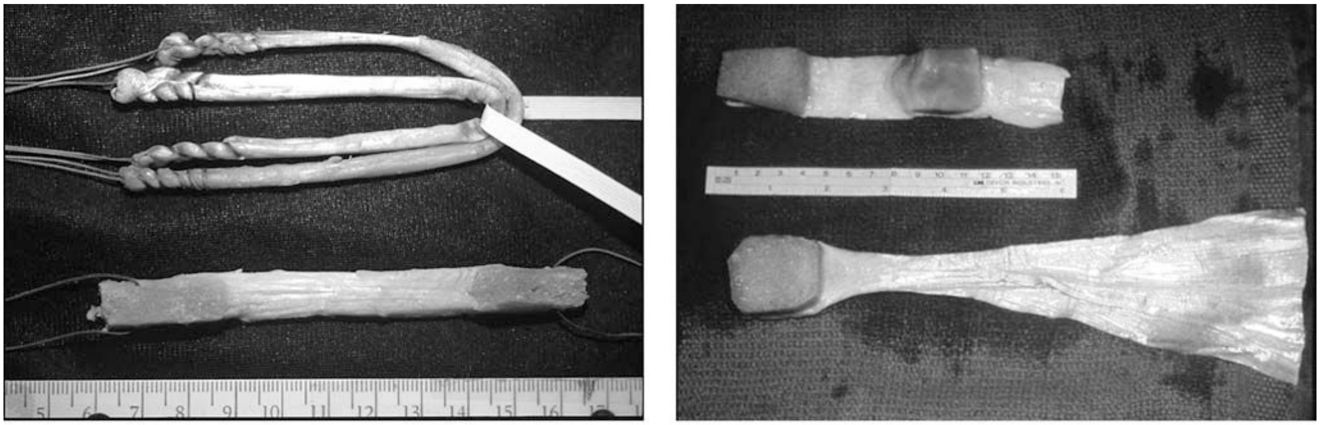

A B

Figure 1 **A,** Autografts. Hamstring (top) and patellar (bottom) tendons. **B,** Allografts. Patellar (top) and Achilles (bottom) tendons.

Anatomy and Biomechanics of the Normal ACL

The normal ACL functions as the primary restraint to anterior translation of the tibia and as a secondary restraint to tibial rotation and varus or valgus stress.[9,10] The native ACL has an average cross-sectional area of 44 mm^2, an ultimate tensile load of up to 2,160 N, a stiffness of 242 N/mm, and a strain rate of 20% before failure.[3,4,11] The forces in the intact ACL range from 100 N during passive knee extension to approximately 400 N on walking and up to 1,700 N with cutting and acceleration-deceleration activities.[6,12] The ACL experiences loads exceeding its failure capacity only with unusual loading patterns on the knee.

Biomechanical Properties of ACL Grafts

The biomechanical properties of the various graft materials have been studied extensively. In one early study, Noyes et al[3] subjected human ligament graft tissues of varying sizes to high-strain-rate failure tests. To assess the relative strength of these grafts, the results of the failure tests were compared with the mechanical properties of normal ACLs in young adults. The mean ultimate tensile strength and mean stiffness of the normal ACLs were 1,725 N and 182 N/mm, respectively. The bone–patellar tendon–bone graft (14 mm) had 168% the tensile strength and almost four times the

Table 1
Comparison of Anterior Cruciate Ligament Graft Types

	Biomechanical Property					
Graft	Tensile load (N)	Stiffness (N/mm)	Biologic Incorporation	Method of Fixation	Graft Site Morbidity	Outcomes/ Return to Play (months)
Patellar tendon autograft[3,4]	2,977	620	Bone-to-bone healing (6 wks)	Interference screw	Anterior knee pain; larger incision	4-6
Quadruple semitendinosus/ gracilis[5]	4,090	776	Soft-tissue healing (8-12 wks)	Variable	Hamstring weakness	Increased laxity/6
Patellar tendon allograft[6]	Similar to patellar tendon autograft	Similar to patellar tendon autograft	Bone-to-bone healing, slow incorporation (>6 mos)	Interference screw	None	>6
Quadriceps tendon[7,8]	2,352	463	Bone-to-bone and soft-tissue (6-12 wks)	Variable	Similar to patellar tendon autograft	Limited data

stiffness of the normal ACL. The semitendinosus and gracilis tendons provided 70% and 49% of the reported strength of the normal ACL, respectively. The patellar tendon graft was the only one of those tested (of the gracilis tendon, semitendinosus tendon, quadriceps tendon, fascia lata, iliotibial band) that was stronger than the normal ACL. Because the mechanical properties of the grafts are altered during incorporation into the host bone, these results represent the strength only at the time of initial implantation. Currently, the results of the grafts tested have little clinical significance because single-bundle hamstring and 14-mm patellar tendon grafts are rarely used. Smaller patellar tendon grafts (<12 mm) and quadrupled hamstring grafts are more commonly used in ACL reconstruction.

In that initial study, Noyes et al[3] tested graft strength without addressing the anatomic position of the normal ACL or the direction of tension on the tested fibers. Both the knee flexion angle and the direction of the applied tensile load affect the strength of the femur–ACL–tibia complex. Woo et al[4] evaluated the biomechanical properties of the femur–ACL–tibia complex in specimens of various ages to determine the effects of donor age and the direction of applied load. They reported a substantially higher stiffness (242 N/mm) and ultimate load to failure (2,160 N) of the ACL than had previously been reported. The value for ultimate load to failure was 30% higher when tested in the anatomic orientation of the ACL, and there was a notable age-related decrease in the structural properties of the ACL.

Staubli et al[7] studied the mechanical properties of 16 10-mm wide full-thickness patellar tendon and quadriceps tendon grafts from eight paired male donors. They found a Young's modulus of 200 ± 47 N/mm^2 for quadriceps tendons and 363 ± 94 N/mm^2 for patellar tendons when tested at 200 N ($P < 0.024$). Young's modulus was 304 ± 70 N/mm^2 for quadriceps tendons and 459 ± 83 N/mm^2 for patellar ligaments when tested at 800 N ($P = 0.016$). In their study of the biomechanical properties of quadriceps and patellar tendon grafts, Harris et al[8] reported a mean load to ultimate failure of 1,075 N and 876 N, respectively.

Comparing studies of the biomechanical properties of ACL grafts is difficult because results can vary markedly depending on the age of the donor, size of the graft, and methods of testing (Table 2). Additionally, clamp design can result in slippage of the graft during testing, with subsequent errors in elongation measurements. Alternatively, the clamp can crush the graft, resulting in premature failure and lower strength values.

Historically, the high-dose radiation used for sterilization of allografts resulted in weakened structural properties of the graft tissue. The alternative use of ethylene oxide sterilization resulted in adverse surgical reactions, most commonly chronic effusions. Ethylene oxide does not alter the mechanical properties of the graft and can effectively remove microorganisms. However, the chemical residue that ethylene leaves behind can cause chronic synovitis and subsequent graft failure.[13]

The current sterilization techniques are cryopreservation and gamma radiation. Cryopreservation has been shown to have no effect on the structural properties of ligaments, tendons, or meniscal tissue. Gamma radiation is an effective method of sterilization, but doses >3.0 Mrad, which are necessary to kill viruses, have detrimental effects on graft strength. Therefore, aseptic harvest and a cleaning process consisting of antibiotic soaks, multiple cultures, and low-dose radiation (<3.0 Mrad) is the most commonly used method for producing a sterile ACL graft.[14] Low-temperature chemical sterilization methods with good tissue penetration seem to be sporicidal and do not adversely affect the biomechanical properties of tissue. Other sterilization techniques, such as supercritical CO_2 and the use of antioxidants in combination with gamma irradiation, are being developed.[15]

The Biology of Healing

All ACL grafts undergo a sequential process of incorporation into the host knee.[16-19] The first phase of incorporation consists of an inflammatory response, during which the graft undergoes degeneration. The donor fibroblasts undergo cell death, and the remaining tissue serves as a scaffold for host cell migration and matrix production. The second phase consists of a period of revascularization, with migration of host fibroblasts into the graft tissue. This phase begins within 20 days of implantation and usually is complete 3 to 6 months after surgery.[16] The material properties of the graft change as the revascularization (ligamentization) process occurs. During graft maturation, graft strength drops to as low as 11% of that

Table 2
Biomechanical Properties of Selected ACL Graft Tissues

Tissue	Ultimate Tensile Load (N)	Stiffness (N/mm)	Cross-sectional Area (mm^2)
Intact anterior cruciate ligament[3]	2,160	242	44
Bone–patellar tendon–bone (10 mm)[6]	2,977	620	35
Quadruple hamstring[5]	4,090	776	53
Quadriceps tendon (10 mm)[7,8]	2,352	463	62

of the normal ACL and stiffness to as low as 13%.[17] The final phase consists of graft healing, with remodeling of the collagen structure into a more organized pattern. As the graft heals, its mechanical properties improve, but it never reaches the stiffness and strength of the graft material at the time of implantation.[17]

Healing of the graft attachment site may be responsible for most of the graft strength after transplantation. From a biologic standpoint, patellar tendon grafts have the advantage of bone-to-bone healing compared with soft-tissue grafts. Bone-to-bone healing is similar to fracture healing, and it is stronger and faster than soft-tissue healing. With bone-to-bone healing, the graft can be healed to the host bone within 6 weeks. Soft-tissue grafts usually incorporate into the host bone within 8 to 12 weeks.[18]

Autografts and allografts undergo a similar process of incorporation, including graft necrosis, cellular repopulation, revascularization, and collagen remodeling. However, allografts have a slower rate of biologic incorporation. Jackson et al[19] compared the histologic and microvascular status of patellar tendon autografts and allografts in a goat model. At 6 weeks, the allografts demonstrated increased vascularity and inflammatory response. The autografts had a notably greater cross-sectional area compared with the allografts at 6 weeks. The allografts had smaller cross-sectional areas, persistence of more original large collagen fibers, and fewer small-diameter collagen fibers. The autografts had a robust response and proliferation of small-diameter fibers. At 6 months, the allografts had a persistence of large collagen fibers, indicating a delay in remodeling. Mechanical testing of the allograft and autograft groups showed a statistically significant ($P < 0.01$) difference in anteroposterior translation at 6 months. The autograft displacement was 3.4 ± 0.5 mm, compared with 5.3 ± 1.0 mm in the allograft group ($P < 0.01$). The patellar tendon autograft demonstrated a more robust biologic response, improved stability, and increased strength-to-failure values. The authors suggested a longer period of protection for patients with allograft ACL reconstructions than for those with autograft reconstructions.

Nikolaou et al[20] compared the strength, histology, and revascularization of patellar tendon allografts and autografts. The mechanical integrity of the allografts was similar to that of the autografts; both achieved nearly 90% of control ligament strength by 36 weeks. Revascularization approached normal by 24 weeks in both the autograft and allograft.

Graft Harvesting

The goal of graft harvest should be to obtain an adequate graft specimen while minimizing donor site morbidity. The ease of graft harvest is surgeon-dependent. Each graft represents a unique set of technical challenges and potential pitfalls that should be thoroughly understood before harvest.

Patellar tendon autografts require harvesting of a tibial tubercle and patellar bone plug. Large, deep cuts can increase the risk for stress fracture in the proximal tibia and patella, as well as endanger the patellar articular cartilage. Trapezoidal bone cuts, instead of triangular ones, have been described that reduce the risk of articular cartilage penetration.

The quadriceps tendon is more difficult to harvest than the patellar tendon because of its denser cortical bone, curved proximal surface, and close adherence to the suprapatellar pouch. Fulkerson and colleagues[21,22] have described a technique to harvest the quadriceps tendon safely and efficiently. Through a short midline incision, starting mid-patella and extending proximally, a 10-mm wide and 20-mm long bone plug is harvested from the proximal patella. The bone plug should be 6 to 8 mm thick, leaving a tendon graft approximately 6 mm thick. The tendon is then harvested about 7 cm proximally, taking care to avoid entering the suprapatellar pouch. A drill hole is then made in the bone plug, and a no. 5 suture is passed through the plug.

Hamstring tendon harvest requires elevating the sartorius to expose the underlying semitendinosus and gracilis tendons. The tendons can be either left on their insertion or detached from the tibia during harvest. A closed or open tendon stripper then is used to retrieve the tendons. Care should be taken to harvest the entire tendon and not amputate it prematurely.

Mechanics of Initial Fixation

Graft fixation is crucial in ACL reconstruction and is the weakest link in the initial 6- to 12-week period, during which healing of the graft to the host bone occurs. The graft must be able to withstand early rehabilitation, which can consist of forces as high as 450 to 500 N.[11] If fixation is poor, the graft may slip or the fixation may fail altogether, resulting in an unstable knee. Fixation failure usually occurs on the tibial side.[23]

It is difficult to compare fixation studies because of the wide variation in fixation and testing methods (Table 3). Interference screw fixation for bone block patellar tendon grafts has demonstrated fixation strength and stiffness superior to that of alternative fixation methods. The average failure strength of bone block fixation with an interference screw is 423 to 558 N.[26] Factors that may affect fixation strength of interference screws include screw diameter and screw divergence from the bone block. Screw diameter, usually 7 or 9 mm, has been shown to have a negative effect on the pull-out strength only when the gap between the bone block and the tunnel wall exceeds 2 mm.[27] Placement

Table 3
Failure Strength of Various Techniques of Graft Fixation

Fixation	Ultimate Failure Load (N)	Stiffness (N/m)
Patellar Tendon		
Metal interference screw[19]	558	—
Bioabsorbable interference screw[19]	552	—
Soft Tissue (Femoral)		
Bone Mulch Screw (Arthrotek, Warsaw, IN)[24]	1,112	115
EndoButton (Smith & Nephew Endoscopy, Andover, MA)[24]	1,086	79
RigidFix (Ethicon, Somerville, NJ)[24]	868	77
SmartScrew ACL (Linvatec, Largo, FL)[24]	794	96
BioScrew (Linvatec)[24]	589	66
RCI Screw (Smith & Nephew Endoscopy)[24]	546	68
Soft Tissue (Tibial)		
Intrafix (Ethicon)[25]	1,332	223
WasherLoc (Arthrotek)[25]	975	87
Tandem spiked washer[25]	769	69
SmartScrew ACL[25]	665	115
BioScrew[25]	612	91
SoftSilk (Acufex Microsurgical, Mansfield, MS)[25]	471	61

of interference screws with a divergence angle >30° from the bone block results in failure at lower loads compared with screw placement parallel to the bone block.[28]

Fixation strength of soft-tissue grafts varies depending on the choice of fixation; different methods are available for the tibial and femoral sides. Commonly used tibial fixation devices include suture posts, staples, screw-and-washer constructs, and interference screws (Fig. 2, A). Femoral fixation devices are similar to those for the tibial side but also include cross-pins and buttons (Fig. 2, B).

Kousa et al[24,25] reviewed the fixation strength of six hamstring tendon graft-fixation devices for the femoral and the tibial sides during ACL reconstruction. On the femoral side, the Bone Mulch Screw offered superior fixation ($P < 0.001$) compared with the other devices in the single-cycle load-to-failure test (Table 3). The yield load of the Bone Mulch Screw was significantly greater ($P < 0.001$) than that of the BioScrew and the RCI Screw. The stiffness of the Bone Mulch Screw fixation was significantly ($P < 0.001$) greater than the stiffness of the EndoButton, RigidFix, BioScrew, and the RCI screw. The stiffness of the Bone Mulch Screw was not significantly greater than that of the SmartScrew ACL.[24]

On the tibial side, the Intrafix was the strongest ($P < 0.01$) in the single-cycle load-to-failure test (Table 3). The Intrafix also had a significantly greater stiffness ($P < 0.01$) than the WasherLoc, the tandem spiked washer, the SmartScrew, the BioScrew, and the SoftSilk.

Graft Morbidity

Graft morbidity is caused by associated symptoms (eg, anterior knee pain, quadriceps and hamstring weakness), donor site and synthetic graft complications, strength deficits, stiffness, and infection.

Anterior Knee Pain

Anterior knee pain is common after ACL reconstruction, with symptoms occurring anywhere along the extensor mechanism (ie, patellar or quadriceps tendons, patellofemoral joint, peripatellar soft tissues). The pain may be related to the choice of graft material; most studies show a tendency for decreased pain with the use of hamstring autografts compared with patellar tendon autografts.[1,29-34] However, there is no difference in the incidence of anterior knee pain between patients with patellar tendon autografts and allografts.[35] Some authors have suggested that anterior knee pain is related more to loss of motion and poor rehabilitation techniques than to graft choice. Sachs et al[36] demonstrated a correlation between the development of patellofemoral symptoms and the presence of a flexion contracture and quadriceps weakness. Shelbourne and Nitz[37] noted a decrease in patellofemoral symptoms after an accelerated rehabilitation protocol; they attributed the decrease in symptoms to the early restoration of range of motion (ROM) and quadriceps strength. In a meta-analysis of 21 studies using patellar tendon autografts and 13 studies using hamstring grafts, the incidence of anterior knee pain was 17.4% in the patellar tendon group versus 11.5% in the hamstring group.[1]

No specific studies compare anterior knee symptoms between quadriceps tendon, patellar tendon, and hamstring tendon autografts. However, Chen et al[38] reported only mild harvest site tenderness in 12 patients at an average of 18 months after ACL reconstruction with quadriceps autograft. Fulkerson and Langeland[21] reported no early quadriceps morbidity in their series of 28 patients.

Quadriceps and Hamstring Tendon Strength

Persistent quadriceps and hamstring weakness is another problem after graft harvest. Rosenberg et al[39]

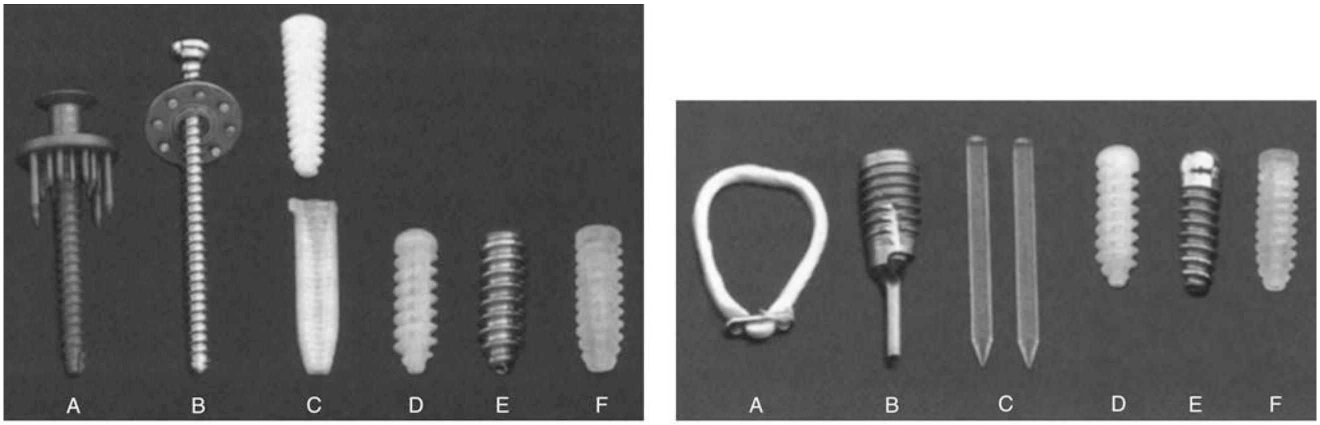

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Figure 2 **A,** Tibial side hamstring fixation devices. A = WasherLoc, B = spiked washer, C = Intrafix, D = BioScrew, E = SoftSilk, F = SmartScrew. **B,** Femoral side hamstring fixation devices. A = EndoButton, B = Bone Mulch Screw, C = RigidFix, D = Bioscrew, E = RCI Screw, F = SmartScrew. (Panel A reproduced with permission from Kousa P, Järvinen TL, Vihavainen M, Kannus P, Järvinen M: The fixation strength of six hamstring tendon graft fixation devices in anterior cruciate ligament reconstruction: II. Tibial site. *Am J Sports Med* 2003;31:182-188. Panel B reproduced with permission from Kousa P, Järvinen TL, Vihavainen M, Konnus P, Järvinen M: The fixation strength of six hamstring tendon fixation devices in anterior cruciate ligament reconstruction: I. Femoral revision. *Am J Sports Med* 2003;31:174-181.)

evaluated extensor mechanism function in 10 randomly selected patients 12 to 24 months after ACL reconstruction using the central third of the patellar tendon. Although all patients were satisfied with their results and considered their knees to be stable, many had subjective complaints of anterior knee pain and weakness. Only 3 of the 10 patients returned to participation in all of their preinjury sports. Isokinetic testing at 60°/sec angular velocity showed an average quadriceps deficit of 18% compared with the normal extremity. Axial computed tomography scans revealed a marked decrease in the quadriceps cross-sectional area.

Lephart et al[40] compared objective measurements of quadriceps strength and functional capacity in athletes after patellar tendon autograft and allograft ACL reconstruction. They reported no significant difference between the autograft and allograft groups with regard to thigh circumference, quadriceps strength and power, and functional performance tests. The quadriceps index, which is calculated by comparing the involved leg with the uninvolved leg at 60°/sec angular velocity, indicated similar results between the allografts and autografts, with the indexes averaging 90% to 95%. The findings suggest that harvesting the central third of the patellar tendon does not diminish quadriceps strength or functional capacity in highly active patients who undergo intense rehabilitation.

Carter and Edinger[41] compared hamstring and quadriceps isokinetic test results 6 months postoperatively in 106 randomly selected patients who had ACL reconstruction with either patellar tendon or hamstring autografts. No statistically significant differences were found between the different graft sources with regard to knee extension or flexion strength. However, at 6 months postoperatively, most patients had not achieved adequate strength to safely partake in unlimited activities.

Nakamura et al[42] evaluated hamstring strength at 2 years postoperatively in 74 consecutive patients who had had hamstring ACL reconstruction. Similar to the results of other studies, recovery of peak flexion torque was more than 90%. However, the recovery was less at 90° knee flexion. These results suggest that loss of hamstring strength after harvesting may be more prominent at deep flexion angles.

There are no studies evaluating hamstring or quadriceps tendon strength recovery after reconstruction with a quadriceps tendon autograft. Because quadriceps harvest is similar to patellar tendon harvest in regard to extensor mechanism disruption, similar strength testing results have been inferred.

Donor Site Complications

Although infrequent, reported complications with patellar tendon autograft include patellar fractures,[43] patellar tendon ruptures,[44] tendinitis, localized tenderness, and numbness. Numbness also can occur with hamstring autograft as a result of injury to the superficial branch of the saphenous nerve.[45] The infrapatellar branch of the saphenous nerve passes on the inferior medial aspect of the knee; therefore, the risk of nerve injury would seem to be low after quadriceps tendon harvest. The risk of patellar fracture also should be low because the proximal patellar bone is more dense.

A serious potential problem with the use of allografts is disease transmission, although the problem has largely been eliminated with the development of better donor screening and testing procedures. Guidelines issued by the American Association of Tissue Banks have been revised and updated six times since they were instituted in 1986 to ensure sterility and quality during allograft processing. A detailed medical, social, and sexual history must be obtained for each potential cadaveric donor. Extensive testing includes blood cultures, harvested tissue cultures, and screening for antibodies to human immunodeficiency virus (HIV)-1 and HIV-2, hepatitis B surface antigen, hepatitis C, syphilis, and human T-cell lymphotropic virus.[14]

To decrease the window of vulnerability between the infection and the production of antibodies by the donor, more than half of tissue banks now use polymerase chain reaction testing to directly detect viral antigens. Polymerase chain reaction testing is sensitive enough to detect as few as 5 to 20 viral DNA copies of HIV per sample tested.[14] To date, there have been three reported cases of disease transmission from bone–patellar tendon–bone allografts used to reconstruct the ACL.[14] The first case of HIV was reported in 1985; the other two were cases of hepatitis C, reported in 1991.[46]

Synthetic Grafts

Synthetic ligaments have a higher complication rate than do allograft and autograft reconstructions. Carbon fiber scaffolds have had very limited success. They have been associated with a high rate of synovitis, and an in vitro study in pigs found that ingrowth into the scaffold does not occur.[2] Also, the carbon fibers do not adhere to the bony channels, and the peak tensile strength of the ligaments after reconstruction with a carbon scaffold was one third the strength of a normal ACL at 4 months postoperatively.[2,47]

Prosthetic implants also have had very limited success. They have been associated with recurrent instability, chronic effusions, and synovitis. The Kennedy ligament-augmentation device (LAD) was devised to protect the biologic graft during the early phases of weakness and degeneration. The LAD goes through a revascularization process similar to that of biologic grafts, but the collagen produced is abnormal. The connective tissue has an insufficient exposure to tensile forces, which causes failure of the collagen alignment. LAD–related complications range from 0% to 63% in the literature.[2] Effusions and reactive synovitis are the most commonly reported complications. The LAD also may have a higher association with infections.[2,48]

Clinical Outcome by Graft Type

Freedman et al[1] performed a meta-analysis of 21 studies (1,348 patients) from 1966 to 2000 (minimum follow-up, 24 months) and reported a significantly ($P < 0.001$) lower rate of failure in the patellar tendon autograft group than in the hamstring tendon autograft group (1.9% versus 4.9%). Laxity was measured clinically with the KT-1000 arthrometer and pivot-shift testing. A significantly ($P = 0.017$) higher proportion of the patellar tendon group (79%) had a side-to-side difference of <3 mm compared with the hamstring group (73.8%). The patellar tendon group had a significantly ($P = 0.009$) higher rate of subjects requiring lysis of adhesions than did the hamstring group (6.3% versus 3.3%). The patellar group also demonstrated a higher rate ($P = 0.007$) of anterior knee pain (17.4% versus 11.5%). The hamstring group had a higher rate of hardware removal after reconstruction (5.5% versus 3.1%) ($P = 0.017$). Infection rates were not significantly different between the two groups (0.5% in the patellar group versus 0.4% in the hamstring group).

Colombet et al[49] reported good clinical results in a series of 200 patients who underwent ACL reconstruction with a four-strand hamstring autograft and metal interference screw fixation. Eighty-six percent of the patients returned to high-performance athletics at a national or international competition level.

Revision Surgery

Revision ACL reconstruction is essentially a salvage procedure; the cause of failure of the initial reconstruction (eg, trauma, poor surgical technique, fixation failure) must be established. Also, it is critical to determine the desires and aspirations of the patient. Meticulous preoperative planning is essential, including weight-bearing radiographs and a thorough knee examination to determine associated instabilities. Possible available graft donor sites include the ipsilateral or contralateral hamstrings, patellar tendon, quadriceps tendon, fascia lata, and allograft.

Noyes and Barber-Westin[50] prospectively studied the outcomes of patellar tendon allografts and autografts used for revision ACL surgery in 65 patients (mean follow-up, 42 months). Notable improvement in symptoms, function, anteroposterior displacement, and overall ratings was noted in all patients. Although not statistically significant, the KT-2000 results showed <3 mm increased displacement in 53% of the allograft group and in 67% of the autograft group. Overall failure rates were 33% for the allografts and 27% for the autografts.[50]

Kartus et al[51] compared 12 patients who underwent revision ACL surgery with a reharvested ipsilateral patellar tendon autograft with 12 patients who underwent the revision reconstruction with a contralateral patellar tendon graft. Postoperative KT-1000 arthrometer measurements showed no significant differences between the two groups. However, the Lysholm scores were significantly (*P* = 0.002) higher in the patients with the contralateral patellar tendon graft. Functional outcomes and the Tegner activity levels were similar for both groups. Two major complications occurred—one patellar fracture and one patellar tendon rupture—both in the ipsilateral patellar tendon harvest group.

Uribe et al[52] reported the results of revision ACL reconstruction in 54 patients with use of ipsilateral patellar tendon autograft (31%), contralateral patellar tendon autograft (30%), patellar tendon allograft (35%), and hamstring autograft (4%). At a mean follow-up of 32 months, autogenous grafts provided greater objective stability compared with allografts, with average KT-1000 readings of 2.2 and 3.3, respectively. There were no functional differences between the groups, and harvesting the contralateral tendon had no adverse long-term effects. The subjective results were markedly worse depending on the degree of articular cartilage degeneration. Only 54% of the patients returned to their pre-ACL injury activity level.

Reharvesting the ipsilateral patellar tendon has been recommended. Woods et al[53] reported on long-term results in 10 patients who underwent 13 revision ACL reconstructions using the lateral third of the ipsilateral patellar tendon as a graft. All of the primary reconstructions had used the central third of the ipsilateral patellar tendon as autograft. At a mean follow-up of 43 months, the average KT-1000 difference between knees was 2.4 mm. All patients had a negative pivot shift, and the mean bilateral comparison ratios of isokinetic strength testing were 84% for extension and 96% for flexion. All patients returned to their previous work levels, and 80% returned to moderate sports activities.

Colosimo et al[54] reviewed 13 patients who underwent revision ACL reconstruction with the reharvested ipsilateral patellar tendon. At an average follow-up of 39.4 months, 11 patients had good or excellent results and 2 had fair results. Postoperative KT-1000 testing showed an average side-to-side difference of 1.92 mm. The average extension and flexion deficits were 10% and 1.7%, respectively. Only one patient reported moderate patellofemoral problems.

Several studies have addressed the biomechanical and histologic properties of the patellar tendon after reharvest. In their evaluation of the harvest site in 14 patients, Nixon et al[55] found that the central third of the patellar tendon reconstituted itself and was nearly identical to normal tendon tissue by 24 months postoperatively. Burks et al[56] examined the biomechanical and histologic changes in remaining tissue following a central third patellar tendon harvest. They found a marked increase in tendon cross-sectional area at 3 months, with a further increase at 6 months. However, in a canine study, LaPrade et al[57] demonstrated that the average load to failure of reharvested patellar tendon was 54% that of contralateral controls after 1 year. Proctor et al[58] reported that the maximum force to failure and ultimate stress of reharvested tendons in a goat model had decreased by 51% and 65%, respectively, compared with the contralateral side.

Return to Play

Functional testing, clinical evaluation, and subjective assessment should be used to determine when a patient may return to full activity. Complete ROM is needed prior to return to sports; regaining less than complete ROM places the extremity at a mechanical disadvantage and increases the risk for reinjury. Muscle strength and balance must be achieved to provide the required dynamic stability. Determination of successful return to play is subjective. It may be based on an earlier return to play, level of competition, or stability and strength of the knee. Most data, which are surgeon- and technique-dependent, support the use of patellar tendon autograft for a quicker return to play.

The bone-to-bone healing of patellar tendon autografts offers the quickest incorporation into the host bone. Soft-tissue grafts, such as hamstring autografts, can take up to 6 weeks longer to incorporate than patellar tendon autografts. Allografts have a longer biologic incorporation—sometimes up to 1 year for complete integration.[18,19] However, return to play is based not only on graft healing but also on strength, agility, and stability of the knee.

O'Neill[59] performed a prospective randomized analysis of 125 patients who underwent one of three autograft ACL reconstruction techniques: hamstring autograft, two-incision patellar tendon autograft, or single-incision patellar tendon autograft. Return to preinjury level of activity was 88% in the hamstring group, 95% in the two-incision group, and 89% in the single-incision group. In another prospective randomized comparison,[31] there was a notable reduction in activities after ACL reconstruction with both the patellar tendon and hamstring autografts. Activity reduction was 45% in the patellar group and 37% in the hamstring group. However, many patients reported a decrease in activity because they were no longer participating in high school or college sports.

Bach et al[60] retrospectively studied the results of 97 patients who underwent ACL reconstruction with a two-incision patellar tendon autograft technique. Fifty-three patients (55%) returned to their preinjury sports levels; 18 (19%) indicated a decrease in activity level because of the knee.

Fourteen patients (14%) reported a decrease in activity unrelated to the knee, and four (4%) stopped all sports for problems unrelated to the knee. Three patients (3%) stopped all sports because of knee problems.

Yunes et al[61] compared patellar tendon and hamstring autografts in their meta-analysis of four studies with at least a 2-year follow-up. The patellar tendon group had significantly ($P = 0.01$) better results: a 75% return to preinjury activity level compared with a 64% return with the hamstring reconstruction. No real differences could be demonstrated between the types of autografts.

Shino et al[62] reported that 79 of 84 patients who had ACL reconstruction with soft-tissue allografts returned to their desired activity levels. No direct comparisons have been done with other types of grafts.

For patients whose priority is a quick return to sports, Shelbourne and Urch[63] recommend ACL reconstruction with a contralateral patellar tendon autograft. They reviewed patients who had had primary ACL reconstruction with either the contralateral (434 patients) or ipsilateral (228 patients) patellar tendon to determine the difference between the groups regarding ROM, quadriceps strength, and return to sports. The patients were divided into three subgroups. The competitive subgroup consisted of 260 athletes who competed in twisting, pivoting, or jumping sports at either a high school, collegiate, or professional level. The recreational subgroup consisted of 172 patients older than age 26 years who competed in similar activities at a recreational level. The third subgroup consisted of 230 patients who were either participating in sports that did not involve jumping or pivoting, or who did not meet the age requirement for the recreational subgroup. The average times to return to full preinjury sport participation for the contralateral and ipsilateral groups were 4.9 and 6.1 months, respectively. The competitive subgroup returned to full preinjury sports activity at an average of 4.1 months (contralateral group) and 5.5 months (ipsilateral group).

Return-to-play results after revision ACL surgery are much more variable. Only a few studies have been published on outcomes following revision surgery, and many of them do not document return-to-play results. Eberhardt et al[64] reviewed 44 patients who underwent a revision ACL reconstruction with patellar tendon autograft (average follow-up, 41 months). Sixteen patients (36%) did not reach their preinjury activity level; 4 were unable to return to play, and 10 elected not to. In one study of 54 patients who underwent revision ACL reconstruction, only 46% returned to their preinjury activity level.[52]

Many of the reported ACL series do not address preinjury or postinjury activity level. After ACL reconstruction, many patients do not return to their preinjury levels because of a variety of factors, such as lifestyle changes (out of school, no longer competing), fear of recurrent knee injury, instability, and pain. Return-to-play criteria should incorporate factors such as agility, strength, clinical stability, and ROM. These criteria are difficult to correlate with a particular graft type or surgical technique.

Summary

The patellar tendon autograft has the largest number of reported outcomes in the literature and is the most widely used graft source.[45] Patellar tendon autografts may have some relative advantages for high-demand patients who participate in cutting, pivoting, or jumping sports or who desire a quick return to play. Preexisting anterior knee pain and certain lifestyle activities (eg, kneeling for work or religion) are relative contraindications to the patellar tendon autograft. Quadriceps tendon autografts are less commonly used but have been reported to have excellent results with a low rate of morbidity.

Hamstring grafts are increasing in popularity, primarily because of their excellent stiffness and tensile load properties, improved fixation techniques, reduced harvest morbidity, and excellent outcome and patient satisfaction scores. However, there is a higher reported degree of instrumented (KT-1000) tested laxity for hamstring reconstruction and a lower return to preinjury activity levels.[29-32,49] Quadruple hamstring autograft is preferable in lower-demand patients, recreational athletes, younger patients with open growth plates, and patients who are concerned about cosmesis. Contraindications to hamstring autograft include generalized increased ligamentous laxity, competitive sprinters (terminal flexion weakness), or previous hamstring injury.

Allografts have had a recent resurgence. Improved sterilization techniques, along with a wide range of graft sources (eg, tibialis, Achilles, and patellar tendons), have led to increased safety and availability. However, the benefits of decreased surgical morbidity and easier rehabilitation must be weighed against the higher costs of the allografts and the slower period of incorporation.[19] Patellar tendon allografts have some advantage in lower-demand patients, in older patients who prefer an easier rehabilitation, and for patients with knees that have multiple injured ligaments.

There is no evidence that routine use of synthetic ligaments should be advocated. Synthetic grafts are associated with a higher risk of complications, including recurrent instability, effusions, and, possibly, infections.[2,47,48]

Graft selection for revision ACL reconstruction depends on the etiology of the failure and on patient preference. Patellar tendon allografts may be used in patients who have failed autograft (particularly patellar tendon) and in complex revisions with secondary restraint failures (meniscal or collateral injury). Autografts also are optimal for revision when the primary etiology of failure is failure of an allograft.

The ideal graft for ACL reconstruction should have biomechanical properties similar to those of the native ACL, enable stable initial fixation and rapid biologic incorporation, and offer a low rate of morbidity. Understanding the technical challenges and potential pitfalls involved with each graft is important. The morbidity of the harvest is surgeon- and technique-dependent. Graft selection depends on many factors, including the surgeon's philosophy and experience, tissue availability, patient activity level, comorbidities, prior surgery, and patient preference.

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