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Graft choice in ACL reconstruction

Introduction

The anterior cruciate ligament (ACL) reconstruction is the sixth most common procedure in orthopaedic surgery, with more than 100,000 surgeries performed in the United States per year (1). Although widely accepted and investigated, ACL reconstruction still continues to evolve with many technical issues under debate and dependent on surgeon preference. These include tunnel placement, use of double- vs. single-bundle technique, type of fixation, and graft selection (2).

The ideal graft for ACL reconstruction would consist of the following : reproduce the histological and biomechanical characteristics of the native ligament ; incorporate fully and quickly within bone tunnels ; have no risk of rejection or disease transmission ; minimal donor-site morbidity ; be of sufficient length and diameter ; and be cost-effective as well as readily available (2). The ideal graft and a "gold standard" do not really exist. Many grafts are available (Table 1), each one with advantages and disadvantages. One of the surgeon's roles in ACL reconstructive surgery is to individualize the graft choice for each patient's need (3). In planning the surgery and deciding the graft type, the clinical examination, i.e., isolated vs. multiligament knee instabilities, the age, the activity level, as well as the occupational and recreational activities of the patient should be considered.

As means of developing an ideal graft, without donor-site morbidity, proper mechanical strength, and no risk of disease transmission, many investigators have attempted to develop and use synthetic ligament substitutes. Synthetic grafts can be classified as (1) scaffolds, (2) stents, or (3) prostheses (4). A scaffold is made of synthetic tissue (e.g., carbon fiber) that stimulated the fibrous tissue ingrowth ; a stent (e.g., Kennedy ligament augmentation device, LAD) is designed to protect the healing of the biologic graft during its incorporation phase into the joint ; a prosthesis, mainly made of polyethylene and Gore-Tex, substitutes the biologic graft. Unfortunately, these devices reported a higher rate of complications compared to autograft and allograft. Carbon fiber scaffolds have been associated with synovitis, lack of fibrous tissue ingrowth (4,5), and failed adhesion to the bone tunnels with subsequent poor biomechanical properties (4–6). Moreover the prosthetic implants were correlated to an increased risk of developing chronic instability, joint effusions, and synovitis (4). The LAD's outcomes are not more encouraging, reporting complication rates from 0 % to 63 %, with effusion, synovitis, and infection as the more frequent causes of failure (4,5,7). For all these reasons, their use is not widely accepted, and autograft along with allograft remain the graft type of choice in ACL reconstruction. The question now revolves around which autograft : patellar tendon vs. soft tissue graft (i.e., hamstring) or allograft vs. autograft choices.

Table 1 – Grafts available for ACL reconstruction.

Autograft	Allograft	Synthetic grafts
Bone patellar-tendon bone Hamstrings Quadriceps tendon Fascia lata	Bone patellar-tendon bone Hamstrings Quadriceps tendon Tibialis anterior or posterior tendon Achilles tendon Fascia lata	Scaffolds Stents Prostheses

Both autograft and allograft have reported excellent results and are the most commonly used options in ACL reconstruction. The advantages of autograft include (2) improved measured stability, lower graft failure rate (8), lower infection rate (9), no risk of infectious disease transmission, no risk of immune reaction (10), lower cost (11), faster graft incorporation, and prompt return to full activities (12). On the other hand, the advantages of the allograft tissues (Fig. 1) are (2) a faster immediate post-operative recovery, less post-operative pain, no need for graft harvest, no donor-site morbidity, larger variety of graft sizes and shapes available, and improved cosmesis.

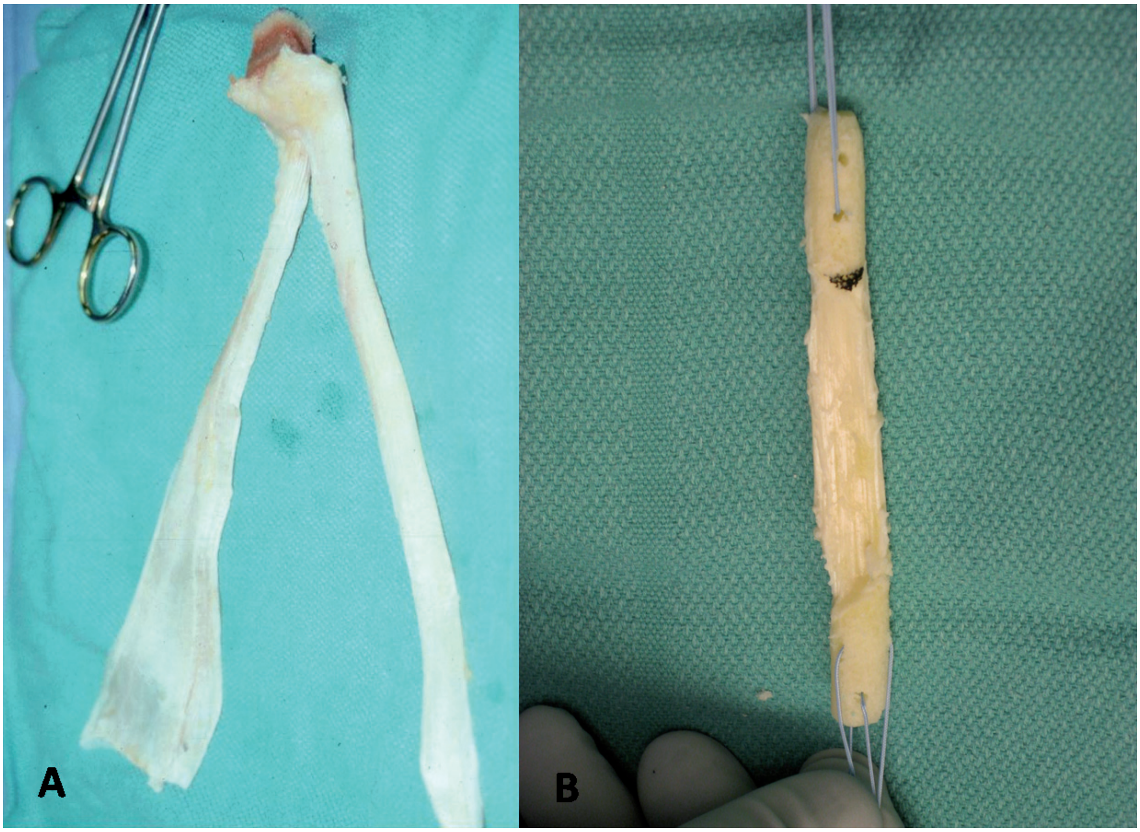

Fig. 1 – Allografts. (A) Achilles tendon allograft. (B) Patellar tendon allograft.

Biological healing of the graft

When deciding which biologic graft to utilize in an ACL reconstruction, it is necessary first to understand the basic science of what the graft ultimately develops into. Both autograft and allograft undergo an incorporation process in the joint that involves many phases (4).

The first phase is mainly centered on the degeneration (inflammatory response mediated) of the graft, where the fibroblasts undergo cell death and the graft acts as a scaffold for host cell migration. The second phase (from 20 days to 3–6 months after surgery) consists of the revascularization of the neo-ligament and the host fibroblasts'migration (4,13). During and after the vascularization, the "ligamentization" or "biochemichal metamorphosis" phase occurs and the fibroblasts lay down a new matrix (4,14). In this phase at the light microscope level, there is no detectable difference between tendons and ligaments, although they appear completely different at biochemical analysis (15). The final (healing) phase is centered on the remodeling of the collagen fibrils in a more organized pattern with improvement of the graft's strength (4). Nevertheless, the biomechanical properties of the neo-ligament never reach those of the un-implanted grafts (16).

Biology is very important at the graft insertion site as well. Two are the possible types of healing : bone-to-bone (grafts with a bone plug) and tendon-to-bone healing (soft tissue grafts). It is widely believed that bone-to-bone healing is stronger and faster compared to soft tissue healing. A bone plug autograft can heal in the femoral or tibial tunnel within 6 weeks (4), while the soft tissue autograft healing occurs at 8–12 weeks from surgery (17). The allograft healing time is usually longer (6–9 months) (3). Jackson *et al.* (4,18) compared the histologic and microvascular status of patellar tendon autografts and allografts in a goat model. Mechanical testing of the allograft and autograft groups showed a statistically significant ($p < 0.01$) difference in anteroposterior translation at 6 months. The 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 (4,18).

Another factor that may influence the healing of the graft is the magnitude of the neo-ligament motion in the tunnel (19). This should be particularly considered when using soft tissue grafts and a tendon-to-bone healing, with Sharpey fiber formation, is involved (17). Rodeo *et al.* (19) performed an in vivo study on a rabbit model, demonstrating that graft-tunnel motion was greatest at the tunnel apertures and least at the tunnel exit, and that graft healing in the femoral tunnel was inversely proportional to the magnitude of graft-tunnel motion. Given these considerations, the retrograde drilling of the tibial socket, with minimum aperture "blow-out," may be a solution to minimize the osteoclast-mediated bone resorption, the synovialization of the graft, and, therefore, the tunnel widening (20,21).

Biomechanics of the grafts

Many studies summarized in Table 2 reported the biomechanical properties of the native ACL and the grafts available for ACL reconstruction (3,4).
As shown in Table 2, the strength of the different grafts is superior to that of the native ACL. Nevertheless, all these tests were performed on the unimplanted graft and, therefore, before the incorporation phases and the subsequent weakening that takes place in vivo. These data simply suggest that every graft evaluated has mechanical properties superior to the normal ACL in the very first postoperative period and that the graft alone (without considering the graft fixation biomechanics) may allow an early aggressive rehabilitation.
Another consideration that may be inferred from these studies is that the currently used sterilization techniques (cryopreservation and gamma radiation < 3 Mrad) do not impair the allografts'strength (4). In the past, high dose radiation resulted in allograft weakening, and ethylene oxide sterilization caused effusions, chronic synovitis, and graft failures (27).

Table 2 – Biomechanical properties of different grafts available for ACL reconstruction.

Graft	Ultimate tensile load (N)	Stiffness (N/mm)	Cross-sectional area (mm^2)
Native ACL (22)	2160	242	44
BPTB (10 mm) auto- and allograft (23)	2977	455(auto) 620 (allo)	32 (auto) 35 (allo)
Quadrupled hamstring auto- and allograft (24)	4090	776	53
Quadriceps tend (10-mm) autograft (25)	2174	463	62
Achilles tendon (26)	4617	685	67
Tibialis anterior allograft (26)	4122	460	48
Tibialis posterior allograft (26)	3594	379	44

Note : BPTB, bone-patellar tendon-bone.

Harvesting, donor-site morbidity, and possible graft-related complications

The patellar tendon autograft requires the harvest of both a tibial tubercle and a patellar bone plug (Fig. 2). The main risks consist in patellar fractures (intra-operative and post-operative) (Fig. 3), tibial stress fractures, patellar articular cartilage damage, and tendon ruptures. It has been suggested that trapezoidal bone cuts, instead of triangular ones, may reduce the risk of cartilage lesions (4). The patellar tendon autograft is associated with an increased risk of anterior knee pain (most of all during kneeling), and many studies showed that the use of hamstring autograft reduces this risk (28). The incidence of anterior knee pain is 17.4 % with patellar tendon autograft and 11.5 % with hamstring autograft (28). Nevertheless, there is no difference in the incidence of anterior knee pain between patients with patellar tendon autografts and allografts (4,29). Some authors suggested that anterior knee pain is mainly caused by poor rehabilitation techniques and loss of knee motion (4,30,31). Other complications described for patellar tendon autograft include patellar tendonitis and numbness in the anterolateral knee aspect (damage to the infrapatellar branch of the saphenous nerve). Harvesting the central third of the patellar tendon does not diminish quadriceps strength or functional capacity in highly active patients who undergo intense rehabilitation (32).
During hamstring harvesting, care should be taken in withdrawing the whole tendons, without truncating them prematurely (Fig. 4). This may be achieved by a close digital release of all the distal vincula of the gracilis and semitendinosus tendons. Also the posterior mini-incision harvest technique (33) allows a good visualization and differentiation of the tendons and their cross-connections, which, if not properly released, may cause premature amputation. Complications associated with this procedure include saphenous nerve and vein injury, femoral arterial and vein injury, sciatic nerve damage, and residual muscle weakness and discomfort (3). Mild knee flexion weakness

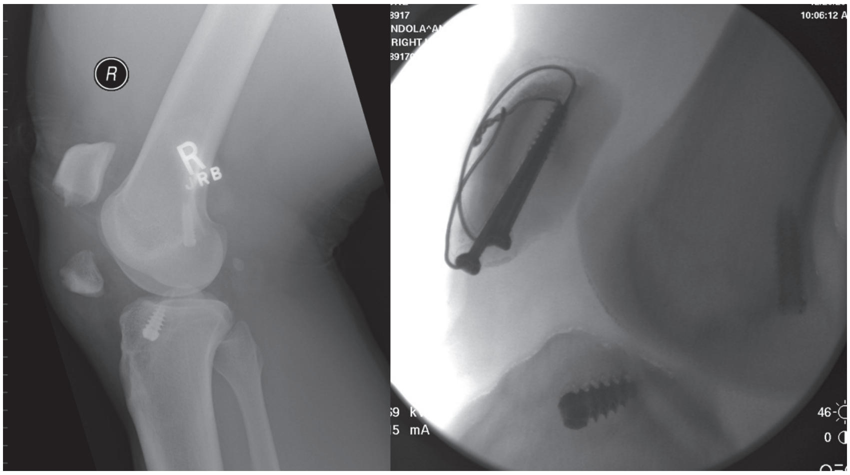

Fig. 2 – Patellar tendon autograft.

Fig. 3 – Post-operative patellar fracture after ACL reconstruction with patellar tendon autograft (before and after fixation).

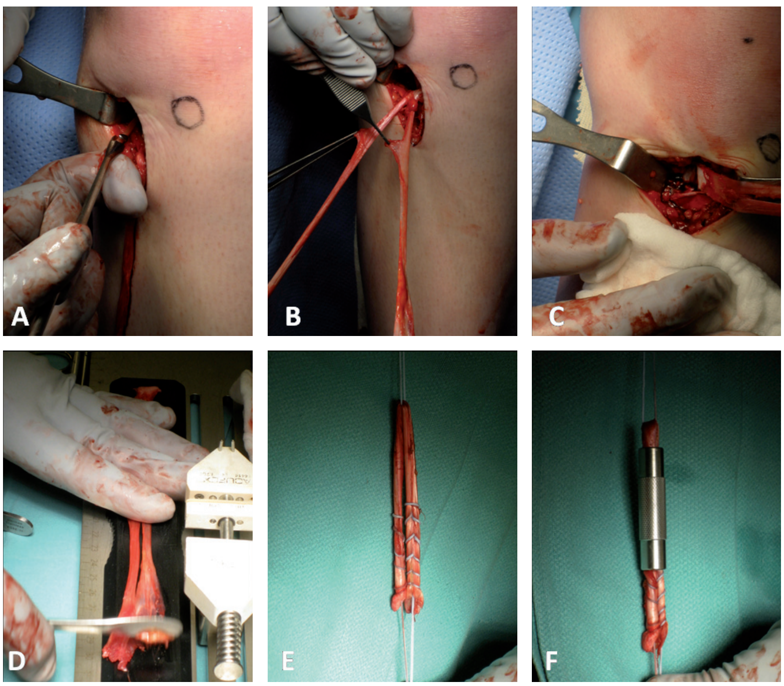

Fig. 4 – Hamstring harvesting. (A) Identification of the gracilis and semitendinosus tendons below the sartorial fascia, release of the vincula, and proximal detachment with "pigtail" tendon stripper. The distal insertion of the tendons is maintained. (B) Vincula that require the release before the harvest. (C) Cut of the periosteum and distal detachment of the graft. (D) Debridement of the graft from the muscular tissue. (E) Guide sutures to the four-stranded hamstring graft. (F) Measurement of the tendon before tunnel drilling.

and mild internal rotation weakness are described after hamstring ACL reconstruction, but both are seen only at relatively high knee flexion angles and do not cause clinical performance deficits (2).

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 (4). Fulkerson *et al.* (34,35) described a technique to harvest the quadriceps tendon safely. Through a short midline incision, starting mid-patella, and extending proximally, a bone plug (10 mm × 20 mm) is harvested from the proximal patella. The tendon graft should be 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 (4).

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 (4). There are no studies evaluating anterior knee pain with this graft type (4). Nevertheless, Chen *et al.* (36) reported only mild harvest site tenderness in 12 patients at an average of 18 months after ACL reconstruction with quadriceps autograft. Fulkerson and Langeland (34) reported no early quadriceps morbidity in their series of 28 patients.

The obvious advantage of allografts and synthetic grafts is that harvesting is not required during surgery and that no donor-site morbidity will occur. Nevertheless, a potential problem with allografts is the infectious disease transmission. For this reason, currently the controls on the tissue and the donors are very strict and the risk of undergoing an infection from the allograft is only theoretical. The American Association of Tissue Banks stated the necessity for a detailed medical, social, and sexual history 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 (4). In the literature, only one case of HIV transmission and two of hepatitis C were described (4,37). The estimated risk for HIV transmission with connective tissue allografts is estimated to be 1 : 600,000 (38) and for bacterial infections 26 : 1,000,000 (3).

Initial fixation

The graft fixation is a crucial issue in ACL reconstruction. A stable fixation in the immediate postoperative period is required to avoid the slippage and allow graft healing as well as early aggressive rehabilitation. During rehabilitation, forces as high as 450–500 N are usually applied to the graft (4,39). Regarding fixation, the grafts should be distinguished in bone plug grafts and soft tissue grafts.

The gold standard in bone plug graft fixation is the interference screw for both tibia and femur. Both metallic and bio-absorbable screws showed comparable results and strength of fixation ranging from 552 to 558 N (18). The factors affecting interference screws fixation are (1) screw diameter and (2) screw divergence from the bone block. When the gap between the bone block and the tunnel wall is over 2 mm, the slippage of the graft is more likely to occur (40). Positioning of the interference screw with a divergence angle > 30° from the bone tunnel has higher fixation failure rates (41).

The most reliable soft tissue graft fixation device is controversial. The fixation techniques may be divided in (1) interference fixation (interference screws) (2) extracortical fixation (e.g., screws, staples, and Endobutton), and (3) transverse fixation (e.g., Rigidfix and Bio-Transfix). Ahmad *et al.* (42) used 33 porcine femora to study interference screw, Endobutton, Rigidfix cross-pin, and Bio-Transfix cross-pin femoral fixation methods. Fixation slippage was evaluated under cyclical load from 50 to 250 N using a soft tissue single-bundle technique. Ultimate load was determined with a single load to failure. The interference screw and the Rigidfix fixation demonstrated inferior fixation biomechanics compared to the Bio-Transfix and the Endobutton techniques. Kleweno *et al.* (43) evaluated graft slippage in five different soft tissue ACL femoral fixation techniques (Bio-Transfix cross-pin technique, Stratis ST cross-pin technique, Bilok ST transverse femoral screw, Delta tapered bio-interference screw, and single-loop TensionLok). A cyclic loading of double-bundle grafts was performed in porcine femurs. Cross-pin constructs appeared to be superior to certain other available fixation systems. The weak point in an ACL reconstruction immediately after surgery is the tibial fixation of the soft tissue graft.

Coleridge and Amis (44) compared five tibial fixation devices (WasherLoc, Intrafix fastener, and RCI, Delta Tapered, and Bicortical interference screws) for hamstring ACL reconstruction. Cyclic loads representing normal walking activity (1000 cycles from 70 to 220 N) and ultimate strength tests were done, using calf tibiae and four-strand tendon grafts. The WasherLoc gave the highest ultimate strength (945 N, $p < 0.001$, range 490–945 N). They concluded that all devices performed well under cyclic loads that represented normal walking activity, but the ultimate strengths differed.

Historically, widening of the tunnel, a late complication in ACL reconstruction, was attributed to excessive movement of the graft in the tunnel when using extracortical fixation devices (45,46). Clatworthy *et al.* (45,47) recently evaluated tunnel widening in 259 patients who had undergone hamstring ACL reconstruction with four different fixation devices to test this "bungy cord effect." The Endobutton/staples construct had significantly less widening than metal interference screws, bio-absorbable interference screws and a bone mulch screw/staples construct. This suggests that there is a significant biological component that could be attributed to a variable cytokine response to surgery or a reaction to synovial fluid.

Outcomes

The literature shows good to excellent results of ACL reconstruction with almost every type of autograft and allograft.

Patellar tendon

Numerous studies with a minimum follow-up of 5 years have been published (45,48–51). Using International Knee Documentation Committee (IKDC), Tegner, or Lysholm scores, a satisfactory outcome was found in 78–90 % of patients. Giving-way was eradicated in 78–98 %. The best results were found in a group of 90 patients who had normal menisci at the time of surgery. The patients'scores were normal or nearly normal in the 90 %, 98 % had a grade 0 pivot shift, and in 97 % no degenerative changes were seen radiographically (45,48). Better results were reported with early surgery and with no lesions to cartilage and menisci (49,51).

The advantages of a patellar tendon graft are (45) (1) rapid healing of the bone blocks within ; (2) direct rigid fixation of the bone blocks close to the aperture ; and (3) good preservation of load to failure and stiffness. The disadvantages are predominantly related to the donor site and include (45) (1) anterior knee pain ; (2) patellar tendonitis ; (3) rupture of the patellar tendon ; (4) fracture of the patella ; (5) increased joint stiffness ; (6) late chondromalacia ; and (7) injury to the infrapatellar branch of the saphenous nerve (45).

Hamstring tendon

Four-strand hamstring grafts have become widely used, consisting of either doubled semitendinosus/gracilis or quadrupled semitendinosus tendons. Numerous studies in the literature report results comparable to patellar tendon grafts (52–58). The advantages of hamstring grafts are (45) (1) high load to failure and stiffness ; (2) a greater cross-sectional area of tendon ; (3) easier passage of the graft ; (4) a small incision ; (5) low post-operative morbidity ; and (6) less donor-site morbidity. The disadvantages are (45) (1) slower tendon-to-bone healing in the tunnel ; (2) the possibility of injury to the saphenous nerve ; (3) weakness of the hamstring muscles after operation ; and (4) widening of the tunnel.

In a meta-analysis, Freedman *et al.* (28) pooled data from 34 studies. The study found in 1976 patients significantly lower rates of graft failure, less laxity, and higher patient satisfaction in the BPTB group. However, there was a higher incidence of anterior knee pain in the BPTB group (59). Another meta-analysis performed 2 years earlier by Yunes *et al.* (60) only allowed 4 studies (411 patients) to fit into the inclusion criteria. The authors found that the BPTB group had significantly less laxity than the hamstring group when evaluated by the KT-1000 at 20 lb. Furthermore, all the studies included in the meta-analysis suggested that the BPTB group had a higher rate of "return to pre-injury level of activity." The study was unable to compare donor-site morbidity between groups because the included studies did not have comparable information (59).

Quadriceps tendon

The use of the quadriceps tendon as a graft for the ACL has been advocated by Staubli *et al.* (25) and Fulkerson and Langeland (34), who documented the good biomechanical properties of this tendon (45). Chen *et al.* (36) described the results of arthroscopic reconstruction of the ACL using quadriceps tendon-patellar bone autograft in 12 patients. After a follow-up of 15–24 months, 10 returned to their level of pre-injury sports and 10 had a normal or near-normal IKDC score. However, after 1 year, the quadriceps strength was only 80 % of the normal knee in 11 patients. The advantages of this graft are (45) (1) a thick tendon, (2) good biomechanical properties, and (3) decreased anterior knee pain. The disadvantages are (45) (1) weakness of the quadriceps after operation, (2) an unsightly scar, and (3) graft harvest, which is technically more difficult.

Allografts

Animal studies have shown that allografts can be used successfully in intra-articular reconstruction of the knee (45). The absence of morbidity at the donor site and the small incisions required for implantation have led to consideration of the use of allograft in reconstruction of the ACL

(45). Several studies have compared the results of allografts with autografts in reconstruction of the ACL with no significant difference in knee laxity or outcome (29,61–63). The results of reconstruction with allograft patellar tendon appear to be durable. Noyes and Barber-Westin (64) found no significant change in knee laxity or in the overall knee score when assessing their patients at 3 and 7 years. Studies of goat patellar tendon autograft and allograft suggest that autografts are slightly superior (18) with more rapid incorporation and slightly better stability 6 months after operation. So despite a quicker immediate recovery, allografts have a longer incorporation time with subsequent slower rehabilitation, compared to autografts.

Conclusions

Both autografts and allografts are excellent alternative options in ACL reconstruction. Synthetic grafts are still not recommended because of the poor clinical results. The choice of the graft should be personalized according to the patient (age, gender, activity level, compliance, and occupational and recreational activities) and his or her physical examination with possible multi-ligamentous injuries. The senior author algorithm for graft choice is described in Table 3.

Table 3 – Algorithm for graft choice in ACL reconstruction.

Patellar tendon
– When a prompt return to play is required – In athletes subjected to hamstring lesions (football, sprinting sports) – In patients not compliant with rehabilitation and restrictions – If physical examination reveals hyperextension of the knee
Hamstrings
– In patients with open growth plates – In women with esthetic issues – In patients with kneeling activities – In athletes subjected to patellar tendon pathologies (basketball, volleyball, tennis) – In double-bundle ACL reconstruction
Allograft
– In ACL reconstruction revisions – In multi-ligamentous knee injuries – When all-inside technique is required by the patient with esthetic issues – In patients more than 40 years old, with low activity level

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