Autogenous graft choices in ACL reconstruction
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This review compares the harvest technique, graft morbidity, biomechanical properties, biologic incorporation, tunnel widening, fixation, and aggressive rehabilitation of an autogenous bone-patellar tendon-bone (BPTB) graft and doubled semitendinosus and gracilis tendons (DLSTG) graft as a replacement tissue for a torn anterior cruciate ligament (ACL). The harvest of the DLSTG graft is more difficult; however, this difficulty can be overcome by understanding the anatomy. There is less morbidity associated with the DLSTG graft and the strength and stiffness are superior to the BPTB graft. Aligning the four strands in parallel form without braiding or weaving, and applying equal tension to each strand optimizes the strength and stiffness of the DLSTG. The cells of a DLSTG graft probably survive intra-articular implantation, but the cells of a BPTB graft do not. The DLSTG graft is nourished by synovial fluid and does not depend on revascularization for viability. Tunnel widening occurs commonly with the DLSTG graft and is worse with suture (endobutton) and bioresorbable interference screw fixation. Tunnel widening does not affect the clinical outcome, but may complicate revision surgery. There are a wide variety of fixation devices for the DLSTG graft; however only a few provide better strength and stiffness than interference screw fixation of a BPTB graft at implantation. Aggressive rehabilitation is safe with both types of autogenous grafts as long as strong, stiff fixation methods are used. Curr Opin Orthop 2001, 12:149–155 © 2001 Lippincott Williams & Wilkins, Inc.

There are a variety of autogenous graft materials that can be used for anterior cruciate ligament reconstruction (ACL) including bone-patellar tendon-bone, hamstring tendons, quadiceps tendon, and iliotibial band. Of these four graft sources the two most commonly used are the bone-patellar tendon-bone (BPTB) and hamstring tendons. Although a BPTB autograft remains the graft choice for many surgeons, the doubled semitendinosus and gracilis tendons (DLSTG) have recently gained popularity [1]. This review compares the harvest technique, graft morbidity, biomechanical properties, biologic incorporation, tunnel widening, fixation, and aggressive rehabilitation of a BPTB graft and DLSTG graft as a replacement tissue for a torn ACL.

Harvest technique
The BPTB graft is easier to harvest than a hamstring graft. Harvesting a BPTB graft is relatively simple because the patellar tendon is subcutaneous. On the other hand, harvesting a hamstring graft may be daunting to the inexperienced surgeon: the tendons may be difficult to isolate and identify because they are concealed beneath several tissue layers. The two difficulties that surgeons must overcome when harvesting a hamstring graft are identifying the semitendinosus and gracilis tendons and avoiding premature tendon amputation.

Understanding the anatomy on the posteromedial aspect of the proximal tibia is key to consistently identifying the hamstring tendons [2]. The gracilis tendon is more proximal than the semitendinosus tendon, and can be palpated as it courses deep to the sartorius fascia, but only at the tibia’s posterior medial edge. After determining the course of the gracilis tendon, the sartorius fascia is incised parallel to the proximal edge of the gracilis. A finger is inserted through the window created in the sartorius, and the interval between the medial collateral ligament (MCL) and the undersurface of the sartorius fascia is dissected (Fig. 1). The gracilis and semitendinosus are adherent to the deep side of the sartorius fascia superficial to the MCL.

Cutting all fascial slips that course distally from the hamstring tendons and using a blunt or dull tip tendon stripper are two tips for avoiding premature amputation of the hamstring tendons. Premature amputation is more common with the semitendinosus tendon than the gracilis tendon because the fascial slips are stouter and more numerous (up to five slips). Fascial slips can be detected by palpating circumferentially around the tendon using a
fingert. The best way to verify that all the fascial slips have been released is to apply traction on the tendon and observe skin dimpling in the proximal medial thigh.

**Graft morbidity**

The BPTB graft has greater morbidity than a hamstring graft. Harvesting a BPTB graft can cause chronic disabling complications including quadriceps weakness [3], patellar fracture [4], patellar tendon rupture [5], quadriceps tendon rupture [6], anterior knee pain [7], and degeneration of the articular surface of the patella-femoral joint [8]. The occurrence of any of these complications can result in a nonfunctional knee and dissatisfy the patient even though the graft may be stabilizing the knee.

On the other hand, the hamstring graft has minimal morbidity and is not associated with chronic disabling complications. Harvesting the hamstring tendons does not cause knee flexion weakness at one [9], two [10], and three years [11] after the reconstruction. However, the harvest may cause a small reduction (2–3 foot/lbs) in internal rotation torque. Fortunately, this negligible loss of internal rotation torque does not affect athletic performance [12].

One explanation for the minimal loss of muscle strength from harvesting the hamstring tendons is that the hamstring tendons regenerate (Fig. 2). At 18 and 24 months, a regenerated semitendinosus tendon was clearly identified inserting about 4 cm proximal to the pes anserinus using ultrasonography [13•]. When the location of the insertion of the regenerated semitendinosus tendon is more normal (ie, distal) in the pes anserinus, there seems to be less muscle atrophy [14]. The use of a regenerated hamstring tendon as an ACL graft in revision surgery has not been reported.

**Biomechanical properties**

The BPTB graft is weaker and less stiff than a DLSTG graft. For the DLSTG to be stronger and stiffer than a BPTB graft, it must be constructed of multiple parallel strands that are equally tensioned [15•,16••]. Another biomechanical disadvantage of the single strand BPTB graft is that it cannot replicate the reciprocal tensile behavior of the functional bands of the anteromedial and posterolateral of the ACL [17]. The replication of the reciprocal tensile behavior by the DLSTG graft depends on the placement of the femoral tunnel and the type of femoral fixation [18]. This section discusses the method for constructing, tensioning, and implanting a DSLTG graft to optimize strength and stiffness and provide reciprocal tensile behavior at implantation.

**Use multiple strands of tendon**

The first principle in constructing an ACL graft from hamstring tendons is to use multiple strands. Multiple strands are needed because a single hamstring tendon has a cross-sectional area less than the normal ACL and is neither strong nor stiff enough at implantation to function as a graft. For example, the 11 mm² cross-sectional area of a one-strand semitendinosus tendon is only 22%,
and the 7.4 mm² cross-sectional area of a one-strand gracilis tendon [16] is only 15% of the 50 mm² cross-sectional area of the normal ACL [19]. Because the strength of a tendon ACL graft increases linearly as the cross-sectional area increases, multiple strands of tendon are needed to provide an ACL graft with sufficient strength and stiffness at implantation [16].

Combining the semitendinosus and gracilis tendons forms an ACL graft with a cross-sectional area that approximates the normal ACL and functions well clinically [20,21]. A 30 mm in length DLSTG graft has a cross-sectional area of 50 mm², strength of 4590 N, and a stiffness of 861 N/mm [16], which is stronger and stiffer than a femur-ACL- tibia complex [22,23] and a 10-mm-wide BPTB graft [22,24] at implantation.

**Don’t braid or weave the DLSTG graft**
The strands of a DLSTG graft should be aligned in parallel and neither braided nor weaved. A biomechanical study using a four-stranded ovine tendon compared two braiding techniques to a graft with parallel strands. The braided samples were 58% weaker and 85% less stiffness than the tendon graft with parallel strands. These results indicate that braiding strands is not advisable because it significantly reduces both strength and stiffness of a tendon ACL graft at implantation [25•].

**Tension the strands equally**
The strands must be equally tensioned for a DLSTG graft to have its optimum biomechanical properties. Manually applying tension to each strand of a four-strand DLSTG graft does not produce equal tension. Unequal tension between strands must be avoided because it reduces the strength and stiffness of a DLSTG to that of a two-stranded graft made from a loop of semitendinosus tendon [16].

There are two methods for applying equal tension to a four-strand DLSTG graft. In the laboratory, a weight can be hung from each strand [16]. In the operating room, manual tension can be applied to the DLSTG graft after it is transformed into a continuous loop (Fig. 3). The transformation of a DLSTG graft into a continuous loop requires that the insertion of the semitendinosus and gracilis tendon be left attached to the tibia. The two tendons are then passed through the knee around a rigid fixation post in the femoral tunnel. The sutures attached to the free strand of each tendon are tied together outside the bone tunnel. A metal rod is inserted into the loop of suture, and the knee is positioned in full extension. A manual tension applied to the loop equally tensions all four strands of the DLSTG graft because the fixation post functions like a pulley [18,26].

Equal tensioning of each strand of a DLSTG graft may not be possible with some methods of graft preparation and fixation. Preparing the quadruple hamstring, “all-inside technique,” and the bone-hamstring-bone construct by sewing the strands either together or to bone plugs [27–30] is not likely to produce equal tension between strands. Fixation with an interference screw may cause unequal tension because the strands twist during insertion of the screw [31]. Fixation by tying the sutures attached to each strand to a post is unlikely to result in equal tension between strands because the tension in each strand is not controllable while tying the knots. Surgeons should understand that the methods chosen to harvest, prepare, and fix a DLSTG graft may compromise the strength and stiffness of the graft at implantation [26].
Reciprocal tensile behavior

Four conditions must be met for an ACL graft to replicate the reciprocal tensile behavior of the anteromedial and posterolateral bundles of the normal ACL (Fig. 4). First, the graft must consist of multiple strands, which explains why the DLSTG graft exhibits reciprocal tensile behavior and the single-strand BPTB graft does not. Second, the femoral tunnel must be properly positioned. The back wall of the femoral tunnel should be thin (1-mm-thick) and the center of the tunnel should be oriented at 10:30 (right knee) or 1:30 (left knee) when looking at the outlet of the intercondylar notch with the knee in 90° of flexion. Two femoral tunnels are not required for reciprocal tensile behavior. Third, the graft must be wrapped around a rigid post (Bone Mulch Screw, Arthrotek Inc., Warsaw, IN) inside the femoral tunnel. Finally, bone must be compacted inside the femoral tunnel to increase friction between the strands of each tendon loop so that tension in each strand is independent of the other [18].

Biologic incorporation

The intra-articular biologic incorporation of a BPTB graft is different than a DLSTG graft. The cells of a BPTB graft die [32], whereas the cells of a hamstring tendon survive intra-articular transplantation [33–35]. The viability of a BPTB graft depends on revascularization [34], whereas the viability of a DLSTG graft does not depend on revascularization but depends on synovial diffusion [35]. Because hamstring tendons live in a synovial environment extra-articularly, and retain viability when transplanted intra-articularly without revascularizing, the DLSTG graft may have the potential to remodel more rapidly and completely than a BPTB graft.

Tunnel widening

Tunnel widening occurs with the BPTB graft [36,37] and DLSTG graft [38,39,40,41,42], but is greater with the DLSTG graft [36]. With the BPTB graft, the resorbability of the fixation device determines the amount of tunnel widening. Tunnel widening is minimal with a metal interference screw [36], and increases an average of 2 mm in diameter with the bioresorbable interference screw [37]. There may be a relation between the degradation of the resorbable interference screw and the tunnel widening, because the maximum tunnel width occurs at the time the screw is no longer visible on MRI [37]. In spite of the difference in tunnel widening between these two screw materials, the clinical outcome of a BPTB graft is not affected by the amount of tunnel widening [36,37].

With the hamstring graft, the amount of tunnel widening is related to the stiffness and the resorbability of the fixation device. It is believed that low stiffness suture fixation allows high shear forces acting on the wall of the bone tunnel, which could delay osseous incorporation and lead to tunnel widening [43]. This theory explains why there is greater femoral tunnel widening than tibial tunnel widening with femoral fixation with an endobutton [39,40,41,42], which is the least stiff fixation technique for a DLSTG graft [15,44].

It has been proposed that interference screw fixation of a hamstring graft may limit tunnel widening by overcoming the shear forces associated with low stiffness fixation methods [45,46]. However, a recent study comparing the tunnel widening of four different fixation constructs using hamstring tendons showed that the bioabsorbable interference screw caused the greatest tunnel widening of three other fixation constructs including metal interference screw fixation [38]. As with the BPTB graft, the clinical outcome of a hamstring graft is not affected by the amount of tunnel widening [38–40,41,42].

Although the clinical outcome of a BPTB and DLSTG graft is not affected by tunnel widening, tunnel widening can complicate revision surgery. When revision ACL surgery is performed in a knee with extensive tunnel widening, a two-stage reconstruction is often required (Fig. 5). The first stage consists of removing the bioresorbable interference screw and bone grafting the osteolytic defect in the tunnels. The second stage of implanting the ACL graft can be performed three to four months later after the bone graft has healed.

Fixation

Depending on the type of fixation device, the fixation of a BPTB graft can be inferior in strength and stiffness to...
Figure 5. Failed bone-patellar tendon-bone graft fixed with bioresorbable interference screws

Anterior tibial and femoral tunnels probably contributed to the failure. MRI revealed extensive osteolysis of the femoral tunnel (arrows) and tibial tunnel (detected in another slice) from resorption of the interference screw. A two-staged revision surgery was performed in which the tunnels were grafted in the first stage, and a DLSTG graft was implanted in the second stage. The lateral roentgenogram of the revised knee in full extension demonstrates a more posterior, unimpinged tibial tunnel (parallel lines), and a more posterior femoral tunnel. The corral bone graft substitute has healed in the original improperly placed anterior femoral and tibial tunnels (arrows). Tunnel expansion associated with bioresorbable interference screws [37] complicates revision surgery.

the fixation of a DLSTG graft. Interference screw fixation of a BPTB graft has long been held as the standard to which new fixation methods should be compared.

Recent biomechanical studies using young human bone question the validity of this claim [15••,47••]. The strength and stiffness of interference screw fixation of a BPTB graft in young human knees is only 412 N and 51 N/mm respectively [48]. The strength and stiffness of femoral fixation of a DLSTG around a post with bone compaction (Bone Mulch Screw, Arthrotek Inc., Warsaw, IN) in young human knees is 1126 N and 225 N/mm respectively [15••]. The strength and stiffness of tibial fixation of a DLSTG with either a WasherLoc (Arthrotek Inc., Warsaw, IN) or tandem washers in young human knees is 905 N and 248 N/mm, and 1159 N and 259 N/mm respectively [47••]. Therefore, fixation with any combination of these three hamstring fixation methods provides a two-fold to three-fold increase in strength and a five-fold increase in stiffness than interference screw fixation of a BPTB graft. Surgeons need no longer be concerned that soft-tissue fixation of a DLSTG graft is inferior to interference screw fixation of a BPTB graft [49]. In fact, the opposite is true [47••].

Removing hardware continues to be the most common reason for additional surgery using the hamstring tendons as a graft [50]. The incidence of hardware removal ranges from 12 to 26% and is most common with screws, washers, and staples that are placed subcutaneously on the tibia [50,51,52]. The most effective way to reduce postoperative morbidity and the associated costs of additional surgery is to improve tibial fixation [52]. The WasherLoc, which is recessed inside the tibial tunnel, provides strong, stiff tibial fixation and has reduced the incidence of hardware removal [21].

The fixation characteristics of several other fixation methods in use at the time of this review were not dis-

Figure 6. Comparison of the stability of knees reconstructed with a hamstring ACL graft using different fixation methods

Comparison of the stability of knees reconstructed with a hamstring ACL graft using different fixation methods (MMT-manual maximum anterior load approximately 200-300N, 134N-anterior load) [21,30,40,51]. The incidence of a stable knee (<3 mm increase in anterior laxity compared to the intact knee) was greatest for the bone mulch screw (93%), least for the endobutton (70 and 59%) and least with interference screw fixation (35%). The best stability occurred with the bone mulch screw in which the knees were treated without a brace and returned to unrestricted activities four months after the reconstruction [21]. Slowing the rehabilitation and using an immobulator or brace with either the endobutton or interference screw does not prevent loss of stability with these low-strength, low-stiffness, and high-slippage fixation techniques [30,40,51]. Bone Mulch Screw, Arthrotek Inc., Warsaw, IN; Endobutton, Smith and Nephew, Memphie, TN; Interference Screw, Bio Screw, Linvatec, Largo, FL.
cussed in this section because results from testing in young human bone were not available. These fixation methods include the closed loop endobutton (Smith and Nephew, Memphis, TN), cross-pins (Arthrex (Naples, FL), Innovative (Westwood, MA (Mitek)), and intra tunnel fixations such as the bioabsorbable interference screw and Intrafix (Innovative, Westwood, MA (Mitek)).

Aggressive rehabilitation
Aggressive rehabilitation is safe with a BPTB [53,54] and the DLSTG graft [20,21]. The safety of aggressive rehabilitation depends on the strength, stiffness, and resistance to slippage of the fixation methods [21,49] because the BPTB and DLSTG graft are both stronger and stiffer than the fixation methods [15,47].

Patients with a DLSTG graft fixed with strong, stiff fixation methods have been safely rehabilitated without a brace and returned to sport at three to four months with no deterioration in stability at two years after the reconstruction [21,49]. Aggressive rehabilitation has not been shown to be safe and effective at restoring stability when a hamstring graft is fixed with either a suture bridge or interference screws. Because these fixation methods may either fail or slip excessively at loads up to 500 N, their use with aggressive rehabilitation should be approached cautiously [47,49]. Slowing the rehabilitation and using an immobilizer or brace with fixation techniques such as the endobutton and interference screw still results in a higher incidence of instability at two years [30,40,51,55], especially in women [55,56,57] (Fig. 6).

References and recommended reading
Papers of particular interest, published within the annual period of review, have been highlighted as: **Of special interest**  
**Of outstanding interest**


21. This report establishes that brace-free rehabilitation and early return to sport at four months is safe with a hamstring graft.


27. This study shows that placing the strands of multi-bundle tendon ACL graft in parallel provides superior strength and stiff compared to braiding or weaving the strands, which results in a weaker, more elastic graft.


