Technical Note

Minimally Invasive Quadriceps Tendon Single-Bundle, Arthroscopic, Anatomic Anterior Cruciate Ligament Reconstruction With Rectangular Bone Tunnels

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Abstract: Many surgeons use quadriceps tendon (QT) graft for anterior cruciate ligament (ACL) revision surgery; however, despite excellent clinical results, the QT has not achieved universal acceptance for primary ACL reconstruction. One of the reasons for this may be that the QT is technically demanding to harvest and the scar from open harvesting techniques is less cosmetically favorable than that from hamstring tendon techniques. Recent evidence has suggested that broad flat QT grafts may more closely mimic native ACL "ribbon-like" morphology than hamstring tendon grafts. Furthermore, rectangular bone tunnels may more accurately re-create native ACL attachments, allowing grafts to simulate native ACL rotation during knee flexion and potentially improving biomechanics. Rectangular tunnels have further advantages in revision cases, in which—in comparison with round tunnels—they have reduced overlap with pre-existing transtibial tunnels, increasing the chance of bypassing primary tunnels during revision surgery. Finally, instrumentation for minimally invasive QT harvesting has reduced technical difficulty and improved cosmetic results. Hence, technical and cosmetic concerns are no longer barriers to QT use. These anatomic and biomechanical advantages and technical developments make the QT an increasingly attractive option for both primary and revision ACL reconstruction.

The discussion about double- versus single-bundle anterior cruciate ligament (ACL) reconstruction has led to a productive period of research and deeper understanding of native ACL anatomy and biomechanics. Recent evidence has suggested that the intraligamentous part of the native ACL resembles a ribbon (approximately 11-16 mm wide and 2.5-3.4 mm thick)[1] and that the "double-bundle appearance" observed arthroscopically arises from a twist in this flat structure (Fig 1 A-C).

The native femoral origin has a narrow "direct" component arising in continuity from the posterior femoral cortex, extending along the lateral intercondylar ridge, and fanlike "indirect" fibers, extending toward the posterior chondral margin of the femoral condyle (Fig 1 D and E). The tibial insertion forms a crescent C, J, or Cc shape around the anterior horn of the lateral meniscus (Fig 1 F and G).[2]

Because neither the bony attachments nor the midsubstance of the native ACL is round, the use of round tunnels and tubular hamstring tendon (HT) grafts as the optimum reconstruction technique has been questioned. Anatomically oriented rectangular bone tunnels may more closely replicate the native anatomy, allowing graft rotation during knee flexion that is similar to the biomechanics of the native ACL (Fig 1).

Rectangular bone tunnels have been described with patellar tendon (PT) graft by Hayashi et al.[3] and with
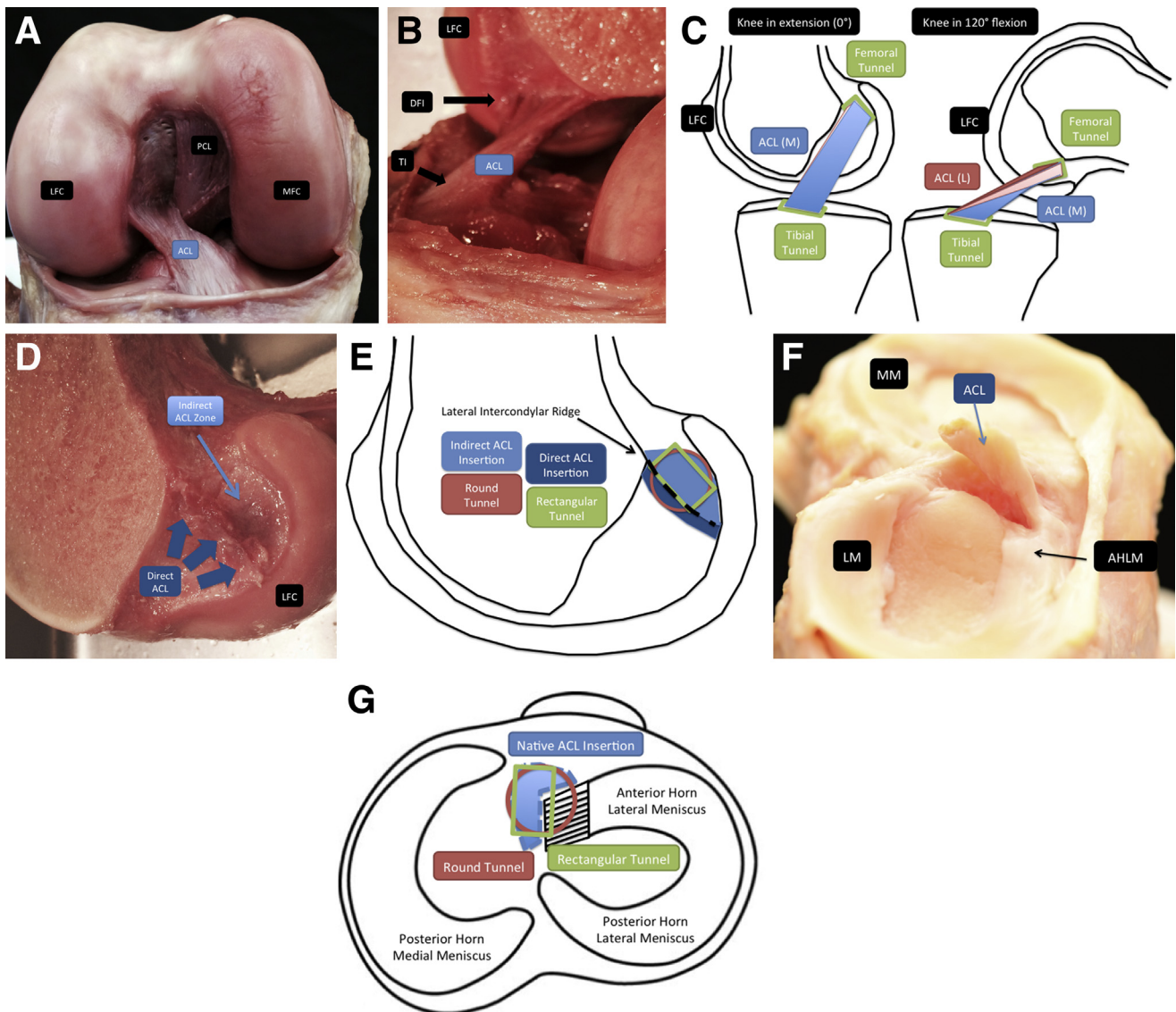
Fig 1. Anterior cruciate ligament (ACL) anatomy and biomechanics. (A) Śmigielski et al.[1] described the intraligamentous part of the ACL as a ribbon, seen here in the femoral notch of a cadaveric right knee viewed from anteriorly with the knee flexed. The ACL appears as a broad flat structure, shown here in the femoral notch, with its relations to the posterior cruciate ligament (PCL), medial femoral condyle (MFC), and lateral femoral condyle (LFC). (B) A cadaveric right knee flexed to approximately 120° is shown with the LFC viewed from medially, with the MFC removed. The direct femoral insertion (DFI) of the ACL is seen superiorly in continuity with the posterior cortex of the femur. A "twist" is observed in the midsubstance of the flat ribbon-like ACL, seen most clearly just proximal to the "ACL" label. The tibial insertion (TI) is seen distally, toward the anterior aspect of the tibial plateau. (C) A right knee in extension (0°) and 120° of flexion, viewing the medial aspect of the LFC from medially, with the MFC removed. Femoral and tibial rectangular tunnels are illustrated with a rectangular ACL graft. The medial surface of the graft in extension is shown in blue [ACL (M)], and the lateral surface of the graft in extension is shown in red [ACL (L)]. The schematic illustrates rotation of the graft with knee flexion and how rotation of a flat ribbon-like graft can simulate native ACL rotation. (D) A cadaveric right knee is shown with the LFC viewed from medially, with the MFC removed. The insertion of the native ACL into the lateral wall of the femoral notch is shown. As described by Śmigielski et al.,1 the native femoral ACL insertion comprises a direct component (shown in dark blue) arising in continuity from the posterior femoral cortex and extending along the lateral intercondylar ridge. The fanlike indirect fibers extend from the lateral intercondylar ridge posteriorly toward the posterior margin of the LFC (indirect ACL zone, shown in light blue). (E) Schema of cadaveric image shown in D. The LFC of a right knee is shown viewed from medially, with the medial condyle removed. The direct femoral ACL insertion is shown in dark blue. The indirect femoral insertion is shown in light blue. The locations of a 9-mm round femoral tunnel (red) and a 9mm × 5-mm rectangular tunnel (green) are shown in relation to these landmarks. (F) A cadaveric right tibial plateau is viewed from laterally. The ACL has been divided proximally, so that the ACL stump and tibial insertion can be illustrated. In particular, the relation between the tibial ACL insertion and the anterior horn of the lateral meniscus (AHLM) can be observed. The medial meniscus (MM) and lateral meniscus (LM) are both labeled at their posterior aspect. Śmigielski et al.[1] described the tibial

quadriceps tendon (QT) graft by Fink and Hoser[4] (in German). Both PT and QT grafts are broader and flatter than HT grafts and hence morphologically more similar to the ribbon-like ACL. However, the QT in particular is technically demanding to harvest, and the longitudinal incision used for open harvesting is cosmetically less favorable than the approach for HT harvesting.

Hence, the aims in developing the described technique were as follows: (1) optimization of tunnel shape to achieve anatomic graft orientation and biomechanics and (2) standardization of QT harvest to reduce technical difficulty and cosmetic morbidity.

Technique

Positioning

The patient is positioned supine with a thigh tourniquet. Positioning must allow knee motion between 0° and 120°. We prefer the use of an electric leg holder (Maquet, Rastatt, Germany).

Graft Harvesting

Graft harvesting is performed as described and illustrated by Fink et al.[5] using specialized instrumentation (Karl Storz, Tuttlingen, Germany)[6]:

1. In 90° of knee flexion, a 2.5- to 3-cm transverse skin incision is made over the superior pole of the patella (Fig 2A, Video 1).
2. A long Langenbeck retractor is introduced, and an inverted-T incision is made in the bursa and paratenon to expose the QT subcutaneously (Video 1).
3. A double knife (Karl Storz) with a depth of 6 mm and a chosen width of 8, 10, or 12 mm is introduced to incise the QT in the sagittal plane. Insertion of the instrument is started with the midpoint of the double knife slightly lateral to the midpoint of the superior border of the patella to capture the longest axis of the QT. The double knife is inserted to a minimum depth of 75 mm (calibrations are marked on the instrument shaft) (Fig 2B, Video 1). The width is chosen according to patient anatomy and operation type. Eight millimeters is typically used for primary reconstruction in smaller patients including most female patients. Ten millimeters is used for primary reconstruction in most male patients and larger female patients, as well as for most revisions in female patients. Twelve millimeters is used for primary reconstruction in larger male patients, most revisions in male patients, and some revisions in female patients. Table 1 shows a comparison of the cross-sectional area of rectangular and round grafts.

4. The thickness of the graft in the coronal plane is determined with a tendon separator (Karl Storz). The separator has a blunt reference side, which rests on the superior aspect of the tendon, and a sharp cutting blade at a depth of 5 mm, which incises the tendon in the coronal plane. It is inserted proximally as in step 3, undercutting the QT at a depth of 5 mm (Fig 2C, Video 1).
5. By use of a special tendon cutter (Karl Storz), the tendon strip is cut subcutaneously at the desired length and the tendinous end of the graft is retrieved (Fig 2D, Video 1).
6. The anterosuperior patellar periosteum is scored to outline the desired 15-mm (longitudinal) by 8-, 9-, 10-, or 12-mm (transverse) bone block or periosteal strip (Video 1). If one is using the bone block technique, a 6-mm-wide calibrated oscillating saw is used to make sequential sagittal, axial, and coronal cuts in the patella at a depth of 6 mm (determined using calibrations marked on the saw blade) (Fig 2E, Video 1). The final coronal separation of the bone block is made with an osteotome for increased tactile feedback and control. If one is harvesting the QT without a bone block, a strip of periosteum is harvested from the anterior patella (as scored in this step) by gradual subperiosteal dissection, peeling back the graft under tension (Video 1).
7. To close the defect, the long Langenbeck retractor is reintroduced. The tendon defect is closed with absorbable sutures (No. 0 Vicryl; Ethicon). A short-radius needle is used for maneuverability, and closure can be arthroscopically assisted if desired. The stitches should be placed in the superficial aspect of the tendon to avoid shortening of the tendon ("fanlike closure"). The prepatellar bursa is carefully closed over a bony defect. Figure 2F shows the typical dimensions of the adult QT. In most cases tendon harvesting will be partial thickness. To minimize leakage of arthroscopy fluid during surgery, after closure of the tendon, a swab is inserted between the tendon and skin superficially. The skin is closed at the end of the procedure.

Femoral Tunnel

1. After routine diagnostic arthroscopy, the ACL remnants are removed, preserving the tibial and femoral footprints.
2. With knee flexion of 120°, a 2.4-mm guidewire is drilled into the native femoral ACL insertion through

insertion of the ACL as forming a crescent C shape in 67% of specimens, a J shape in 24%, and a Cc shape in 9%, with the tibial insertion curving around the attachment of the AHLM. (G) In a right tibial plateau viewed from superiorly, the location of the menisci and native ACL insertion (blue) is shown in relation to a 9-mm round femoral tunnel (red) and a 9-mm × 5-mm rectangular tunnel (green).
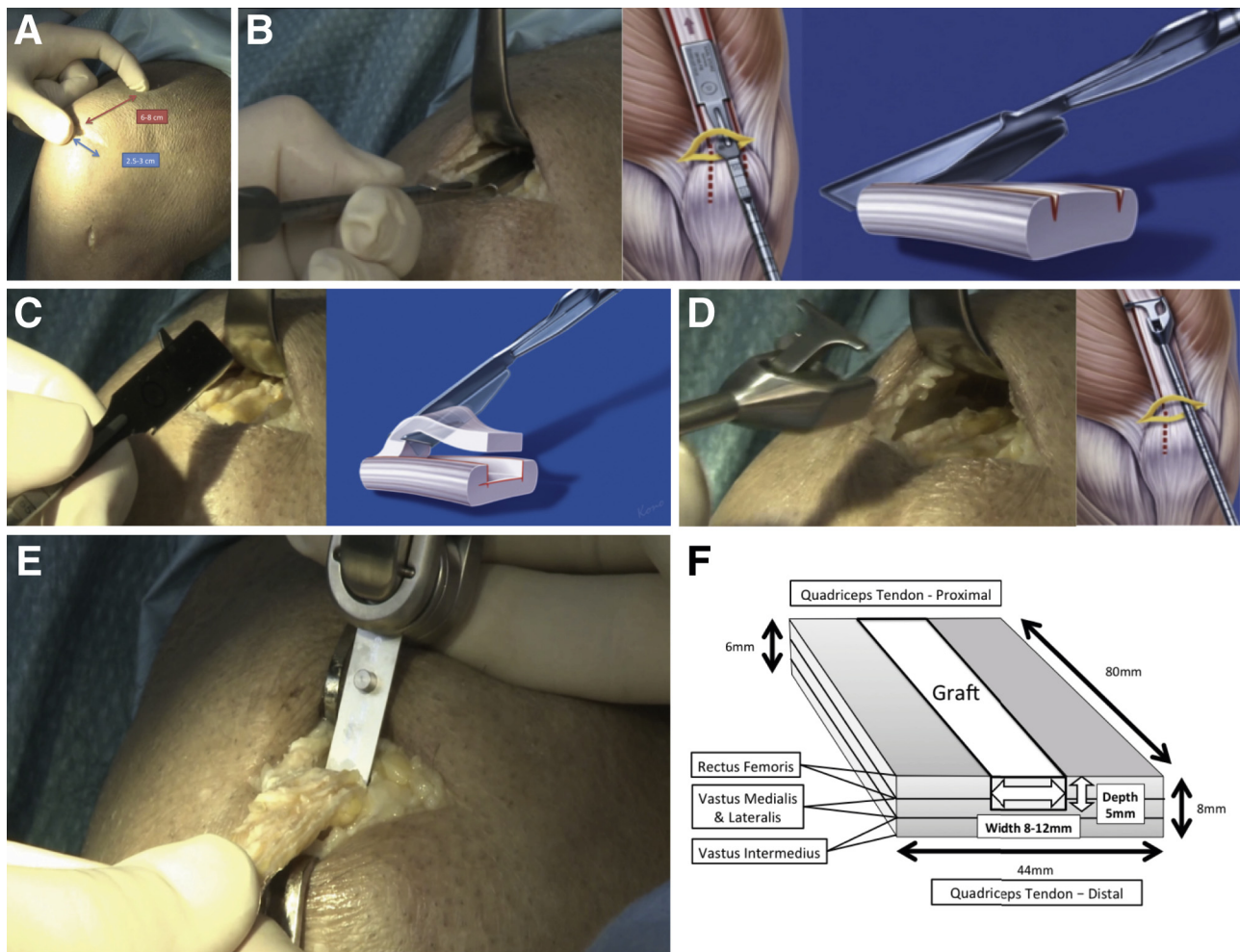
Fig 2. Quadriceps tendon (QT) graft harvesting. (A) The transverse skin incision for minimally invasive QT harvest is shown in a cadaveric right knee. By use of minimally invasive instrumentation, a QT graft 6 to 8 cm long (indicated by the surgeon and illustrated in red) and 8 to 12 mm wide can be harvested subcutaneously through a 2.5- to 3-cm transverse incision (shown in blue). (B) Double-knife insertion is shown in a cadaveric right knee viewed from medially and schematically. After exposure of the tendon, a double knife (Karl Storz) with a width of 8, 10, or 12 mm is inserted, starting at the middle of the superior patellar border, to a minimum depth of 75 mm (judged using calibrations on the instrument handle). (C) Tendon separator insertion is shown in a cadaveric right knee and schematically. The graft thickness is determined with a 5-mm tendon separator, which undercuts the QT as shown. The separator is inserted to the same length as the parallel bladed double knife (minimum of 75 mm) as determined by calibrations on the instrument handle. (D) Proximal tendon division and retrieval are shown in a cadaveric right knee and schematically. Both are accomplished using a specially developed tendon cutter−grasper (Karl Storz). Firm compression of the handle divides the tendon proximally subcutaneously. The tendon cutter is then closed around the tendon less sharply and used as a grasper to retrieve the tendon end. (E) Bone block harvesting is shown in a cadaveric right knee. After pre-scoring of the periosteum with a scalpel to outline the desired 15-mm-long by 8-, 9-, or 10-mm-wide and 5-mm-deep bone block, an oscillating saw is used for medial and lateral sagittal cuts, the distal transverse cut, and last, the final posterior coronal cut (illustrated in panel E). Use of an osteotome is recommended to give extra control in final block separation and to reduce the risk of patellar or bone block fracture. (F) The QT is a trilaminar structure formed from the confluence of the rectus femoris superficially, vastus lateralis and medialis in the middle layer, and vastus intermedius in the deepest layer. The laminae fuse with a degree of individual variation over a 13- to 90-mm region (mean, 44 mm) proximal to the superior pole of the patella.[7] The width of the QT at the patellar insertion in adults is 44 mm on average (range, 34-54 mm), and the tendon shape is asymmetrical, with a maximum length of 89 mm on average (range, 78-100 mm) typically occurring 62% from the medial border of the QTpatellar insertion. The QT increases in thickness from proximal to distal as aponeurotic layers of the extensor apparatus merge, reaching a mean maximum thickness of 7.9 mm (range, 6.5-9.5 mm) at the distal insertion.[7] Hence, QT graft harvesting may be full thickness, partial thickness, or a mixture of both at different distances along the proximal-to-distal axis. Even in cases of full-thickness harvesting, the synovium is often not breached. When one is closing the tendon defect, placement of stitches in the superficial aspect of the tendon is recommended to avoid bunching or shortening of the tendon (fanlike closure).

Table 1. Surface Area Equivalence According to Diameter (Round) and Width (Rectangular) of Tunnels

Round		Rectangular	
Diameter	Area = $\pi \times$ (Diameter/2)^2	Width	Area = 5 $\times$ Width
7 mm	38 mm^2	8 mm	40 mm^2
7.5 mm	44 mm^2	9 mm	45 mm^2
8 mm	50 mm^2	10 mm	50 mm^2
8.5 mm	57 mm^2	11 mm	55 mm^2
9 mm	64 mm^2	12 mm	60 mm^2

the medial portal until the mark on the wire is flush with the femoral condyle. The entry point for the guidewire is slightly proximal and posterior to the midpoint of the direct origin of the ACL (Fig 3A, Video 1). The position is double-checked while viewing from both portals.

3. The tunnel length is measured extra-articularly over the guidewire, referencing from the lateral femoral cortex and the laser marking on the wire.
4. The guidewire is overdrilled bicortically with a 4.5mm drill bit.
5. The rectangular rasp (Karl Storz) matching the graft diameter (8 mm for 8- and 9-mm grafts and 10 mm for 10- and 12-mm grafts) is inserted over the guidewire intra-articularly. With knee flexion of 120°, the rasp should be horizontally aligned with the smooth side facing the posterior cruciate ligament (as shown in Fig 3B and Video 1). The tunnel is

rasped to a depth of 25 to 30 mm. This is 10 mm deeper than the length of the bone block to allow space for the femoral fixation button to flip.
6. After rasping, a dilator (Karl Storz) of the same size as the graft is inserted. Any rough edges can be removed with an arthroscopic shaver. The finished tunnel is shown in Figure 3C, viewed arthroscopically from the medial portal.

Tibial Tunnel

1. The tibial aimer (Karl Storz) is inserted through the medial portal and placed with reference to the anterior horn of the lateral meniscus and ACL remnant (Fig 4 A and B, Video 1). The first 2.4-mm guidewire is drilled through the central hole of the aimer (Video 1).
2. If a round tibial tunnel is to be used, the knee is extended to check for notch impingement and, if satisfactory, a round tunnel of the desired diameter is drilled over the guidewire.
3. If a rectangular tibial tunnel is used, positioning of the initial guidewire will depend on graft size. Two guidewires are necessary for 8- and 10-mm grafts and 3 for 12-mm grafts. The initial guidewire is drilled through the central hole of the aimer. This will usually be the anterior wire if 2 wires are used (8- and 10-mm grafts as shown in Video 1) or the central wire if 3 are used (12-mm grafts). If the
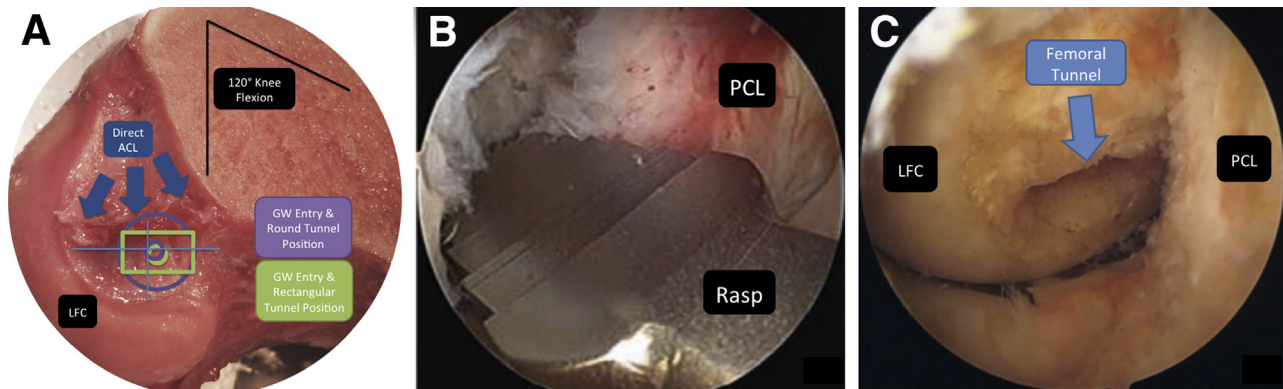

Fig 3. Femoral tunnel. (A) The lateral femoral condyle (LFC) of a cadaveric right knee dissection specimen viewed from medial, with the medial femoral condyle removed, in 120° of knee flexion. The direct femoral origin of the anterior cruciate ligament (ACL) is marked with blue arrows. The guidewire (GW) entry point and final bone tunnel position of both round (9 mm, in purple) and rectangular (9 × 5 mm, in green) tunnels are shown in relation to the midpoint of the posterior LFC. The ideal entry point is slightly posterior to the midpoint of the condyle to allow for obliquity of the GW inserted through a low anteromedial portal. The asymmetrical profile of rectangular tunnels allows for more posterior positioning (within the footprint of the indirect femoral attachment). (B) A right knee viewed from the lateral portal looking laterally toward the lateral wall of the intercondylar notch with the rasp inserted over a GW via the medial portal. After a 2.4-mm GW is passed at the desired femoral tunnel location, the rectangular rasp is inserted over the GW to a depth of 25 mm. The rasp should be horizontally aligned (parallel to the floor) at 120° of knee flexion, with the smooth side facing the posterior cruciate ligament (PCL) to avoid ligament abrasion (Video 1). Then, a dilator matching the size of the graft is inserted over the GW to the same depth (Video 1). (C) A right knee viewed from the medial portal looking laterally toward the lateral wall of the intercondylar notch. The prepared rectangular femoral tunnel is shown, and the LFC and PCL are labeled.
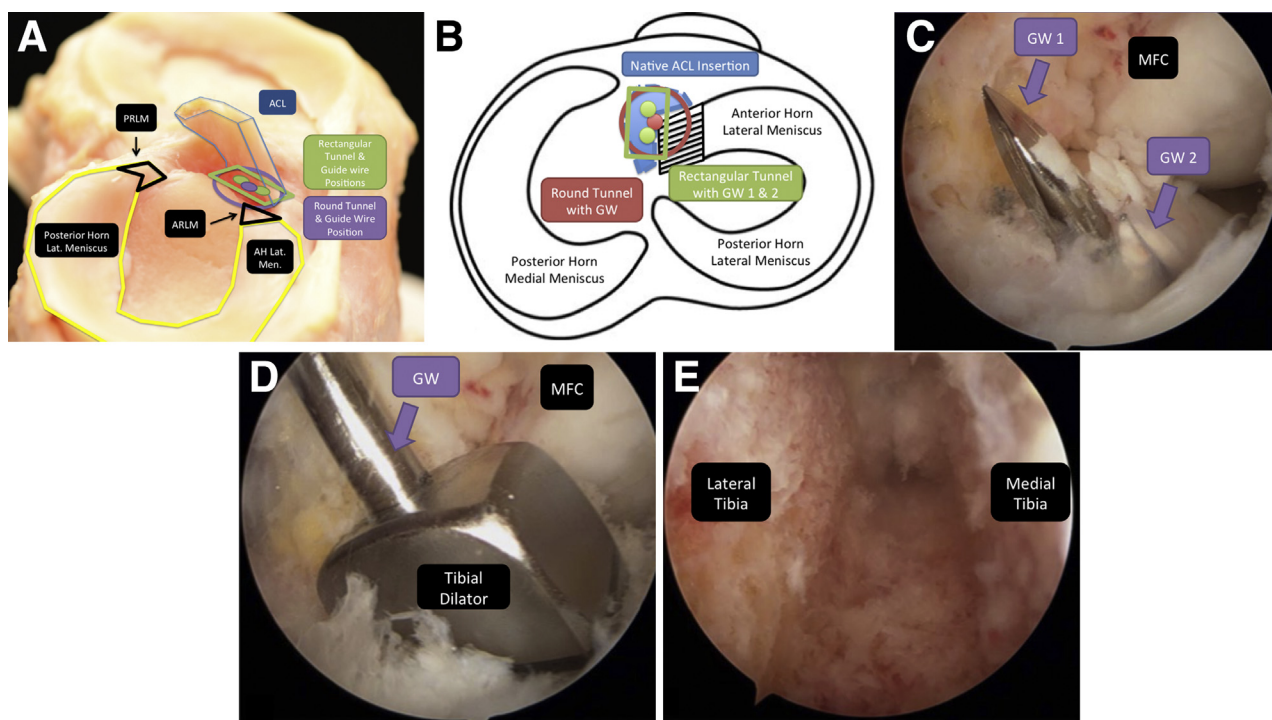
Fig 4. Tibial tunnel. (A) Cadaveric right knee dissection specimen viewed from laterally showing the relation between the anterior horn of the lateral meniscus (AH Lat Men), the anterior root of the lateral meniscus (ARLM), the anterior cruciate ligament (ACL) remnant, and the ideal guidewire positions for round and rectangular tunnels. The technical aim is to align the tibial tunnel with the native tibial ACL insertion. The position of a round tunnel can be seen to encroach slightly on the ARLM. (Lat, lateral; PRLM, posterior root of lateral meniscus.) (B) A right knee viewed from above showing the relation between the anterior horn of the lateral meniscus, the anterior root of the lateral meniscus (black and white stripes), the native ACL insertion, and the ideal guidewire (GW) position for a round tunnel, as well as the 2 GW positions (GW 1 and 2) for a rectangular 8- or 10-mm tibial tunnel. The technical aim is to align the tibial tunnel with the native tibial ACL insertion. The position of a round tunnel can be seen to encroach slightly on the anterior root of the lateral meniscus. (C) Cadaveric right knee viewed arthroscopically from the lateral portal looking posteromedially and showing the medial femoral condyle (MFC) and the position of 2 parallel 2.4-mm GWs. The first 2.4-mm GW is inserted using the central sleeve of the tibial aimer into the native ACL footprint. Additional GWs are then inserted ventrally and/or dorsally to the first wire. Two wires are required for 8- and 10-mm tunnels (as shown) and 3 wires for 12-mm tunnels. After one checks for notch impingement with the knee in extension, the wires are overdrilled with a cannulated 5-mm drill and any remaining bone bridges are removed with a shaver. (D) A cadaveric right knee viewed arthroscopically from the lateral portal looking posteromedially and showing the MFC and a tibial dilator inserted over a central GW. The rectangular tibial dilator (0.5 mm larger than the graft) is used to finish the rectangular tunnel. (E) The finished rectangular tibial tunnel of a right knee is shown viewed from distal to proximal from the entrance of the tibial tunnel.

guidewire position is satisfactory, after one checks for notch impingement, it is overdrilled with a 10-mm drill bit distally to open the cortex to a depth of 5 mm. Additional parallel guidewires are then inserted dorsally and/or ventrally using the tibial aiming jig depending on graft size (Fig 4C, Video 1).
4. The parallel wires are overdrilled using a 5-mm cannulated drill, and remaining bone bridges are removed with an arthroscopic shaver.
5. A central guidewire is reintroduced, and rectangular tibial dilators (Karl Storz) 0.5 mm larger than the width and depth of the graft are inserted over the guidewire to finish the tunnel (Fig 4D, Video 1). As with the femoral tunnel, any rough edges can be smoothed with an arthroscopic shaver. The finished tunnel is shown viewed from distally in Figure 4E.

Graft Preparation

1. The proximal (tendinous) end of the graft, which will become the tibial end of the implanted graft, is prepared using an interlocking suturing technique with 2 No. 2 nonabsorbable sutures (FiberWire; Arthrex) (Fig 5).
2. The bone block is trimmed to fit the chosen rectangular graft template (5 mm by 8, 9, or 10 mm) (Karl Storz). Two slightly offset 1.5-mm holes are then drilled into the block at the junction of the distal and middle third and the middle and proximal third of the block. A No. 2 nonabsorbable suture (FiberWire) is looped through the block and the middle 2 holes of the femoral fixation button (Flipptack; Karl Storz)
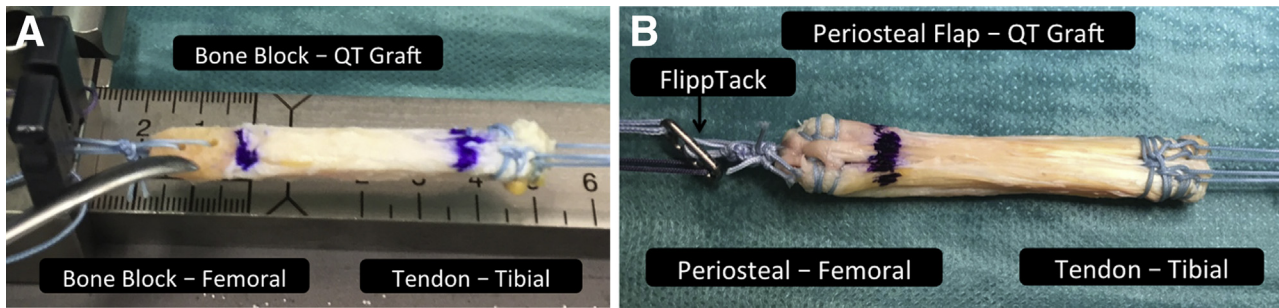
Fig 5. Graft preparation. (A) The bone block—quadriceps tendon (QT) graft is prepared for suspensory and press-fit fixation proximally and hybrid fixation distally. The graft is rotated 180° for implantation so that the distally harvested bone block will be implanted proximally (femoral) and the tendinous proximally harvested end of the graft will be implanted distally (tibial). The bone block is trimmed to fit the chosen rectangular (5-mm × 8-, 9-, or 10-mm) template and chamfered proximally to create a bullet-shaped tip that aids graft maneuverability and entry into the femoral tunnel. For suspensory fixation, two 1.5-mm holes are drilled into the block to pass a nonabsorbable suture (No. 2 FiberWire). The suture is double looped through the drill holes and through the central holes of the femoral fixation button (Flipptack). The distal margin of the bone block is marked and the loop tied such that the bone block will be flush or slightly recessed in the femoral tunnel aperture. The tendinous (proximally harvested, tibially implanted) end of the graft is prepared using an interlocking suturing technique with 2 No. 2 nonabsorbable sutures (FiberWire) and will be secured distally with hybrid fixation (shown in B and Fig 6C). (B) The periosteal flap—QT graft is prepared for suspensory fixation proximally and hybrid fixation distally. As with bone block grafts, the graft is rotated 180° for implantation so that the distally harvested periosteal flap end of the graft will be implanted proximally (femoral) and the tendinous proximally harvested end of the graft will be implanted distally (tibial). Periosteum is harvested in preference to a purely tendinous graft both to elongate the graft and to enhance graft-to-bone healing. The periosteal strip is folded back to create a smooth leading edge for the graft, and the flap is incorporated into the interlocking suture technique with 2 No. 2 nonabsorbable sutures (FiberWire) (Video 1). Both graft ends are prepared similarly, with 2 No. 2 nonabsorbable sutures (FiberWire). At the femoral or periosteal end, the suture loop is tied through the femoral fixation button (Flipptack) and marked so that at least 15 mm of graft will lie within the femoral tunnel. The tip of the graft is chamfered to aid entry into the femoral tunnel. Preparation of the tendinous or tibial end of the graft is identical to the technique described for bone block grafts in A.

(Fig 5A). A bone block graft is preferred over a periosteal flap graft in revision cases for increased primary graft stability and bone-to-bone healing. If the QT has been harvested without a bone block, the periosteum is folded back to the graft to form a smooth leading edge and the flap is incorporated into the interlocking suture technique with 2 No. 2 nonabsorbable sutures (FiberWire) (Video 1, Fig 5B). Periosteum is harvested in preference to a purely tendinous graft to enhance graft-to-bone healing.

3. The nonabsorbable suture loop (No. 2 FiberWire) from the bone block or periosteal end of the graft to the femoral fixation button is tied at the appropriate length for the femoral bone tunnel as shown in Figure 5. The ideal length is such that the bone block will be flush or slightly recessed in the femoral tunnel aperture (Fig 5A). Alternatively, if no bone block is used, the ideal length is such that at least 15 mm of the graft will lie within the tunnel (Fig 5B).

Graft Insertion

1. A Beath pin is introduced through the medial portal and used to pass a Vicryl suture through the femoral tunnel. The suture loop is grasped intra-articularly through the tibial tunnel and pulled extra-articularly distally. The loop is then used to pull the lead sutures for the Flipptack Extracortical Femoral Fixation Device through the knee and out through the femoral tunnel aperture proximolaterally.

2. The graft is introduced by pulling on the lead sutures. The correct orientation within the tibial tunnel is with the cancellous bone block surface facing laterally for rectangular tunnels or anteriorly for round tibial tunnels.

3. Flipping of the Flipptack Extracortical Femoral Fixation Device is confirmed under arthroscopic vision to ensure there is no entanglement of the lead sutures.

4. A key maneuver is that once the graft emerges from the proximal tibial tunnel into the joint space, before insertion into the femoral tunnel, the bone block is guided and correctly rotated intra-articularly with the aid of a standard arthroscopic palpation hook (Fig 6A, Video 1). Clockwise rotation is required for right knees (Fig 6B, Video 1) and counterclockwise for left knees. This step may be achieved more easily with the knee in extension, because less rotation of the graft is required the closer the knee is to full extension (Fig 1C).

5. When the bone block is in correct rotation, the knee is flexed again to 90° and the graft is pulled completely into the rectangular bone tunnel until the femoral
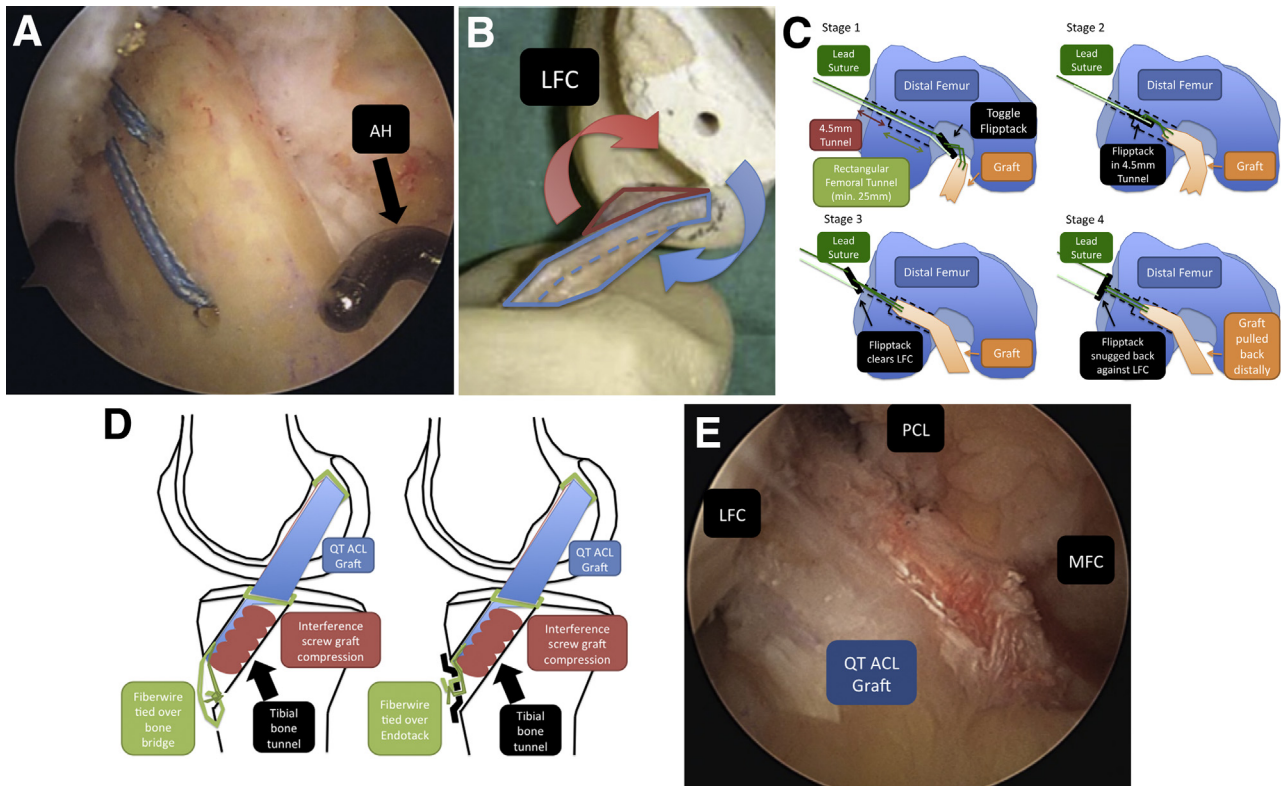
Fig 6. Graft insertion. (A) Graft insertion is shown in a cadaveric right knee viewed arthroscopically from the lateral portal looking centrally at the intercondylar notch. The cancellous surface of the bone block is facing laterally, and a standard arthroscopy hook (AH) inserted through the medial portal is being used to guide and control clockwise rotation of the bone block before it enters the femoral tunnel. (B) This cadaveric rectangular quadriceps tendon (QT) anterior cruciate ligament (ACL) reconstruction in a synthetic bone model shows the right knee viewed from medial looking laterally toward the lateral wall of the intercondylar notch with the medial femoral condyle removed and the lateral femoral condyle (LFC) labeled. The medial aspect of the QT ACL graft is outlined in blue, and the lateral aspect is outlined in red. In a right knee, clockwise rotation of the native ACL or the ACL graft occurs with knee flexion. Hence, the correct introduction of the bone block is with the cancellous side facing laterally as it enters the tibial tunnel. After passing through the tibial tunnel, before entering the femoral tunnel (for a right knee), clockwise rotation of the bone block or graft is required (counterclockwise for a left knee), which is controlled intraoperatively using a standard arthroscopy hook inserted through the medial portal (as shown in A). (C) Graft introduction and femoral fixation button (Flipptack Extracortical Femoral Fixation Device) deployment. This is achieved in 4 stages: In stage 1, toggling of the Flipptack is confirmed intra-articularly by arthroscopy. In stage 2, manual traction on the leading end of the Flipptack is used to pull the graft into the femoral tunnel. The bone block or periosteal end of the graft is confirmed to enter the femoral tunnel in the correct orientation. Slack is gradually taken up on the trailing edge sutures as the graft progresses until both the leading and trailing ends of the button have cleared the lateral cortical bone. There is a palpable reduction in resistance as the trailing end of the Flipptack clears the 4.5-mm proximal tunnel. In stage 3, clearance is confirmed by toggling both of the lead sutures. In stage 4, the distal or tibial sutures are tensioned to snug the Flipptack against the lateral femur. (LFC, lateral femoral condyle; min, minimum.) (D) Bone bridge and bio-interference screw hybrid distal fixation. A fully threaded, cannulated bio-absorbable interference screw matching the tunnel diameter and typically 28 mm in length (23 mm in smaller patients) is inserted over a guidewire lateral to the graft, aiming for graft compression against the anteromedial tunnel margin. The position of the screw is confirmed arthroscopically to avoid intra-articular protrusion before the suture ends are tied over either a cortical bone bridge or an Endotack Tibial Fixation Button. If one is using a bone bridge, a 2.5-mm drill hole is made approximately 5 mm inferior to the tibial tunnel and 2 of the 4 distal FiberWire sutures are passed through this drill hole into the tibial tunnel in an out-to-in manner using a separate thread-able curved needle or using the original FiberWire needle. The sutures are tied to the remaining distal FiberWire sutures such that the final knot lies within the tibial tunnel and is not palpable subcutaneously. If one is using an Endotack, the FiberWire is tied so that the knot is recessed within the Endotack. (QT, quadriceps tendon.) (E) In a right knee viewing arthroscopically from the lateral portal, the final quadriceps tendon (QT) ACL graft position is shown in relation to the lateral femoral condyle (LFC), medial femoral condyle (MFC), and posterior cruciate ligament (PCL).

Table 2. Pearls and Pitfalls

Surgical Step	Pearls and Pitfalls
Graft harvesting	
Double knife	The surgeon should ensure the double knife has cut deeply enough medially and laterally by repeating the insertion inclining the blades slightly left and right.
Tendon separator	The surgeon should avoid anterior cutout when using the tendon separator by checking the correct depth of insertion both medially and laterally before harvest and by maintaining downward pressure during insertion. If cutout occurs and the graft is too thin, a further slip that remains attached to the patella distally can be harvested and sutured to the primary slip.
Donor-site repair	The arthroscope can be used both to visualize the quadriceps tendon before harvest to identify the border of the vastus medialis and to visualize the defect, aiding closure or repair. To avoid tendon shortening, stitches should be placed superficially (fanlike closure).
Graft preparation	The surgeon should chamfer the bone block leading edges to facilitate block maneuverability during insertion into the femoral tunnel. The posterolateral block corner is the most important.
Femoral tunnel	The surgeon should use the medial portal as a viewing portal after marking the desired position of the femoral tunnel to double-check that the planned tunnel is in the correct position.
Tibial tunnel	The surgeon should check the correct position of the tibial guidewires with the knee in extension to avoid notch impingement.
Graft insertion	Before insertion into the femoral tunnel, the surgeon should guide and control rotation of the bone block intra-articularly with the aid of an arthroscopic hook to simulate native ACL orientation.
Tibial fixation	With tension on the distal sutures of the graft, the surgeon should perform knee movement from 0° to 90° ten times to condition the graft before tibial fixation.

ACL, anterior cruciate ligament.

fixation button (Flipptack Extracortical Femoral Fixation Device) is flipped. This is achieved by pulling initially on the leading end of the Flipptack until the trailing end has also cleared the lateral cortical bone. There is usually a palpable reduction in resistance as the trailing end of the Flipptack clears the 4.5-mm proximal tunnel. Clearance is confirmed by toggling both of the lead sutures, before pulling on the distal or tibial sutures to snug the Flipptack against the lateral femur (Fig 6C).

6. With tension on the distal sutures of the graft, the knee is cycled from 0° to 90° ten times to condition the graft.
7. Hybrid fixation is used distally. A fully threaded, cannulated bioabsorbable interference screw matching the tunnel diameter and typically 28 mm long (23 mm in smaller patients) is inserted over a guidewire lateral to the graft, aiming for graft compression anteromedially. The position of the screw is confirmed arthroscopically to avoid intra-articular protrusion before the suture ends are tied over either a cortical bone bridge or an Endotack Tibial Fixation Button (Karl Storz). If one is using a bone bridge, a 2.5-mm drill hole is made approximately 3 to 5 mm inferiorly to the tibial tunnel and 2 of the 4 distal FiberWire sutures are passed through this drill hole in an out-to-in manner using a separate thread-able curved needle or using the original FiberWire needle if not cut off. The sutures are tied to the remaining distal FiberWire sutures so that the final knot lies within the tibial tunnel and is not palpable subcutaneously. If one is using an Endotack, the FiberWire is tied so that the knot is recessed within the Endotack (Fig 6D).

Table 3. Advantages and Disadvantages

Technical Aspect	Advantages	Neutral	Disadvantages
Minimally invasive approach	Smaller skin incision that follows the Langer lines—improved cosmesis vs open	—	Additional incision required vs HT; specialized instruments required
QT graft	Flat ribbon-like graft re-creates native fiber arrangement; reduced laxity over HT[8]; reduced morbidity over PT[8]	No difference in morbidity vs HT[9-11]	Less surgeon familiarity with harvesting technique and graft preparation
Rectangular femoral tunnel	Re-creates anatomic ACL femoral origin; increased chance of bypassing transtibial tunnels in revision	—	More surgical steps in tunnel preparation; graft rotation must be controlled during introduction
Rectangular tibial tunnel	Potentially approximates anatomic J-shaped insertion	—	2-3 guidewires required—more steps in tunnel preparation
Round tibial tunnel	Potentially simulates anatomic C- or Cc-shaped insertion	—	Not applicable; round tunnels are standard practice

ACL, anterior cruciate ligament; HT, hamstring tendon; QT, quadriceps tendon.
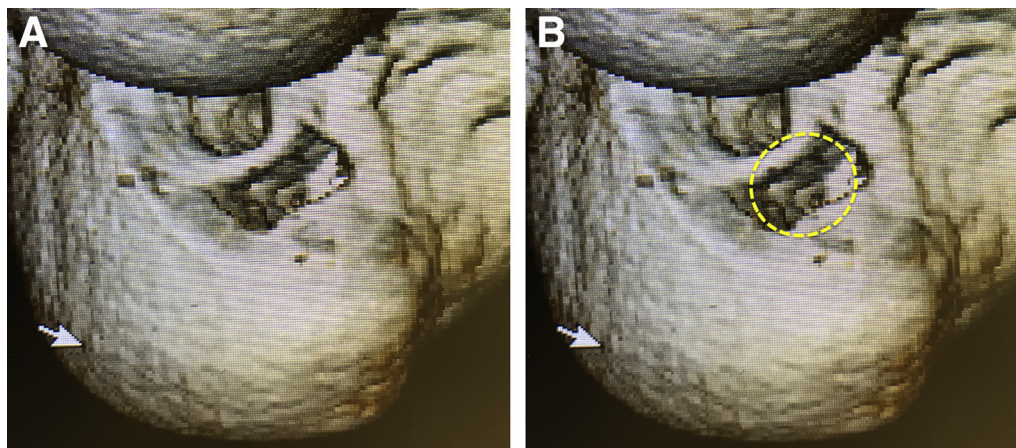
Fig 7. Revision tunnels. (A) A 3-dimensional computed tomography scan of a right knee after revision anterior cruciate ligament reconstruction using a rectangular femoral tunnel has been rotated so that the position of the femoral condyles approximates the arthroscopic view from a medial viewing portal with the knee in flexion. The tunnel position on the medial aspect of the lateral femoral condyle (lateral wall of the intercondylar notch) is shown. Use of a rectangular femoral tunnel enabled the previous round transtibial tunnel to be bypassed during single-stage revision surgery, avoiding the need for bone grafting and 2-stage surgery. (B) A round tunnel of equivalent size to the rectangular tunnel used for single-stage revision has been superimposed (yellow dotted line) onto the same 3-dimensional computed tomography scan shown in A. A round tunnel centered in the same position overlaps the previous transtibial tunnel, risking tunnel breakthrough and necessitating bone grafting and 2-stage revision.

8. The final position and tension of the graft are confirmed arthroscopically with the aid of a standard arthroscopic hook as shown in Figure 6E and Video 1.

Postoperative Care

A knee brace limiting flexion to 90° is used. Passive range-of-motion exercises are initiated immediately. The patient is mobilized with partial weight bearing (20 kg) for 2 weeks. Full weight bearing and free range of motion are commenced thereafter. Physical therapy is recommended 2 to 3 times per week for at least 8 to 12 weeks.

Discussion

We describe a versatile QT single-bundle anatomic ACL reconstruction technique that can be performed with or without a bone block and with rectangular tunnels on both sides or with a rectangular femoral tunnel and round tibial tunnel. Pearls and pitfalls are shown in Table 2, and advantages and disadvantages are listed in Table 3.

Graft Orientation and Tunnel Geometry

Only the process of drilling suggests the choice of round tunnels because neither grafts nor the native ACL are round. Bone blocks in conventional techniques serve only to fill up the round tunnels. Rectangular tunnels offer potential advantages.

On the femoral side, the combination of a rectangular tunnel and a ribbon-like graft mimics the native ACL direct insertion, facilitating graft rotation during knee flexion and simulating native ACL biomechanics

(Figs 1C and 6B). The flat nature of QT grafts also means that increasing graft size only increases the width of the tunnel required because the graft and tunnel depth remains constant at 5 mm. Hence, rectangular femoral tunnels have reduced overlap with in situ transtibial tunnels, avoiding the need for bone grafting and 2-stage surgery in some revision cases (Fig 7). Shino et al.[12] reported achieving single-stage revision in 29 of 31 patients with a similar rectangular bone-PT-bone grafting technique. Comparative dimensions of rectangular and round grafts are shown in Table 1.

On the tibial side, the advantages of rectangular tunnels are less clear-cut. Because the native tibial ACL insertion has been shown to follow a curved C, Cc, or J shape, both round and rectangular tunnels represent a compromise in relation to the native anatomy. With the described technique, after arthroscopy and inspection of the ACL remnant, the surgeon can decide intra-operatively which tunnel shape to use.

In theory, interference screw compression of a ribbon-like graft against the anteromedial rim of a round tunnel may achieve aperture fixation similar to the anatomic C-shaped tibial ACL insertion. Hence, round tunnels may allow a closer approximation of native C- and Cc-shaped insertions, present in 67% and 9% of specimens, respectively, in the anatomic study by Siebold et al.[2] Rectangular tunnels may achieve a closer approximation of a J-shaped insertion, present in 24% of specimens in the same study.[2] Hence, we use a rectangular femoral tunnel in combination with a round tibial tunnel in most cases.

Clinical Results

A large meta-analysis comparing single-bundle QT, HT, and PT grafts showed no difference in the overall clinical outcome.[8] However, the PT and QT both had advantages over the HT in objective laxity. The QT had less donor-site morbidity than the PT.[8] The few studies comparing HT and QT directly have found no differences in donor-site morbidity but showed a trend toward better functional results with QT.[9-11]

Runer et al.[9] reported the results of 40 patients with at least 2 years' follow-up who underwent minimally invasive single-bundle QT autograft ACL reconstruction using the described technique. No reruptures were registered. None of the patients reported tenderness, numbness, or irritation over the graft harvest site. At final follow-up, 37 patients (92.5%) reported good or excellent results, 33 patients (82.5%) reported no or slight pain during severe exertion, and 27 patients (67.5%) returned to their preinjury Tegner activity level.

Minimally Invasive Harvesting Technique

By use of minimally invasive instrumentation, QT graft harvesting can be performed through a transverse incision similar in length to that in HT harvesting techniques. With this technique, cosmetic results are significantly better than with open harvesting, and cosmetic concerns should no longer be a barrier to QT graft use (Fig 8).

Risks and Limitations

The perceived barriers to widespread adoption of the QT for ACL reconstruction are concerns about the technical difficulty of harvesting a standardized graft and cosmetic and functional donor-site morbidity. The development of minimally invasive instrumentation has addressed both the technical and cosmetic issues through standardization of the harvesting technique and minimization of the skin incision.

Although there is a theoretical risk of patellar fracture, no fractures have been reported using the described technique.[9] Clinical studies have shown noninferiority or better donor-site morbidity when compared with the HT and PT.[9-11]

The use of asymmetrical tunnels means that extra care must be taken regarding the correct orientation. On the femoral side, the correct orientation of the rasp is parallel to the direct femoral ACL origin, which is parallel to the floor with the knee flexed to 120°. On the tibial side, rectangular tunnels require 2 or 3 parallel wires to be inserted using a parallel aiming guide, and judging the correct orientation can be more difficult. We combine a rectangular femoral tunnel with a round tibial tunnel in most cases, using a single guidewire technique for both tunnels. Correctly controlling graft rotation intra-articularly during introduction requires care and attention. With the aid of an arthroscopic hook, this can be reliably achieved.

In conclusion, cadaveric studies have suggested that rectangular tunnels in combination with a QT graft may better reproduce the native anatomy, including simulating ACL rotation that occurs with knee flexion, compared with round tunnels.[13,14] Furthermore, rectangular femoral tunnels have reduced overlap with pre-existing transtibial tunnels, reducing the need for bone grafting in some revision cases. Minimally invasive QT harvesting has superior cosmetic results to open techniques, suggesting that cosmetic concerns should not be a barrier to QT graft use. These advantages make QT graft an increasingly attractive option for both primary and revision ACL reconstruction.

Fig 8. Wound cosmesis. The healed incisions for minimally invasive (MI) quadriceps tendon (QT) arthroscopic anterior cruciate ligament (ACL) reconstruction are shown in a right knee. The incision for MI QT graft harvest is along the Langer lines and is made in line with the superior border of the patella with the knee in flexion. The scar appears slightly more distal in this image because of knee extension and quadriceps muscle contraction. The incision is similar in size to that required for hamstring tendon graft harvesting. Furthermore, the cosmetic results from MI QT harvest are significantly better than those with open surgery, suggesting that cosmetic concerns should no longer be a barrier to QT graft use.

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