Review Article

Anatomic anterior cruciate ligament reconstruction using the quadriceps tendon

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Abstract: Bone-patellar tendon-bone (BPTB) and hamstring tendon (HT) grafts are the most commonly used autografts in anterior cruciate ligament (ACL) reconstruction at present. However, they have considerable limitations. Recently, accumulating evidence from biomechanical and clinical data supports interest in the clinical feasibility of the quadriceps tendon (QT) autograft. The QT autograft is characterized by a greater cross-sectional area and provides better biomechanical properties than BPTB or HT. Herein, a single-bundle and modified transtibial anatomical ACL reconstruction technique using the QT graft is introduced in detail, and the clinical results and usefulness of anatomical ACL reconstruction using the QT graft are thoroughly reviewed. Single-bundle and modified transtibial anatomical ACL reconstruction using the QT autograft is a robust, reliable, and reproducible surgical technique and graft choice that can be considered in primary ACL reconstruction.

Keywords: Anterior cruciate ligament reconstruction (ACL reconstruction); anatomic; quadriceps tendon (QT)

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Introduction

Anterior cruciate ligament (ACL) injuries are the most common ligament injuries, with an incidence of 100,000 to 200,000 per year (1). ACL reconstruction surgery has achieved largely satisfactory outcomes in 75% to 95% of patients. For a successful ACL reconstruction, choice of graft, anatomical tunnel positioning, adequate footprint coverage, and prevention of complications and morbidity are important issues to be considered.

Currently, bone-patellar tendon-bone (BPTB) and hamstring tendon (HT) autografts are most commonly used in ACL reconstruction (2,3). ACL reconstruction using the quadriceps tendon (QT) was firstly introduced by Marshall *et al.* (4) and Blauth (5). Staubli and Jakob (6) reported that the QT is characterized by adequate substance and mechanical properties with minimal donor site morbidity such that it is feasible for use as a graft in ACL reconstruction. A survey across 20 countries conducted in 2014 found that the QT was used in 11% of ACL reconstructions (7). A recent systematic review (3) concluded that the QT is a reliable and reproducible graft that should be considered in ACL reconstruction. The increase of QT use in ACL reconstruction could be predicted given its excellent mechanical characteristics, attributed its larger cross-sectional area compared to the patellar tendon (PT) (8,9). Furthermore, a systematic review found that the donor-site morbidity was minimal with QT (2).

The concept of anatomic ACL reconstruction has been well established and has achieved good clinical outcomes. Previous studies have demonstrated better knee stability and function according to anatomic positioning of the femoral bone tunnels in ACL reconstruction than isometric, vertical positioning of the tunnels (7,10-12). Anatomic ACL

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reconstruction can be defined as an operation using the anatomic insertion area of both the tibial and femoral origin of the ACL for positioning of the tunnels. A limitation of the traditional transtibial technique is that the femoral tunnel position is constrained greatly by the position and angle of the tibial tunnel. The femoral tunnel can be made in a position superior to the native femoral insertion, which results in a vertical graft orientation that leads to residual rotational laxity (10). This has led to a preference for the trans-portal technique or the outside-in technique, which allow to easily creating the tunnel in an anatomical position. However, both techniques also present some disadvantages. When applying the anteromedial trans-portal technique, deep knee bending is required while creating a femoral tunnel, which results in a difficulty maintaining good arthroscopic view and short femoral tunnel (13). Moreover, there is a risk of cartilage damage to the medial femoral condyle. The outside-in technique also makes an acute femoral tunnel obliquity and an abrupt graft bending angle (GBA), which has been suggested to be a biomechanical factor contributing to poor graft healing or graft failure (14). We have modified the traditional transtibial technique by applying a forward drawer force, a varus force, and an external rotational force to the proximal tibia and rotating the femoral guide, followed by insertion of the femoral guide pin.

The most frequent complications of ACL reconstruction include loss of quadriceps and hamstring strength, extension deficit, and anterior knee pain (15,16), with a higher incidence of these complications observed when using BPTB. The quadrupled HT is widely used due to high load to failure (>4,000 N), low morbidity rates, and small incisions (17). However, some authors have reported tunnel widening relying on tendon-to-bone healing and increased failure of HT grafts compared to BPTB grafts (18,19). Comparative studies with the QT and BPTB graft in ACL reconstruction found similar good results in graft stability (20-22), and favorable functional outcomes with the QT graft (smaller thigh strength deficit and less donor site morbidity) (23,24). Moreover, the QT harvest induces minimal quadriceps inhibition and the residual strength of the extensor mechanism is less impaired by a QT harvest than by harvest of a BPTB graft.

Herein, a single-bundle and modified transtibial anatomical ACL reconstruction using the QT graft will be introduced in detail, and clinical outcomes and usefulness of anatomical ACL reconstruction using the QT graft will be reviewed.

Anatomy

The QT graft presents many anatomical advantages for primary ACL reconstruction. It has a larger cross-sectional area compared to other grafts (25). Harris *et al.* (26) reported that the QT was 1.8 times thicker than the PT. The QT is average 30 mm wide enough to allow harvesting 10-mm wide grafts. The variability in the cross-sectional area has been reported to be similar in both tendons (27).

Staubli and Jakob (6) have indicated that the QT has a wide attachment to the patella. In anatomical studies, the mean lengths of the QT and PT averaged 85–87 and 51–52 mm, respectively (8). The mean cross-sectional area of the QT graft with 10 mm width was measured as 64.6±8.4 mm^2, which is considerably larger than the mean values of the PT, at 36.8±5.7 mm^2.

Recently, preoperative magnetic resonance imaging (MRI) has been explored as a suitable tool for predicting intraoperative graft size for ACL reconstruction (28). Comparing preoperative MRI measurements with direct intraoperative measurements, the correlation was very highly positive for the QT, highly positive for the PT, negligible-highly positive for the semitendinosus-only tendon, and negligible-moderately positive for the gracilis-only tendon. The QT has also been shown to be a promising graft option particularly for patients with predicted insufficient hamstring grafts (29). All 54 knees had predicted QT graft diameters of >8 mm.

One study reported a histological comparison of the QT and PT to show that the QT comprised 20% more collagen than the PT, suggesting the superiority of the QT as an ACL graft (30).

Biomechanical properties

Biomechanical and cadaveric studies found that normal ACL has an ultimate load to failure of 1,725–2,160 N, and the tensile strengths of intact QT are averaged as 3,660±830 N, which is 90% higher than those of intact PT (17,31,32). Shani *et al.* (27) reported that ultimate strain was similar between the QT (10.7% change) and the PT (11.4% change). Young's modulus of elasticity of the QT was significantly smaller than that of the PT. The mean stiffness of the QT was larger than that of the PT.

Surgical techniques

After anesthesia, a complete physical and arthroscopic

Figure 1 Prepared quadriceps tendon graft. The bone block is perforated transversely with drill holes and passed with 2 PDS sutures. The tendinous portion is secured with two No. 5 Ethibond sutures using Krackow-type stitches.

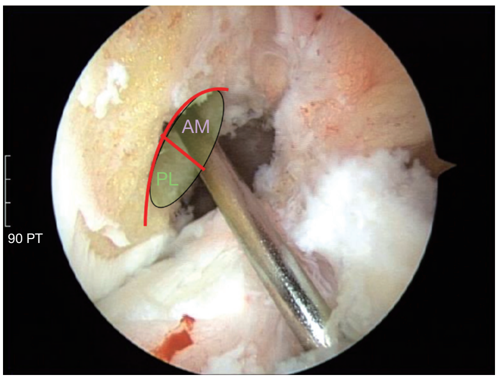

Figure 2 Arthroscopic view of anatomical femoral tunnel following creation. AM, anteromedial bundle; PL, posterolateral bundle.

examination is performed to evaluate the torn ligament and other intra-articular lesions. Next, all additional procedures are performed before the ACL reconstruction. Following the arthroscopic confirmation of a complete ACL rupture, a QT-patellar bone (QTPB) autograft from the ipsilateral limb is harvested.

Harvest of the QTPB autograft

The QTPB is harvested through 4–6 cm midline incision over the middle of the proximal border of the patella. The graft consists of a proximal patellar bone plug and the central QT. Keeping the knee flexed to 80° facilitates the harvest by maintaining tension on the QT. A 10 mm wide, 20 mm long, 7–8 mm thick trapezoidal bone block is obtained from the proximal patella using a saw and osteotome. Next, a 10 mm wide, 6 to 7 mm thick, and 70 to 80 mm long strip of the QT including the full thickness of the rectus femoris tendon and partial thickness of the vastus intermedius tendon is excised in continuity with the patellar bone block initially using a 10-mm Harvester (ConMed Linvatec, Largo, FL, USA) and then finishing with Metzenbaum scissors. Care is taken not to enter the suprapatellar pouch. If entry occurs, the synovial membrane is repaired with an absorbable suture. The superficial layer of the remaining tendon is closed transversely with absorbable closing sutures. The patellar bone defect is not grafted.

Graft preparation

The QTPB graft is prepared to allow passage through 10-mm-diameter tunnels. The bone plug is trimmed to a bullet shape using a saw and a rongeur. The bone block from proximal patella is perforated transversely with drill, and two absorbable sutures are passed through the transverse holes. The tendinous portion of the graft is secured with No. 5 Ethibond™ sutures (Ethicon, Somerville, NJ, USA) using Krackow-type stitches leaving approximately 30 mm intra-articular portion (*Figure 1*).

Tunnel placement (a modified trans-tibial technique)

Every effort is made to preserve the remnant tissues of the ruptured ACL as much as possible. However, a remnant may be sacrificed if the preservation is impossible or not useful. The conventional transtibial technique is modified to create the femoral tunnel in the anatomical position (*Figure 2*). A 3-cm longitudinal skin incision is made at the anteromedial side of the proximal tibia. The entry point of the tibial tunnel is created 4–5 cm distal to the medial tibial plateau, 2–3 cm medial to the tibial tuberosity, just superior to the attachment of the pes anserinus, and just anterior to the medial collateral ligament. Using a tibial drill guide (Acufex, Andover, MA, USA) a guide pin is inserted at an angle of 60° to the tibial plateau, which is aimed at the center of the ACL tibial footprint between the anteromedial and posterolateral bundles. A 10-mm tibial tunnel is made along the guide pin using a cannulated reamer. To create the femoral tunnel, a 7-mm offset femoral guide (Acufex) is directed at the center of the ACL femoral footprint (the lateral bifurcate ridge on the inner wall of the lateral femoral condyle) through the tibial tunnel with the knee flexed to 90° and applying an anterior drawer force to

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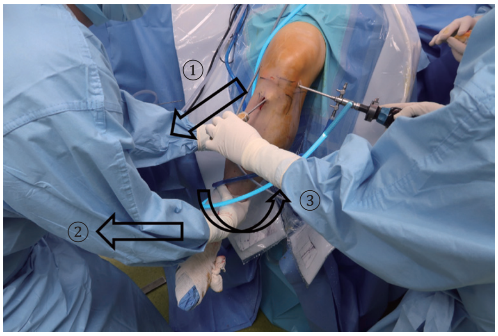

Figure 3 Modified transtibial technique maneuver. ①: application of an anterior drawer force to the proximal tibia; ②: application of an additional varus force to the proximal tibia; ③: application of an additional external rotation force to the proximal tibia and externally rotation of the guide.

the proximal tibia, a varus force, and an external rotation force to the lower leg while externally rotating the guide (*Figure 3*). Applying a varus force to the lower leg, with the thigh fixed to the leg holder, provides lateral opening of the knee joint, which enables to aim the femoral guide to the anatomical footprint. Then, a femoral tunnel guide pin is inserted through the guide and a 10-mm-diameter, 20- or 25-mm-long femoral tunnel is drilled through the tibial tunnel using a cannulated reamer. Next, a slot is created for the screw guide pin on the anterior aspect of the femoral tunnel.

Piasecki *et al.* (33) has made an effort to modify the trans-tibial technique by making the entry point of the tibial tunnel far medial and proximal to achieve a more oblique trajectory of the ACL graft. However, this modification has resulted in other problems, a shorter tibial tunnel and intra-articular aperture widening to an elliptical shape (34). Previously, we have compared the anteromedial trans-portal technique and the modified trans-tibial technique, and reported the radiological and clinical comparison results (12). The mean values of the angle between the longitudinal axis of the femoral tunnel and the anteroposterior axis of the distal femur on oblique computed tomography (CT) views in the patients treated with our modified trans-tibial technique were significantly smaller than in the patients treated with the anteromedial trans-portal technique. However, there was no significant difference between the two groups in the mean values of the angle between the joint line and the graft (graft obliquity) on coronal and sagittal CT images. The mean femoral tunnel length was significantly greater in the modified trans-tibial technique group compared with the anteromedial trans-portal technique group. Evaluated using the quadrant method, the femoral tunnel position was slightly anterior and inferior in the modified trans-tibial technique group. However, the mean difference in tunnel position between the 2 groups was less than 2 mm and not statistically significant. Regarding the tibial tunnel, the 2 groups showed no significant differences in the ratio of the long-axis length to the short-axis length or the area of the intra-articular aperture, which was checked because of concerns of resultant intra-articular aperture widening due to the modified trans-tibial technique. The tibial tunnel length was slightly shorter in the modified trans-tibial technique; however, the mean length was over 32 mm (minimum 28 mm), which was enough for graft fixation and healing. There were no significant differences in the clinical results (joint stability using manual laxity tests and arthrometry or clinical scores) between the 2 groups.

Graft fixation

Secure graft fixation, graft tension during fixation, and graft fixation level are crucial aspects in ACL reconstruction. The bone block was inserted to the femoral tunnel with the bony part facing forward. Then a metal interference screw (ConMed Linvatec) is used to fix the bone block with the knee flexed. On the tibial side, the tendinous portion of the graft is firstly fixed with a bioabsorbable screw (BioScrew; ConMed Linvatec) in the tibial tunnel without any rotation of the graft and is tightened by tying sutures over a bicortical screw, which is inserted 1–2 cm inferior to the tibial tunnel with the knee extended.

Rehabilitation

Immediately after surgery, full extension was achieved, and full flexion was obtained by 6 weeks. A motion-controlled brace set at 0° to 90° was applied for 4 weeks, then 0° to full flexion for an additional 2 months postoperatively. Partial weight-bearing was permitted for 6 weeks and progressed as tolerated. Full strenuous activity and sports were allowed after 6 months postoperatively, confirming the recovery of quadriceps muscle strength.

Clinical results

The QT autograft has been gaining support from recent studies including systematic reviews, where it has demonstrated clinical outcomes and biomechanical features

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similar or superior to those achieved with BPTB and HT grafts (2,3,20,35,36).

Stability

In our case series (21), 227 patients (94.6%) demonstrated grade 0 or 1 laxity on the Lachman test, the anterior drawer test, or the pivot-shift test. KT-1000 arthrometric measurement also showed a significant improvement in side-to-side differences on manual maximum test, with a mean of 2.4±1.7 mm at a minimum 2-year follow-up, at which time 11 knees (5%) showed laxity of more than 5 mm. A recent systematic review including 8 studies (1 level II, 7 level III) and 368 patients that underwent primary ACL reconstruction with QT autografts, including 225 patients with BPTB and 150 patients with HT, showed that QT patients showed less knee laxity postoperatively compared with HT patients. However, there were no significant differences in graft failure rates between groups (36).

Functional outcome

In 2004, we reported that ACL reconstruction using a QT autograft resulted in satisfactory clinical outcomes with reduced donor-site morbidity (22). Sixty-seven ACL reconstructions were evaluated at minimum 2 years follow-up. The Lysholm score improved from 71 to 90, postoperatively. In the International Knee Documentation Committee (IKDC) scale, 94% of patients were grade A or B. The peak extension torque of the quadriceps muscle was found to be 82% and 89% of that of the contralateral knee at 1 and 2 years after surgery, respectively. The patellar position showed no significant change after the QT autograft was harvested. Only 6% of patients complained of difficulty in stair-climbing and anterior knee pain, and one patient complained of harvest-site tenderness.

Few studies have reported long-term results. Howe *et al.* (37) reported a 10-year (mean, 5.5 years) follow-up study of 83 patients with ACL reconstructions using the QT graft. Of these, 92% were satisfied with the results, 93% reported no significant pain, and 92% had no more than a mild dysfunction. Chen *et al.* (38) evaluated 34 patients with a 4–7-year follow-up, and reported 94% good and excellent results on the Lysholm score. Return to moderate or strenuous sports was possible in 76% of patients. In the IKDC scale, 91% of these patients reported a normal or nearly normal knee.

Several systematic reviews and comparative studies have concluded that the QT autograft achieved clinical (stability) and functional outcomes similar to those reported for BPTB and HT grafts (2,3,36,39,40).

Muscle strength recovery

Although low incidence of anterior knee pain has been consistently reported as an advantage of the QT graft, the effects deriving from the graft harvest on the extensor mechanism have been a relevant concern. Joseph *et al.* (41) prospectively compared early physical findings of ACL reconstruction using QT, HT, and BPTB grafts. They reported that the QT group achieved knee extension earlier than those reconstructed with BPTB and required less pain medication postoperatively than either the HT or BPTB group. In another study, the QT group had better outcomes in extensor mechanism strength at postoperative 6 months (23).

It is known that knee extensor strength is impaired for more than 1 year after ACL reconstruction, which is especially true when BPTB grafts are used (42-45). The extensor mechanism of the knee is weakened not only following the use of either the BPTB or QT, but also after ACL surgery with HT autografts (46,47). Conversely, knee flexor strength is negatively influenced by the use of HT, whereas QT or BPTB grafts have only a temporary effect (48,49). As against previous finding (50), no evidence for improvement of knee flexor strength over time has been detected in the injured side after HT graft harvesting (51).

In 20 patients undergoing anatomical single-bundle ACL reconstruction using a QT autograft, the average quadriceps strength changed from preoperative 90.5% to 85.1% after 12 months (52). Within 6 months after surgery, quadriceps hypotrophy was observed in all subjects, which nevertheless recovered after postoperative 1 year. No patients complained of donor site pain postoperatively.

Complications and morbidity

Postoperative donor-site morbidity and anterior knee pain following ACL reconstruction result in functional impairment. Injury to the infrapatellar branch of the saphenous nerve in PT harvesting causes paresthesia or numbness on anterior aspect of the knee and is correlated with an inability to kneel. The remaining PT at the donor site exhibited significant clinical, radiological, and histological abnormalities 2 years after harvest (53). Previous studies found lower incidences of sensory loss, anterior knee pain, and donor-site morbidity after QT harvesting

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when compared with BPTB or HT harvesting (35,53-55). We have previously reported that the prevalence of a patellar fracture was below 2% when using a QT autograft (22).

The tensile strength of the remaining QT and PT after harvesting was measured and compared with that of intact QT and PT in a cadaveric study (32). Removing a 10-mm-wide graft from the distal QT reduced average 34% of tensile strength. The strength of the QT after graft harvesting was higher than that of the intact PT, which suggests that the risk of extensor mechanism rupture may be less in QT than in PT.

Harvesting the HT autograft can cause complications of injury to the surrounding neurovascular structures, tendon amputation during the harvest, and a decrease in knee flexor strength (53). Furthermore, complications including medial thigh and calf hematoma and spasm pain are common after harvesting the HT autografts (56). The advantages of QT autografting include preservation of flexor function, early achievement of knee extensor strength, less analgesics requirement, and a reduced incidence of anterior numbness (41,57,58).

Comparative study: versus BPTB autografts

We compared the clinical outcomes following ACL reconstructions using central QTPB and BPTB autografts (20). Seventy-two patients who underwent unilateral ACL reconstruction using BPTB were selected and matched for age and sex with 72 patients receiving QTPB grafts. More patients [28 (39%)] in the BPTB group reported anterior knee pain than in the QTPB group [6 (8.3%)]. Sixty-eight patients (94%) in the BPTB group and 66 (92%) in the QTPB group graded their knees as normal or nearly normal at final follow-up.

Previous studies have compared the effectiveness of QT autografts with those of BPTB autografts and have shown that the QT autograft produced similar outcomes in anteroposterior stability and functional scores (Lysholm and IKDC subjective scores) (2,20,24,59-61). Moreover, patients who underwent ACL reconstruction with QT autografts experienced less anterior knee pain than those with BPTB autografts (20,54,59,60).

Gorschewsky *et al.* (24) reported similar stability between QT and BPTB in manual tests and in KT-1000 arthrometric measurements. Lund *et al.* (54) and Kim *et al.* (60) also reported similar anterior knee laxity. However, they reported that rotational stability evaluated by pivot shift test was better with QT. Geib at al. reported that the QT autograft showed better results, with less anterior knee pain, less anterior numbness, a higher percentage of a side-to-side difference of less than 3 mm in arthrometric measurements, and less extension loss (59). They suggested that the larger cross-sectional area of the QT reduced tunnel-mismatch and tibial tunnel widening (62). Pigozzi *et al.* (23). Compared the isokinetic results of patients receiving either the BPTB or the QT graft, and concluded that the thigh muscle strength deficit in the QT group was smaller after 6 months postoperatively.

The results of a systematic review suggest that no significant difference existed in the graft failure rate or in patient reported outcomes (PROs) between primary ACL reconstruction with a QT, BPTB, or HT autografts at a minimum 2-year follow-up (36). PROs of QT patients were generally improved more than those of BPTB or HT patients. The most common disadvantages of BPTB autografts include anterior knee pain and knee extensor weakness. Delayed graft incorporation and reduced knee flexor strength have been reported as the main disadvantages of the HT autograft (63,64). Joseph *et al.* (41) compared QT grafts with two other grafts for ACL reconstruction. They found that the QT group required fewer analgesics and achieved active extension more rapidly than the BPTB group.

Comparative study: versus HT autografts

We have previously reported a cohort study of 96 patients who underwent ACL reconstruction with either double-bundle HT or single-bundle QT autograft (35). The maximum KT-2000 arthrometer side-to-side difference improved in both HT and QT groups. The modified Lysholm scores, IKDC subjective evaluation scores, and Tegner activity scores also improved in both groups. There were no between-group differences in postoperative anterior knee pain, nor were there differences in thigh extensor strength recovery evaluated with isokinetic test. However, thigh flexor strength recovery was better in the QT group. Anatomic ACL reconstruction with the QT autograft showed similar knee stability and functional outcome compared to the HT autograft.

A recent cohort study of 86 patients reported that ACL reconstruction using QT grafts showed equal or better functional outcomes when compared to ACL reconstruction using HT grafts (65). The number of cases with negative Lachman test after surgery was higher in the QT group than in the HT group (90% *vs.* 46%). Also, the number of

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cases with negative pivot-shift test was higher in the QT group than in the HT group (90% *vs.* 64%). Farber *et al.* (66) reported that hamstring weakness was the greatest concern among surgeons treating elite soccer players. A randomized controlled trial of 56 soccer players comparing HT and QT grafts showed a significant difference in the hamstring/quadriceps (H/Q) ratio and peak torque values in the extensor muscle strength over time (67). ACL reconstruction with a QT graft showed similar functional outcomes with a better isokinetic H/Q ratio compared to ACL reconstruction with the HT at the 1-year follow-up in soccer players.

In a recent systematic review of 15 clinical trials including 1,910 patients, there was no difference in the graft rupture rate among QT, BPTB and HT in any of the studies (39). Two studies reported that QT resulted in better knee stability than BPTB or HT. In addition, 2 studies found that QT resulted in greater functional outcomes than BPTB or HT.

Radiological results

Twenty-six patients subjected anatomic single-bundle ACL reconstruction with either HT or QTPB autografts underwent postoperative MRI 6 months after surgery (68). The maturity of QTPB was better in comparison with HT. Bone-to-bone healing in the femoral tunnel may have a positive effect on the intra-articular graft healing process. During biological graft healing process, the microenvironment around the graft plays an important role. Bone-bone healing is more secure and faster than tendon-to-bone healing (69).

In an *in vivo* analysis, signal intensities of the reconstructed QT graft were reported to be highest in the proximal region and lowest in the distal region at 6 months postoperatively (14). An acute GBA was correlated with high signal intensity of the proximal graft. The authors suggested that an acute GBA might negatively affect proximal graft healing after ACL reconstruction using QT grafts. We conducted transmission electron microscopic evaluation of the biopsy specimen from QT grafts. Twenty-eight (76%) of the 37 specimens showed the original bimodal pattern of fibrils composed of small and large-diameter fibrils, which may indicate the mechanical superiority of the QT (21).

Conclusions

The single-bundle and modified transtibial anatomical ACL reconstruction using the QT autograft is supported by the current literature. It is a robust, reliable, and reproducible surgical technique and graft choice that can be considered in primary ACL reconstruction.

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Footnote

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Ethical Statement: The authors are accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

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