# Bone–Patellar Tendon–Bone Versus Quadriceps Tendon–Bone Autografts in Anatomic Rectangular Tunnel Anterior Cruciate Ligament Reconstruction

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**Background:** Anatomic rectangular tunnel anterior cruciate ligament reconstruction (ART-ACLR) can mimic the fiber arrangement of the native ACL and restore normal knee biomechanics, compared with the conventional round tunnel ACLR. ART-ACLR using a bone–patellar tendon–bone (BPTB) graft can provide satisfactory clinical outcomes; however, some issues such as secondary ACL injury and donor-site morbidity, including postoperative anterior knee pain (AKP), remain to be solved. Due to these issues, quadriceps tendon–bone (QTB) grafts have recently become more popular.

**Purpose:** To compare the 2-year clinical outcomes of ART-ACLR with BPTB and QTB autografts.

**Study Design:** Cohort study; Level of evidence, 3.

**Methods:** A total of 134 patients underwent primary ART-ACLR with BPTB (n = 70) or QTB (n = 64). All patients had a minimum follow-up period of 2 years postoperatively. Outcome evaluations included the International Knee Documentation Committee (IKDC), Knee injury and Osteoarthritis Outcome Score (KOOS), side-to-side differences (SSDs) with the KT-1000 knee arthrometer, rate of secondary ACL injury, and incidence of AKP.

**Results:** Regarding age, sex, height, weight,and concomitant procedures, there were no significant differences between the 2 groups. All clinical scores significantly improved from preoperatively to 6 months postoperatively and further increased throughout the 2-year postoperative period in both groups. The IKDC and all subscales of the KOOS, except Sport and Recreation, were equivalent between the BPTB and QTB groups at each postoperative time point. There were no significant differences in the SSD value of KT-1000 arthrometer between the 2 groups. The rates of secondary ACL injury were 10.0% on the ipsilateral side and 2.9% on the contralateral side in the BPTB group and 3.1% on the ipsilateral side and 4.7% on the contralateral side in the QTB group, with no significant difference between both groups. The incidence of AKP was 17.1% and 4.9% in the BPTB group and QTB group, respectively, with significance of $P$ = .02).

**Conclusion:** The clinical scores, SSD value of the KT-1000 arthrometer, and secondary ACL injury rates were equivalent between the BPTB and QTB groups. However, the incidence of AKP was significantly lower in the QTB group, suggesting that QTB could be a favorable graft for ACLR.

**Keywords:** knee ligaments; ACL; knee, meniscus; anatomic; rectangular tunnel; bone–patellar tendon–bone; quadriceps tendon–bone

Anterior cruciate ligament (ACL) injuries are common in sports orthopaedics, particularly in young athletes. Patients with ACL injuries may complain of knee instability, and delays in treatment may lead to an increased risk of meniscal tears, chondral injuries, and early knee osteoarthritis.[2,18] In symptomatic patients who desire to return to sports, ACL reconstruction (ACLR) is recommended to facilitate early return to full sports function and reduce the risk of long-term complications. The most commonly used grafts for ACLR include

The Orthopaedic Journal of Sports Medicine, 12(11), 23259671241297104
DOI: 10.1177/23259671241297104

hamstring tendon, bone–patellar tendon–bone (BPTB), and quadriceps tendon (QT)/quadriceps tendon–bone (QTB) autografts.[13] However, there is no consensus on the ideal graft choice for ACLR.

A BPTB graft was commonly used until the 1980s; however, several complications, including donor-site morbidity such as anterior knee pain (AKP), kneeling pain, extensor strength deficit, patellar fracture, and patellar tendon rupture, have been reported.[3,42] Subsequently, hamstring tendon grafts became popular in the 1990s.[13] More recently, the BPTB graft has been revived, as several studies have shown that a BPTB graft has a lower revision rate than a hamstring tendon graft.[7,24] As an alternative, the QT/QTB graft has gained popularity in recent years owing to the drawbacks of other graft choices.[5,15] In addition, the QT/QTB graft has higher tensile strength and is thicker than the BPTB graft.[4] A recent systematic review compared the clinical results of BPTB and QT autografts after ACLR, showing that knee stability, functional outcomes, overall patient satisfaction, range of motion, and complications were similar between both grafts, but less donor-site morbidity such as AKP and kneeling pain was observed when using a QT graft.[33] Thus, it is likely that the QT/QTB graft could reduce the rate of secondary ACL injury and postoperative complications such as donor-site morbidity, possibly due to the superior material properties and different graft harvest site from BPTB. Shino et al[30] developed an anatomic rectangular tunnel ACLR (ART-ACLR) using a BPTB graft with rectangular tunnels, which mimics the natural fiber arrangement inside the native ACL and minimizes the tunnel size, created inside anatomical attachment areas. This technique displayed significantly superior biomechanical characteristics compared with the isometric round tunnel procedure.[35] Additionally, this technique using a BPTB graft was reported to provide satisfactory clinical outcomes both subjectively and objectively in >95% of patients.[36] However, no studies have investigated ART-ACLR using QT/QTB grafts. Thus, this study aimed to directly compare the clinical outcomes of ART-ACLR with BPTB and QTB autografts up to 2 years postoperatively. The reconstructions were performed under the same conditions regarding the surgical method, fixation devices, initial tension of each graft, and postoperative rehabilitation. We hypothesized that ART-ACLR using a QTB graft would reduce the rate of secondary ACL injury and donor-site morbidity, including AKP.

## METHODS

### Patients

This study was designed in accordance with the Declaration of Helsinki and approved by the institutional review board of Hoshigaoka Medical Center. Informed consent was obtained from all patients preoperatively. This study assessed 191 patients who underwent ART-ACLR for primary unilateral ACL injury between April 2018 and March 2021 at our institution (Hoshigaoka Medical Center). Experienced surgeons (K.S., A.T., M.H., Y.Y.) performed all ACLR procedures. The inclusion criteria were as follows: healthy contralateral knees, no radiological osteoarthritic changes, and outpatient follow-up evaluations for up to 2 years postoperatively. Of the 191, 57 patients were excluded as they did not meet the inclusion criteria. Consequently, 134 patients were included in this study.

### Graft Selection

BPTB grafts were selected for all patients between April 2018 and June 2019. From July 2019 to March 2021, a QTB graft was mostly selected; however, a BPTB graft was used in some cases based on the patient's and/or the surgeon's decision. In this study, the graft distribution was 70 BPTB and 64 QTB for primary ART-ACLR.

### Surgical Procedure

An autologous 10 mm–wide BPTB graft was harvested from the central portion of the patellar tendon with 15 mm–long bone plugs at both ends, whereas an autologous 10 mm–wide QTB graft with a 50 to 60 mm–long tendon was harvested from the center of the quadriceps tendon with a 15 mm–long bone plug at one end. Each bone plug was shaped into a rectangular parallelepiped with a thickness of 5 mm, 5.5 mm, or 6 mm; a width of 10 mm; and a length of 15 mm (Figure 1). The bone plug thickness (5 mm, 5.5 mm, or 6 mm) was determined based on the graft thickness of the tendon. Before the graft was passed, the cross-sectional area (CSA) of each graft was measured at the center of the graft tendon using a custom-made area micrometer.[8] Regarding graft passage, the tibial bone plug was assigned to the femoral tunnel, whereas the patellar bone plug was designated for the tibial tunnel

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Final revision submitted April 30, 2024; accepted May 7, 2024.
One or more of the authors has declared the following potential conflict of interest or source of funding: K.S. has received research support from JSPS KAKENHI Grant Number JP23K08676. AOSSM checks author disclosures against the Open Payments Database (OPD). AOSSM has not conducted an independent investigation on the OPD and disclaims any liability or responsibility relating thereto.
Ethical approval for this study was obtained from the institutional review board of Hoshigaoka Medical Center (No. 2239).


**Figure 1.** A quadriceps tendon–bone graft prior to the passage. The bone plug (left side) was assigned to the femoral tunnel, whereas the other end of the tendon (right side) was designated for the tibial tunnel.

for a BPTB graft. For a QTB graft, the patellar bone plug was assigned to the femoral tunnel, whereas the other end of the tendon was designated for the tibial tunnel.

The detailed procedure of ART-ACLR has been reported previously, and both the femoral and the tibial tunnels were created based on the bony landmark strategy.[30] Briefly, before tunnel creation, the remnant of the torn ACL around the ACL femoral attachment was completely removed with a shaver and a radiofrequency device to clearly visualize the femoral attachment area delineated by the resident's ridges[10,11,31] and the posterior/proximal cartilage.[11,26] Similarly, the ACL tibial remnant was removed to identify the tibial attachment area surrounded by the anterior ridge (Parsons knob),[1,39] medial intercondylar ridge,[25,39] and anterior horn insertion of the lateral meniscus.[14,20,43]

To create the femoral tunnel, an outside-in technique using a lateral femoral incision was applied with the knee in 90° of flexion. Two guide pins (2.4-mm Kirschner wire) were inserted in parallel into the anteromedial and posterolateral parts of the femoral attachment area and were overdrilled with a 5-mm, 5.5-mm, or 6-mm cannulated drill, which matched the size of the graft. The 2 drill holes were dilated into a rectangular tunnel using a rectangular dilator (Smith + Nephew Endoscopy).

To create the tibial tunnel, an outside-in technique was applied with the knee in 90° of flexion in the same manner as for the femoral tunnel. Two guide pins (2.4-mm Kirschner wire) were inserted in parallel into the anteromedial and posterolateral parts of the tibial attachment area and were overdrilled with a 5-mm, 5.5-mm, or 6-mm cannulated drill, which matched the size of the graft. The 2 drill holes were dilated into a rectangular tunnel using a dilator (Smith + Nephew Endoscopy).

An autologous BPTB or QTB graft was passed through the tibial tunnel and into the femoral tunnel using a leading suture. After the tendon-bone interface was adjusted to the femoral tunnel aperture, femoral fixation was performed using a bioabsorbable interference screw (MILAGRO, Depuy Synthes; BIOSURE, Smith + Nephew; or ThreadTight, Arthrex). For the tibia, the sutures from the graft were tied to a double-spike plate (MEIRA Corp),[28] and the double-spike plate was fixed to the tibia with a screw under an initial tension of 10 N at 20° of knee flexion after using the tensioning boot system to remove the creep in the graft by repetitive manual pulls.[29] No notchplasty was needed in any case because there was no graft impingement on the notch or the posterior cruciate ligament.

## Postoperative Rehabilitation

The protocol for postoperative rehabilitation was described in previous studies.[29,36] Knees were immobilized with a fixed knee brace for the first week postoperatively to reduce pain or swelling during the acute inflammatory phase, and only quadriceps muscle setting and straight-leg raising exercises with a knee brace were permitted. After immobilization for 1 week, range-of-motion exercises began. Partial weightbearing was permitted postoperatively at 1 to 2 weeks, followed by full weightbearing at 2 to 3 weeks. Jogging was allowed after 3 months. Return to previous sporting activities was allowed ≥8 months after ACLR.

## Assessments of Outcomes

All patients were assessed regarding the knee condition, including range of motion, adverse events, and subsequent procedures until the final follow-up. Additionally, the patients were clinically evaluated using patient-reported outcome measures, including the International Knee Documentation Committee (IKDC) subjective knee evaluation form and the Knee injury and Osteoarthritis Outcome Score (KOOS) tools, preoperatively and at 6 months, 1 year, and 2 years postoperatively. Instrumented anterior knee laxity was measured using a KT-1000 arthrometer (MEDmetric) 6 months or later post-ACLR, and the side-to-side difference at the manual maximal anterior tibial load was adopted as a parameter.

The rates of graft rupture, contralateral ACL injury, and overall secondary ACL injury (ipsilateral or contralateral knee) were calculated for both groups. The incidence of AKP was assessed in both groups until the final follow-up. To further investigate the influence of AKP on clinical scores, all patients in both the BPTB and the QTB groups were divided into 2 groups: AKP-negative (n = 119) and AKP-positive (n = 15). In this series, AKP in all patients was evaluated by a questionnaire regarding peripatellar pain, including pain at the graft harvesting site, that affected activities of daily living. The scores for AKP were graded as "normal," "uncomfortable," "difficult," or "impossible" based on a previous study.[16] When the 2 lower scores (difficult and impossible) were observed at least once during the follow-up, the case was defined as AKP-positive. Additionally, the difference in incidence of AKP between both groups was defined as a primary endpoint of this study.

## Imaging Analysis

Anatomic rectangular tunnels for the femur and tibia were created based on the bony landmarks. For all patients, we

TABLE 1
Patient Characteristics[a]

| | BPTB (n = 70) | QTB (n = 64) | *P* |
|---|---|---|---|
| Age, y | 27.0 ± 12.9 | 25.5 ± 12.1 | .47 |
| Male/female | 28/42 | 22/42 | .50 |
| Right/left | 34/36 | 36/28 | .37 |
| Height, cm | 164.6 ± 7.4 | 163.7 ± 7.7 | .65 |
| Weight, kg | 60.1 ± 10.3 | 62.2 ± 10.7 | .32 |

[a]Data are presented as mean ± SD or n. BPTB, bone–patellar tendon–bone; QTB, quadriceps tendon–bone.

TABLE 2
Concomitant Procedures[a]

| | BPTB (n = 70) | QTB (n = 64) | *P* |
|---|---|---|---|
| Meniscal repair | 28.6 (20) | 37.5 (24) | .27 |
| Meniscectomy | 10.0 (7) | 14.1 (9) | .47 |
| Cartilage drilling | 0 (0) | 4.7 (3) | .07 |

[a]Data are presented as percentage (number of cases). BPTB, bone–patellar tendon–bone; QTB, quadriceps tendon–bone.

TABLE 3
Secondary ACL Injury[a]

| | BPTB (n = 70) | QTB (n = 64) | *P* |
|---|---|---|---|
| Ipsilateral knee | 10.0 (7) | 3.1 (2) | .11 |
| Contralateral knee | 2.9 (2) | 4.7 (3) | .58 |
| Total | 12.9 (9) | 7.8 (5) | .34 |

[a]Data are presented as percentage (number of cases). ACL, anterior cruciate ligament; BPTB, bone–patellar tendon–bone; QTB, quadriceps tendon–bone.

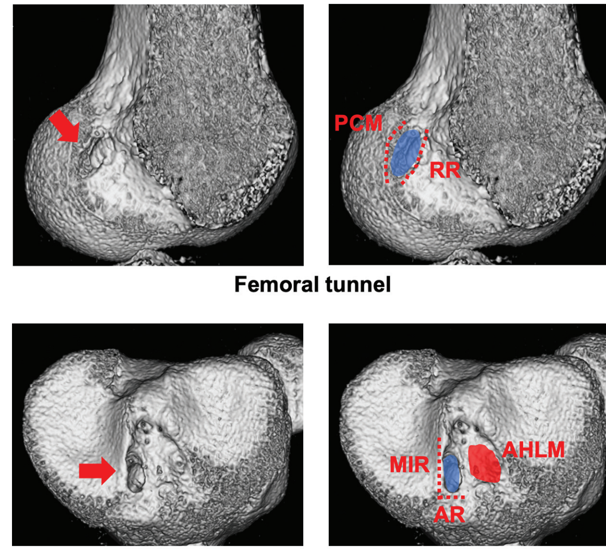


**Figure 2.** Tunnel apertures after anatomic rectangular tunnel anterior cruciate ligament reconstruction on 3-dimensional computed tomography. The femoral tunnel in the quadriceps tendon–bone group (left knee of a 21-year-old male patient) and the tibial tunnel in the bone–patellar tendon–bone group (left knee of an 18-year-old male patient). The femoral tunnel aperture is viewed from the medial side (medial half of the femur is removed), whereas the tibial tunnel aperture is viewed from above. Both tunnels were precisely created in the anatomical positions. The red arrows indicate tunnel apertures. The blue areas represent tunnel apertures. Red area represents anterior horn insertion of the lateral meniscus (AHLM). AR, anterior ridge; MIR, medial intercondylar ridge; PCM, posterior/proximal cartilage margin; RR, resident's ridge.

assessed whether both the femoral and the tibial tunnels were precisely created in anatomic positions using intraoperative arthroscopy and 3-dimensional computed tomography (3D CT) images, which were obtained ≤1 week postoperatively. According to the previous study for the assessment of the bone tunnel postoperatively by 3D CT,[36] the femoral tunnel aperture was viewed from the medial side (medial half of the femur was removed), whereas the tibial tunnel aperture was viewed from above.

## Statistical Analysis

An analysis of variance with repeated measures was performed to compare changes in clinical scores between the preoperative and 6-month, 1-year, and 2-year postoperative values, followed by a post hoc Wilcoxon signed-rank test (Figures 3 and 4). Two-group comparisons between the BPTB and QTB groups for patient demographic data (Table 1), CSA of grafts, clinical scores (Figures 3 and 4), and side-to-side differences in KT-1000 arthrometer were analyzed using the Wilcoxon rank-sum test, whereas those for the number of concomitant procedures (Table 2), rate of secondary ACL injury (Table 3), and incidence of AKP were assessed using Pearson chi-square test. In addition, the AKP-negative and AKP-positive groups were compared using the Wilcoxon rank-sum test (Table 4). A pilot study for 20 patients (10 BPTB versus 10 QTB) was performed prior to the current study. In this pilot study, the incidence of AKP in the BPTB group was 30% of cases (3 cases), whereas that of QTB was 0% of cases (0 cases). The sample size was calculated based on 80% power and a significance level of 5%. The power analysis showed that a sample of ≥37 patients (19 BPTB and 18 QTB) was necessary. Thus, the sample size of 134 patients in this study was acceptable for the power analysis. Data were analyzed using JMP 16 (SAS Institute), with significance set at $P < .05$.

# RESULTS

## Patient Demographics

Patient demographic data for each group are presented in Table 1. Table 2 shows the procedures performed

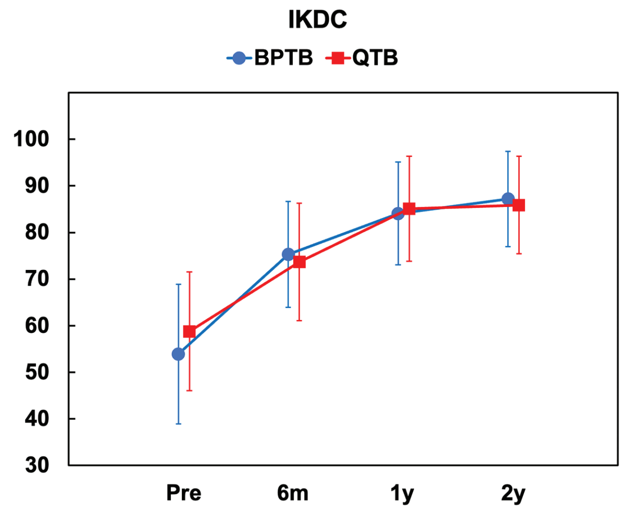


**Figure 3.** IKDC subjective scores in the BPTB and the QTB groups from preoperatively (Pre) throughout the 2-year follow-up. Clinical improvements from baseline to 1 year were maintained stably up to 2 years. IKDC, International Knee Documentation Committee; BPTB, bone–patellar tendon–bone; QTB, quadriceps tendon–bone.

concomitantly with ACLR, including meniscal repair, meniscectomy, and cartilage drilling, for each group. Regarding age, sex, height, weight, and concomitant procedures, there were no significant differences between the 2 groups.

## Assessment of Femoral and Tibial Tunnels

Anatomic rectangular tunnels for the femur and tibia were successfully created intraoperatively in all patients, as confirmed by arthroscopy. Similarly, the postoperative 3D CT images showed that both the femoral and the tibial tunnels were precisely created at the anatomic locations in all patients (Figure 2).

## Cross-Sectional Area of the Grafts

The mean CSA of the BPTB graft measured intraoperatively was 27.7 ± 4.9 $mm^2$, whereas that of the QTB graft was 42.0 ± 6.1 $mm^2$. The CSA of the QTB graft was significantly larger than that of the BPTB graft ($P < .001$).

## Clinical Outcomes

Regarding the clinical evaluation, there were no patients with loss of extension and flexion exceeding 5° at the final follow-up. No serious adverse events such as postoperative infections and deep vein thrombosis were observed as of the final follow-up at 2 years postoperatively. Superficial suture abscess was observed in 1 patient in the BPTB group at the early stage after surgery, but this was immediately improved by debridement.

TABLE 4
Influence of AKP on 2-Year Clinical Scores[a]

| | AKP − | AKP + | *P* |
|---|---|---|---|
| IKDC | 87.3 ± 10.3 | 81.0 ± 9.7 | .02 |
| KOOS Symptoms | 93.7 ± 7.2 | 89.3 ± 10.0 | .05 |
| KOOS Pain | 95.0 ± 6.7 | 92.4 ± 6.1 | .05 |
| KOOS ADL | 98.1 ± 4.5 | 96.6 ± 5.4 | .03 |
| KOOS Sport/Rec | 90.0 ± 10.3 | 82.3 ± 16.8 | .04 |
| KOOS QoL | 85.0 ± 13.8 | 75.4 ± 18.2 | .04 |

[a]Data are presented as mean ± SD. ADL, Activities of Daily Living; AKP, anterior knee pain; IKDC, International Knee Documentation Committee; KOOS, Knee injury and Osteoarthritis Outcome Score; QoL, Quality of Life; Sport/Rec, Sports and Recreation.

In the BPTB group, 9 subsequent procedures were performed as of the final follow-up: 7 revision ACLRs on the ipsilateral knee and 2 primary ACLRs on the contralateral knee. In the QTB group, 6 subsequent procedures were performed: 2 revision ACLRs on the ipsilateral knee, 3 primary ACLRs on the contralateral knee, and 1 medial meniscal repair on the ipsilateral knee.

IKDC subjective scores significantly improved from preoperatively (BPTB: 53.9 ± 15.0; QTB: 58.8 ± 12.7) to 6 months (BPTB: 75.3 ± 11.4; QTB: 73.7 ± 12.6), 1 year (BPTB: 84.1 ± 11.0; QTB: 85.1 ± 11.3) and 2 years (BPTB: 87.2 ± 10.2; QTB: 85.9 ± 10.5) postoperatively (Figure 3). No significant differences were observed between the BPTB and QTB groups at any time point. Similarly, all KOOS subscales, including Symptoms, Pain, Activities of Daily Living (ADL), Sport and Recreation (Sport/Rec), and Quality of Life (QoL), significantly improved from preoperative values at 6 months, and these scores remained high throughout the 2 year postoperative period (Figure 4, A-E). There were no significant differences between the BPTB and QTB groups at any postoperative time point regarding all subscales of the KOOS except for Sport/Rec. The Sport/Rec subscale scores in the QTB group were significantly higher than those in the BPTB group preoperatively (BPTB: 40.6 ± 27.4; QTB: 51.4 ± 23.1; $P = .048$) and at 1 year (BPTB: 82.3 ± 16.4; QTB: 87.9 ± 14.1; $P = .03$) and 2 years (BPTB: 87.7 ± 12.4; QTB: 92.7 ± 9.5; $P = .02$), whereas no significant difference was detected between both groups at 6 months postoperatively (BPTB: 72.6 ± 19.5; QTB: 76.8 ± 19.2; $P = .20$) (Figure 4D).

Regarding the KT-1000 arthrometer evaluation, the mean side-to-side difference in the BPTB group was 0.24 ± 0.92 mm, whereas that of the QTB group was 0.31 ± 1.24 mm. No significant difference was detected between the BPTB and QTB groups ($P = .63$). Additionally, 94.0% of patients in the BPTB group and 92.1% of patients in the QTB group were distributed between −1 and +2 mm (Figure 5).

## Secondary ACL Injury

The rates of secondary ACL injury were 10.0% on the ipsilateral side and 2.9% on the contralateral side in the BPTB

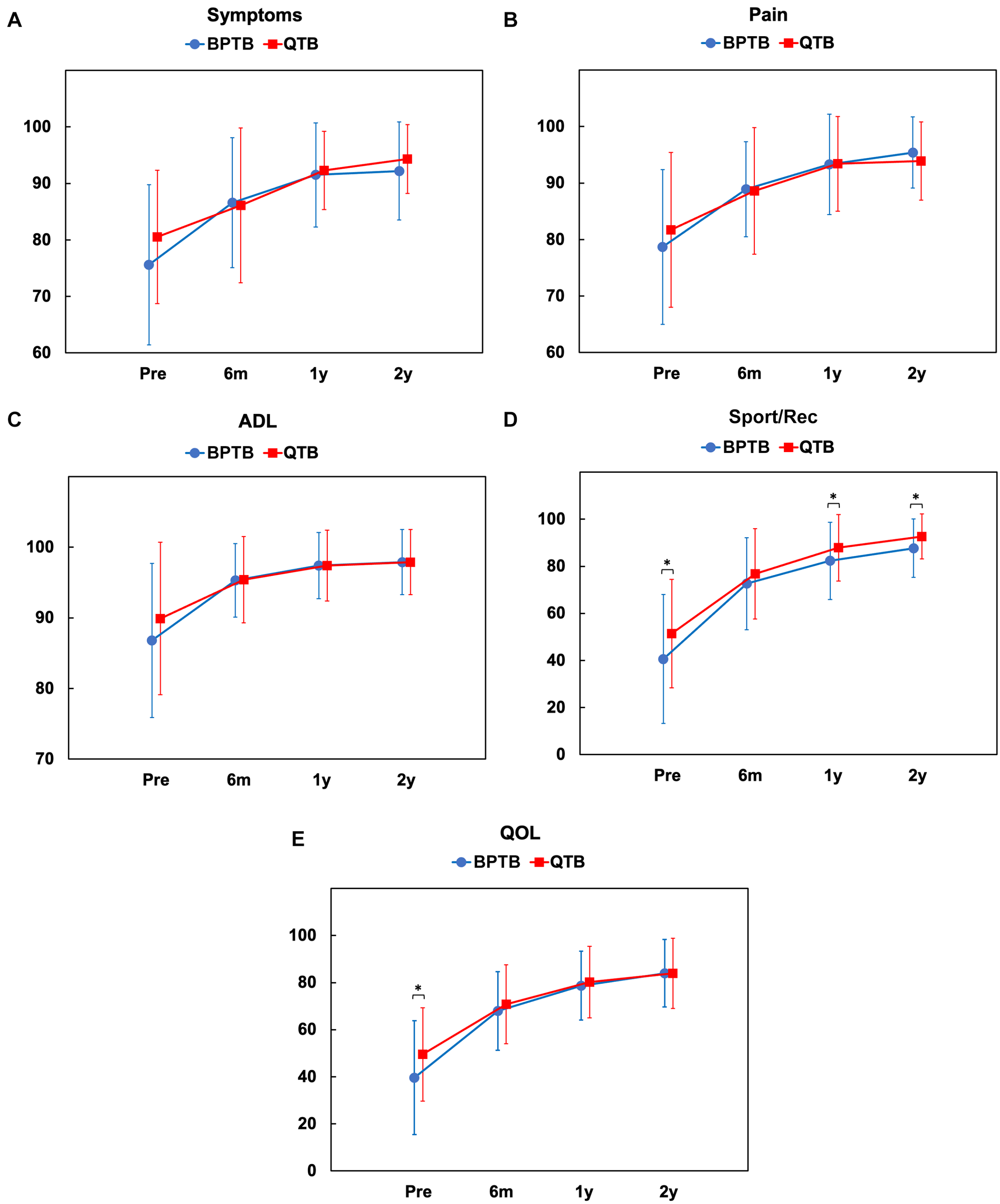


**Figure 4.** KOOS in the BPTB and the QTB groups from preoperatively (Pre) throughout the 2-year follow-up. Subscales of KOOS include (A) Symptoms, (B) Pain, (C) Activities of Daily Living (ADL), (D) Sport and Recreation (Sport/Rec), and (E) Quality of Life (QoL). Scores of each subscale significantly improved from baseline to 6 months and further increased up to 2 years in both groups. Statistically significant differences: *BPTB versus QTB ($P < .05$). KOOS, Knee injury and Osteoarthritis Outcome Score; BPTB, bone–patellar tendon–bone; QTB, quadriceps tendon–bone.

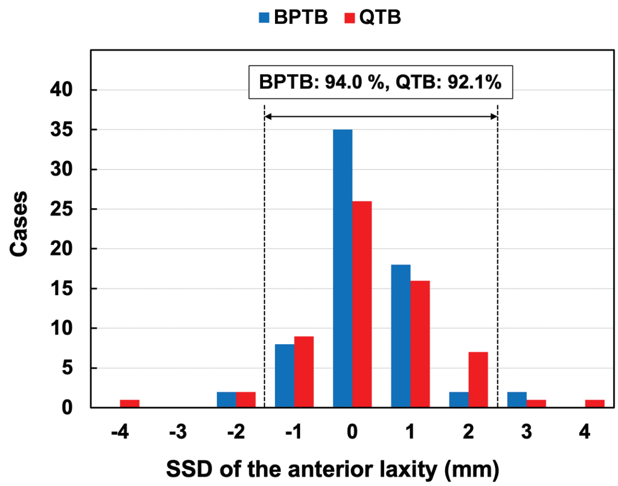


**Figure 5.** Side-to-side differences (SSDs) in anterior laxity with a KT-1000 arthrometer under the manual maximal anterior load after surgery. BPTB, bone–patellar tendon–bone; QTB, quadriceps tendon–bone.

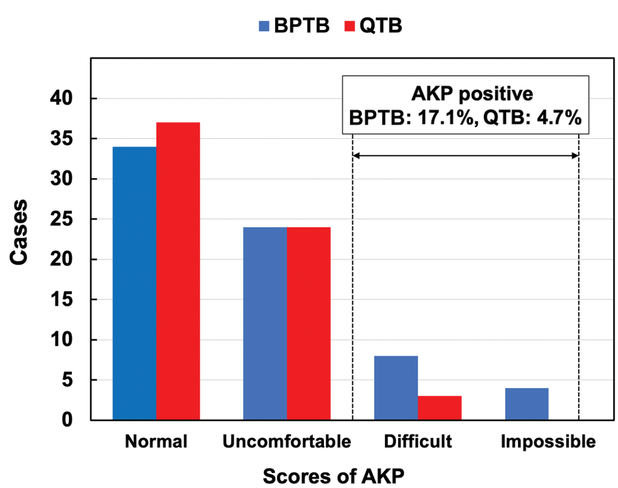


**Figure 6.** Scores of AKP. Two lower scores (difficult and impossible) were defined as AKP-positive. The incidence of AKP in the BPTB group was significantly higher than that of the QTB group. AKP, anterior knee pain; BPTB, bone–patellar tendon–bone; QTB, quadriceps tendon–bone.

group and 3.1% on the ipsilateral side and 4.7% on the contralateral side in the QTB group. No significant differences were detected between groups (Table 3).

## Anterior Knee Pain

The number of AKP-positive cases including the score "difficult" and "impossible" was 12 cases (17.1%) in the BPTB group and 3 cases (4.7 %) in the QTB group, which was significant ($P$ = .02) (Figure 6).

In the AKP-positive group (n = 15), the 2-year IKDC subjective scores and KOOS subscale scores, including ADL, Sport/Rec, and QoL, were significantly lower than in the AKP-negative group (n = 119) (Table 4).

## DISCUSSION

The present study directly compared the 2-year clinical outcomes of ART-ACLR between BPTB and QTB autografts performed under the same conditions regarding the surgical method, fixation devices, initial tension of each graft, and postoperative rehabilitation. The findings of the study demonstrate that clinical scores and postoperative anterior stability were equivalent between the BPTB and QTB groups. Contrary to our hypothesis, there were no significant differences in the rates of secondary ACL injury between the groups. However, the incidence of AKP was significantly lower in the QTB group, suggesting that QTB could be a favorable graft for ART-ACLR.

ART-ACLR is a novel surgical procedure involving the creation of rectangular tunnels inside the anatomical femoral and tibial attachment areas based on the bony landmark strategy.[12,17,21,29,30,37] This procedure mimics the natural fiber arrangement of the native ACL and minimizes tunnel size. A biomechanical study using cadaveric knees demonstrated that ART-ACLR more closely resembled the normal knee in terms of biomechanical behavior than conventional round tunnel ACLR.[35] Conversely, ACLR with a round tunnel could control the anterior translation with a larger initial tensioning of the graft; however, the normal positional relationship between the tibia and femur was impaired. Tachibana et al[36] reported that ART-ACLR using a BPTB graft could provide satisfactory outcomes both subjectively and objectively in >95% of patients with properly created tunnels inside the anatomical attachment areas. Notably, these authors addressed the entire femoral tunnel aperture, and ≥75% of the entire tibial tunnel aperture area was consistently located inside the anatomical attachment areas by identifying arthroscopic landmarks. The present study is the first to report the clinical outcomes of ART-ACLR using a QTB graft and to demonstrate equivalent clinical outcomes, including clinical scores, postoperative anterior knee stability, and the rate of secondary ACL injury, to those of a BPTB graft. In contrast, the incidence of donor-site morbidities, such as AKP, was significantly lower in the QTB group. Thus, one can conclude that a QTB graft is favorable for ACLR.

Several factors, such as surgical technique, graft choice, graft fixation, postoperative rehabilitation, and patient education, affect clinical outcomes after ACLR.[41] Unfortunately, secondary ACL injuries, such as graft failure and contralateral ACL rupture, can occur even after successful ACLR. A previous study reported that graft failure rates after ACLR ranged from 3% to 25%.[6] The causes of secondary ACL injury remain unclear, but researchers have suggested the involvement of genetic and environmental factors.[41] To reduce secondary ACL injuries, it is important to improve environmental factors such as surgical techniques, postoperative rehabilitation, and patient education. Additionally, graft choice may contribute to an improvement in the graft survival rate. In the previous studies, comparison with BPTB, the material property of QT was thicker (4.3 ± 0.8 vs 8.4 ± 1.5 mm), had a larger CSA (48.4 ± 8.1 vs 91.2 ± 10.9 $mm^2$), was stiffer (278.0 ± 75 vs 466.2 ± 133 N/mm), and had a larger ultimate load to failure ratio (1580.6 ± 479.4 vs 2185.9 ± 758.8 N), although the Young modulus of elasticity of QT was lower (337.8. ± 67.7 vs 255.3 ± 64.1 MPa).[19,27] Thus, a QT/QTB graft would be expected to reduce the rate of ACL reinjury, as the material properties of the QT are better than those of the BPTB. However, in this study, the rates of secondary ACL injury were equivalent between the BPTB and QTB groups. These results suggest that patient background (eg, psychological factors and innate bony shape) and/or restoration of knee function might have a greater influence on secondary ACL injuries than graft choice. Thus, further follow-up is required to draw definitive conclusions.

One of the complications after ACLR, especially when using a BPTB graft, is donor-site morbidity, such as AKP and kneeling pain.[3,32,42] Pretibial patellar tendon adhesion and/or a decrease in patellar mobility after the harvest of a BPTB graft could be the cause of AKP.[22,23] Similarly, this study showed that the incidence of AKP was significantly greater in the BPTB group than in the QTB group. Considering the differences in the incision site for graft harvesting between the BPTB and QTB grafts, incision of the patellar tendon and/or its surrounding tissues might be closely related to the occurrence of AKP. This indicates that the harvest of a BPTB graft would strongly affect donor-site morbidity compared with that of a QTB graft.

Moreover, AKP impaired postoperative daily and sporting activities (Table 4). The Sport/Rec subscale scores in the QTB group were significantly greater than those in the BPTB group at 1 and 2 years postoperatively (Figure 4D). Thus, it would be reasonable to choose a QTB graft for ART-ACLR, especially in athletes, as avoidable postoperative complications, such as donor-site morbidity, can be reduced. However, surgeons should independently assess AKP after ART-ACLR for accurate evaluation of postoperative pain, considering that commonly used clinical scores, such as KOOS Pain, might not detect differences (Table 4).

### Limitations

A potential limitation of this study is that it was not a randomized controlled study. Furthermore, muscle strength, especially in the extensors, and the rate of return to preinjury activity levels were not examined in this study. Since such evaluations are important for successful ACLR, further studies incorporating the above are needed. In some cases, a graft choice was performed based on the patient's and/or surgeon's decisions, which could be a potential limitation. However, the present study demonstrated the superiority of a QTB graft over a BPTB graft, providing important evidence to assist graft choice. Another limitation is CT-related radiation exposure for patients, although it was approved by our institutional review board. CT would be able to precisely assess the bone tunnel postoperatively[9,34,38,40]; however, their risk-benefit should always be considered to reduce the patient risks.

## CONCLUSION

In ART-ACLR, clinical scores, postoperative knee stability, and rates of secondary ACL injury were equivalent between the BPTB and QTB groups. However, the incidence of AKP was significantly lower in the QTB group, suggesting that QTB could be a favorable graft for ACLR.

## ACKNOWLEDGMENT

We would like to thank Editage (www.editage.jp) for English-language editing.

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