Original Article
Clinics in Orthopedic Surgery 2024;16:925-931 • https://doi.org/10.4055/cios24081

Oval Tunnel Shows Better Rotational Stability Than Round Tunnel in Anatomical Single-Bundle Anterior Cruciate Ligament Reconstruction: Biomechanical Study in a Porcine Model

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Background: To compare knee laxity between the conventional round tunnel and oval tunnel techniques in primary anterior cruciate ligament (ACL) reconstruction in a porcine knee model.

Methods: Twenty porcine knees were used for evaluating laxity in terms of anterior translation and anterolateral rotation. The study determined porcine knee kinematics on the Instron instruments under simulated Lachman (89 N anterior tibial load) at 15°, 30°, and 60° of flexion and a simulated pivot shift test (89 N anterior tibial load, 10 Nm valgus, and 4 Nm internal tibial torque) at 30° of flexion. Kinematics were recorded for intact (n = 10), ACL-deficient (n = 10), and conventional round (n = 10) or oval tunnel (n = 10) techniques. All measurements were repeated twice, and the average was used for comparison.

Results: Under the Lachman test, the conventional round tunnel and oval tunnel both showed significantly larger anterior tibial translation (ATT) at 30° and 60° compared to the intact knee ($p < 0.05$), but smaller ATT compared to the ACL-deficient knees ($p < 0.05$). However, there were no differences in ATT between the conventional round tunnel and oval tunnel techniques ($p > 0.05$). Under simulated pivot shift at 30° flexion, there was a significant difference between the conventional round tunnel and oval tunnel techniques (round vs. oval: 4.27 ± 0.87 mm vs. 3.52 ± 0.49 mm, $p = 0.028$).

Conclusions: Both conventional round tunnel and oval tunnel techniques reduced ATT compared to ACL-deficient knees but failed to restore normal knee stability. However, the oval tunnel technique showed better rotational stability at 30° than the round tunnel technique. These findings suggest that the oval tunnel technique would be a reasonable option in anatomical single-bundle ACL reconstruction.

Keywords: *Anterior cruciate ligament, Anterior cruciate ligament injuries, Anterior cruciate ligament reconstruction*

Received February 16, 2024; Revised August 26, 2024;
Accepted August 26, 2024
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Anterior cruciate ligament (ACL) rupture is a common sports injury treated with ACL reconstruction. However, 10%–20% of primary ACL reconstructions have poor long-term outcomes due to residual rotational instability.[1)] Previous biomechanical studies showed that conventional over-the-top single-bundle ACL reconstructions did not fully restore knee kinematics and rotatory stability.[2)] Thus, many surgical techniques, such as anatomical single-bundle reconstruction, double-bundle reconstruction, or rectangular tunnel single-bundle reconstruction, were introduced to improve postoperative stability and clinical outcomes.[3,4] In previous biomechanical studies, anatomical single-bundle ACL reconstruction or double-bundle ACL reconstruction showed better rotational stability than traditional single-bundle ACL reconstruction.[5-8] However, double-bundle ACL reconstructions also had many limitations, such as technical difficulties, graft impingement, fracture risk, and difficulties in revision.[9,10] Moreover, there were no differences in rotational control between single-bundle and double-bundle ACL reconstruction in gait analysis.[11,12]

Recently, native insertion and location of ACL have been emphasized in ACL reconstruction for restoring normal knee kinematics. According to a recent cadaveric study, the ACL femoral footprint was flat and ribbon-like, and the ACL tibial footprint was not round but oval or C-shaped.[13,14] Previous conventional ACL reconstructions using round tunnels had the disadvantage of rotational instability because the cross-sectional shape of the tunnel was circular, while the actual attachment of the ACL was oval. Surgical procedures using oval dilators can obtain an anatomical shape and larger area containing ACL footprints in the same cross-sectional area as the method using round tunnels.[15,16] Some studies suggest that ACL reconstructions using oval tunnels are superior to those using round tunnels for better knee function and stability.[12,17] However, biomechanical studies on ACL reconstructions using oval tunnels are lacking.

The purpose of this study was to compare knee laxity between the conventional round tunnel and oval tunnel techniques in primary ACL reconstruction in a porcine model. It was hypothesized that ACL reconstruction using oval tunnels would be superior to ACL reconstruction using round tunnels in restoring normal knee kinematics.

METHODS

Since this experiment used porcine carcasses, Institutional Review Board approval was not required.

Specimen Preparation

Twenty fresh frozen adult porcine knees were used. The femur and tibia were cut transversely 15 cm from the knee joint. The specimens were frozen at –20 °C and thawed at room temperature overnight before the experiment.[18] All surgeries were performed by a single orthopedic surgeon (YBP). A bovine tendon was used as a graft for ACL reconstruction. Open arthrotomy was used for resecting normal ACL in a porcine model. During the establishment of the oval femoral tunnel, a guide pin was placed at the center of the porcine ACL femoral footprint using the outside-in technique. A 6-mm reamer was used initially through the guide pin to avoid femoral condyle fracture. The long axis of an 8-mm oval dilator was aligned parallel to the ACL femoral footprint and was gently hammered. A tibial tunnel was positioned at the center of the porcine ACL tibial footprint with a 55° tibial guide angle. Similar

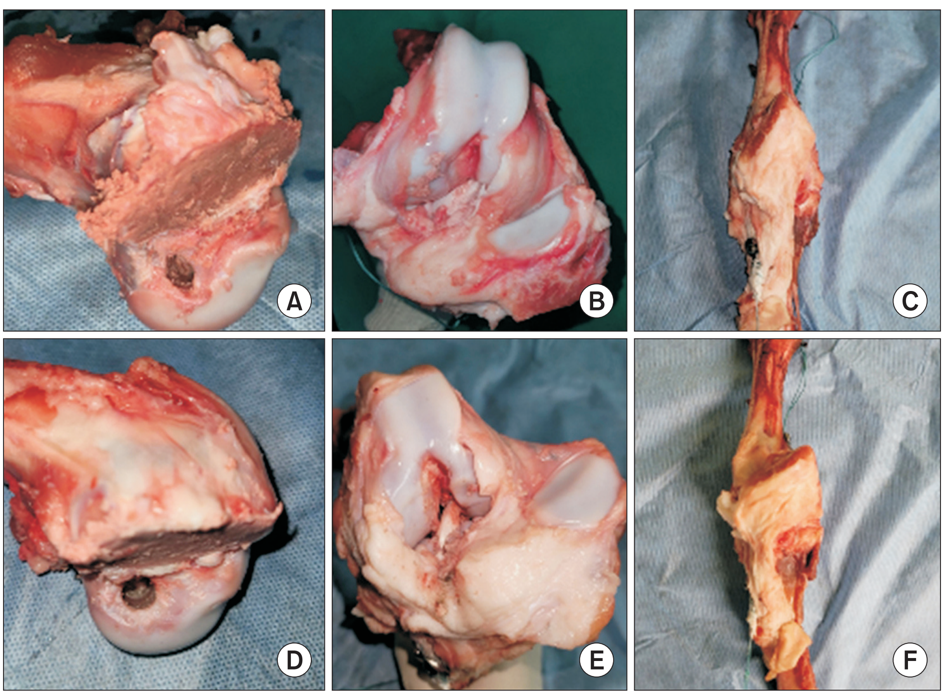

Fig. 1. (A) Femoral tunnel with an oval dilator. (B) Intra-articular graft for anterior cruciate ligament (ACL) reconstruction using an oval dilator. (C) Overall appearance of a porcine leg after ACL reconstruction with an oval dilator. (D) Femoral tunnel with a round dilator. (E) Intra-articular graft of ACL reconstruction using a round dilator. (F) Overall appearance of a porcine leg after ACL reconstruction with a round dilator.

to the femoral tunnel, a 6-mm reamer was used first; then, the long axis of an 8-mm oval dilator was aligned parallel to the ACL tibial footprint and was hammered from the anteromedial tibial cortex to the center of the ACL footprint. A bovine tendon was prepared at 8 mm thickness, and each tendon end was whipstitched using nonabsorbable sutures. The graft tendon passed through the tibial and femoral tunnels, fixed with a 6.5-mm cannulated screw and ligament washer at the femoral side first. The tibial side was fixed with the knee of 15° flexion under maximal pulling of the graft (Fig. 1A-C). The same process was carried out for ACL reconstruction with the round tunnel technique using an 8-mm round reamer instead of an oval dilator (Fig. 1D-F).[18,19]

Apparatus

A customized jig was designed in collaboration with the Department of Mechanical Engineering at Chung-Ang University to allow the tibia 5 degrees of freedom (anterior-posterior, medial-lateral, internal-external rotation, valgus-varus, and flexion-extension) (Fig. 2). The femur was fixed rigidly to the customized jig using 2 screws. A cable-pulley system was used to apply valgus and internal rotation by hanging weights. Valgus force was represented by weights connected to knee joints. Internal rotation was represented by weights connected to the distal tibia. Anterior tibial translation (ATT) of porcine knees was measured using a universal testing machine.[20]

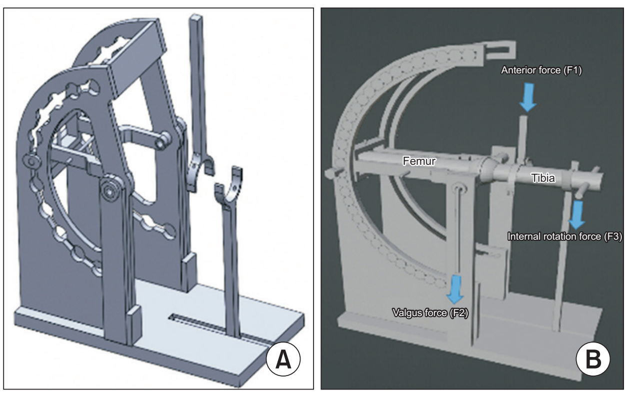

Fig. 2. (A) Schematic design of the customized jig. (B) Schematic setup of the position and force under Instron instrument.

Testing Protocol

The experiment was performed in 2 sequences. First, the ATT in porcine knees was measured at 15°, 30°, and 60° of flexion under 89 N anterior draw force to simulate the Lachman test. Anterior draw force was applied using the universal testing machine. Then ATT in porcine knees was measured at 30° of flexion under 89 N anterior draw force combined with 7 Nm valgus and 4 Nm internal tibial torque to simulate the pivot shift test. The distal tibia was fixed at a distance of 12 cm from the knee joint. Thus, 7 kg weight was used for valgus force through the pulley system, and 8 kg weight was hung at a distance of 5 cm from the distal tibia for internal tibial torque (Fig. 3).

Soft tissues outside the joint capsule were removed on either side of the femur and tibia before the application to the customized zig. Prepared specimens were secured in a customized jig. Porcine knees were connected to the Instron instrument (Universal Testing Machine, MET TECH) to apply anterior draw force. Intact porcine knees (n = 10) and ACL-deficient knees (n = 10) were tested. Then we reconstructed the ACL with a round tunnel (n = 10) and an oval tunnel (n = 10) using intact and ACL-deficient knees. The same experiments described above were performed equally.[18,19] All measurements were repeated twice, and the average was used for comparison.[19,20]

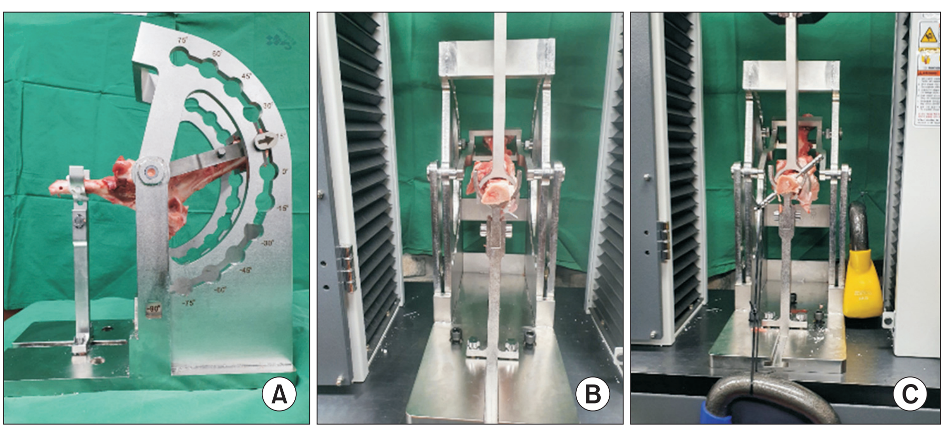

Fig. 3. (A) Setting a porcine knee in the customized zig. (B) Experimental setup under Instron instrument for the anterior draw test. (C) Experimental setup under Instron instrument for the pivot shift test.

Statistical Analysis

Shapiro-Wilk test was used to test normality. Independent *t*-tests and paired *t*-tests were used to compare differences in ATT in ACL intact, ACL reconstruction with round tunnels, and ACL reconstruction with oval tunnels. All statistical analyses were performed using SPSS version 28.0 (IBM Corp.). Statistical significance was set at $p < 0.05$.

RESULTS

ATT under Anterior Draw Force Protocol

Compared to ACL intact knees, ATT in ACL-deficient knees increased significantly in all experimental conditions under 89 N anterior draw force (intact vs. deficient: 15°, 3.27 ± 0.88 mm vs. 7.14 ± 3.13 mm; 30°, 2.75 ± 0.73 mm vs. 7.33 ± 2.60 mm; 60°, 2.47 ± 0.96 mm vs. 7.39 ± 3.53 mm; all $p < 0.001$). Conventional round and oval tunnels showed significantly larger ATT at 30° and 60° compared to the intact knee (round vs. intact: 30°, 4.17 ± 1.65 mm vs. 2.75 ± 0.73 mm, $p = 0.022$; 60°, 3.52 ± 1.05 mm vs. 2.47 ± 0.96 mm, $p = 0.033$; oval vs. intact: 30°, 4.27 ± 1.29 mm vs. 2.75 ± 0.73 mm, $p = 0.005$; 60°, 4.51 ± 1.59 mm vs. 2.47 ± 0.96 mm, $p = 0.003$), but the smaller ATT was found compared to ACL-deficient knees (Fig. 4). However, there were no differences in ATT between the conventional round tunnel and oval tunnel techniques (round vs. oval: 15°, 4.14 ± 1.29 mm vs. 3.91 ± 0.64 mm; 30°, 4.17 ±1.65 mm vs. 4.27 ± 1.29 mm; 60°, 3.52 ± 1.05 mm vs. 4.51 ± 1.59 mm; all $p > 0.05$) (Fig. 5).

ATT under the Pivot Shift Test Protocol

Under the simulated pivot shift test (89 N anterior draw force, 7 Nm valgus force, and 4 Nm internal rotation force) at 30° flexion, there was a significant difference in ATT between the conventional round tunnel and oval tunnel techniques (round vs. oval: 4.27 ± 0.87 mm vs. 3.52 ± 0.49 mm, $p = 0.028$) (Fig. 5).

DISCUSSION

The most important finding of this study is that ACL reconstruction with oval tunnels showed better knee rotational stability in the pivot shift test than ACL reconstruction with conventional round tunnels. The conventional round tunnel and the novel oval tunnel ACL reconstructions showed similar results in restoring anteroposterior stability regardless of knee flexion positions but still failed to restore normal anteroposterior stability.

As an aspect of the injury mechanism, most ACL ruptures occur due to non-contact indirect injury.[21] The main injury mechanism of ACL is pivot shift, which means valgus force combined with internal rotation of the tibia in knee flexion.[22] In this study, the stability of ACL reconstructions with oval dilators was significantly better than that with conventional round tunnels when

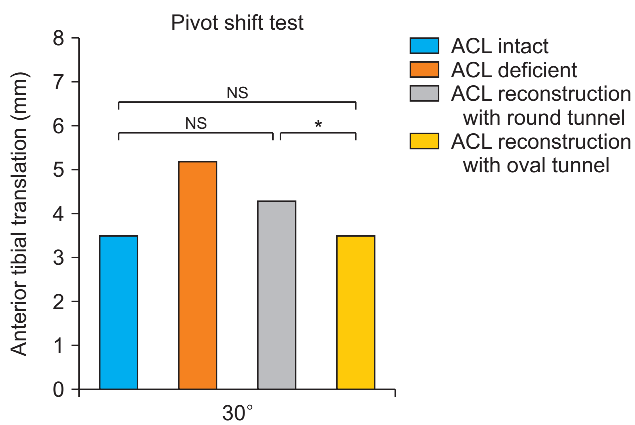

Fig. 5. Anterior tibial translation in the pivot shift test (89 N anterior draw force, 7 Nm valgus force, and 4 Nm internal rotation force) in different experimental conditions. Anterior tibial translation in anterior cruciate ligament (ACL) reconstruction with an oval tunnel decreased compared to that in ACL reconstruction with a round tunnel ($p = 0.028$). NS: nonsignificant.

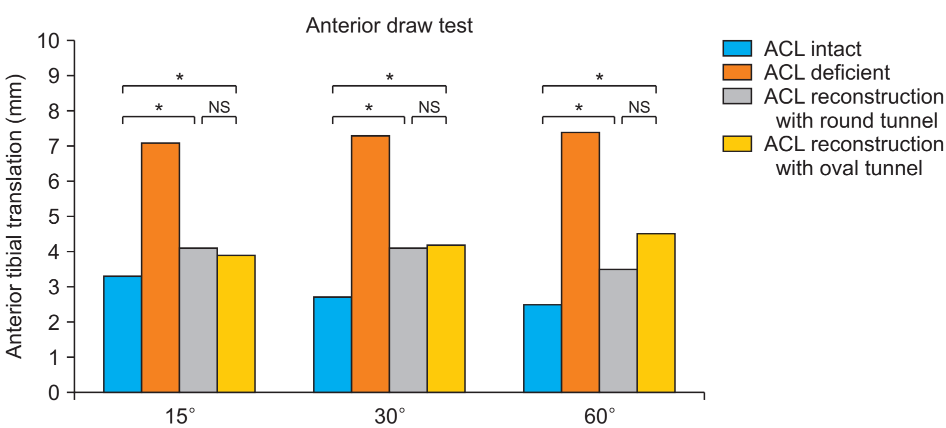

Fig. 4. Anterior tibial translation in the anterior draw test (89 N anterior draw force) in different experimental conditions. Anterior tibial translation of anterior cruciate ligament (ACL) reconstruction with the conventional round tunnel and the oval tunnel showed no significant difference at all flexion angles. NS: nonsignificant. $^{*}p < 0.05$.

combined with rotatory force. Due to the anatomical characteristics of oval tunnels designed to have the anatomical shape and larger cross-sectional areas than corresponding conventional round tunnels (Table 1), restoration of knee rotational stability would be sufficient by better coverage of ACL footprints, especially the posterolateral aspect of ACL substance (known to be associated with knee rotation). Consistent with our study results, Shao et al. reported better coverage of ACL tibial footprints using rectangular tunnels in a cadaveric study.[23] In addition, a previous clinical study about oval tunnel technique reported that patients who underwent ACL reconstruction with an oval tunnel showed better clinical outcomes (International Knee Documentation Committee and Lysholm scores) than those who had ACL reconstruction with a round tunnel.[12] In the study, the round tunnel group had significantly more patients with grade 1 in positive pivot shift test than the oval femoral group (10/65 vs. 1/37). This result is consistent with our study's result as the oval tunnel showed better rotational stability in the pivot shift test. Taken together, these results suggest that ACL reconstructions using oval tunnels could obtain better rotational stability than round tunnel ACL reconstructions and might have better survival.

According to many recent anatomical studies, the ACL footprint is not round but has a flat ribbon-like appearance in mid-substance fiber.[13,14,24] Thus, many attempts have been made to establish anatomical tunnels and cover the footprint as much as possible. Several studies on ACL reconstructions using rectangular dilators showed advantages in restoring knee stability, less eccentric tunnel enlargement, and larger cross-sectional area than ACL reconstructions with round tunnels.[6,25] Accordingly, clinical studies were conducted using rectangular ACL reconstructions, but the results showed discrepancies in clinical scores or stability.[26,27] Furthermore, difficulties in surgical techniques using rectangular dilators led to complications, such as fractures due to stress concentration at the edge of the rectangular and alignment mismatch between the long axis of the dilator and ACL footprints.[26] To overcome the disadvantages of the rectangular dilator, this study introduced new surgical instruments with oval dilators using the advantages of rectangular dilators. Moreover, a cadaver study reported that the cross-sectional shape of the 4-folded semi-tendinous tendon was oval, not round, implying that the fitting of the tendon in an oval-shaped tunnel might be better than in a round tunnel.[28] Thus, oval dilators are as effective as rectangular dilators in restoring knee stability and are safer than rectangular dilators. The rounded-rectangular tunnel in ACL reconstruction is recently introduced in anatomical single-bundle ACL reconstruction.[29] Although the shape of the rounded-rectangular tunnel is not exactly similar to that of the oval tunnel, it is also designed to cover a large area of the ACL footprint during anatomical single-bundle reconstruction. The efficacy of the rounded-rectangular tunnel in ACL reconstruction also warrants further research.

Table 1. The Cross-sectional Area of the Conventional Round Reamer and Oval Dilator

Diameter of conventional round reamer (mm)	Area (mm^2)	Diameter of oval dilator (major axis × minor axis, mm)	Area (mm^2)
8	50.24	11 × 6	51.81
9	63.59	12 × 7	65.94
10	78.50	13.5 × 7.5	79.50
11	94.86	14.5 × 8.5	96.75
12	113.04	15.5 × 9.5	115.59

The strength of this study is that, as far as we know, this is the first biomechanical study of ACL reconstruction using the oval tunnel technique. This biomechanical study has important meaning in that it proved ACL reconstruction with an oval tunnel has advantages in the pivot shift test, which had been reported in a previous clinical study.[12] This study has several limitations. First, there may be differences in biomechanical stability between porcine models and human cadavers. According to an animal study, after normalization to the tibial plateau width, the porcine ACL was longer than the human ACL. Also, the human notch was proportionally wider than the porcine notch.[30] However, due to anatomical similarities, many experimental studies use porcine knees.[18,31] Second, this study is an in vitro biomechanical study; therefore, other factors, such as muscle load, weight, limb alignment, graft healing, and preoperative grades of laxity, could affect the stability in vivo. Third, although the study used a sophisticated calculation to apply the stress force for the pivot shift test, other biomechanical instruments, such as robot-controlled machines, may produce different results in rotational stability.[18,19] Fourth, randomized controlled clinical studies are needed to prove the theoretical advantages. Previous researchers have shown superior results in biomechanical studies but not in in vivo clinical studies.[32]

Both conventional round tunnel and oval tunnel techniques reduced ATT compared to ACL-deficient knees, but failed to restore normal knee stability. However, the oval tunnel technique showed better rotational stability at 30° than the round tunnel technique. These findings suggest that the oval tunnel technique would be a reasonable option in anatomical single-bundle ACL reconstruction.

CONFLICT OF INTEREST

No potential conflict of interest relevant to this article was reported.

ACKNOWLEDGEMENTS

This study was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education (grant No. NRF-2022R1F1A1074940).

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