Biomechanical Comparisons of Knee Stability After Anterior Cruciate Ligament Reconstruction Between 2 Clinically Available Transtibial Procedures

Anatomic Double Bundle Versus Single Bundle

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Background: Several trials have compared the clinical results between anatomic double-bundle and single-bundle anterior cruciate ligament reconstruction procedures. However, it remains controversial whether the anatomic double-bundle procedure is superior to the single-bundle procedure.

Hypothesis: The anatomic double-bundle procedure will be better than the single-bundle procedure at resisting anterior laxity, internal rotation laxity, and pivot-shift instability.

Study Design: Controlled laboratory study.

Methods: Eight cadaveric knees were tested in a 6 degrees of freedom rig using the following loading conditions: 90-N anterior tibial force, 5-N/cm internal and external tibial torques, and a simulated pivot-shift test. Tibiofemoral kinematics during the flexion-extension cycle were recorded with an optical tracking system for (1) intact, (2) anterior cruciate ligament–deficient knee, (3) anatomic double-bundle reconstruction, and (4) single-bundle reconstruction placed at 11 o'clock in the intercondylar notch.

Results: There were significant reductions of anterior laxity of 3.5 mm at 20° of flexion, internal rotational laxity of 2.5° at 20° of flexion, and anterior translations (2 mm) and internal rotations (5°) in the simulated pivot-shift test in the double-bundle reconstruction compared with the single-bundle reconstruction. There were no significant differences between the 2 procedures for external rotation laxity.

Conclusion: The postoperative anterior translation and internal rotation stability after anatomic double-bundle anterior cruciate ligament reconstruction were significantly better than after single-bundle reconstruction, in both static tests and the pivot shift.

Clinical Relevance: Unlike previous laboratory studies, this work used clinical arthroscopic methods for anterior cruciate ligament reconstruction, and found that the anatomic reconstruction was superior to a single graft placed at 11 o'clock.

Keywords: anterior cruciate ligament; anatomic double-bundle reconstruction; biomechanics; hamstring tendon autograft; pivot-shift instability

To reconstruct the injured anterior cruciate ligament (ACL), the single-bundle procedure has been a standard surgical option. However, recent biomechanical studies have reported that single-bundle ACL reconstruction cannot restore normal anterior translation or rotatory laxity. Kinematic studies have shown that the single-bundle reconstruction cannot completely restore the patient’s rotatory stability during walking or more strenuous activities. To improve such biomechanical disadvantages, a clinical procedure to anatomically reconstruct both the antero-medial (AM) and posterolateral (PL) bundles was reported by Yasuda et al. Since then, many prospective studies...
have compared the clinical results between anatomic double-bundle and single-bundle procedures. Most reported that their anatomic double-bundle procedures gave significantly better postoperative stability, but others did not find significant differences. Thus, it remains controversial whether the anatomic double-bundle procedure is superior in knee stability to a single-bundle procedure. A possible cause of this controversy in the clinical field is considered to be that clinically performed procedures were variable, so that the tunnel positions were different among them and, consequently, the actually reconstructed graft functions were different.

Biomechanical studies with cadaveric knees have played an important role to compare surgical procedures. These have found significantly better knee stability after anatomic double-bundle reconstruction than after single-bundle and nonanatomic double-bundle reconstructions. However, these biomechanical studies did not simulate clinically available procedures for ACL reconstruction, because the knee joints were widely exposed to directly identify the anatomic attachments of the 2 bundles so that the tunnel locations could be idealized. In actual arthroscopic surgery for patients, however, there is a possibility that the tunnel locations have differed among the previously reported clinical procedures. To compare clinical procedures in a biomechanical study, surgery performed in cadaveric knees must simulate clinical procedures. Therefore, the data available from the previously reported biomechanical studies remain insufficient.

Thus, we have conducted a series of biomechanical studies to compare the clinical procedures in experimental conditions that simulated clinical surgery. In the present study, we have compared the first clinically available transtibial procedure to anatomically reconstruct both the AM and PL bundles, with the standard single-bundle reconstruction procedure. On the basis of previously reported clinical results, we hypothesized that an anatomic reconstruction of both the AM and PL bundles would be significantly better than the standard single-bundle reconstruction in restoring normal anterior and rotational laxity. The purpose of this study was to test this hypothesis.

MATERIALS AND METHODS

Specimen Preparation

Eight fresh-frozen cadaveric knees from consented donations (mean age, 62.1 years; range, 31-72 years) were obtained from the International Institute for the Advancement of Medicine (Jessup, Pennsylvania). Ethical permission was granted by the Riverside Research Ethics Committee. The knees were stored at -20°C, thawed a day before experimentation and then kept moist with water spray. The knee was prepared on one day, kept overnight in a refrigerator, and the experiment was completed the following day. The semitendinosus and gracilis tendons were harvested with a tendon stripper. The femur and tibia were cut approximately 20 cm from the joint line, and the surrounding skin and muscles that were more than 10 cm away from the joint line were removed to expose the bone. The iliotibial band was preserved. The fibular head was transfixed to the tibia by 2 cortical screws to maintain its anatomic position and then the distal part was excised. Aluminum intramedullary rods 400 mm long were cemented into the femur and tibia using polymethylmethacrylate; they were aligned accurately to the anatomic axes by use of an outrigger alignment rod. The femoral end was cemented in a steel sleeve aligned coaxial with the tibial intramedullary rod while the knee was held at 0° of extension with the tibial rod vertical. This minimized the varus-valgus moment during passive flexion-extension. The femoral steel sleeve was secured in a rig that allowed manual passive knee flexion-extension by moving the femur with the unconstrained tibia hanging vertically (Figure 1). A Steinmann pin was drilled medially across the proximal tibia and a semicircular hoop was mounted on this. This could be connected to weights via pulleys and strings, to impose an anterior drawer force without inhibiting natural coupled tibial rotation. A polyethylene disc (200 mm) was secured to the distal end of the tibial rod. Hanging weights connected via pulleys and strings to opposite poles of the disc produced an internal or external rotation torque. Similarly, another hanging weight was attached by a string taken over a pulley lateral to the distal end of the intramedullary rod to apply a valgus moment when needed.

Figure 1. Specimen position in the rig was adjusted to approximately match knee and rig flexion-extension axes. Manual passive flexion-extension movements were applied to the femur; the motion of the hanging tibia was otherwise unconstrained. The anterior or posterior force was applied with weights connected to the proximal tibia by cables passed over pulleys. Internal or external rotation torque was applied with weights connected to both sides of a polyethylene disc secured at the end of the tibial intramedullary rod.
Measurement System

The kinematics of the tibiofemoral joint was measured using a Polaris optical system (Northern Digital Incorporated, Waterlo, Ontario, Canada) with active trackers. One optical tracker was mounted securely on each of the tibia and femur. Landmarks were digitized using an optical stylus to construct the coordinate systems for the femur and tibia. The femoral coordinate system was centered on the anatomic axis and rotationally aligned with a transepicondylar axis. The epicondyles were exposed through 2 small incisions to minimize variability in identification of these points. The intramedullary rods had digitization points machined into them, to define the anatomic axes accurately. Similarly, the tibial coordinate system used the intramedullary axis and the most medial and lateral points of the tibial plateau; these defined a coronal reference plane. The kinematic data were processed with Visual3D (C-Motion Inc, Germantown, Maryland). Zero-degree knee extension was defined when the intramedullary rods were parallel in the sagittal plane. The anterior-posterior translation was defined from the perpendicular distance of the midpoint of the femoral epicondylar axis from the tibial coronal reference plane.

The 6 degrees of freedom data on the relative position of the tibia with respect to the femur were recorded with no external loads applied while the knee was intact; the only loading was the weight of the hanging tibia, plus the intramedullary rod and pulley. The femur was flexed/extended in the test rig above the hanging tibia, which was free to float in the other degrees of freedom and rotate. The intramedullary rods had digitization points machined into them, to define the anatomic axes accurately. Similarly, the tibial coordinate system used the intramedullary axis and the most medial and lateral points of the tibial plateau; these defined a coronal reference plane. The kinematic data were processed with Visual3D (C-Motion Inc, Germantown, Maryland). Zero-degree knee extension was defined when the intramedullary rods were parallel in the sagittal plane. The anterior-posterior translation was defined from the perpendicular distance of the midpoint of the femoral epicondylar axis from the tibial coronal reference plane.

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Testing Protocol

The intact knee was tested with the following loads applied: (1) 90-N tibial anterior drawer force, (2) 5-N m tibial internal rotation torque, (3) 5-N m tibial external rotation torque, and (4) a combined load to simulate the pivot-shift test——50-N iliobibial tract tension, 5-N m valgus moment, and 1-N m tibial internal rotation torque, according to our previous works.\(^6\)\(^{20}\) The iliobibial tract was loaded by linking it with a nylon cable to a pneumatic cylinder. In each loading condition, 3 cycles of knee flexion-extension between 0° and 110° were repeated manually.

This test regimen was repeated with the knee in 3 further states: (1) after arthroscopic transection of the ACL, (2) after arthroscopically assisted anatomic double-bundle ACL reconstruction, and (3) after arthroscopically assisted single-bundle ACL reconstruction. The bone tunnels were filled with polyester resin paste (Stevens Automotive Body Fillers Ltd, Cheshire, United Kingdom). The resin paste was injected from outside in until visible at the joint surface. When set, this filler avoided any collapse of the otherwise empty bone tunnels when the single-bundle graft tunnels were drilled and when the graft was tested.

After surgery, the distal femur was cut in the mid-sagittal plane to examine the tunnel outlet positions.

Photographs of the lateral femoral condyle were taken in a true lateral direction using a single-lens reflex digital camera (D40X, Nikon, Tokyo, Japan) and the alignment method of Zavras and Amis.\(^3\)\(^9\) A measurement grid was superimposed onto the lateral view pictures with the notch roof as its superior limit, with its shallow, deep, and lower edges matching the edges of the articular cartilage and divided into 16 equal zones.\(^11\)

Surgical Procedures

**Graft Preparation.** Anterior cruciate ligament reconstructions used the semitendinosus and gracilis tendons. Each reconstruction used the same fixation methods. For anatomic double-bundle reconstruction, the gracilis graft was passed through a 20-mm continuous-loop EndoButton CL (Smith & Nephew Endoscopy, Mansfield, Massachusetts). A 20- to 30-mm EndoButton CL was used for the semitendinosus tendon graft. Each graft was then placed on a tensioning board and the ends of the tendons were whipstitched with a No.5 TiCron suture (Davis & Geck, Danbury, Connecticut) for 40 mm. The 2 grafts were measured and the matching tunnel diameters were drilled, within ±0.5 mm. The 2-stranded grafts were on average 7 mm in diameter and 100 mm long for the AM bundle and 6 mm and 90 mm for the PL bundle. For single-bundle reconstruction, the undamaged semitendinosus and gracilis tendons were reused; they were both passed through a 20- to 30-mm continuous-loop EndoButton CL and their distal ends whip-stitched. The 4-stranded grafts were on average 8 mm in diameter and 90 mm long. The distal sutures were left long, for later attachment to the tibial fixation, for all grafts.

**The Anatomic Double-Bundle Procedure.** The anatomic procedure has been described previously.\(^3\)\(^6\)\(^7\) The ACL remnant was resected, leaving 1-mm-long stumps at the attachments to obtain landmarks for inserting guidewires. First, the tibial tunnel for the PL bundle was created. A Wire-navigator (Smith & Nephew Endoscopy) was used to insert a guidewire (Figure 2). The tibia was held at 90° of knee flexion, keeping the femur horizontal. The tibial indicator of the Navi-tip (Smith & Nephew Endoscopy) was placed at the center of the PL bundle attachment on the tibia, between the tibial eminences and approximately 6 mm anterior to the posterior cruciate ligament. Then, keeping the tibial indicator at this point, we aimed the femoral indicator at the center of the PL bundle attachment on the femur. A Kirschner wire (K-wire) was drilled through the sleeve in the tibia. The tibial indicator of the Navi-tip was then placed at the center of the tibial attachment of the AM bundle, approximately 8 mm anterior to the K-wire for the PL bundle. Keeping the tibial indicator at this point, the femoral indicator was aimed at the center of the femoral attachment of the AM bundle, 5 mm anterior to the most posterior aspect of the notch at the junction of the roof and the lateral wall of the intercondylar notch, at the 1-o’clock (or 11-o’clock) position. The knee was extended to ensure the tip of the AM bundle wire would be 5 mm posterior to the anterior edge of the roof in the
intercondylar notch. A K-wire was drilled through the sleeve in the tibia. The tibial tunnels were drilled to match the diameters of the grafts. To create the femoral tunnels, first a K-wire was drilled at the center of the femoral attachment of the AM bundle through the AM tibial tunnel, using a 5-mm or 6-mm offset guide (Arthrex, Naples, Florida). This wire was overdrilled to 4.5 mm, through the condyle. The length of the tunnel was measured with a scaled probe. The arthroscope was then moved to the medial infrapatellar portal. The surgeon again held the tibia at 90° of knee flexion, keeping the femur horizontal. The surgeon manually held the K-wire and aimed it at the center of the PL bundle attachment on the femur through the tibial tunnel. The surgeon first hammered the wire into the femur and then drilled it. A 4.5-mm-diameter tunnel was drilled, and its length was measured in the same manner. Finally, 2 sockets were drilled to match the AM and PL grafts (Figure 3).

The grafts were introduced from distal to proximal, and secured at the lateral femoral cortex with the EndoButtons. The distal sutures on each of the grafts were tensioned manually and tied to a double-spike plate (Smith & Nephew Endoscopy). A further tensioning suture was attached distally from each of the 2 double-spike plates to 30-N weights hanging via pulleys. The knee was cycled from 120° to full extension 10 times. The graft was fixed proximally with an EndoButton and the tibial side with a double-spiked plate and cancellous screw, as before. Before the fixation, the graft was tensed to 60 N using a hanging weight while a 40-N posterior tibial load was applied. The knee was cycled from 120° to full extension, 10 times, then the graft was fixed at 20° of knee flexion (Figure 4).

The Single-Bundle Procedure. The single-bundle reconstruction procedure was performed using techniques described previously.16,35,36 Finally, each double-spiked plate was fixed to the surface of the tibia with a cancellous bone screw.

The pointer of the guide was placed at the center of the posterior aspect of the normal ACL attachment between the medial and lateral tibial eminences and a 2.4-mm guidewire was inserted into the tibia. A cannulated drill created the tibial tunnel with a diameter matching the graft (Figure 4). Because the single-bundle graft had a larger diameter than the double-bundle graft, the resin-filled tunnel was drilled out and the new graft was surrounded by bone where it entered the joint. A 2.4-mm guidewire was drilled into the lateral femoral condyle at the 1-o’clock (or 11-o’clock) orientation, using a 6-mm offset guide system (Transstibial Femoral ACL Drill Guide, Arthrex) placed transtibially. This was at the center of the femoral AM bundle attachment. The femur was prepared for Endo-Button graft fixation: the guidewire was overdrilled to 4.5 mm through the condyle and the tunnel was opened out to form a socket to match the graft diameter as described for the anatomic procedure (Figure 4). The graft was fixed proximally with an EndoButton and the tibial side with a double-spiked plate and cancellous screw, as before. Before the fixation, the graft was tensed to 60 N using a hanging weight while a 40-N posterior tibial load was applied. The knee was cycled from 120° to full extension, 10 times, then the graft was fixed at 20° of knee flexion (Figure 4).

Statistical Analysis

The kinematic data for the intact, ACL-deficient, and ACL-reconstructed knees were analyzed using a 2-factor repeated-measures analysis of variance and paired Student t test (StatView, SAS Institute, Cary, North Carolina). Because all tests were performed on the same
specimen, multiple contrasts were performed. The 2 factors evaluated were the condition of the knee and the knee flexion angle. The dependent variables evaluated were knee kinematics with the differing ACL conditions. The significance level was set at $P = 0.05$.

RESULTS

Tibial anterior translation in response to a 90-N anterior force increased significantly at all flexion angles after the ACL was sectioned, by a mean of 12.9 mm at 30° of knee flexion, for example (Figure 5). The anterior translation versus flexion curves for single- and double-bundle reconstruction were significantly less than in the ACL-deficient knee ($P = 0.0001$ and $P = 0.0235$ by analysis of variance, respectively). Overall, a significant difference was not found between the double- and single-bundle reconstructions. However, tibial anterior translation with the double-bundle reconstruction was a mean of 3.5 mm less than with the single-bundle reconstruction at 20° of knee flexion, and post hoc testing found that this difference was significant at all flexion angles from 0° to 75° ($P < 0.0119$).

Tibial internal rotation with 5-N·m torque increased by a mean of 5° after the ACL was cut when the knee was near the extended posture (Figure 6). The internal rotation versus flexion curves were significantly different among the ACL-deficient knee and the double- and single-bundle reconstructions ($P < 0.0001$ by analysis of variance). The internal rotation versus flexion curve for the double-bundle reconstruction was significantly less than that for the single-bundle reconstruction ($P < 0.0001$). Tibial internal rotation with the double-bundle reconstruction was a mean of 2.5° less than that with the single-bundle reconstruction near knee extension. Post hoc testing showed that this was significantly less from 0° to 45° of knee flexion ($P < 0.0347$). Significant differences were not found between the ACL-deficient knee and the single-bundle reconstruction.

Under the simulated pivot-shift test, tibial anterior translation of the ACL-deficient knee increased significantly, by a mean of 3 mm compared with the intact knee, when the knee was near extension (Figure 7). The anterior translation versus flexion curves were significantly different among the ACL-deficient knee and the double- and single-bundle reconstructions ($P < 0.0001$) (Figure 7). The anterior translation versus flexion curves were significantly less for the double-bundle and the single-bundle reconstructions than for the ACL-deficient knee ($P < 0.0001$ and $P = 0.003$, respectively). During the pivot shift, the anterior translation with the double-bundle reconstruction was significantly less than with the single-bundle reconstruction ($P = 0.006$); the post hoc tests found significant differences ($P < 0.0387$) at 20° and 25° of knee flexion, where the mean difference in the anterior shift.
was 2 mm. Under the simulated pivot-shift test, the internal rotation versus flexion curves were significantly different among the ACL-deficient knee and the double- and single-bundle reconstructions ($P = .0037$) (Figure 8). The internal rotation curve pattern was significantly different in the double-bundle reconstruction than in the single-bundle reconstruction ($P = .0002$). The mean increase in the internal rotation component of the shift was $5.5^\circ$ when the ACL was cut; this decreased by a mean of $2^\circ$ with the single-bundle reconstruction and $7^\circ$ with the double-bundle reconstruction. Thus, the double-bundle reconstructions tended to overconstrain tibial internal rotation, compared with the normal knee, by a mean of $1.5^\circ$.

For tibial external rotation torque, no significant differences were found between the ACL-deficient knee and the double- and single-bundle reconstructions.

On the femur, the center of the AM tunnel entrance was located primarily in zone 1, with 5 in zone 1, 1 in zone 2, and 2 in zone 5 (Figure 9). The center of the PL tunnel entrance was found primarily in zone 7, with 6 in zone 7, 1 in zone 3 and 1 in zone 8. With the measurement grid defined as starting at 0% at the proximal, anterior (ie, deep, high, in arthroscopic terms) corner, and ending at 100% at the distal, posterior (shallow, low) corner, then the AM tunnel was at a mean of 22% shallow and 70% down from the notch roof, and the PL tunnel at 31% shallow and 70% down from the roof.

**DISCUSSION**

In this study, the biomechanics of the knee after the anatomic double-bundle reconstruction were compared with those of the single-bundle reconstruction. Specifically, the knee kinematics of the intact and the ACL-reconstructed conditions for 8 human cadaveric knees were quantitatively evaluated using an optical tracking system in a 6 degrees of freedom test rig. This methodology has the benefit of collecting experimental data from the same cadaveric knee specimen under different experimental conditions (eg, intact, ACL deficient, and ACL reconstructed),
thus eliminating interspecimen variation by repeated-measures statistical analyses. The kinematics of the intact knee in this study were consistent with previous work.9 This study showed that anterior laxity under anterior tibial load, rotational laxity under internal tibial torque, and anterior laxity under pivot-shift loading were significantly less after the anatomic double-bundle reconstruction than after the single-bundle reconstruction. There were no significant changes at any stage with external tibial torque. In addition, the femoral tunnel positions in the double-bundle reconstruction were similar to the reported anatomic attachments of the AM and PL bundles.11

The anterior translation laxity in response to a 90-N anterior drawer force was significantly less after the anatomic double-bundle reconstruction than after the single-bundle reconstruction from 0° to 75° of knee flexion, although this difference in anterior laxity was small, typically 3.5 mm. The normal ACL consists of the AM and PL bundles, which have different functions.4,17,38 When the knee is subjected to an anterior tibial load, the PL bundle of the intact ACL carries one-half to two-thirds of the total force in the ACL near full extension of the knee. As the conventional single-bundle reconstruction reproduces the AM bundle, these reconstructions can help to stabilize the knee near flexion position in response to anterior tibial load but are not configured to reproduce the function of the natural PL bundle. Yamamoto et al34 reported that the PL bundle reconstruction cannot restrain anterior tibial translation at high flexion angles of the knee; the in situ force in the PL graft in the anatomic double-bundle reconstruction decreases with increasing flexion angle. In the anatomic double-bundle reconstruction, anterior tibial translations were slightly overconstrained immediately after surgery. However, after ACL reconstruction, stress-relaxation occurs immediately after surgery even after rigorous preconditioning.5 This should be taken into account, independent of the type of fixation device.25

For tibial internal rotation torque, the anatomic double-bundle reconstruction restored the tibial rotation of the ACL to the level of the intact knee, whereas the single-bundle reconstruction did not: cutting the ACL increased the laxity by a mean of 4° at 20° of knee flexion, the single-bundle reconstruction only reduced this by a mean of 1° while the double-bundle reconstruction reduced it by a mean of 3.5°. Because the single-bundle reconstruction approximated the AM bundle, the graft was more vertical than the PL bundle of the ACL so it could not effectively stabilize knee rotation near the full extension position. Yasuda et al35 measured the AM and PL graft tensions intraoperatively and found that tension of the PL graft was increased significantly by internal rotation at 15° and 30° of knee flexion. As the single-bundle reconstruction reproduced the AM bundle, these reconstructions did not stabilize the knee near extension in response to 5-Nm internal rotation torque. In the anatomic double-bundle reconstruction, the degree of improvement in the rotational stability was only a few degrees immediately
after surgery, but this improvement may have a beneficial effect on postoperative internal rotation laxity.

In the pivot-shift loading, we applied 50-N iliotibial tract loading, 5-N-m valgus moment, and 1-N-m internal tibial torque. The conventional single-bundle reconstruction allowed a “mini-pivot” to persist. In previous biomechanical and clinical studies, it was reported that single-bundle ACL reconstruction frequently leaves a residual mini-pivot. Amis et al reported that 6 of 9 knees showed evidence of persistent residual laxity, giving rise to the phrase mini-pivot, with objective measurements of transient subluxations during pivot-shift testing at the end of ACL surgery. In previous clinical studies to evaluate single-bundle reconstruction, however, sufficient attention was not paid to the residual mini-pivot; the focus was on anterior laxity. Recent clinical studies have reported that 32% to 49% of the patients had a positive pivot shift, grade 1 or 2, at a few years after single-bundle ACL reconstruction using a hamstring graft fixed with various devices including staples, Endo-Buttons, screws, and WasherLocs (Biomet, Warsaw, Indiana). These studies implied that clinical results for the pivot-shift test after common single-bundle reconstruction procedures may be worse than the previously expected result. Woo et al reported that the single-bundle reconstruction using the hamstring tendon graft or the bone–patellar tendon–bone graft cannot completely restore the normal anterior laxity, and that it is not effective for rotatory instability. In addition, kinematic studies demonstrated that single-bundle reconstruction with the bone–patellar tendon–bone or hamstring tendon graft did not have a significant effect on the rotatory instability during walking or more active activities. This study supported the evidence that the rotatory instability may persist after conventional single-bundle reconstruction.

This experiment inevitably suffered the drawbacks associated with work on elderly specimens in vitro. Furthermore, the conclusions reached refer to time-zero conditions and may be influenced subsequently by the effects of chronic graft relaxation and graft remodeling, which have been demonstrated to affect the fate of ACL reconstruction. These limitations have been offset by the ability to make a series of comparative intraspecimen tests on a range of ACL reconstruction protocols. Further, the test setup allowed carefully controlled loads to be applied and full 6 degrees of freedom kinematic data to be collected by motion sensors attached directly to the bones. It has been shown that anteroposterior laxity measurements in vitro duplicate clinical laxity tests of the passive ligament restraints, but there is a lack of knowledge about clinical rotational laxity. The other limitation is that because we only evaluated ACL reconstructions with hamstring tendon grafts, we cannot refer to ACL reconstruction with the bone–patellar tendon–bone graft. The relatively simple external loading conditions used in this study could only simulate those used in clinical examinations. To more accurately mimic in vivo loading conditions, larger forces such as those from the quadriceps and hamstring muscles will be needed. The objective of this study was to compare a commonly used single-bundle reconstruction (placed from the femoral AM bundle attachment to the tibial PL bundle attachment) and anatomic double-bundle ACL reconstruction (reproducing the AM and PL bundles) for restoring knee kinematic parameters to those of the intact knee. This study found that the anatomic double-bundle ACL reconstructions provided significantly better control of anterior translation, internal rotation, and pivot-shift laxity than the single-bundle reconstructions when the knee was near extension. These differences were not found when the knee was at high flexion angles. Thus, to reproduce the functional complexity of the ACL, both the AM and PL bundles may need to be replicated during ACL reconstructions.

Recently, prospective clinical trials with level 2 evidence have become available for comparison with the present study. Yasuda et al reported that their anatomic double-bundle reconstructions were better in both the pivot-shift test and the quantified anterior laxity than their single-bundle reconstructions. Yagi et al reported that their anatomic double-bundle reconstructions were better in the pivot-shift test measured with magnetic sensors than their single-bundle reconstructions, and Jarvela showed similar results with the conventional pivot-shift test. The present study has supported the results of Yasuda et al and Aglietti et al. We believe that the anatomic double-bundle reconstruction procedure can more frequently obtain better anterior and rotatory stability of the knee than single-bundle reconstruction procedures. However, it should be remembered that some studies did not find significant advantages for the anatomic reconstructions, as reviewed in the meta-analysis by Meredith et al. It is an essential goal of ACL reconstruction to obtain a stable knee with characteristics close to the normal knee. However, because the present study evaluated knees immediately after surgery, we cannot estimate the clinical benefits for each patient in long-term follow-up evaluations, which may result from such short-term improvement in stability. Therefore, relatively long-term studies, such as cyclic loading or displacement tests, are also needed.

Other experimental studies, in vitro and in vivo, have found that knee stability was superior in the anatomic double-bundle reconstructions compared with single-bundle reconstructions. Studies using a robotic manipulator found that the anatomic double-bundle reconstruction gave less anterior and rotatory laxity of the knee, specifically in the extension positions of less than 30°, compared with the single-bundle reconstruction. In vivo studies using position or force sensors have found that knee kinematics and graft functions similar to those obtained in the above-described cadaveric studies could be obtained in clinical arthroscopic procedures. An arthroscopic second-look study found that both the AM and PL bundles were reconstructed in 96% of 132 patients with the anatomic double-bundle ACL reconstruction. These in vitro and in vivo studies support the present results with superior knee stability after the anatomic double-bundle ACL reconstruction in comparison with the conventional single-bundle reconstruction. Although some of the laxity and pivot-shift measurements had small magnitudes of difference between the single- and double-bundle reconstructions, the corrections obtained by the double bundles were enough to return all measures so that they did not then differ significantly from the intact knee, whereas the
single-bundle reconstructions allowed most of the internal rotational abnormalities to persist. These differences are likely to be clinically relevant.

The recent studies on anatomic double-bundle ACL reconstruction have led surgeons to think again about the positions used for single-bundle grafts. It has been shown in a clinical study\textsuperscript{18} that there was less rotatory instability if the femoral graft tunnel was moved laterally, away from the roof of the intercondylar notch. The results of the present study demonstrate the related inability of the graft placed in the AM bundle attachment to fully control rotational laxity and pivot-shift kinematics of the knee. Loh et al\textsuperscript{21} suggested that moving the femoral tunnel from 11 o’clock to 10 o’clock improved knee stability. This evidence supports the need to search for more optimal reconstruction methods than the single-bundle graft position used in this study.

This study has used the measurement grid method\textsuperscript{11} to define the centers of the femoral tunnel entrances. Edwards et al\textsuperscript{11} reported that the AM bundle was at a mean of 21% shallow and 24% down from the notch roof, and the PL bundle at 27% shallow and 57% down from the roof. Our tunnel positions were similar to these “normal” attachments of the AM and PL bundles.

Finally, although the present study showed promising results for the anatomic double-bundle ACL reconstruction procedure, further clinical studies, including quantitative evaluation of the effects on rotatory stability, long-term survival of the graft functions, comparisons with other procedures involving the reconstruction with a single graft with a more laterally placed femoral tunnel, the bone–patellar tendon–bone graft, and so forth, are needed to establish the clinical utility of the anatomic double-bundle ACL reconstruction for the ACL-deficient knee.

CONCLUSION

The postoperative anterior and rotational laxity and pivot-shift stability after the anatomic double-bundle ACL reconstruction were significantly better than after the single-bundle reconstruction using a hamstring tendon graft placed between the femoral AM bundle attachment and the tibial PL bundle attachment.

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REFERENCES


