

Anatomical versus Non-Anatomical Single Bundle Anterior Cruciate Ligament Reconstruction: A Cadaveric Study of Comparison of Knee Stability

Hong-Chul Lim, MD, Yong-Cheol Yoon, MD, Joon-Ho Wang, MD*, Ji-Hoon Bae, MD[†]

Department of Orthopaedic Surgery, Korea University Guro Hospital, Korea University College of Medicine, Seoul,

**Department of Orthopaedic Surgery, Samsung Medical Center, Sungkyunkwan University School of Medicine, Seoul,*

†Department of Orthopaedic Surgery, Korea University Ansan Hospital, Korea University College of Medicine, Ansan, Korea

Background: The purpose of this study was to compare the initial stability of anatomical and non-anatomical single bundle anterior cruciate ligament (ACL) reconstruction and to determine which would better restore intact knee kinematics. Our hypothesis was that the initial stability of anatomical single bundle ACL reconstruction would be superior to that of non-anatomical single bundle ACL reconstruction.

Methods: Anterior tibial translation (ATT) and internal rotation of the tibia were measured with a computer navigation system in seven pairs of fresh-frozen cadaveric knees under two testing conditions (manual maximum anterior force, and a manual maximum anterior force combined with an internal rotational force). Tests were performed at 0, 30, 60, and 90 degrees of flexion with the ACL intact, the ACL transected, and after reconstruction of one side of a pair with either anatomical or non-anatomical single bundle ACL reconstruction.

Results: Under manual maximal anterior force, both reconstruction techniques showed no significant difference of ATT when compared to ACL intact knee state at 30° of knee flexion ($p > 0.05$). Under the combined anterior and internal rotatory force, non-anatomical single-bundle ACL reconstruction showed significant difference of ATT compared to those in ACL intact group ($p < 0.05$). In contrast, central anatomical single bundle ACL reconstruction showed no significant difference of ATT compared to those in ACL intact group ($p > 0.05$). Internal rotation of the tibia showed no significant difference in the ACL intact, the ACL transected, non-anatomical reconstructed and anatomical reconstructed knees.

Conclusions: Anatomical single bundle ACL reconstruction restored the initial stability closer to the native ACL under combined anterior and internal rotational forces when compared to non-anatomical ACL single bundle reconstruction.

Keywords: *Anatomic, Non-anatomic, Anterior cruciate ligament, Transtibial, Single bundle*

Transtibial single bundle anterior cruciate ligament (ACL) reconstruction with over the top femoral tunnel position generally provides successful clinical results. However,

some patients still have residual knee instability and do not return to pre-injury activity level.¹⁻³ Long-term clinical results have shown that 11% to 30% of the patients treated with traditional techniques had arthritic changes.^{4,5} A critical evaluation of ACL reconstruction techniques has revealed that single bundle grafts placed by conventional transtibial drilling cannot provide adequate restraint to translational and rotatory forces.⁶⁻⁸ One of the reasons for these unsatisfactory results may be a non-anatomic vertical graft position.^{7,9-14} With this transtibial technique, the tibia tunnel is in most cases placed near the posterolateral

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Correspondence to: Ji-Hoon Bae, MD

Department of Orthopaedic Surgery, Korea University Ansan Hospital, Korea University College of Medicine, 123 Jeokgeum-ro, Danwon-gu, Ansan 425-707, Korea

Tel: +82-31-412-5043, Fax: +82-31-487-9502

E-mail: osman@korea.ac.kr

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bundle insertion site and the femoral tunnel is placed in a higher position in the intercondylar notch.^{15,16)}

The kinematics of the reconstructed knee can be affected by the location of the tibial and femoral tunnels. Recommendations for tunnel placement have changed, and recently there has been an emphasis on anatomical graft placements to recreate normal physiologic graft tension and more knee kinematics. Single bundle ACL grafts placed in the center of their anatomic insertions can provide nearly normal knee kinematics comparable to double bundle procedures.^{6,7,17-19)} However, there are incomplete *in vitro* data on the comparison of an anatomical single-bundle ACL reconstruction with non-anatomic single bundle ACL reconstruction. The purpose of this study was to compare the initial stability of anatomical and non-anatomical single bundle ACL reconstruction and to determine which would better restore intact knee kinematics. Our hypothesis was that the initial stability of anatomical single bundle ACL reconstruction would be superior to that of non-anatomical single bundle ACL reconstruction. To test our hypothesis, a navigation system was used to measure the kinematics of the knee, in particular anterior translation of the tibia and internal rotation of the tibia.

METHODS

Specimen Preparation

This study was approved by our Institutional Review Board. Seven fresh-frozen whole body human cadavers (Korean population; age, 63.4 ± 7.5 years; range, 59 to 83 years; stored at -20°C) from donors who had died of cardiopulmonary diseases were used in this study. Before testing, each specimen was thawed to room temperature. The lower extremities and pelvis were inspected; there were no gross abnormalities or deformities or ligamentous laxity or contracture. Both anteroposterior and lateral radiographs of the knee were obtained; if there were radiographic evidence of malalignment, deformity, or osteoarthritis, those specimens were excluded. Left and right limbs of each specimen were randomly assigned to 2 groups; non-anatomical single bundle ACL group (group A, $n = 7$) and anatomical single bundle ACL reconstruction group (group B, $n = 7$).

Testing Protocol

An imageless navigation system (OrthoPilot ACL ver. 2.1, B. Braun-Aesculap, Tuttlingen, Germany) was used to evaluate the kinematics of the knee, in particular anterior translation of the tibia and internal rotation of the tibia (Fig. 1).¹⁸⁻²⁰⁾ To track the position of the femur and tibia and to

digitize the knee anatomy, two rigid bodies with infra-red emitters were fixed to the proximal femur and distal tibia. To measure the motion of femur and tibia, extra-articular landmarks (including the tibia tuberosity, the anterior edge of the tibia, and the medial and lateral points of the tibia plateau) were registered. The intra-articular landmarks were not registered because we used the navigation system only to collect the motion measurements with 6 degrees of freedom per bone and to provide real time calculation of translation and rotation at all degrees of knee flexion while the surgeon manipulated the knee joint.

In the cadaveric experimental set-up, the assessment for stability consisted of the following steps: 1) initial set-up of the femoral and tibial rigid bodies, 2) anatomical registration of intact knee, 3) kinematic tests on the intact knee, 4) ACL resection, 5) kinematic tests on the ACL-deficient knee, 6) ACL reconstruction according to the chosen technique, 7) kinematic tests on the reconstructed knee.

Tests were performed sequentially with 2 loading conditions. 1) Manual maximum anterior force, 2) combined manual maximum anterior and internal rotation of the tibia. The amount of anterior translation of tibia, internal rotation of tibia were assessed at 0° , 30° , 60° , and 90° of knee flexion in each group. Values of anterior translation of the tibia were recorded by the navigation system and expressed in millimeters; values of internal rotation of the

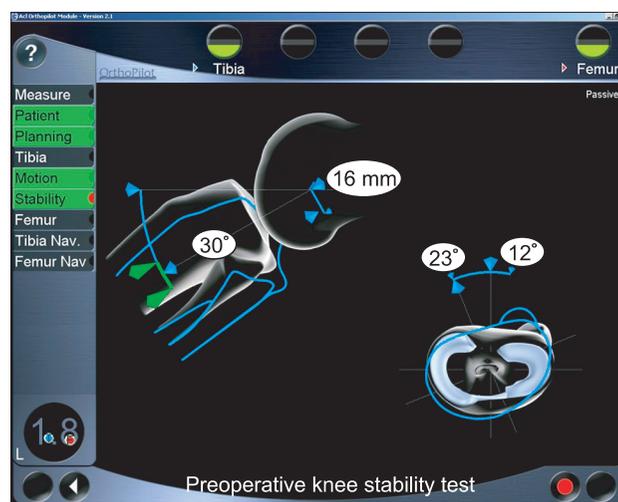


Fig. 1. Navigation software system (OrthoPilot ACL ver. 2.1, B. Braun-Aesculap) allowing the surgeon to measure the anterior translation of the tibia in millimeters and internal and external rotation of the tibia in degrees. This picture showed 16 mm of anterior translation of the tibia, 23° of internal rotation and 12° of external rotation of the tibia at 30° of knee flexion under manual maximal anterior force in ACL deficient knee specimen. ACL: anterior cruciate ligament.

tibia were expressed in degrees. The accuracy of navigation system is estimated to be 0 to 1 mm or 0° to 1° if the landmarks are registered correctly²¹⁾ All of them were assessed by the same experienced surgeon who performed all surgical procedures to minimize inter-operator variability.

Surgical Procedure

Non-anatomical (tibia posterolateral to femoral high anteromedial tunnel) reconstruction technique

All procedures were performed using medial parapatellar open approach. After 10 cm midline skin incision, medial parapatellar capsulotomy was made. We first investigated intra-articular pathology, and proceeded further if there was no significant pathology. The intact ACL was cut and knee kinematics were measured using navigation system. After completion of testing for ACL deficient knee, the gracilis and semitendinosus tendons were harvested from each knee and prepared for a quadruple graft.

For the trans-tibial technique, a commercial tibial tunnel ACL guide (Acuflex Director; Smith & Nephew Arthroscopy, Andover, MA, USA) was set at 45° to prepare 7 to 9 mm tunnel determined by the size of quadrupled hamstring grafts. The intra-articular exit point of the guide pin was directed 5 mm lateral to the medial tibial spine and inner margin of the anterior horn of the lateral meniscus.²²⁾ The external starting point was placed at the anterior border of the medial collateral ligament (MCL) insertional fibers in all cases to allow for oblique orientation of the guide of approximately 45° from the horizontal plane. The guide pin was placed and over-reamed to a corresponding graft size. After completion of the tibial tunnels, a commercially available 6-mm offset femoral tunnel aimer (Smith & Nephew Arthroscopy) was passed through the tibia tunnel and placed in the over-the-top position on the posterior cortex of the femur (10:30 o'clock on right knee, 1:30 o'clock on left knee). A beath pin was retrograded through the tibial tunnel to the selected point. The femoral tunnel was then drilled to a depth of 30 mm. The graft was introduced distal to proximal. After we confirmed that a minimum 25 mm length of the graft was placed in the femoral tunnel, the folded end of the hamstring graft was first secured at the lateral femoral cortex with the bioabsorbable interference screw (BioRCI, Smith & Nephew Arthroscopy) 1 mm larger in diameter than the graft size and 25 mm in length. The graft was tensioned before fixation with 20 lb of force applied equally to all strands by use of the spring gauge force applicator while the knee was slowly cycled between 0° and 90° 10 times. While 20 lb of graft tension was being maintained, fixation on the tibial side was performed at 10° of knee flexion

with a bioabsorbable interference screw (BioRCI, Smith & Nephew Arthroscopy) 1 mm larger in diameter than the graft size and 25 mm in length. The distal sutures in each of the grafts were tensioned manually. After completion of reconstruction, wound was closed layer by layer.

Anatomical reconstruction technique

Medial parapatellar approach was used to perform central anatomical single bundle ACL reconstruction. After completion of testing for ACL deficient knee and harvesting hamstring graft, the tibial and femoral footprints of the ACL were outlined with an indelible marker. The femoral tunnel center was placed approximately 25% from the posterior femoral cortex and 25% from the Blumensaat line. The tibial tunnel center was placed in the center of the tibial insertion based on radiographic imaging of the ACL insertion; 45% from the medial tibial cortex and 45% from the anterior tibial cortex.

A commercial tibial tunnel ACL guide (Acuflex Director; Smith & Nephew Arthroscopy) with a 45° angle was directed to the center of tibial insertion. The external starting point was placed at the anterior border of the MCL insertional fibers in all cases to allow for oblique orientation. For the anatomical femoral tunnel, independent drilling with low anteromedial portal technique was used.^{6,23)} After creating the tibial tunnel and performing soft tissue clearance of the notch, the knee was flexed to 120° and the guide pin was placed into the starting point previously marked as the center of the footprint of native ACL bundle. The guide pin was drilled out the lateral femoral cortex and a cannulated acorn reamer was used to produce a femoral tunnel 30 mm in length. Graft passage, graft tension, and graft fixation technique were identical with non-anatomical single bundle ACL reconstruction.

Statistical Analysis

Statistical analysis was performed using SAS ver. 9.1 (SAS Institute Inc., Cary, NC, USA). Due to small sample sizes, a Wilcoxon signed ranks test was used to compare the kinematic data of the ACL intact knee with ACL-deficient, and to compare two different single-bundle ACL reconstructions. The normal left and right knees in each specimen were compared and no statistically significant differences were found. Similarly, the ACL deficient left and right knees were compared and no statistically significant differences were found. Therefore, normal knees were pooled and ACL deficient knees were pooled for comparison between normal and ACL deficient knees. To compare two different reconstructions with normal state, kinematic data of the normal knees were randomly selected. Null

hypotheses of no difference were rejected if p -values were less than 0.05.

RESULTS

Normal Knees versus ACL Deficient Knees

Under manual maximal anterior force, after the ACL was sectioned, the anterior tibial translation (ATT) increased significantly at 30° of knee flexion ($p < 0.05$) (Table 1). Under the combined manual maximal anterior and internal rotatory force, the values increased significantly after sectioning of the ACL at 30° of knee flexion ($p < 0.05$) (Table 1). There was no significant change of the internal rotation of the tibia after sectioning of the ACL (Table 2).

Two Different Single Bundle Reconstructed Knees versus Normal Knees

Under manual maximal anterior force, both reconstruction techniques showed no significant difference of ATT when compared to ACL intact knee state at 30° of knee flexion ($p > 0.05$) (Table 1). Under the combined anterior and internal rotatory force, non-anatomical single-bundle ACL reconstruction showed significant difference of ATT compared to those in ACL intact group ($p < 0.05$) (Table 1). In contrast, anatomical single bundle ACL reconstruction showed no significant difference of ATT compared to those in ACL intact group at 30° of knee flexion ($p > 0.05$) (Table 1). Internal rotation of the tibia showed no significant difference in the normal, non-anatomical reconstructed and anatomical reconstructed knees (Table 2).

Table 1. Anterior Tibial Translation (mm) at Different Flexion Angles of the Knee

	Normal (n = 14)	ACL deficient (n = 14)	Anatomical (n = 7)	Non-anatomical (n = 7)
ANT (°)				
0	2 (1–8)	5 (1–7)	3 (2–4)	4 (2–5)
30	6 (2–10)	12 (7–17)*	5 (1–8)	7 (5–11)
60	5 (1–9)	7 (3–11)	3 (1–10)	5 (3–9)
90	4 (1–6)	7 (3–8)	3 (1–9)	4 (2–8)
ANT/IR (°)				
0	3 (2–9)	5 (2–8)	5 (2–6)	4 (2–6)
30	7 (2–13)	15 (9–19)*	6 (5–11)	10 (6–15)*,†
60	6 (1–9)	8 (6–13)	7 (2–9)	8 (4–9)
90	5 (2–7)	7 (4–9)	4 (3–9)	6 (4–11)

Values are presented as anterior tibial translation (mm) and median (range).

ACL: anterior cruciate ligament, ANT: manual maximal anterior force, ANT/IR: combined manual maximal anterior and internal rotational force.

* $p < 0.05$ compared with normal knees at same flexion angle. † $p < 0.05$ compared with anatomical reconstructed group at same flexion angle.

Table 2. Internal Rotation of the Tibia (°) at Different Flexion Angles of the Knee

ANT/IR (°)	Normal* (n = 14)	ACL deficient* (n = 14)	Anatomical [†] (n = 7)	Non-anatomical [†] (n = 7)
0	7 (3–10)	9 (1–17)	7 (5–15)	8 (3–10)
30	12 (6–18)	14 (9–22)	11 (6–13)	10 (10–18)
60	15 (3–19)	17 (11–24)	12 (5–21)	14 (12–20)
90	13 (4–16)	16 (12–25)	11 (10–18)	12 (10–14)

Values are presented as internal rotation of the tibia (°) and median (range).

ANT/IR: combined manual maximal anterior and internal rotational force, ACL: anterior cruciate ligament.

*No significant differences between normal and ACL deficient knees at each flexion angle. †No significant differences between anatomical and non-anatomical reconstructed knees at each flexion angle.

DISCUSSION

The present study demonstrated that the anatomic single bundle ACL reconstruction provides better initial stability when compared to the non-anatomic single bundle ACL reconstruction under the combined anterior and internal rotatory forces. No difference in knee stability was observed between the intact ACL and after anatomical single bundle ACL reconstruction. Several studies have extensively examined tunnel position in ACL reconstruction and found that inappropriate graft placement had significant adverse effect on graft incorporation and knee function.²⁴⁻²⁸⁾ Theoretically, anatomically located ACL can reproduce more closely normal knee kinematics.

Recent studies comparing an anatomical single bundle reconstruction with a double bundle reconstruction support the finding that the double bundle reconstruction may not be a better method to restore knee stability. Ho et al.¹⁷⁾ compared the kinematics of a central anatomic single bundle ACL reconstruction with a double bundle ACL reconstruction. They found that anatomical single bundle and double bundle ACL reconstruction are equally effective in restoring normal anterior translation to the knee under both anterior and rotational loads. Ferretti et al.¹⁹⁾ conducted a comprehensive kinematic study using computer navigation. The addition of the posterolateral bundle to the anteromedial bundle did not significantly reduce internal and external rotation of the tibia. They concluded that the effective role of the anatomical double bundle procedure in better restoring knee kinematics and allowing better clinical outcomes is questionable. With this new attention, we focused our study on an anatomical single bundle ACL reconstruction.

The present study supports recent studies comparing anatomical single bundle ACL reconstruction with non-anatomical single bundle ACL reconstruction. Steiner et al.⁶⁾ compared the knee laxity between a central anatomical and conventional non-anatomical single bundle ACL reconstruction. They concluded that a central anatomical single bundle ACL reconstruction using independent drilling technique is superior to restore normal anterior and rotational knee laxity compared with non-anatomical single bundle ACL reconstruction using conventional transtibial drilling technique. Kato et al.⁸⁾ investigated the effect of tunnel position for anatomic single bundle ACL reconstruction on knee biomechanics in a porcine model. They found that the anatomic mid-mid (central) single bundle ACL reconstruction provided the better stability when compared to the non-anatomic single bundle ACL reconstruction (tibia posterolateral to femoral high

anteromedial tunnel) and more closely restored normal knee kinematics. In our study, under an anterior force, a combined anterior force plus internal rotation torque, central anatomic single bundle ACL reconstruction restored normal ATT at all knee flexion testing angles while non-anatomical single-bundle ACL reconstruction reduced ATT significantly when compared to the ACL deficient knee but not to ACL intact knee state.

ACL deficient knees result in increased internal tibial rotation relative to uninjured knees.^{6,11,17)} In contrast to these studies, the results of present study shows that cutting the ACL resulted in no significant increase in internal rotation of the tibia under manual maximal combined anterior + internal rotatory force. Two recent studies support the results of the current study. Diermann et al.²⁹⁾ investigated whether ACL deficiency leads to increased internal rotation under a simulated pivot shift test in human cadaveric knees. They found that ACL deficiency does not increase the internal tibial rotation under a simulated pivot shift test. Monaco et al.³⁰⁾ evaluated the role of the ACL and its secondary restraint in controlling knee stability using a navigation system. The primary kinematic effect of an ACL injury is an increase in anterior tibial translation, but there is no significant change in internal or external rotation. It is difficult to compare our results with previous studies due to large variations (loading conditions, measurement methods, knee flexion angles) between examiners during testing the ACL deficient knees. The amount of internal tibial rotation elicited depends on the amount of the rotational force during the test. Thus it is difficult to obtain reproducible results with the coupled motions in cadaver knees. However, it is our belief that the increase in ATT is the primary abnormality in ACL deficient knees. Cutting the ACL alone may produce a small increase (significant or not) in internal tibial rotation, but the increases are so small that they are clinically not relevant.

Rotational instability after ACL injury can be explained by the combined motions of ATT and internal rotation of the tibia with shifting the axis medially. Therefore, it is very hard to quantify the objective amount of rotational instability following ACL reconstructions with different techniques clinically. In the present study, the internal rotation of tibia is not significantly changed by the integrity of the ACL. Instead, the addition of internal rotatory force to the anterior force accentuated the amount of ATT in ACL deficient knees. In addition, significant difference of ATT under the anterior and internal rotatory forces was detected between anatomical and non-anatomical single bundle ACL reconstruction groups. These findings are very important in clinical practice. When we com-

pare the rotational stability between anatomical and non-anatomical groups or single bundle or double bundle ACL reconstruction group, ATT under the combined anterior and internal rotatory forces rather than internal rotation of the tibia should be assessed.

Several limitations of the present study should be addressed. First, the age of human cadavers did not represent the typical age for population that sustains ACL rupture. Inferior bone quality, low viscoelastic character of ligament and degenerative status of the meniscus may affect the results of this study. However, the number of young human donors is rare. Even though the cadaveric biomechanical model was not representative of *in vivo* clinical situation, we could obtain the comparative data between the intact, ACL deficient knee and ACL reconstructed knee using the same specimen. Second, it is a cadaveric model of time zero biomechanical stability and cannot simulate the dynamic contributions of the musculature even though we used whole body human cadavers. Third, the values of the ATT and rotation may be different *in vivo* setting. In addition, external loads were applied manually to measure the kinematic changes, so forces may not be consistent. However, all measurements were recorded under a manual maximum force applied by the same experienced surgeon, who made every effort to apply a similar loading to the knee. Fourth, we did not perform a true pivot shift test, which is a dynamic motion involving knee flexion combined with an internal rotation and valgus torque. The pivot shift test is a complex multiplanar

maneuver. As such, quantitative kinematic analysis of the pivot shift examination is far more challenging to describe and track compared with uniplanar stress testing. Finally, the relatively limited number of human cadavers makes it difficult to draw major conclusions. However, it was difficult to obtain enough human cadavers in our country. Our specimen number was similar with other biomechanical studies using human cadavers.

In conclusions, the present study demonstrated that both techniques were effective in controlling anterior translation, but anatomical reconstruction restored the stability closer to the native ACL under combined anterior and internal rotational forces. Therefore, we recommend that the anatomic single-bundle ACL reconstruction should be considered when single bundle ACL reconstruction is performed.

CONFLICT OF INTEREST

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

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