The American Journal of Sports Medicine

http://ajs.sagepub.com/

Single-Tunnel Double-Bundle Anterior Cruciate Ligament Reconstruction With Anatomical Placement of Hamstring Tendon Graft: Can It Restore Normal Knee Joint Kinematics?

Hemanth R. Gadikota, Jia-Lin Wu, Jong Keun Seon, Karen Sutton, Thomas J. Gill and Guoan Li

Am J Sports Med 2010 38: 713 originally published online February 5, 2010
DOI: 10.1177/0363546509353406

The online version of this article can be found at:
http://ajs.sagepub.com/content/38/4/713

Published by:
SAGE
http://www.sagepublications.com

On behalf of:
American Orthopaedic Society for Sports Medicine
AOSSM

Single-Tunnel Double-Bundle Anterior Cruciate Ligament Reconstruction With Anatomical Placement of Hamstring Tendon Graft

Can It Restore Normal Knee Joint Kinematics?

Hemanth R. Gadikota,* MS, Jia-Lin Wu,*† MD, Jong Keun Seon,*‡ MD, Karen Sutton,* MD, Thomas J. Gill,* MD, and Guoan Li,*§ PhD

*From the *Bioengineering Laboratory, Department of Orthopaedic Surgery, Massachusetts General Hospital and Harvard Medical School, Boston, Massachusetts, †Department of Orthopaedic Surgery, Tri-Service General Hospital, National Defense Medical Center, Taipei, Taiwan, and the ‡Department of Orthopaedics, Chonnam National University Hwasun Hospital, Jeonnam, South Korea*

Background: Anatomical reconstruction techniques that can restore normal joint kinematics without increasing surgical complications could potentially improve clinical outcomes and help manage anterior cruciate ligament injuries more efficiently.

Hypothesis: Single-tunnel double-bundle anterior cruciate ligament reconstruction with anatomical placement of hamstring tendon graft can more closely restore normal knee anterior-posterior, medial-lateral, and internal-external kinematics than can conventional single-bundle anterior cruciate ligament reconstruction.

Study Design: Controlled laboratory study.

Methods: Kinematic responses after single-bundle anterior cruciate ligament reconstruction and single-tunnel double-bundle anterior cruciate ligament reconstruction with anatomical placement of hamstring tendon graft were compared with the intact knee in 9 fresh-frozen human cadaveric knee specimens using a robotic testing system. Kinematics of each knee were determined under an anterior tibial load (134 N), a simulated quadriceps load (400 N), and combined torques (10 N·m valgus and 5 N·m internal tibial torques) at 0°, 15°, 30°, 60°, and 90° of flexion.

Results: Anterior tibial translations were more closely restored to the intact knee level after single-tunnel double-bundle reconstruction with anatomical placement of hamstring tendon graft than with a single-bundle reconstruction under the 3 external loading conditions. Under simulated quadriceps load, the mean internal tibial rotations after both reconstructions were lower than that of the anterior cruciate ligament–intact knee with no significant differences between these 3 knee conditions at 0° and 30° of flexion ($P > .05$).The increased medial tibial shifts of the anterior cruciate ligament–deficient knees were restored to the intact level by both reconstruction techniques under the 3 external loading conditions.

Conclusion: Single-tunnel double-bundle anterior cruciate ligament reconstruction with anatomical placement of hamstring tendon graft can better restore the anterior knee stability compared with a conventional single-bundle reconstruction. Both reconstruction techniques are efficient in restoring the normal medial-lateral stability but overcorrect the internal tibial rotations.

Clinical Relevance: Single-tunnel double-bundle anterior cruciate ligament reconstruction with anatomical placement of hamstring tendon graft could provide improved clinical outcomes over a conventional single-bundle reconstruction.

Keywords: anterior cruciate ligament (ACL); anatomical single-tunnel double-bundle reconstruction; single-bundle reconstruction; knee kinematics; robotic testing system

The American Journal of Sports Medicine, Vol. 38, No. 4
DOI: 10.1177/0363546509353406

Surgical reconstruction of a ruptured ACL is the most commonly adopted treatment option for patients with repeated episodes of giving way with activities of daily living or a lifestyle including high-demand activities.[4,23] Single-bundle ACL reconstruction techniques using either a bone–patellar tendon–bone graft or a quadrupled hamstring tendon graft have been shown to successfully restore normal anterior stability of the knee joint.[16,33] However, some studies have reported persistent rotational instability and long-term degenerative changes even after such a surgical intervention.[1,11,15,29] Both in vitro and in vivo studies have indicated that a single-bundle ACL reconstruction could not restore the normal 6 degrees of freedom knee kinematics.[26,38]

With a greater understanding of the ACL anatomy and function, several anatomical ACL reconstruction techniques have been proposed. Some authors have described that an anatomical ACL reconstruction can be achieved by reconstructing both the anteromedial (AM) and posterolateral (PL) bundles of the ACL by using various combinations of femoral and tibial tunnels.[8,21,27,28,31,37] A few other techniques described in the literature to achieve anatomical ACL reconstructions include placing the femoral and tibial tunnels at the center of the anatomical footprints, aperture fixation of the graft, creating an oval-shaped opening of the femoral tunnel, and creating a rectangular femoral tunnel and a half rectangular, half round tibial tunnel.[2,5,7,13,30]

Some biomechanical studies have reported that an anatomical double-tunnel double-bundle ACL reconstruction can sufficiently restore the intact knee kinematics under various external loads.[21,35,36] However, a consensus on the superiority of such techniques over the single-bundle ACL reconstruction in clinical outcomes is yet to be established. A recent meta-analysis of randomized controlled trials reported that no clinically significant differences between the single-bundle and double-bundle ACL reconstruction exist with respect to KT-1000 arthrometer and pivot-shift testing.[24] Therefore, a debate on the need for such a technically challenging procedure as an alternative to the conventional single-bundle ACL reconstruction is yet to be resolved.[16,22,24]

Recently, some authors have proposed anatomical ACL reconstruction techniques by using a single femoral and tibial tunnel as opposed to creating multiple tunnels.[7,10,30,31] However, few studies have investigated the efficacy of such ACL reconstruction techniques using hamstring tendon grafts, especially under physiological loading conditions.[10] Hence, this study was designed to evaluate if an anatomical ACL reconstruction using a single femoral and tibial tunnel that places a hamstring tendon graft posteriorly along the contour of the posterior border of the lateral femoral condyle, restoring the anatomical joint line attachment at the native ACL footprint and the 2 bundles of the ACL, could provide superior joint stability compared with a conventional hamstring tendon graft single-bundle ACL reconstruction by using a robotic testing system. We hypothesized that single-tunnel double-bundle anterior cruciate ligament reconstruction with anatomical placement of hamstring tendon graft ("anatomical single-tunnel ACL reconstruction") can more closely restore the intact knee kinematics than can a conventional single-bundle ACL reconstruction.

MATERIALS AND METHODS

This study was performed by using 9 fresh-frozen human cadaveric knee specimens from 7 male and 2 female donors with a mean age of 55 years (range, 47-60 years). All specimens were stored at –20°C until 1 day before the experiment when they were thawed at room temperature for 24 hours. Each specimen was examined for osteoarthritis and ACL injury by using fluoroscopy and manual stability tests. Specimens with either of these conditions were excluded from this study. To facilitate the fixation of the femur and tibia, musculature surrounding the diaphyses was stripped. A bone screw was used to firmly secure the fibula to the tibia in its anatomical position. The tibial and the femoral diaphyses were then potted in hollow cylindrical cardboard tubes by using bone cement. After the bone cement solidified, the cardboard tubes were removed, leaving solid cylinders of bone cement with the femur or tibia embedded in them. These constructs were then secured in thick-walled aluminum cylinders that were attached to the robotic testing system.

The specimen was then installed on a robotic testing system and tested under various loading conditions. Details on how this robotic testing system can be used to study knee joint kinematics have been described in previous studies.[10,18,38] The robotic testing system was used to determine a passive flexion path of the ACL-intact knee from 0° to 120° in 1° increments of knee flexion. This passive flexion path was repeated 5 times before the determination of kinematics under the external loads at each knee condition. After the determination of the passive flexion path, kinematic responses of each ACL-intact knee were obtained under 3 different external loading conditions (an anterior tibial load of 134 N, a simulated quadriceps load of 400 N, and combined torques of 10 N·m valgus tibial torque and 5 N·m internal tibial torque) at selected flexion angles of 0°, 15°, 30°, 60°, and 90°. At each selected flexion angle, a selected external load was applied to the tibia by the robot while it simultaneously recorded the kinematic responses.

After the intact knee kinematics were determined, the ACL was resected through a small medial arthrotomy under arthroscopy guide to simulate an ACL-deficient knee condition. The arthrotomy and skin were repaired in layers by sutures. After the resection of the ACL, kinematics of the ACL-deficient knee were determined under the same external loading conditions that were used to test the ACL-intact knee.

[§]Address correspondence to Guoan Li, PhD, Bioengineering Laboratory, Massachusetts General Hospital/Harvard Medical School, 55 Fruit Street, GRJ 1215, Boston, MA 02114 (e-mail: gli1@partners.org).

The authors declared that they had no conflicts of interests in their authorship and publication of this contribution.

Single-Bundle ACL Reconstruction Surgical Technique

Both reconstructions were performed under arthroscopic-assisted techniques by a single surgeon while the specimen was still installed on the robotic testing system. The surgery began by harvesting the semitendinosus and gracilis tendons that were used as the graft material for both ACL reconstructions. The harvested grafts were pretensioned on a graft preparation board (DePuy Mitek, Raynham, Massachusetts) with 20 lb of force while the tibial and femoral tunnels were prepared (20-25 minutes). First, the tibial tunnel was placed at the center of the ACL remnant through the AM surface of the tibia at the level of the tibial tubercle using a tibial guide (DePuy Mitek) set at 55°. After the tibial tunnel placement, a K-wire was placed into the lateral femoral condyle at 1:30 or 10:30 position through the AM portal with the knee flexed to 120° using an offset guide (DePuy Mitek). With the inserted K-wire as the reference, a femoral tunnel was reamed to the lateral cortex of the distal femur using a 4.5-mm EndoButton drill (Smith & Nephew Endoscopy, Andover, Massachusetts). A 30-mm-long femoral socket was then created by a cannulated reamer that matched the prepared graft diameter. After both tunnels were created, the prepared quadrupled hamstring tendon graft was passed through the tibial tunnel into the joint and finally through the femoral socket and was secured with a 20-mm EndoButton CL (Smith & Nephew Endoscopy) on the lateral cortex of the femur. A tibial INTRAFIX system (DePuy Mitek), which consists of a sheath with 4 quadrants and an interference screw, was used to secure the distal end of the quadrupled graft. All 4 strands were placed within a single quadrant of the sheath, and an interference screw was then inserted into the sheath while 40 N of axial graft tension was applied at full extension. After the graft was fixed at both ends, arthrotomy and skin incisions were repaired by sutures. After the single-bundle ACL reconstruction (Figure 1A), the kinematic responses of the reconstructed knee were determined under the 3 external loading conditions.

Anatomical Single-Tunnel Double-Bundle ACL Reconstruction Surgical Technique

After the determination of the single-bundle ACL-reconstructed knee kinematics, the graft was released from the joint and was examined for any damage. If there was no noticeable damage, the same graft was reused for anatomical single-tunnel double-bundle ACL reconstruction (Figure 1B). The femoral and tibial tunnels that were used for single-bundle ACL reconstruction were reused after dilating both tunnels by 1 mm for anatomical single-tunnel ACL reconstruction. The semitendinosus and gracilis tendons were looped over a single strand of suture, and only the AM bundle was colored on the proximal end of the graft to easily identify the bundle. To achieve a desired position for the AM and PL bundles, a graft-positioning tool (DePuy Mitek) was used. The graft was placed in the fork of the positioning tool with 1 bundle on either side of the fork. The single strand of the suture

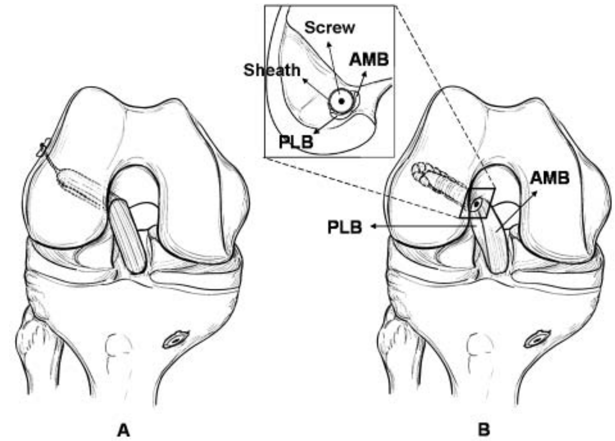

Figure 1. Single-bundle (A) and anatomical single-tunnel (B) ACL reconstructions. AMB, anteromedial bundle; PLB, posterolateral bundle.

over which the graft was looped was passed through the femoral tunnel and out the lateral thigh. This suture was used to pull the graft into the tunnel, and the graft-positioning tool was advanced through the tibial tunnel until it reached the aperture of the femoral tunnel. At this point, the AM and PL bundles were rotated by rotating the positioning tool to achieve the desired positions of the 2 bundles before they were advanced into the femoral tunnel. The keel of a sheath trial (DePuy Mitek) was placed between the strands to separate the 2 bundles within the single tunnel. After aligning the AM and PL bundles into their anatomical orientation posteriorly in the femoral tunnel (Figure 1B), a femoral INTRAFIX sheath (DePuy Mitek) was then carefully inserted into the tunnel without altering the position of the 2 bundles. The graft was then secured by driving a femoral INTRAFIX screw into the sheath that was inserted previously. This femoral INTRAFIX system places the graft posteriorly along the posterior border of the lateral femoral condyle. After the graft is secured in the femoral tunnel, the knee was fully extended by the robotic testing system. At this position, the tibial tunnel fixation was achieved by the tibial INTRAFIX system with the AM and PL bundles placed in 2 opposite quadrants of the sheath at their anatomical insertion sites on the tibial plateau. A 40-N graft tension was applied while the graft was secured in the tibial tunnel by an interference screw at full extension. The arthrotomy and skin incisions were then repaired by sutures, and kinematics of the anatomical single-tunnel ACL-reconstructed knee were determined using the same protocol as described above.

Data Analysis

For each specimen in this study, kinematic responses to the 3 external loads were measured under the 4 different knee conditions (ACL intact, ACL deficient, single-bundle ACL reconstructed, and anatomical single-tunnel double-bundle ACL reconstructed). A 1-way repeated-measures

TABLE 1
Anterior (+)/Posterior (−) Tibial Translation (mean ± SD, mm) Under 3 External Loading Conditions

Loading Condition	Flexion Angle, deg	ACL Intact	ACL Deficient	Single-Bundle ACL Reconstruction	Anatomical ACL Reconstruction
Anterior tibial load	0	4.8 ± 1.4	12.8 ± 1.9[a1]	7.1 ± 1.0[a6,b1]	5.0 ± 1.0[b6,c1]
	15	7.1 ± 2.7	17.9 ± 4.4[a2]	10.2 ± 1.8[a7,b2]	8.3 ± 1.7[b7,c2]
	30	7.9 ± 2.7	18.3 ± 5.3[a3]	11.1 ± 2.0[a8,b3]	9.5 ± 1.9[b8]
	60	6.8 ± 3.0	13.4 ± 5.0[a4]	9.5 ± 2.5[a9,b4]	8.6 ± 2.3[b9]
	90	6.3 ± 3.1	10.9 ± 3.3[a5]	8.4 ± 2.2[a10,b5]	8.1 ± 2.2[a11,b10]
Simulated quadriceps load	0	2.5 ± 1.8	5.4 ± 2.6[a12]	4.0 ± 1.3[a15,b11]	2.2 ± 1.3[b14,c3]
	15	4.7 ± 3.4	10.5 ± 5.0[a13]	7.0 ± 2.6[a16,b12]	5.2 ± 2.0[b15]
	30	5.2 ± 3.3	9.4 ± 4.2[a14]	7.4 ± 2.9[a17,b13]	5.9 ± 2.3[b16]
	60	2.5 ± 1.7	2.5 ± 2.6	2.6 ± 2.6	1.9 ± 2.0
	90	0.3 ± 0.5	0.3 ± 0.8	0.4 ± 0.9	0.1 ± 0.4
Combined tibial torques	0	0.1 ± 2.1	2.7 ± 2.3[a18]	1.1 ± 1.1[a20,b17]	−0.5 ± 1.1[b18,c4]
	30	2.1 ± 4.3	4.5 ± 4.7[a19]	3.6 ± 3.8	2.7 ± 3.9[b19]

[a]a1-5, a13: P = .0002; a6: P = .0017; a7: P = .0050; a8: P = .0115; a9: P = .0341; a10: P = .0326; a11: P = .0275; a12: P = .0005; a14: P = .0003; a15: P = .0236; a16: P = .0435; a17: P = .0260; a18: P = .0001; a19: P = .0052; a20: P = .0185 (significantly different from ACL-intact knee).
[b]b1-b3, b18: P = .0002; b4: P = .0010; b5: P = .0047; b6-b8, b15: P = .0001; b9, b14: P = .0004; b10: P = .0054; b11: P = .0435; b12: P = .0013; b13: P = .0226; b16: P = .0008; b17: P = .0016; b19: P = .0230 (significantly different from ACL-deficient knee).
[c]c1: P = .0019; c2: P = .0349; c3: P = .0205; c4: P = .0035 (significantly different from single-bundle ACL reconstruction).

analysis of variance was used to detect statistically significant differences in the kinematic responses of the knee under the 4 different knee conditions. When significant differences were found, post hoc comparisons were made using the Student Newman-Keuls test. Differences were considered statistically significant at $P < .05$. The statistical analysis was performed in STATISTICA (StatSoft, Inc, Tulsa, Oklahoma).

RESULTS

Kinematic Responses to an Anterior Tibial Load of 134 N

An anterior tibial load of 134 N induced an anterior tibial translation at all selected flexion angles ranging from 4.8 ± 1.4 mm at 0° to 7.9 ± 2.7 mm at 30° of flexion in the ACL-intact knee (Table 1). After the resection of the ACL, anterior tibial translations significantly increased at all selected flexion angles compared with those of the ACL-intact knee ($P < .05$). Both the single-bundle and anatomical single-tunnel ACL reconstructions significantly reduced these increased anterior tibial translations of the ACL-deficient knee at all selected flexion angles ($P < .05$). However, the anterior tibial translations after single-bundle ACL reconstruction were significantly greater than those of the ACL-intact knee at all selected flexion angles ($P < .05$). On the contrary, the anterior tibial translations after the anatomical single-tunnel ACL reconstruction were not significantly different compared with the intact knee from 0° to 60° of flexion ($P > .05$). Significant differences in the anterior tibial translations of the ACL-intact knee and anatomical single-tunnel ACL-reconstructed knee were observed at 90° of flexion with a mean difference of 1.9 mm ($P < .05$).

Application of anterior tibial load significantly shifted the ACL-deficient tibia medially compared with the ACL-intact knee at 0°, 15°, 30°, and 60° of flexion ($P < .05$) (Table 2). The mean maximum ACL-deficient knee tibial medial shift of 2.7 mm occurred at 30° of flexion. The increased medial shifts were restored to the ACL-intact knee level by both reconstruction techniques at all selected flexion angles ($P > .05$).

Kinematic Responses to the Action of Simulated Quadriceps Load of 400 N

Simulated quadriceps load increased the anterior tibial translation of the ACL-intact knee at all selected flexion angles with a maximum anterior tibial translation of 5.2 ± 3.3 mm at 30° of flexion (Table 1). The ACL deficiency further increased these anterior tibial translations significantly at 0°, 15°, and 30° of flexion ($P < .05$). Significant differences in the anterior tibial translations of the single-bundle ACL-reconstructed knee and ACL-intact knee were observed at 0°, 15°, and 30° of flexion ($P < .05$). In contrast, no significant differences were observed between the anatomical single-tunnel ACL reconstruction and the ACL-intact knee in terms of the anterior tibial transition at 0°, 15°, and 30° of flexion ($P > .05$). No significant differences were found between all 4 knee conditions at 60° and 90° of flexion ($P > .05$).

Anterior cruciate ligament deficiency significantly increased the mean medial tibial translation (Table 2) compared with that of the ACL-intact knee at 0°, 15°, and 30° of flexion ($P < .05$). Both ACL reconstruction techniques were capable of reducing these increased medial tibial shifts of the ACL-deficient knee close to that of the ACL-intact knee level ($P > .05$). Under the action of simulated quadriceps load, the tibia of the ACL-intact knee internally rotated at all selected flexion angles. The mean internal tibial rotations (Table 3) after both ACL reconstructions were lower than that of the ACL-intact knee with no

TABLE 2
Medial (+)/Lateral(–) Tibial Translation (mean ± SD, mm) Under 3 External Loading Conditions

Loading Condition	Flexion Angle, deg	ACL Intact	ACL Deficient	Single-Bundle ACL Reconstruction	Anatomical ACL Reconstruction
Anterior tibial load	0	−0.5 ± 0.6	0.6 ± 2.0[a1]	−0.5 ± 1.1[b1]	−0.7 ± 1.0[b5]
	15	−0.4 ± 0.9	2.1 ± 3.2[a2]	−0.4 ± 1.9[b2]	−0.6 ± 1.8[b6]
	30	−0.1 ± 1.3	2.7 ± 3.5[a3]	0.1 ± 2.5[b3]	−0.1 ± 2.3[b7]
	60	1.0 ± 1.0	2.6 ± 3.2[a4]	1.2 ± 2.3[b4]	1.1 ± 2.1[b8]
	90	1.4 ± 1.6	2.6 ± 3.4[a5]	1.3 ± 2.3	1.3 ± 2.2
Simulated quadriceps load	0	0.2 ± 0.4	1.0 ± 1.1[a6]	0.6 ± 0.7	0.3 ± 0.6[b10]
	15	1.0 ± 1.0	2.1 ± 1.9[a7]	1.2 ± 1.5[b9]	0.9 ± 1.2[b11]
	30	1.1 ± 1.1	2.0 ± 2.2[a8]	1.4 ± 1.6	1.2 ± 1.3[b12]
	60	0.9 ± 0.7	0.9 ± 1.0	0.9 ± 0.8	0.7 ± 0.7
	90	0.4 ± 0.4	0.3 ± 0.7	0.3 ± 0.6	0.3 ± 0.5
Combined tibial torques	0	2.2 ± 1.2	4.4 ± 1.8[a9]	2.9 ± 1.3[b13]	2.3 ± 1.2[b14]
	30	3.9 ± 1.8	5.5 ± 2.4[a10]	4.8 ± 1.9[a11]	4.5 ± 1.6[b15]

[a]a1: $P = .0345$; a2: $P = .0014$; a3: $P = .0030$; a4: $P = .0423$; a5: $P = .0505$; a6: $P = .0089$; a7: $P = .0021$; a8: $P = .0432$; a9: $P = .0002$; a10: $P = .0013$; a11: $P = .0489$ (significantly different from ACL-intact knee).

[b]b1: $P = .0194$; b2: $P = .0035$; b3: $P = .0012$; b4: $P = .0212$; b5: $P = .0302$; b6: $P = .0026$; b7: $P = .0017$; b8: $P = .0363$; b9: $P = .0040$; b10: $P = .0054$; b11: $P = .0022$; b12: $P = .0389$; b13: $P = .0006$; b14: $P = .0001$; b15: $P = .0209$ (significantly different from ACL-deficient knee).

significant differences between these 3 knee conditions at 0° and 30° of flexion ($P > .05$).

Kinematic Responses to Combined Tibial Torques of 5 N·m of Internal Torque and 10 N·m of Valgus Torque

Under the combined tibial torques, anterior tibial translations of the ACL-intact knee were 0.1 ± 2.1 mm at 0° of flexion and 2.1 ± 4.3 mm at 30° of flexion (Table 1). Significant increases in the mean anterior tibial translations at 0° and 30° of flexion were observed due to ACL deficiency compared with that of the ACL-intact knee ($P < .05$). The anterior tibial translation after the single-bundle ACL reconstruction was significantly higher than that of the ACL-intact knee at 0° of flexion ($P < .05$). In contrast, no significant differences were found in the anterior tibial translations of the anatomical single-tunnel ACL reconstruction and the ACL-intact knee at 0° and 30° of flexion ($P > .05$).

The ACL deficiency significantly increased the mean medial tibial translation (Table 2) at 0° and 30° of flexion compared with that of the ACL-intact knee ($P < .05$). These increased medial tibial translations were closely restored to ACL-intact knee level by both reconstruction techniques at 0° of flexion ($P > .05$). Although there was a significant difference in the medial tibial translation between the single-bundle ACL reconstruction and the ACL-intact knee, no significant difference was found between anatomical single-tunnel ACL reconstruction and the ACL-intact knee at 30° of flexion. The ACL deficiency increased the internal tibial rotations at 0° and 30° of flexion compared with that of the ACL-intact knee (Table 3). These increased internal tibial rotations were restored to the ACL-intact knee level by both ACL reconstructions at 0° and 30° of flexion ($P > .05$).

DISCUSSION

In the current study, an anatomical ACL reconstruction using a single tibial and femoral tunnel in which the graft is placed posteriorly along the contour of the posterior border of the lateral femoral condyle to mimic the ACL insertion geometry was found to more closely restore the increased anterior tibial translations of the ACL-deficient knee to the ACL-intact knee level than did a conventional single-bundle ACL reconstruction under the 3 external loading conditions. Both ACL reconstruction techniques could sufficiently reduce the increased medial tibial translations of the ACL-deficient knee to the ACL-intact knee level under anterior tibial load and simulated quadriceps load. However, both reconstructions overcorrected the internal tibial rotations under the simulated quadriceps load. These data partially support our initial hypothesis that a single-tunnel double-bundle ACL reconstruction with anatomical placement of hamstring tendon graft can more closely restore the intact knee kinematics than can a conventional single-bundle ACL reconstruction.

In our study, we observed that ACL deficiency not only increases the anterior tibial translation but also significantly increases the medial tibial translations compared with that of the ACL-intact knee under the 3 external loading conditions. The increased anterior and medial tibial translations of the ACL-deficient knee are consistent with the observations of other studies.[10,18] These findings reiterate the importance of restoring the 6 degrees of freedom kinematics of the normal knee after an ACL reconstruction, which could potentially prevent abnormal articular cartilage contact patterns. Our data showed that both reconstruction techniques were capable of restoring the normal medial tibial translations under anterior tibial load and simulated quadriceps load.

In vitro studies have investigated the efficacy of single-bundle ACL reconstruction under various loading

TABLE 3
Internal (+)/ External (−) Tibial Rotation (mean ± SD, deg) Under 3 External Loading Conditions

Loading Condition	Flexion Angle, deg	ACL Intact	ACL Deficient	Single-Bundle ACL Reconstruction	Anatomical ACL Reconstruction
Anterior tibial load	0	−0.1 ± 5.5	0.2 ± 3.7	−2.1 ± 6.5	−2.6 ± 6.1
	15	1.9 ± 6.6	1.7 ± 4.5	−0.5 ± 8.7	−1.3 ± 9.1
	30	1.0 ± 8.3	2.3 ± 4.9	0.7 ± 8.8	0.1 ± 9.3
	60	3.1 ± 5.4	3.3 ± 4.5	2.7 ± 4.3	1.7 ± 5.9
	90	3.7 ± 4.5	3.2 ± 4.5	2.4 ± 3.3	1.5 ± 3.7
Simulated quadriceps load	0	4.2 ± 2.7	3.3 ± 3.6	2.7 ± 3.5	2.7 ± 3.2
	15	8.9 ± 2.8	6.9 ± 3.4	5.7 ± 4.2[a1]	5.7 ± 4.0[a2]
	30	8.5 ± 4.0	7.3 ± 4.0	5.9 ± 4.9	6.0 ± 4.9
	60	4.3 ± 2.6	3.6 ± 3.3	3.7 ± 3.4	3.3 ± 3.2
	90	0.8 ± 0.9	1.0 ± 1.4	0.9 ± 1.7	0.8 ± 1.4
Combined tibial torques	0	11.9 ± 3.2	13.7 ± 3.3[a3]	12.2 ± 3.6[b1]	11.1 ± 3.8[b2]
	30	20.6 ± 4.3	21.1 ± 3.9	20.3 ± 4.2	20.4 ± 4.0

[a]a1: P = .0209; a2: P = .0125; a3: P = .0263 (significantly different from ACL-intact knee).
[b]b1: P = .0292; b2: P = .0025 (significantly different from ACL-deficient knee).

conditions.[10,34,35] Similar to our findings, these studies have concluded that a single-bundle ACL reconstruction can restore the anterior tibial translation to a clinically satisfactory level but not to the ACL-intact knee level. To improve knee joint stability, especially the rotational stability, some authors have proposed to reconstruct both functional bundles of the ACL by using 2 independent tunnels for each of the bundles. Yagi et al[35] reported that a double-bundle ACL reconstruction was capable of significantly reducing the increased anterior tibial translations of the ACL-deficient knee but could not restore them to the intact-knee level at 0° and 30° of flexion under an anterior tibial load of 134 N. In another study using a robotic testing system, Yamamoto et al[36] found no significant differences in the anterior tibial translations of ACL-intact and double-bundle ACL-reconstructed knees under an anterior tibial load. More recently, Markolf et al[22] demonstrated that a double-bundle ACL reconstruction significantly overconstrained the anterior tibial translations compared with the ACL-intact knee from 30° to 90° of flexion. In our study, the anatomical single-tunnel ACL reconstruction sufficiently restored the ACL-intact knee anterior stability under the anterior tibial load and simulated quadriceps load. Similar results were observed in another study that evaluated the efficacy of a single-tunnel double-bundle ACL reconstruction technique in restoring normal knee kinematics.[10] Based on our data, the normal anterior stability of the knee joint can be efficiently restored by an anatomical single-tunnel ACL reconstruction.

Combined valgus–internal rotational torques have been used to evaluate the efficacy of ACL reconstructions to resist rotational loads. Yagi et al[35] found that a double-bundle ACL reconstruction could not restore the anterior tibial translations close to the ACL-intact level under combined valgus–internal rotational torques at 15° and 30° of flexion. However, Yamamoto et al[36] reported that the anterior tibial translations of the ACL-intact knee under combined valgus–internal rotational torques were closely restored by the double-bundle ACL reconstruction at 15° and 30° of flexion. In our study, no significant differences in the anterior tibial translations of the intact knee and anatomical single-tunnel ACL-reconstructed knee were observed at 0° and 30° of flexion under the combined valgus–internal rotational torques. Although a significant difference in the anterior tibial translation between the ACL-intact knee and single-bundle ACL-reconstructed knee was found at 0° of flexion, the difference between the 2 groups was ≈1 mm, which may not be detectable in a clinical setting. These results demonstrate that an anatomical single-tunnel ACL reconstruction can sufficiently resist combined rotational loads and could be an efficient alternative to both single-bundle and double-bundle ACL reconstructions to restore the rotational stability of the knee joint.

Few studies have investigated the internal-external tibial rotation after ACL reconstruction under physiological loading condition.[10,38] Our data demonstrated that both the single-bundle and anatomical single-tunnel ACL reconstruction resulted in a lower internal tibial rotation compared with that of the ACL-intact knee under simulated quadriceps load. Similar observations of decreased internal tibial rotation after ACL reconstruction have been reported in various studies.[10,25,26,32,38] Cartilage-to-cartilage contact in a normal tibiofemoral joint is reported to occur at regions of thicker cartilage layers.[19] A shift in the cartilage-to-cartilage contact regions to areas of thinner cartilage layers due to altered knee kinematics may have some undesirable consequences. Furthermore, a decrease in internal rotation is reported to increase the contact pressure in the patellofemoral joint, which may lead to complications in this joint.[17] Therefore, further improvements to the current ACL reconstruction techniques are warranted to restore the normal tibial rotation under physiological loading.

The anatomical ACL reconstruction of this study used a single tibial and femoral tunnel similar to some previously proposed anatomical ACL reconstruction techniques that use a tibialis anterior tendon, hamstrings tendon, or bone–patellar tendon–bone graft.[7,10,30,31] A recent study by

Gadikota et al[10] reported that a single-tunnel double-bundle ACL reconstruction technique using hamstring tendon graft closely restored the anterior laxity to the intact-knee level at low flexion angles ($\leq 30°$) but overconstrained the knee joint at high flexion angles ($\geq 60°$) under the anterior tibial load and at 0° and 30° of flexion under combined torques. The single-tunnel double-bundle ACL reconstruction technique used an AperFix femoral implant (Cayenne Medical, Scottsdale, Arizona) that separates the hamstring tendon graft into 2 bundles in a single tunnel. In the present study, the INTRAFIX system facilitates the fixation of a hamstring tendon graft posteriorly along the contour of the posterior border of the lateral femoral condyle, restoring the anatomical joint line attachment at the native ACL footprint and the 2 bundles of the ACL. Our data showed that an anatomical single-tunnel ACL reconstruction can restore the normal anterior laxity at time zero without overconstraining the joint at high flexion angles. Such techniques could be easily adopted by surgeons who currently practice single-bundle ACL reconstruction to achieve a more anatomical reconstruction of the ACL. However, as with other ACL reconstruction techniques, this technique needs to be further improved to restore normal knee internal tibial rotations under physiological loads. Different femoral and tibial tunnel positions should be investigated to obtain the most optimal anatomical single-tunnel ACL reconstruction.

This current cadaveric biomechanical study has several limitations that need to be addressed. A commonly used femoral tunnel position placed at 10:30/1:30 position was used in this study, and hence it does not evaluate the effect of various tunnel locations. The scope of this study was limited to using hamstring tendon graft for both reconstruction techniques. Therefore, further investigation is required to compare the anatomical single-tunnel ACL reconstruction using hamstring tendon graft to single-bundle ACL reconstructions using other graft sources such as a bone–patellar tendon–bone graft or a quadriceps tendon graft. Furthermore, randomization of the groups for reusing the graft was not performed because the anatomical single-tunnel ACL reconstruction required a larger tunnel than that used for single-bundle ACL reconstruction. The 2 distinct features of the anatomical single-tunnel ACL reconstruction compared with the single-bundle ACL reconstruction are (1) aperture fixation and (2) anatomical reconstruction of both bundles of the ACL. However, from the results of this study, we cannot estimate how much each of these 2 differences contributed to the observed differences in the kinematic results between the 2 reconstruction techniques. Similar to the observations of this study, few biomechanical studies demonstrated that an aperture fixation can provide a more stable joint than that of a peripheral fixation.[12,14] However, both fixation techniques have been reported to provide similar clinical outcomes.[3,6,9,20] Therefore, the true efficacy of this anatomical reconstruction needs to be evaluated by a clinical follow-up study. Nevertheless, the repeated-measures design of this study facilitated a controlled measurement of knee kinematics under various knee conditions using the same specimen.

In conclusion, the current study has shown that at time zero, a single-tunnel double-bundle ACL reconstruction with anatomical placement of hamstring tendon graft can provide a satisfactory anterior stability compared with a single-bundle ACL reconstruction under anterior tibial load, simulated quadriceps load, and combined tibial torques. Both reconstruction techniques can restore the medial-lateral stability under the 3 external loads but overcorrected the internal tibial rotations under the action of simulated quadriceps loads. Further improvements to the current ACL reconstruction techniques are needed to restore normal tibial rotation. Future investigations must evaluate if such an advantage in terms of the stability provided by the anatomical single-tunnel ACL reconstruction carries over to a long-term follow-up and prevents degenerative changes.

ACKNOWLEDGMENT

The authors gratefully acknowledge the support of the National Institutes of Health (R01AR055612) and DePuy Mitek, Raynham, Massachusetts.

REFERENCES

1. Aglietti P, Buzzi R, D'Andria S, Zaccherotti G. Long-term study of anterior cruciate ligament reconstruction for chronic instability using the central one-third patellar tendon and a lateral extraarticular tenodesis. *Am J Sports Med*. 1992;20(1):38-45.
2. Aglietti P, Zaccherotti G, Simeone AJ, Buzzi R. Anatomic versus non-anatomic tibial fixation in anterior cruciate ligament reconstruction with bone–patellar tendon–bone graft. *Knee Surg Sports Traumatol Arthrosc*. 1998;6(suppl 1):S43-S48.
3. Barber FA, Spruill B, Sheluga M. The effect of outlet fixation on tunnel widening. *Arthroscopy*. 2003;19(5):485-492.
4. Beynnon BD, Johnson RJ, Abate JA, Fleming BC, Nichols CE. Treatment of anterior cruciate ligament injuries, part I. *Am J Sports Med*. 2005;33(10):1579-1602.
5. Brucker PU, Lorenz S, Imhoff AB. Aperture fixation in arthroscopic anterior cruciate ligament double-bundle reconstruction. *Arthroscopy*. 2006;22(11):1250 e1251-e1256.
6. Buelow JU, Siebold R, Ellermann A. A prospective evaluation of tunnel enlargement in anterior cruciate ligament reconstruction with hamstrings: extracortical versus anatomical fixation. *Knee Surg Sports Traumatol Arthrosc*. 2002;10(2):80-85.
7. Caborn DN, Chang HC. Single femoral socket double-bundle anterior cruciate ligament reconstruction using tibialis anterior tendon: description of a new technique. *Arthroscopy*. 2005;21(10):1273.
8. Crawford C, Nyland J, Landes S, et al. Anatomic double bundle ACL reconstruction: a literature review. *Knee Surg Sports Traumatol Arthrosc*. 2007;15(8):946-964; discussion 945.
9. Fauno P, Kaalund S. Tunnel widening after hamstring anterior cruciate ligament reconstruction is influenced by the type of graft fixation used: a prospective randomized study. *Arthroscopy*. 2005;21(11):1337-1341.
10. Gadikota HR, Seon JK, Kozanek M, et al. Biomechanical comparison of single-tunnel–double-bundle and single-bundle anterior cruciate ligament reconstructions. *Am J Sports Med*. 2009;37:962-969.
11. Georgoulis AD, Ristanis S, Chouliaras V, Moraiti C, Stergiou N. Tibial rotation is not restored after ACL reconstruction with a hamstring graft. *Clin Orthop Relat Res*. 2007;454:89-94.
12. Grover D, Thompson D, Hull ML, Howell SM. Empirical relationship between lengthening an anterior cruciate ligament graft and increases in knee anterior laxity: a human cadaveric study. *J Biomech Eng*. 2006;128(6):969-972.

13. Ho JY, Gardiner A, Shah V, Steiner ME. Equal kinematics between central anatomic single-bundle and double-bundle anterior cruciate ligament reconstructions. *Arthroscopy*. 2009;25(5):464-472.
14. Ishibashi Y, Rudy TW, Livesay GA, Stone JD, Fu FH, Woo SL. The effect of anterior cruciate ligament graft fixation site at the tibia on knee stability: evaluation using a robotic testing system. *Arthroscopy*. 1997;13(2):177-182.
15. Jomha NM, Borton DC, Clingeleffer AJ, Pinczewski LA. Long-term osteoarthritic changes in anterior cruciate ligament reconstructed knees. *Clin Orthop Relat Res*. 1999;358:188-193.
16. Lewis PB, Parameswaran AD, Rue JP, Bach BR Jr. Systematic review of single-bundle anterior cruciate ligament reconstruction outcomes: a baseline assessment for consideration of double-bundle techniques. *Am J Sports Med*. 2008;36(10):2028-2036.
17. Li G, DeFrate LE, Zayontz S, Park SE, Gill TJ. The effect of tibiofemoral joint kinematics on patellofemoral contact pressures under simulated muscle loads. *J Orthop Res*. 2004;22(4):801-806.
18. Li G, Papannagari R, DeFrate LE, Yoo JD, Park SE, Gill TJ. The effects of ACL deficiency on mediolateral translation and varus-valgus rotation. *Acta Orthop*. 2007;78(3):355-360.
19. Li G, Park SE, DeFrate LE, et al. The cartilage thickness distribution in the tibiofemoral joint and its correlation with cartilage-to-cartilage contact. *Clin Biomech (Bristol, Avon)*. 2005;20(7):736-744.
20. Ma CB, Francis K, Towers J, Irrgang J, Fu FH, Harner CH. Hamstring anterior cruciate ligament reconstruction: a comparison of bioabsorbable interference screw and EndoButton-post fixation. *Arthroscopy*. 2004;20(2):122-128.
21. Mae T, Shino K, Miyama T, et al. Single- versus two-femoral socket anterior cruciate ligament reconstruction technique: biomechanical analysis using a robotic simulator. *Arthroscopy*. 2001;17(7):708-716.
22. Markolf KL, Park S, Jackson SR, McAllister DR. Anterior-posterior and rotatory stability of single and double-bundle anterior cruciate ligament reconstructions. *J Bone Joint Surg Am*. 2009;91(1):107-118.
23. Marx RG, Jones EC, Angel M, Wickiewicz TL, Warren RF. Beliefs and attitudes of members of the American Academy of Orthopaedic Surgeons regarding the treatment of anterior cruciate ligament injury. *Arthroscopy*. 2003;19(7):762-770.
24. Meredick RB, Vance KJ, Appleby D, Lubowitz JH. Outcome of single-bundle versus double-bundle reconstruction of the anterior cruciate ligament: a meta-analysis. *Am J Sports Med*. 2008;36(7):1414-1421.
25. Nordt WE III, Lotfi P, Plotkin E, Williamson B. The in vivo assessment of tibial motion in the transverse plane in anterior cruciate ligament–reconstructed knees. *Am J Sports Med*. 1999;27(5):611-616.
26. Papannagari R, Gill TJ, Defrate LE, Moses JM, Petruska AJ, Li G. In vivo kinematics of the knee after anterior cruciate ligament reconstruction: a clinical and functional evaluation. *Am J Sports Med*. 2006;34(12):2006-2012.
27. Pederzini L, Adriani E, Botticella C, Tosi M. Technical note: double tibial tunnel using quadriceps tendon in anterior cruciate ligament reconstruction. *Arthroscopy*. 2000;16(5):E9.
28. Petersen W, Tretow H, Weimann A, et al. Biomechanical evaluation of two techniques for double-bundle anterior cruciate ligament reconstruction: one tibial tunnel versus two tibial tunnels. *Am J Sports Med*. 2007;35(2):228-234.
29. Ristanis S, Stergiou N, Patras K, Tsepis E, Moraiti C, Georgoulis AD. Follow-up evaluation 2 years after ACL reconstruction with bone–patellar tendon–bone graft shows that excessive tibial rotation persists. *Clin J Sport Med*. 2006;16(2):111-116.
30. Shino K, Nakata K, Nakamura N, et al. Rectangular tunnel double-bundle anterior cruciate ligament reconstruction with bone–patellar tendon–bone graft to mimic natural fiber arrangement. *Arthroscopy*. 2008;24(10):1178-1183.
31. Takeuchi R, Saito T, Mituhashi S, Suzuki E, Yamada I, Koshino T. Double-bundle anatomic anterior cruciate ligament reconstruction using bone-hamstring-bone composite graft. *Arthroscopy*. 2002;18(5):550-555.
32. Tashman S, Collon D, Anderson K, Kolowich P, Anderst W. Abnormal rotational knee motion during running after anterior cruciate ligament reconstruction. *Am J Sports Med*. 2004;32(4):975-983.
33. Williams RJ III, Hyman J, Petrigliano F, Rozental T, Wickiewicz TL. Anterior cruciate ligament reconstruction with a four-strand hamstring tendon autograft: surgical technique. *J Bone Joint Surg Am*. 2005;87(suppl 1., pt 1):51-66.
34. Woo SL, Kanamori A, Zeminski J, Yagi M, Papageorgiou C, Fu FH. The effectiveness of reconstruction of the anterior cruciate ligament with hamstrings and patellar tendon: a cadaveric study comparing anterior tibial and rotational loads. *J Bone Joint Surg Am*. 2002;84(6):907-914.
35. Yagi M, Wong EK, Kanamori A, Debski RE, Fu FH, Woo SL. Biomechanical analysis of an anatomic anterior cruciate ligament reconstruction. *Am J Sports Med*. 2002;30(5):660-666.
36. Yamamoto Y, Hsu WH, Woo SL, Van Scyoc AH, Takakura Y, Debski RE. Knee stability and graft function after anterior cruciate ligament reconstruction: a comparison of a lateral and an anatomical femoral tunnel placement. *Am J Sports Med*. 2004;32(8):1825-1832.
37. Yasuda K, Kondo E, Ichiyama H, Tanabe Y, Tohyama H. Clinical evaluation of anatomic double-bundle anterior cruciate ligament reconstruction procedure using hamstring tendon grafts: comparisons among 3 different procedures. *Arthroscopy*. 2006;22(3):240-251.
38. Yoo JD, Papannagari R, Park SE, DeFrate LE, Gill TH, Li G. The effect of anterior cruciate ligament reconstruction on knee joint kinematics under simulated muscle loads. *Am J Sports Med*. 2005;33(2):240-246.