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Biomechanical Comparison of Single-Tunnel–Double-Bundle and Single-Bundle Anterior Cruciate Ligament Reconstructions

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Background: Anatomic double-bundle reconstruction has been thought to better simulate the anterior cruciate ligament anatomy. It is, however, a technically challenging procedure, associated with longer operation time and higher cost.

Hypothesis: Double-bundle anterior cruciate ligament reconstruction using a single femoral and tibial tunnel can closely reproduce intact knee kinematics.

Study Design: Controlled laboratory study.

Methods: Eight fresh-frozen human cadaveric knee specimens were tested using a robotic testing system to investigate the kinematic response of the knee joint under an anterior tibial load (130 N), simulated quadriceps load (400 N), and combined torques (5 N·m valgus and 5 N·m internal tibial torques) at 0°, 15°, 30°, 60°, and 90° of flexion. Each knee was tested sequentially under 4 conditions: (1) anterior cruciate ligament intact, (2) anterior cruciate ligament deficient, (3) single-bundle anterior cruciate ligament reconstruction using quadrupled hamstring tendon, and (4) single-tunnel–double-bundle anterior cruciate ligament reconstruction using the same tunnels and quadrupled hamstring tendon graft as in the single-bundle anterior cruciate ligament reconstruction.

Results: Single-tunnel–double-bundle anterior cruciate ligament reconstruction more closely restored the intact knee kinematics than single-bundle anterior cruciate ligament reconstruction at low flexion angles (≤30°) under the anterior tibial load and simulated muscle load ($P < .05$). However, single-tunnel–double-bundle anterior cruciate ligament reconstruction overconstrained the knee joint at high flexion angles (≥60°) under the anterior tibial load and at 0° and 30° of flexion under combined torques.

Conclusion: This double-bundle anterior cruciate ligament reconstruction using a single tunnel can better restore anterior tibial translations to the intact level compared with single-bundle anterior cruciate ligament reconstruction at low flexion angles, but it overconstrained the knee joint at high flexion angles.

Clinical Relevance: This technique could be an alternative for both single-bundle and double-tunnel–double-bundle anterior cruciate ligament reconstructions to reproduce intact knee kinematics and native anterior cruciate ligament anatomy.

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

Many clinical outcome studies have demonstrated satisfactory stability of the knee joint after a single-bundle anterior cruciate ligament (ACL) reconstruction.[7,29,35] However, long-term clinical studies have reported a high incidence of osteoarthritis and knee pain in the ACL-reconstructed knee.[3,7,17,18,30,33] Several prospective studies have reported no differences in the rate of osteoarthritis between patients treated operatively or nonoperatively.[12,24,41] Improving ACL reconstruction techniques that may restore normal knee kinematics and prevent joint degeneration remains a subject of continuing debate in sports medicine research.

Double-bundle ACL reconstruction was introduced to reconstruct the 2 functional bundles (anteromedial [AM] and posterolateral [PL]) of the ACL.[10,45] The 2 functional bundles were reconstructed by creating different numbers of femoral and tibial tunnels (2 tibial/2 femoral, 2 tibial/1

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femoral, 1 tibial/2 femoral, and 1 tibial/1 femoral).[11,25,31,32,45,46] There are clinical and biomechanical studies that have reported that double-bundle ACL reconstruction restores the knee joint stability more closely to the intact level than single-bundle ACL reconstruction.[13,26,27,37,43,44,46] On the contrary, there are also clinical and biomechanical studies showing no significant advantage of the double-bundle ACL reconstruction over the conventional single-bundle ACL reconstruction.[‖] Several factors, such as the tunnel position for single-bundle and double-bundle ACL reconstruction techniques, initial graft tension, angle of graft fixation, fixation devices, and clinical examinations, may have contributed to the discrepancies found in these studies that compared single-bundle and double-bundle ACL reconstruction techniques. Accepted standards for these factors are yet to be established. There is no consensus in the literature showing a significant advantage of the double-bundle ACL reconstruction over the single-bundle ACL reconstruction.

Recently, a few authors have proposed surgical techniques to reconstruct both the functional bundles using a single femoral and tibial tunnel.[11,36,39] Using these techniques, the ACL reconstruction could reproduce the 2 functional bundles by separating the bundles in a single femoral and tibial tunnel. Furthermore, such a reconstruction adheres to a more familiar tunnel placement than a technically challenging double-tunnel ACL reconstruction. To our knowledge, there are no biomechanical studies that have investigated the kinematics of a double-bundle ACL-reconstructed knee using a single tunnel. The purpose of this study was to quantitatively measure the kinematics of the knee joint under 3 external loading conditions after single-tunnel–double-bundle ACL reconstruction and to compare these kinematics with those obtained after a single-bundle ACL reconstruction using a robotic testing system. We hypothesized that single-tunnel–double-bundle ACL reconstruction can restore the anterior-posterior and rotational stabilities to the intact level more closely than the single-bundle ACL reconstruction.

MATERIALS AND METHODS

Eight fresh-frozen human cadaveric knee specimens (age range, 59-64 years) were used in this study. Fluoroscopy and manual stability tests were performed to examine the specimens for osteoarthritis and ACL injuries. If the specimen had either of these conditions, they were eliminated from the study. Each specimen was thawed at room temperature for 24 hours before the testing. The femur and the tibia were truncated approximately 25 cm from the joint line without damaging the soft tissues around the knee. The fibula was fixed in its anatomic position to the tibia by using a bone screw. The musculature around the shafts of the femur and tibia was removed to facilitate the installation of the specimen on the robotic testing system.

The robotic testing system consists of a robotic manipulator (Kawasaki UZ150, Kawasaki Robotics USA Inc, Wixom, Michigan) and a 6 degrees of freedom load cell (JR3 Inc, Woodland, California). This system can be used to study the biomechanics of the knee joint. Several studies have been published to describe the operation of this robotic testing system.[21-23,47] To simulate muscle function, quadriceps muscles were sutured to a rope that was passed through a pulley system on the femoral clamp. Quadriceps muscle loading was simulated by hanging weights on the free end of the ropes. Each specimen was manually flexed 10 times, from full extension to full flexion, to precondition the specimen before it was installed on the robotic testing system.

After the specimen was installed on the robotic testing system, the robotic testing system was used to determine a passive flexion path in the unloaded knee. The passive flexion path was determined by finding the passive positions from full extension to 90° of flexion in 1° increments. The passive position is described as a position of the knee at which all resultant forces and moments at the knee center were minimal (<5 N and <0.5 N·m, respectively).

In this study, each knee was tested under 3 different external loading conditions (anterior tibial load [130 N], simulated quadriceps load [400 N], and combined torques [5-N·m valgus and 5-N·m internal tibial torques]) at selected flexion angles of 0°, 15°, 30°, 60°, and 90° along the passive path. The anterior tibial load was used to simulate clinical examinations such as Lachman and anterior drawer tests. The quadriceps load (applied parallel to the femoral shaft) was used to simulate an isometric extension of the knee. The knees were also subjected to combined torques (5-N·m valgus and 5-N·m internal tibial torques) at 0° and 30° of knee flexion. Under each load, the robot manipulated the knee joint in 5 degrees of freedom until the applied load was balanced by the knee at a selected flexion angle. This position of the knee represents the kinematic response of the knee to the applied load. In this article, the anterior-posterior tibial translations and internal-external tibial rotations of the knee are reported under each external loading condition mentioned above at all selected flexion angles.

After the knee was tested in the intact condition, the knee was tested in 3 different conditions sequentially. First, the ACL was resected through a small medial arthrotomy with the knee flexed to 30° to simulate an ACL-deficient knee condition. The arthrotomy and the skin were repaired in layers by sutures. The ACL-deficient knee kinematics were determined under the same external loading conditions used for the intact knee. Second, single-bundle ACL reconstruction (Figure 1A) was then performed using a quadrupled hamstring (semitendinosus and gracilis tendons) graft. Single-bundle ACL-reconstructed knee kinematics were determined under the 3 external loading conditions. Finally, single-tunnel–double-bundle ACL reconstruction (Figure 1B) was then performed using the same quadrupled hamstring (semitendinosus and gracilis tendons) graft and tunnels that were used for the single-bundle ACL reconstruction. The kinematic responses of the single-tunnel–double-bundle ACL-reconstructed knee under the 3 external loading conditions were determined.

For testing the knee under the 4 different conditions (intact, ACL-deficient, single-bundle ACL-reconstructed, and single-tunnel–double-bundle ACL-reconstructed), the

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[‖] References 2, 5, 8, 15, 16, 25, 27, 34, 38, 46.

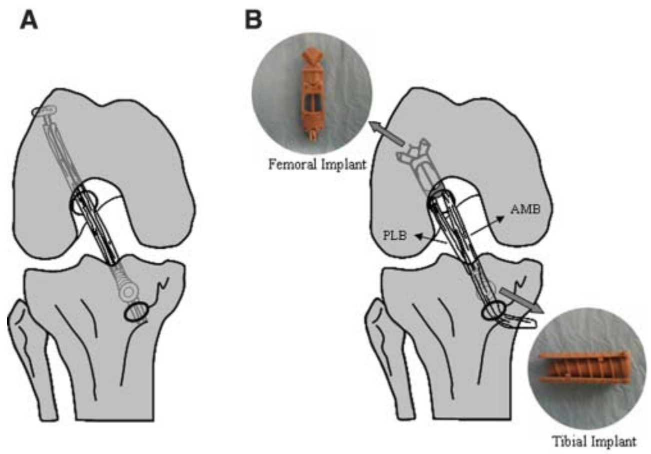

Figure 1. Schematic representation of single-bundle (A) and single-tunnel–double-bundle (B) ACL reconstructions. AMB, anteromedial bundle; PLB, posterolateral bundle.

passive path determined under the intact knee condition was used as the reference position to measure the knee kinematics in response to the external loads. This procedure eliminated any variability in the starting positions before the external loads were applied and facilitated a repeated-measures analysis of the data.

Surgical Techniques

Single-Bundle ACL Reconstruction. The surgery was performed with the specimen installed on the robotic system. All the surgeries were performed by a single surgeon. The surgery began by harvesting the semitendinosus and gracilis tendons used as the graft material for both ACL reconstructions. The tibial tunnel was reamed through the anteromedial surface of the tibia at the level of the tibial tubercle, passing through the landmarks of the center of the ACL remnant. A Kirschner wire was inserted through the tibial tunnel, aimed at the 2- or 10-o'clock position and 7 mm anterior from the posterior bony edge of the intercondylar wall of the femur. The femoral tunnel was reamed through the tibial tunnel with the knee flexed to 90° using a 4.5-mm– diameter EndoButton drill (Smith & Nephew Endoscopy, Andover, Massachusetts) to the lateral cortex of the distal femur. A final 35-mm–long femoral socket was then created by a cannulated reamer that matched the prepared graft diameter (8-8.5 mm). For the single-bundle ACL reconstruction, the graft was passed though the tibial tunnel into the joint and finally through the femoral socket and was secured with an EndoButton CL (Smith & Nephew Endoscopy). The tibia was then loaded posteriorly with a 40-N load at 0° and the graft was secured at the tibial end by a metallic interference screw (Arthrex, Naples, Florida) with 40 N of axial graft tension. The arthrotomy and the skin were repaired using sutures.

Single-Tunnel–Double-Bundle ACL Reconstruction. The femoral and tibial tunnels used for single-bundle ACL reconstruction were dilated to 10 mm and were reused for single-tunnel–double-bundle ACL reconstruction. The graft used in single-bundle ACL reconstruction was reused for the single-tunnel–double-bundle ACL reconstruction. If there was any significant damage noticed to the graft after the single-bundle ACL reconstruction, the specimen was excluded from the study. The semitendinosus tendon and the gracilis tendon were passed through the AperFix femoral implant (Cayenne Medical, Scottsdale, Arizona) separately (Figure 1B) and looped to form 4 strands. Two strands of the semitendinosus tendon were used to represent the AM bundle, while the 2 gracilis tendon strands represented the PL bundle. The design of the AperFix femoral implant facilitates the separation of the AM and PL bundles (Figure 2A). This implant was passed through the tibial tunnel into the femoral tunnel and deployed in standard fashion. Before deployment, the 2 bundles were positioned inside the femoral tunnel in the native ACL bundle positions. After the graft was secured at the femoral end, the distal end of the graft was rotated by 90° in a clockwise direction for the left knee (counterclockwise for the right knee), giving rise to the AM and PL bundles (Figure 2B). The AperFix tibial implant (Figure 1B) was used to fix the tibial end of the graft at the same knee position and posterior load as used for the single-bundle ACL reconstruction. A 40-N graft tension was simultaneously applied to the 2 bundles during the graft fixation.

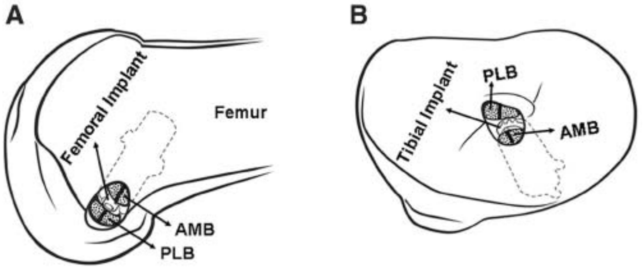

Figure 2. Schematic illustration of the femoral implant and the separation of the 2 bundles in the femoral tunnel (A) and the tibial implant and the separation of the 2 bundles in the tibial tunnel (B). AMB, anteromedial bundle; PLB, posterolateral bundle.

Data Analysis

The study was designed to evaluate the kinematic (anterior tibial translation and internal tibial rotation) response of the same knee under 4 different conditions (ACL intact, ACL deficient, single-bundle ACL reconstructed, and single-tunnel–double-bundle ACL reconstructed). This facilitated a within-subjects analysis of knee kinematics. Repeated-measures analysis of variance was used to detect statistically significant differences in kinematics of the knee under the 4 different conditions. If significant differences were detected, post hoc comparisons were made among the 4 groups using the Student-Newman-Keuls test. Differences were considered statistically significant at $P < .05$.

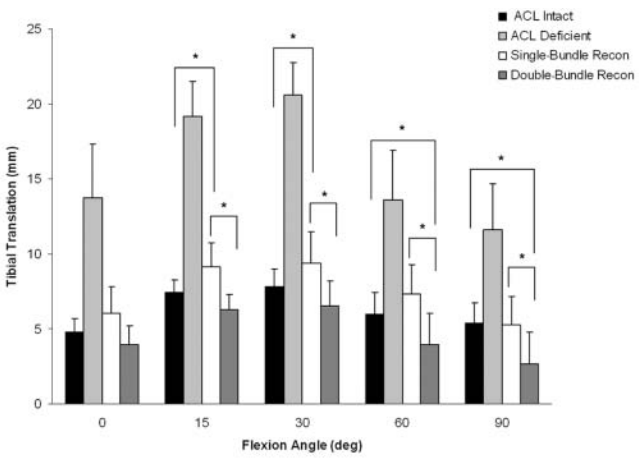

Figure 3. Anterior tibial translation under anterior tibial load in the 4 different knee conditions. Anterior tibial translations of the ACL-deficient knee were significantly different from the intact, single-bundle ACL-reconstructed, and single-tunnel–double-bundle ACL-reconstructed knee at all flexion angles. Error bars represent standard deviation. *$P < .05$. Recon, reconstruction.

RESULTS

Kinematic Response Under Anterior Tibial Load (130 N)

Under the anterior tibial load, the largest anterior tibial translations of the ACL-intact knee were observed at 15° and 30° of flexion as 7.4 ± 0.8 mm and 7.8 ± 1.2 mm, respectively (Figure 3). After the ACL was resected, the anterior tibial translations of the knee increased by 157.6% and by 162.9% at 15° and 30° of flexion, respectively, compared with the intact knee. The anterior tibial translations of the ACL-deficient knee were significantly greater than the ACL-intact knee at all flexion angles ($P < .05$). The anterior tibial translations after the single-bundle ACL reconstruction were greater than the intact knee by 22.9% at 15° and by 20.1% at 30° of flexion. These translations for the single-bundle ACL reconstruction were significantly greater than those of the ACL-intact knee at 15° and 30° of flexion ($P < .05$). No significant differences were observed between the intact knee and single-bundle ACL reconstruction at 0°, 60°, and 90° of flexion ($P > .05$). Anterior tibial translations of the ACL-intact knee were closely reproduced after the single-tunnel–double-bundle ACL reconstruction at 0°, 15° and 30° of flexion ($P > .05$). Anterior tibial translations of the single-tunnel–double-bundle ACL reconstruction were significantly lower than the intact knee by 33.67% and by 50.0% at 60° and 90° of flexion ($P < .05$). Anterior tibial translations for the single-tunnel–double-bundle ACL reconstruction were significantly lower than the single-bundle ACL reconstruction at 15°, 30°, 60°, and 90° of flexion ($P < .05$).

Kinematic Response Under Simulated Quadriceps Load (400 N)

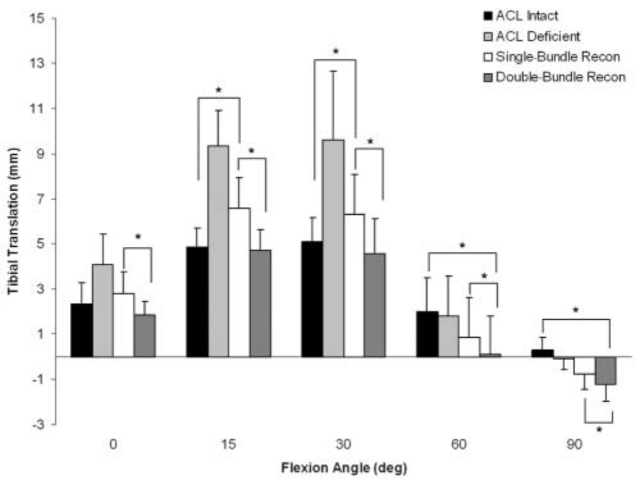

Figure 4. Tibial translation under quadriceps load in the 4 different knee conditions. Tibial translations of the ACL-deficient knee were significantly different from the intact, single-bundle ACL-reconstructed and the single-tunnel–double-bundle ACL-reconstructed knee at all flexion angles. +Anterior tibial translation; –posterior tibial translation; *$P <.05$. Error bars represent standard deviation. Recon, reconstruction.

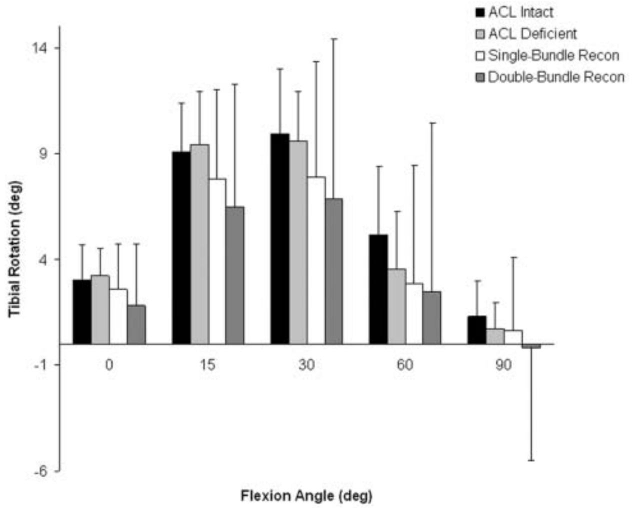

Figure 5. Tibial rotations under the simulated quadriceps load in the 4 different knee conditions. +Internal tibial rotations; –external tibial rotations. Error bars represent standard deviation. Recon, reconstruction.

In response to the quadriceps load, anterior tibial translations of the ACL-intact knee were 4.9 ± 0.8 mm at 15° and 5.1 ± 1.1 mm at 30° of flexion (Figure 4). Anterior tibial translations of the ACL-deficient knee increased by 91.4% at 15° and by 88.8% at 30° of flexion compared with the intact knee. At 0°, 15°, and 30° of flexion, anterior tibial translations of the ACL-deficient knee were significantly greater than the ACL-intact knee ($P < .05$). After single-bundle ACL reconstruction, the anterior tibial translations were significantly greater than the intact knee by 35.3% and by 23.7% at 15° and 30° of flexion ($P < .05$). The tibia of the single-tunnel–double-bundle ACL-reconstructed knee translated 3.4% less than the intact knee at 15° and

TABLE 1
Tibial Translation (Mean ± Standard Deviation [mm]) Under Combined Torques[a]

Flexion Angle	ACL Intact	ACL Deficient	Single-Bundle ACL Reconstruction	Single-Tunnel–Double-Bundle ACL Reconstruction
0°	+1.3 ± 1.2	+3.8 ± 1.9[b]	+1.7 ± 1.2[cd]	–0.2 ± 1.4[bc]
30°	+3.3 ± 1.6	+5.2 ± 2.2[b]	+4.0 ± 2.1[cd]	+2.1 ± 1.4[bc]

[a] +Anterior translation; –posterior translation; ACL, anterior cruciate ligament.

[b] *P* < .05; significantly different from ACL-intact knee.

[c] *P* < .05; significantly different from ACL-deficient knee.

[d] *P* < .05; significantly different from single-tunnel–double-bundle ACL reconstruction.

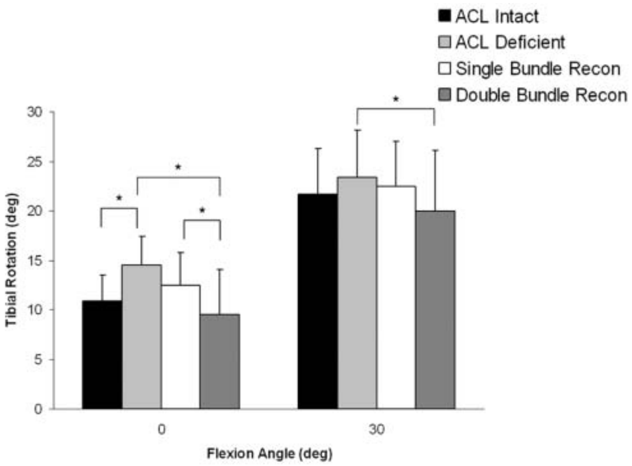

Figure 6. Internal tibial rotations under combined torques in the 4 different knee conditions. Error bars represent standard deviation. **P* < .05. Recon, reconstruction.

10.40% less than the intact knee at 30° of flexion. These translations after single-tunnel–double-bundle ACL reconstruction were statistically similar to the ACL-intact knee at 0°, 15°, and 30° of flexion (*P* > .05). Anterior tibial translations for the single-tunnel–double-bundle ACL reconstruction were significantly lower than those of the single-bundle ACL reconstruction at 0°, 15°, 30°, and 60° of flexion (*P* < .05). Anterior tibial translations of both the ACL reconstructions were significantly different from the intact knee at 60° and 90° of flexion (*P* < .05). There were no significant differences (*P* > .05) in tibial rotations among the 4 different knee conditions at all flexion angles (Figure 5).

Kinematic Response Under Combined Torques (5-N·m Valgus and 5-N·m Internal Tibial Torques)

In response to the combined torques, the tibia of the ACL-intact knee translated anteriorly by 1.3 ± 1.2 mm at 0° and 3.3 ± 1.6 mm at 30° of flexion. The anterior tibial translations of the ACL-deficient knee were significantly increased, by 196.9% at 0° and by 58.2% at 30° of flexion, compared with the ACL-intact knee (*P* < .05). The anterior tibial translations of the single-bundle ACL-reconstructed knee were 33.9% and 22.2% greater than the intact knee at 0° and 30° of flexion, respectively. The anterior tibial translations of the single-tunnel–double-bundle ACL reconstruction were significantly lower than those of the ACL-intact, ACL-deficient, and single-bundle ACL-reconstructed knee at 0° and 30° of flexion (*P* < .05) (Table 1).

The internal tibial rotations of the ACL-intact knee were not significantly different (*P* > .05) from both the single-bundle and single-tunnel–double-bundle ACL-reconstructed knee (Figure 6).

DISCUSSION

Extensive biomechanical studies have been conducted to evaluate the efficiency of single-bundle and double-bundle ACL reconstructions.[34,40,42,44] In this study, we investigated the effectiveness of a single-tunnel–double-bundle ACL reconstruction technique that uses a single femoral and tibial tunnel to restore the knee joint stability to the intact level by using a robotic testing system. Our results demonstrated that the single-tunnel–double-bundle ACL reconstruction was able to closely restore the intact knee kinematics under an anterior tibial load and simulated quadriceps load at low flexion angles (≤30°), but overconstrained the knee joint at high flexion angles (≥60°) under anterior tibial load and under combined torques.

We found that ACL deficiency resulted in increased anterior tibial translations compared with the ACL-intact knee at all flexion angles under the anterior tibial load and simulated quadriceps load. Single-bundle ACL reconstruction reduced these increased anterior tibial translations significantly but could not restore them to the intact level at low flexion angles. These results are consistent with previous biomechanical studies that used similar loading conditions.[42,44,47]

The single-tunnel–double-bundle ACL reconstruction significantly reduced the anterior tibial translations of the ACL-deficient knee at all flexion angles under anterior tibial load and simulated quadriceps load. No significant differences between the anterior tibial translations of the single-tunnel–double-bundle ACL reconstruction and ACL-intact knee were observed at low flexion angles under both the loading conditions. In a biomechanical study conducted by Yagi et al,[44] it was reported that the anatomic double-tunnel–double-bundle ACL reconstruction resulted in significantly greater anterior tibial translations compared with the ACL-intact knee at full extension and 30° of flexion in response to an anterior tibial load of 134 N. In other biomechanical studies, Petersen et al[32] and Zantop et al[48] reported no significant difference in anterior tibial translations between the ACL-intact knee and anatomic double-tunnel–double-bundle ACL-reconstructed knee under the anterior tibial load of 134 N. Our results showed that the single-tunnel–double-bundle ACL reconstruction resulted in a slightly overconstrained knee at 60° and 90° of flexion under the anterior tibial load and simulated quadriceps load. However, the maximum difference in anterior tibial translation between the ACL-intact knee and the single-tunnel–double-bundle ACL-reconstructed knee in response to the 2 loading conditions was less than 3 mm at high flexion angles (≥60°). These results suggest that this single-tunnel–double-bundle ACL reconstruction could produce clinically satisfactory anterior stability.

The internal tibial rotations of the single-bundle ACL-reconstructed and the single-tunnel–double-bundle ACL-reconstructed knee were decreased compared with the intact knee, although no significant differences at all the selected flexion angles under simulated quadriceps load were observed ($P > .05$). Recently, Yoo et al[47] reported significantly reduced internal tibial rotations after bone–patellar tendon–bone reconstruction compared with the intact knee at low flexion angles. These data indicate that ACL reconstruction might result in overconstraining the tibial rotation.

Previously, biomechanical studies have shown that single-bundle ACL reconstruction could not restore the anterior stability under combined torques (10-N·m valgus torque and 5-N·m or 10-N·m internal tibial torque).[42,44] In this study, anterior tibial translations under combined torques (5-N·m valgus and 5-N·m internal tibial torques) showed no significant difference between single-bundle ACL reconstruction and the ACL intact knee at 0° and 30° of flexion, whereas, the single-tunnel–double-bundle ACL reconstruction resulted in an overconstrained knee at 0° and 30° of flexion under the same loading condition. In a recent biomechanical study, Zantop et al[48] reported no significant difference in anterior tibial translation between the ACL-intact and anatomic double-tunnel–double-bundle ACL-reconstructed knee under combined torques, while other biomechanical studies showed that anatomic double-tunnel–double-bundle ACL reconstruction resulted in greater anterior tibial translations than the ACL-intact knee at low flexion angles (≤30°) under combined torques.[32,44] This discrepancy in the anterior tibial translations under combined torques may be due to the different loading conditions and surgical techniques used among these studies.

No significant differences were observed in the internal tibial rotations between ACL-intact, single-bundle ACL-reconstructed, and the single-tunnel–double-bundle ACL-reconstructed knee in this study under combined torques. These results may suggest that combined internal and valgus torques are an inefficient loading condition for investigating the rotational stability in cadaveric specimens. Comprehensive loading conditions are required to truly assess the ability of ACL and ACL graft to restrain tibial rotations.

It should be noted that, in this study, both ACL graft bundles were fixed at 0° with an axial graft tension of 40 N. This was done to simulate widely used operative procedures for single-bundle ACL reconstruction. However, the 2 bundles of the ACL do not function in the same manner along the flexion path.[6,14,19,20] To achieve the native tension pattern in the AM bundle and PL bundle along the flexion path of the knee, different tensioning strategies for the 2 graft bundles and the graft fixation angle may be needed, as practiced in various double-tunnel–double-bundle ACL reconstruction techniques.[4,13,27,46] This study showed that the single-tunnel–double-bundle ACL reconstruction resulted in an overconstrained knee at high flexion angles (≥60°). This may be because both the bundles were tensioned and fixed at 0°, which may have resulted in overtightening of the AM bundle at high flexion angles. However, it is important to understand that these results represent the time-zero responses of the knee joint. It is known that there is a significant decrease in the initial graft tension with cyclic loading after ACL reconstruction, which results in increased laxity of the knee joint.[1,9,28] A long-term clinical follow-up study is required to truly assess the ability of this single-tunnel–double-bundle ACL reconstruction technique to restore the normal knee joint kinematics postoperatively.

The single-tunnel–double-bundle ACL reconstruction technique introduced in this study has distinct differences compared with the double-tunnel–double-bundle ACL reconstruction. Although the double-tunnel–double-bundle ACL reconstruction technique is designed to reproduce the 2 functional bundles, it is a technically challenging procedure. The double-tunnel–double-bundle ACL reconstruction is also associated with an increase in the duration of surgery and higher cost as compared with the traditional single-bundle ACL reconstruction.[11,16,34,45] In addition, the double-tunnel–double-bundle ACL reconstruction makes a revision surgery difficult. The single-tunnel–double-bundle technique introduced in this study is aimed to reproduce both the functional bundles of the ACL by creating a single femoral and tibial tunnel as opposed to creating 2 tunnels in the tibia and femur. The surgical procedure is more familiar to surgeons and a revision could be performed as performed for a single-bundle ACL reconstruction. However, the double-tunnel–double-bundle technique has the advantage of being able to tension the 2 graft bundles at different flexion angles while using different initial graft tensions, whereas in the single-tunnel–double-bundle technique, these various combinations of graft bundle fixation angles and different graft bundle tensions are difficult to perform. The kinematic results observed from this study and the ease of the surgical procedure demonstrate that the single-tunnel–double-bundle technique may be a potential alternative to single-bundle and double-tunnel–double-bundle ACL reconstruction techniques.

There are some limitations to the current study. The study was designed to investigate the combined effect of the 2 bundles and the fixation device in single-tunnel–double-bundle ACL reconstruction on the kinematics of the knee joint. Therefore, the current data do not provide information on the amount of stability provided by the individual bundles of the reconstructed ACL. Because this was a cadaveric study, we cannot speculate on how much of the improvement in the kinematics observed in single-tunnel–double-bundle ACL reconstruction of this study would carry over to clinical outcomes. However, our design facilitated a controlled repeated-measures analysis of kinematics using the same specimen under different loading conditions. The order for testing the 2 surgical techniques was not randomized because the single-tunnel–double-bundle ACL reconstruction required a larger femoral tunnel than that required for single-bundle ACL reconstruction. A 7-mm offset aimer was used for both single-bundle and single-tunnel–double-bundle

ACL reconstructions. The femoral tunnel diameter for the single-bundle ACL reconstruction ranged from 8 to 8.5 mm. Hence, a 7-mm offset aimer might have influenced the kinematic outcomes of the single-bundle ACL reconstruction. These limitations indicate that a patient follow-up study might be necessary to further evaluate the efficacy of the single-tunnel–double-bundle ACL reconstruction technique in restoration of normal knee kinematics and prevention of degenerative changes.

CONCLUSION

On the basis of this investigation, we conclude that the single-tunnel–double-bundle ACL reconstruction is capable of restoring the knee stability more closely to the ACL-intact knee at low flexion angles (≤30°) compared with the single-bundle ACL reconstruction. However, the single-tunnel–double-bundle ACL reconstruction overconstrained the knee joint at high flexion angles (≥60°). Although we cannot speculate on how this overconstrained pattern may affect the clinical outcomes, this technique is similar to the more familiar single-bundle ACL reconstruction and could be an alternative to the technically demanding double-tunnel–double-bundle ACL reconstruction. Clinical follow-up studies need to be performed in the future to analyze the potential benefits of single-tunnel–double-bundle ACL reconstruction.

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