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Biomechanical Evaluation of Knee Joint Laxities and Graft Forces After Anterior Cruciate Ligament Reconstruction by Anteromedial Portal, Outside-In, and Transtibial Techniques

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Abstract

Background—Recently, anatomic anterior cruciate ligament (ACL) reconstruction is emphasized to improve joint laxity and to potentially avert initiation of cartilage degeneration. There is a paucity of information on the efficacy of ACL reconstructions by currently practiced tunnel creation techniques in restoring normal joint laxity.

Study Design—Controlled laboratory study.

Hypothesis—Anterior cruciate ligament reconstruction by the anteromedial (AM) portal technique, outside-in (OI) technique, and modified transtibial (TT) technique can equally restore the normal knee joint laxity and ACL forces.

Methods—Eight fresh-frozen human cadaveric knee specimens were tested using a robotic testing system under an anterior tibial load (134 N) at 0°, 30°, 60°, and 90° of flexion and combined torques (10-N·m valgus and 5-N·m internal tibial torques) at 0° and 30° of flexion. Knee joint kinematics, ACL, and ACL graft forces were measured in each knee specimen under 5 different conditions (ACL-intact knee, ACL-deficient knee, ACL-reconstructed knee by AM portal technique, ACL-reconstructed knee by OI technique, and ACL-reconstructed knee by TT technique).

Results—Under anterior tibial load, no significant difference was observed between the 3 reconstructions in terms of restoring anterior tibial translation ($P > .05$). However, none of the 3 ACL reconstruction techniques could completely restore the normal anterior tibial translations ($P < .05$). Under combined tibial torques, both AM portal and OI techniques closely restored the normal knee anterior tibial translation ($P > .05$) at 0° of flexion but could not do so at 30° of flexion ($P < .05$). The ACL reconstruction by the TT technique was unable to restore normal anterior tibial translations at both 0° and 30° of flexion under combined tibial torques ($P < .05$). Forces experienced by the ACL grafts in the 3 reconstruction techniques were lower than those experienced by normal ACL under both the loading conditions.

Conclusion—Anterior cruciate ligament reconstructions by AM portal, OI, and modified TT techniques are biomechanically comparable with each other in restoring normal knee joint laxity and in situ ACL forces.

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Clinical Relevance—Anterior cruciate ligament reconstructions by AM portal, OI, and modified TT techniques result in similar knee joint laxities. Technical perils and pearls should be carefully considered before choosing a tunnel creating technique.

Keywords

anterior cruciate ligament reconstruction; anteromedial portal; outside-in; transtibial; knee kinematics

The anterior cruciate ligament (ACL) reconstruction has been widely accepted to be the standard of care for ACL-ruptured patients to minimize the risk of further meniscal and chondral injuries, restore preinjury level of activity, and potentially prevent posttraumatic osteoarthritis. Anterior cruciate ligament reconstruction is performed by creating different numbers of bone tunnels in the tibia and femur to facilitate graft fixation within the tunnel. While several authors have proposed creating more than one tunnel in the tibia and femur,^{5,18,21} creation of a single tibial and femoral tunnel remains the most widely practiced technique for ACL reconstruction.¹⁶ There are 3 arthroscopic approaches in creating the femoral tunnel: through the tibial tunnel (tibial tunnel–dependent or more commonly known as transtibial [TT] technique) or independent of the tibial tunnel (via an anteromedial [AM] portal or via a 2-incision technique also known as outside-in [OI] technique).

Since the introduction of the TT approach to create the femoral tunnel, it has been well adopted, with over 70% of the surgeons using this technique as of 2009¹⁶ because of the ease of the procedure, reduction in surgical time, and reduced postoperative morbidity. With recent emphasis on anatomic tunnel placement, the TT approach has been critically scrutinized, as it is believed by some authors to produce nonanatomic tibial and femoral tunnels.¹³ Therefore, a transition to creating a femoral tunnel independent of the tibial tunnel by either the AM portal or a 2-incision technique is recommended by several authors.^{1,3,20} While, technically, each of these 3 approaches have their perils and advantages when compared with one another, there is a paucity of evidence to elicit the relative biomechanical and clinical benefits of these approaches.

Recently, few studies have compared the biomechanical efficacies of ACL reconstructions performed by traditional TT and AM portal techniques in restoring normal knee kinematics.^{3,20} It is reported that the kinematics of the normal knee were better reproduced when the ACL was reconstructed by the AM portal technique than the traditional TT technique. The guidelines for the TT techniques used in these studies resulted in nonanatomic tunnel placement. A modified TT technique, which can achieve a lower femoral tunnel on the lateral intercondylar notch compared with traditional TT technique, could potentially restore the normal knee biomechanics. Therefore, the objective of this study was to compare the knee joint laxities between the 3 femoral tunnel drilling approaches, namely the modified TT technique, AM portal technique, and OI technique. We hypothesized that there will be no significant differences in the knee joint laxities after ACL reconstruction by these 3 techniques.

MATERIALS AND METHODS

To investigate the hypothesis, a repeated-measures study design was implemented in which 5 different knee conditions were tested in each of the 8 knee specimens used. The fresh-frozen human cadaveric knee specimens (mean age, 56.4 years; range, 46–77 years) were obtained from a tissue bank (MedCure Inc, Portland, Oregon) and were stored at our institution at -20°C . Each cadaveric knee was thawed for 24 hours before the testing and was examined for degenerative changes and ACL injury by using fluoroscopy and manual

stability tests. Through a medial parapatellar miniarthrotomy, each specimen was examined for cartilage injury more than grade II of Outerbridge classification and meniscal tears. We did not observe any of the above-mentioned abnormalities in all the specimens used for this study. The musculature surrounding the diaphyses of the femur and tibia was stripped with all the soft tissues around the knee intact (skin, knee ligaments, joint capsule, and musculature). The tibial and femoral shafts were then potted in bone cement to facilitate the attachment of the specimen to the robotic testing system.

Details on the operation of the robotic testing system are presented in the literature.^{6,14} After the installation of the knee specimen on the robotic testing system, a passive flexion path of the knee was determined between 0° and 120° of flexion. During this process, forces and moments at the knee center were minimized (<5.0 N and <0.5 N·m, respectively) at each flexion angle by manipulating the tibia in 5 degrees of freedom. Resultant tibial position at each flexion angle with respect to the fixed femur was recorded for later testing. After the determination of the passive path, each specimen was tested under 5 different conditions by subjecting them to an anterior tibial load of 134 N and combined valgus and internal torques of 10 N·m and 5 N·m, respectively. The kinematic responses for the knee joint and the forces in the ACL and ACL grafts were measured under these loading conditions. The sequence of 5 knee conditions was ACL-intact knee, ACL-deficient knee, and ACL-reconstructed knee by 3 femoral tunnel drilling techniques. The sequence of ACL reconstructions was alternated between the 3 techniques among the 8 specimens.

After the intact knee testing, ACL deficiency was achieved by resecting the ACL through a small medial parapatellar arthrotomy. The ACL-deficient knee was then tested after the arthrotomy and skin were repaired in layers by sutures. Anterior cruciate ligament reconstruction began by harvesting the semitendinosus and gracilis tendons, which were prepared by suturing 30 mm on each end of the 2 grafts. These grafts were then 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). Before the graft was passed through the tunnels, each strand of the graft was doubled over a 20-mm EndoButton CL (Smith & Nephew, Memphis, Tennessee) loop to form a quadruple hamstring graft-implant construct. The size of the prepared quadruple hamstring tendon graft for each of the 8 specimens was 8 mm. All surgeries were performed by a parapatellar arthrotomy incision, and the incision was repaired by sutures after the surgery. Surgical techniques for the 3 ACL reconstructions that followed the ACL-deficient condition are described below.

TT Technique

To facilitate free motion of the tibia for the ease of surgery, the tibial end of the fixation was detached from the robotic arm at full extension position, while the femoral end of the fixation was retained to the pedestal. After the tibial and femoral tunnels were created, the tibial fixation to the robotic arm was accurately restored to its original position. An ACL tibial guide (DePuy Mitek) set to 50° was used for aiming and placing a K-wire. Intra-articularly, the tip of the tibial tunnel guide was positioned at the center of the posterolateral quadrant of the ACL footprint (Figure 1). The extra-articular starting position for the guide pin ranged from a point lateral to the anterior margin of the medial collateral ligament (MCL) to the midpoint of the anterior margin of the MCL and medial border of the tibial tubercle. After a K-wire was inserted with the above-mentioned extra-articular and intra-articular reference points, a cannulated drill bit (diameter of the drill bit was equal to the diameter of the prepared quadrupled hamstring graft) was used to drill the tibial tunnel with the K-wire as the directional guide. For preparation of the femoral tunnel, a 7.5-mm offset guide (DePuy Mitek) was inserted through the tibial tunnel and hooked at the “over-the-top” position at 90° of flexion. The offset guide was then laterally rotated¹⁹ until the K-wire, inserted through the cannula of the offset guide, was located as close to the center of the

femoral ACL footprint as possible. After confirmation of this anatomic position, the K-wire was drilled into the lateral femoral condyle until it exited out of the lateral thigh. With the inserted K-wire as the reference, a femoral tunnel was created to the lateral cortex of the distal femur using a 4.5-mm EndoButton drill (Smith & Nephew Endoscopy, Andover, Massachusetts) followed by a 30-mm-long socket created by a cannulated drill bit that matched the prepared quadruple hamstring graft diameter. The graft-implant construct was then passed through the tibia into the joint and through the femoral socket and was secured by flipping the EndoButton on the outer femoral cortex. The distal end of the graft was then fixed in the tibial tunnel by INTRAFIX screw (DePuy Mitek) with a diameter that matched the tunnel diameter at full extension and 40 N of axial graft tension.

AM Portal Technique

After the biomechanical testing of ACL reconstruction by the TT technique, the graft was removed from the joint by releasing the fixation. The tibial and femoral tunnels created previously were then filled with bone cement to permit reuse of the same specimens for reconstructing the ACL by the AM portal technique. The tibial tunnel was prepared first by drilling a K-wire through the center of the ACL footprint using a tibial guide (DePuy Mitek) set to 50°. With the inserted K-wire as the reference, a cannulated drill bit with a diameter that matched the graft diameter was then used to create the tibial tunnel. After drilling the tibial tunnel, a K-wire was inserted at the anatomic center of the ACL femoral footprint through the AM portal with the knee flexed to 120°. A femoral tunnel was then reamed to the lateral cortex of the distal femur using a 4.5-mm EndoButton drill over the inserted K-wire. Further, a 30-mm-long femoral socket, with a diameter matched to graft diameter, was then created by an acorn-head reamer (DePuy Mitek) to prevent cartilage damage. The previously used graft-implant construct was passed through the tibial tunnel and femoral socket and fixed by flipping the EndoButton on the outer femoral cortex. Again, the tibial end of the graft was fixed by INTRAFIX screw with a diameter that matched the tunnel diameter at full extension while 40 N of axial graft tension was constantly applied.

Two-Incision Technique

After the graft was removed from the joint, both the tibial and femoral tunnels were filled with bone cement. The tibial tunnel for the 2-incision technique was created at the same location as the tibial tunnel in the AM portal technique. For the creation of the femoral tunnel, we made a longitudinal incision over the lateral thigh and split the iliotibial band, and the lateral aspect of the distal femoral metaphysis was accessed by retracting the vastus lateralis muscle. With the tibia flexed to 70°, a tibial guide (DePuy Mitek) set to 70° was inserted through the central portal, and intra-articularly, the tip of the guide was positioned at the anatomic center of the ACL footprint. Extra-articularly, the guide sleeve was placed proximal and anterior to the lateral epicondyle to avoid injury to lateral soft tissue structures and to maximize tunnel length. With these reference points, a K-wire was drilled through the lateral femoral condyle until it protruded at the center of the ACL footprint. Then, a femoral tunnel was established by advancing a reamer through the lateral femoral cortex along the previously inserted K-wire until it was proud at the ACL footprint. A 14-mm spiked washer (DePuy Mitek) was impacted onto the lateral femoral cortex at the entrance of the tunnel to facilitate the use of EndoButton (Figure 2). The graft-implant construct was then passed through the tibial tunnel into the femoral tunnel and fixed here by flipping the EndoButton on the spiked washer (Figure 2). Similar to the other techniques, the tibial end of the graft was fixed by INTRAFIX screw with a diameter that matched the tunnel diameter at full extension and with 40 N of constant axial graft tension.

Data and Statistics

The data obtained from each knee specimen under the 5 different conditions (ACL intact, ACL deficient, ACL reconstruction by TT technique, ACL reconstruction by AM portal technique, and ACL reconstruction by OI technique) included kinematics of the knee joint, ACL, and ACL graft forces. The data represent the responses of the knee joint to 134 N of anterior tibial load at 0°, 30°, 60°, and 90° of flexion and combined valgus and internal torques of 10 N-m and 5 N-m, respectively, at 0° and 30° of flexion. Because each specimen was tested under all 5 different conditions, this within-subjects analysis data were statistically analyzed by repeated-measures analysis of variance (ANOVA). When significant differences were detected, post hoc comparisons were made among the 5 groups using the Newman-Keuls test. Statistical significance was assumed when P value was less than .05.

RESULTS

Knee Kinematics, ACL, and ACL Graft Forces Under Anterior Tibial Load of 134 N

In the ACL-intact knee, anterior tibial translations ranged from 3.9 ± 0.9 mm at 0° to 7.1 ± 2.7 mm at 30° of flexion (Figure 3). After the resection of the ACL, anterior tibial translations significantly increased by a factor of 2.84, 2.91, 2.77, and 2.75 compared with the intact knee at 0°, 30°, 60°, and 90° of flexion, respectively ($P < .05$). These increased anterior tibial translations were significantly decreased by all 3 ACL reconstructions ($P < .05$) (Figure 3). However, none of these ACL reconstructions were able to restore the normal anterior tibial translations at all selected flexion angles ($P < .05$). The maximum differences in anterior tibial translations between the intact knees and ACL-reconstructed knees by AM portal technique, OI technique, and TT technique were 2.7 ± 1.7 mm at 90°, 2.4 ± 1.6 mm at 60°, and 3.1 ± 2.1 mm at 60° of flexion, respectively. No significant differences in anterior tibial translations were observed between the 3 ACL reconstructions ($P > .05$). No significant differences were observed between intact knee ACL force and ACL graft forces in knees reconstructed by any of the 3 reconstructions (Figure 4).

Knee Kinematics, ACL, and ACL Graft Forces Under Combined Valgus (10 N-m) and Internal (5 N-m) Torques

Under combined tibial torques, anterior tibial translations of the ACL-intact knee were 0.3 ± 0.7 mm at 0° of flexion and 3.0 ± 2.2 mm at 30° of flexion (Figure 5). Similar to the anterior tibial load, combined torques produced a significant increase in anterior tibial translations in ACL deficient knees by a factor of 11.7 and 3.2 compared with the intact knees at 0° and 30° of flexion, respectively ($P < .05$). All 3 ACL reconstructions significantly reduced these increased anterior tibial translations observed in ACL-deficient knees ($P < .05$) (Figure 5). Differences in anterior tibial translations between the intact knees and ACL-reconstructed knees by AM portal technique and OI technique were 0.7 ± 1.1 mm and 0.6 ± 1.2 mm at 0° of flexion ($P > .05$) and 1.7 ± 0.5 mm and 1.9 ± 1.0 mm at 30° of flexion ($P < .05$), respectively. Anterior cruciate ligament reconstructions by both AM portal and OI techniques closely restored the normal anterior tibial translations at 0° but failed to do so at 30° of flexion. In contrast, statistically significant differences in anterior tibial translations between the intact knees and ACL-reconstructed knees by the TT technique were observed both at 0° (1.5 ± 1.1 mm) and 30° (3.0 ± 1.6 mm) of flexion ($P < .05$). When comparing the 3 reconstructions, no significant difference in anterior tibial translation was found between them at 0° of flexion, and significant difference between the TT technique reconstruction compared with AM and OI technique reconstructions was found at 30° of flexion (Figure 5). On average, forces experienced by ACL graft in ACL-reconstructed knees by AM and OI techniques were 14.5% and 17.8% lower than the forces experienced by the ACL at 0° of flexion ($P > .05$) (Figure 6), and these values further decreased to 34.7% and 33.6% at 30°

of flexion, respectively ($P < .05$) (Figure 6). The forces experienced by ACL graft in TT technique reconstruction were significantly lower by 41.1% and 35.4% at 0° and 30° flexion, respectively (Figure 6).

DISCUSSION

Restoring normal knee joint laxities is the primary goal of an ACL reconstruction. This study evaluated the efficacies of 3 different tunnel creation techniques for ACL reconstruction in restoring normal knee laxities and ACL forces under 2 different loading conditions. The results of this study support the hypothesis that ACL reconstruction by modified TT, AM portal, and OI techniques results in similar knee joint laxities. Further, none of these techniques were able to restore the normal knee joint laxities under the external loads applied. Similarly, ACL grafts in all techniques carried lower forces than the native ACL.

Persistent joint instability and development of degenerative changes after ACL reconstruction have underscored the importance of anatomic ACL reconstruction.^{5,15,17} The notion of anatomic tunnel placement to improve patient outcomes has raised a contention on the ability of the TT technique, originally proposed during the era when isometric ACL reconstruction was emphasized, to achieve anatomic tibial and femoral tunnels. While some authors proposed modifications to the traditionally practiced TT technique,^{4,9,12,19} others are endorsing the use of tibial tunnel-independent techniques^{1–3,20} such as the AM portal and OI techniques to create tibial and femoral tunnels anatomicallly. However, there is a paucity of information on the comparative efficacies of tibial tunnel-independent (AM portal and OI) and tibial tunnel-dependent (modified TT) techniques in restoring normal knee biomechanics. Recently, some biomechanical studies have compared the knee joint laxities after reconstructions by AM portal and TT techniques.^{3,20} By using an image-guided navigation system, Steiner et al²⁰ demonstrated that the AM portal technique closely restored the normal anterior tibial translations at 30° of knee flexion while the TT technique could not do so. Similarly, Bedi et al³ found that the AM portal technique more closely restored the normal joint laxity than the TT technique. In the current study, all 3 reconstruction techniques could not restore the normal knee joint laxity.

Several different factors could potentially explain the differences observed between these studies. Steiner et al²⁰ used a traditional TT technique where 70% of the tibial tunnels were placed in the posterior third of the tibial footprint and femoral tunnels in the proximal third of the femoral footprint. In the TT technique used by Bedi et al,³ a 10-mm tibial tunnel was placed at the center of the tibial footprint, and then by free hand, a guidewire was positioned eccentrically posterior and lateral in the tibial tunnel for preparation of the femoral tunnel. It is reported that this guidewire was anterior and superior to the center of the femoral footprint. This may have resulted from the constraints imposed by the tibial tunnel placed at the center of the tibial footprint by Bedi et al.³ In the TT technique used for this study, the tip of the tibial tunnel guide is positioned at the center of the posterolateral quadrant of the ACL footprint to create the tibial tunnel. Then, an offset guide was inserted into the tibial tunnel and hooked at the “over-the-top” position at 90° of flexion. This offset guide was then rotated laterally to reach the center of the femoral footprint as closely as possible. Therefore, the femoral tunnels in the TT technique of both previous studies were nonanatomic compared with the current study. Further, in the AM portal technique, Steiner et al²⁰ placed 90% of their tibial tunnels in the anterior third of the tibial footprint, and only 50% of their femoral tunnels were placed at the center of the femoral footprint. Therefore, the grafts were more vertical in the TT and horizontal in the AM portal techniques. This may explain the difference observed in the anterior tibial translations. Further, the graft source, fixation implant, initial graft tension, and graft fixation angle were different for each of these

studies. Steiner et al²⁰ used a 10-mm bone–patellar tendon–bone autograft that was fixed by a 7-mm metal interference screw in the femoral tunnel and a 9-mm interference screw in the tibial tunnel with 22.5 N of initial tension at 10° of knee flexion. A 6-mm synthetic ligament device was used as the graft by Bedi et al³ in a 6-mm femoral tunnel and 10-mm tibial tunnel. The femoral end of the graft was fixed by EndoButton (Smith & Nephew), while the tibial fixation was achieved by a screw and post with 44-N initial graft tension, and the graft fixation angle was not reported by Bedi et al.³ In this study, quadruple hamstring tendon autograft was used as the graft material. EndoButton CL (Smith & Nephew Endoscopy) and INTRAFIX screw (DePuy Mitek) were used to fix the graft in the femoral and tibial tunnels, respectively, at full extension with 40 N of axial graft tension.

Because of improved cosmesis, less surgical morbidity, shorter operation time, and potentially faster return to sports, the single-incision technique has gained popularity over the OI technique.^{7,10,11} In contrast, several advantages of the OI technique have been reported including accurate femoral tunnel placement, eliminated risk of posterior wall violation, eliminated graft-tunnel mismatch, and screw divergence.⁸ With over 80% of the surgeons performing fewer than 10 ACL reconstructions per year in the United States,¹⁶ in conjunction with the knowledge of these 3 techniques in restoring joint laxities, it is highly critical to thoroughly evaluate the technical perils and pearls inherent to each approach prior to clinically adopting them. The TT technique is commonly used because of its simplicity, ease of the technique, and a relatively small learning curve compared with the AM portal and OI techniques. However, it has been criticized for the difficulty in achieving anatomic femoral tunnel because of its dependence on the tibial tunnel. In this study, anatomic femoral tunnel was achieved through a tibial tunnel with an extra-articular starting position ranging from a point lateral to the anterior margin of the MCL to the midpoint of the anterior margin of the MCL and medial border of the tibial tubercle, with the tibial guide set to 50°. It is imperative that the offset guide is rotated laterally after it is hooked onto the over-the-top position to achieve an oblique anatomic placement of the guidewire.

The results of this study are to be interpreted with the following limitation in mind. Bone cement was used to fill the tunnels created to test the 3 different techniques in the same specimen. This step was necessary for a repeated-measures study design. To minimize bias, the order of 3 ACL reconstruction techniques was changed for each specimen. Because a retrograde reamer was not used for the OI technique, a spiked washer had to be used to consistently use EndoButton CL (Smith & Nephew) for all the 3 procedures. A 40-N initial graft tension was used in this study for each reconstruction technique. A larger initial graft tension may have more closely restored the normal joint laxity. However, a clear consensus on optimal initial graft tension that can restore the normal joint laxity, while avoiding other complications, is yet to be realized.

In conclusion, this study demonstrated that both tibial tunnel–independent and –dependent femoral tunnel placement techniques can equally restore the joint laxity and ACL force under external loading. However, none of these 3 techniques could completely restore the normal knee joint laxity and ACL forces, suggesting that in conjunction with the tunnel position, other factors are to be optimized to restore normal knee biomechanics. The results of this study are to be carefully interpreted, as the TT technique used here is a modification of the traditional TT technique.

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References

1. Abebe ES, Moorman CT 3rd, Dziedzic TS, et al. Femoral tunnel placement during anterior cruciate ligament reconstruction: an in vivo imaging analysis comparing transtibial and 2-incision tibial tunnel-independent techniques. *Am J Sports Med.* 2009; 37(10):1904–1911. [PubMed: 19687514]
2. Alentorn-Geli E, Samitier G, Alvarez P, Steinbacher G, Cugat R. Anteromedial portal versus transtibial drilling techniques in ACL reconstruction: a blinded cross-sectional study at two- to five-year follow-up. *Int Orthop.* 2010; 34(5):747–754. [PubMed: 20401753]
3. Bedi A, Musahl V, Steuber V, et al. Transtibial versus anteromedial portal reaming in anterior cruciate ligament reconstruction: an anatomic and biomechanical evaluation of surgical technique. *Arthroscopy.* 2011; 27(3):380–390. [PubMed: 21035990]
4. Chhabra A, Diduch DR, Blessey PB, Miller MD. Recreating an acceptable angle of the tibial tunnel in the coronal plane in anterior cruciate ligament reconstruction using external landmarks. *Arthroscopy.* 2004; 20(3):328–330. [PubMed: 15007325]
5. Fu FH, Shen W, Starman JS, Okeke N, Irrgang JJ. Primary anatomic double-bundle anterior cruciate ligament reconstruction: a preliminary 2-year prospective study. *Am J Sports Med.* 2008; 36(7):1263–1274. [PubMed: 18354141]
6. Fujie H, Mabuchi K, Woo SL, Livesay GA, Arai S, Tsukamoto Y. The use of robotics technology to study human joint kinematics: a new methodology. *J Biomech Eng.* 1993; 115(3):211–217. [PubMed: 8231133]
7. George MS, Huston LJ, Spindler KP. Endoscopic versus rear-entry ACL reconstruction: a systematic review. *Clin Orthop Relat Res.* 2007; 455:158–161. [PubMed: 17146361]
8. Gill TJ, Steadman JR. Anterior cruciate ligament reconstruction the two-incision technique. *Orthop Clin North Am.* 2002; 33(4):727–735. vii. [PubMed: 12528914]
9. Golish SR, Baumfeld JA, Schoderbek RJ, Miller MD. The effect of femoral tunnel starting position on tunnel length in anterior cruciate ligament reconstruction: a cadaveric study. *Arthroscopy.* 2007; 23(11):1187–1192. [PubMed: 17986406]
10. Hardin GT, Bach BR Jr, Bush-Joseph CA, Farr J. Endoscopic single-incision anterior cruciate ligament reconstruction using patellar tendon autograft: surgical technique. 1992 [classical article]. *J Knee Surg.* 2003; 16(3):135–144. discussion 145–147. [PubMed: 12943282]
11. Harner CD, Marks PH, Fu FH, Irrgang JJ, Silby MB, Mengato R. Anterior cruciate ligament reconstruction: endoscopic versus two-incision technique. *Arthroscopy.* 1994; 10(5):502–512. [PubMed: 7999157]
12. Heming JF, Rand J, Steiner ME. Anatomical limitations of transtibial drilling in anterior cruciate ligament reconstruction. *Am J Sports Med.* 2007; 35(10):1708–1715. [PubMed: 17664343]
13. Kasetta MK, DeFrate LE, Charnock BL, Sullivan RT, Garrett WE Jr. Reconstruction technique affects femoral tunnel placement in ACL reconstruction. *Clin Orthop Relat Res.* 2008; 466(6):1467–1474. [PubMed: 18404292]
14. Li G, Gill TJ, DeFrate LE, Zayontz S, Glatt V, Zarins B. Biomechanical consequences of PCL deficiency in the knee under simulated muscle loads: an in vitro experimental study. *J Orthop Res.* 2002; 20(4):887–892. [PubMed: 12168683]
15. Liden M, Sernert N, Rostgard-Christensen L, Kartus C, Ejerhed L. Osteoarthritic changes after anterior cruciate ligament reconstruction using bone-patellar tendon-bone or hamstring tendon autografts: a retrospective, 7-year radiographic and clinical follow-up study. *Arthroscopy.* 2008; 24(8):899–908. [PubMed: 18657738]
16. Lopez-Vidriero E, Hugh Johnson D. Evolving concepts in tunnel placement. *Sports Med Arthrosc.* 2009; 17(4):210–216. [PubMed: 19910778]
17. Marchant BG, Noyes FR, Barber-Westin SD, Fleckenstein C. Prevalence of nonanatomical graft placement in a series of failed anterior cruciate ligament reconstructions. *Am J Sports Med.* 2010; 38(10):1987–1996. [PubMed: 20702859]
18. Muneta T, Sekiya I, Yagishita K, Ogiuchi T, Yamamoto H, Shinomiya K. Two-bundle reconstruction of the anterior cruciate ligament using semitendinosus tendon with endobuttons: operative technique and preliminary results. *Arthroscopy.* 1999; 15(6):618–624. [PubMed: 10495178]

19. Rue JP, Ghodadra N, Lewis PB, Bach BR Jr. Femoral and tibial tunnel position using a transtibial drilled anterior cruciate ligament reconstruction technique. *J Knee Surg.* 2008; 21(3):246–249. [PubMed: 18686488]
20. Steiner ME, Battaglia TC, Heming JF, Rand JD, Festa A, Baria M. Independent drilling outperforms conventional transtibial drilling in anterior cruciate ligament reconstruction. *Am J Sports Med.* 2009; 37(10):1912–1919. [PubMed: 19729364]
21. 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. [PubMed: 16517306]

Figure 1.
Intra-articular position of the tibial guide tip (DePuy Mitek) for transtibial technique.

Figure 2.

Femoral graft fixation in the outside-in technique was achieved by flipping an EndoButton (Smith & Nephew Endos-copy) on a 14-mm spiked washer (DePuy Mitek), which was impacted onto the lateral femoral cortex at the tunnel entrance.

Figure 3.

Anterior tibial translations under 134-N anterior tibial load. “I” and “D” represent statistically significant differences compared with the ACL-intact knee and ACL-deficient knee, respectively ($P < .05$). Error bars represent standard deviation. ACLR-AM, ACL reconstruction by anteromedial portal technique; ACLR-OI, ACL reconstruction by outside-in technique; ACLR-TT, ACL reconstruction by transtibial technique.

Figure 4.

Anterior cruciate ligament (ACL) and ACL graft forces under 134-N anterior tibial load. “I” represents statistically significant difference compared with the ACL-intact knee ($P < .05$). Error bars represent standard deviation. ACLG-AM, ACL graft force in ACL reconstruction by anteromedial portal technique; ACLG-OI, ACL graft force in ACL reconstruction by outside-in technique; ACLR-TT, ACL graft force in ACL reconstruction by transtibial technique.

Figure 5. Anterior tibial translations under 10-N·m valgus and 5-N·m internal tibial combined torques. “I”, “D”, “A”, and “O” represent statistically significant differences compared with the ACL-intact knee, ACL-deficient knee, ACL-reconstructed knee by anteromedial portal technique, and ACL-reconstructed knee by outside-in technique, respectively ($P < .05$). Error bars represent standard deviation. ACLR-AM, ACL reconstruction by anteromedial portal technique; ACLR-OI, ACL reconstruction by outside-in technique; ACLR-TT, ACL reconstruction by transtibial technique.

Figure 6.

Anterior cruciate ligament (ACL) and ACL graft forces under 10-N·m valgus and 5-N·m internal tibial combined torques. “I” and “O” represent statistically significant differences compared with the ACL-intact knee and ACL-reconstructed knee by outside-in technique, respectively ($P < .05$). Error bars represent standard deviation. ACLG-AM, ACL graft force in ACL reconstruction by anteromedial portal technique; ACLG-OI, ACL graft force in ACL reconstruction by outside-in technique; ACLR-TT, ACL graft force in ACL reconstruction by transtibial technique.