Independent Drilling Outperforms Conventional Transtibial Drilling in Anterior Cruciate Ligament Reconstruction

Mark E. Steiner,*[†] MD, Todd C. Battaglia,[‡] MD, MS, James F. Heming,[†] DO, Jason D. Rand,[†] PA-C PT, Anthony Festa,[†] MD, and Michael Baria[†]
From the [†]Sports Medicine Section, Orthopaedic Department, New England Baptist Hospital, Boston, Massachusetts, and [‡]Syracuse Orthopedic Specialists, Syracuse, New York

Background: Optimal tunnel placement is critical in anterior cruciate ligament reconstructive surgery, yet the method used to drill the tunnels may compromise their placement.

Hypothesis: An independent drilling method versus a conventional transtibial drilling method will place tunnels in different locations and produce reconstructions with different kinematics.

Study Design: Controlled laboratory study.

Methods: Ten pairs of knees had anterior cruciate ligament reconstructions produced by either a conventional transtibial drilling method or an independent drilling method. The location of the tunnels was recorded, and the knees were tested for laxity in the normal state, with the anterior cruciate ligament removed, and with the anterior cruciate ligament reconstructed. A surgical navigation system guided the placement of the independently drilled tunnels and measured joint laxity in response to various combinations of anterior force and rotational torques.

Results: The conventional transtibial drilling method used in this study placed tibial tunnels posterior and femoral tunnels superior relative to their footprints and resulted in more vertical grafts. In contrast, the independently drilled tibial and femoral tunnels were more anterior and central in their respective footprints, resulting in more horizontal grafts. The horizontal grafts of the independent drilling method were superior to the vertical grafts of this study's transtibial drilling method in restoring normal anterior and rotational knee laxity.

Conclusion: An independent drilling method can produce tunnels with superior function compared with tunnels produced by a conventional transtibial drilling method.

Clinical Relevance: Single-bundle anterior cruciate ligament reconstructions will be improved if grafts are centered in their anatomical insertions by an independent drilling method versus grafts placed by a conventional transtibial drilling method.

Keywords: anterior cruciate ligament (ACL) reconstruction; transtibial drilling; independent drilling

In ACL reconstructive surgery, the transtibial drilling method has become widely accepted since its introduction more than 25 years ago.[5,9,16,43] However, a disadvantage of the technique is that the trajectory of the tibial tunnel will determine the placement of the femoral tunnel.[§] The placement of both tunnels can be compromised because of the coupled drilling of the tibial and femoral tunnels.[‖]

To address this limitation of transtibial drilling, multiple strategies have been presented to address graft tunnel mismatch, graft impingement, graft alignment, and graft elongation.[5,7,16,23-26,30,34,41] Despite these recommendations, it is controversial whether the limitations of the transtibial technique prevent even its routine use (D. Chao and T. David, personal communication, 2008).[¶]

Against this backdrop, advances in ACL surgery have reemphasized the importance of centering grafts within their anatomical insertions (D. Chao and T. David, personal communication, 2008).[10,13,31,46,53] There has been evidence that nonanatomical vertical grafts do not provide adequate knee stability (D. Chao and T. David, personal communication, 2008).[2,14,24,31,38,45,50,51] There is evidence

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*Address correspondence to Mark E. Steiner, MD, New England Baptist Hospital Orthopaedic Surgery Department, 125 Parker Hill Avenue, Boston, MA 02120 (e-mail: msteiner@caregroup.harvard.edu).
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[‖]References 10, 12, 18, 20, 22, 28, 36, 40, 45, 56.

[¶]References 2, 8, 13, 15, 17, 19, 38, 39, 47, 50.

that tunnels produced by conventional transtibial drilling will result in overly vertical grafts.[#]

A very common or conventional transtibial drilling technique has been to center the intra-articular end of the tibial tunnel 7 mm anterior to the PCL.[34] Morgan et al[34] presented an anatomical rationale for this tibial tunnel placement and recommended starting the tunnel 1 cm proximal to the pes anserinus and 1.5 cm posterior to the tibial tubercle. The concept of centering a tibial tunnel 7 mm or less from the PCL has been a popular drilling method and used in many clinical and cadaveric studies.[**]

Another option for tunnel placement is to uncouple the drilling of the tibial and femoral tunnels or independently drill each tunnel (D. Chao and T. David, personal communication, 2008).[13,15,17,23,38,39] Tibial tunnels can be placed anterior and medial in the tibial footprint provided impingement does not occur, and femoral tunnels can be centered in the femoral footprint (D. Chao and T. David, personal communication, 2008).[1,10,15,19,26,31,37,54] Independent drilling of the femoral tunnel will require drilling through an anteromedial portal or drilling antegrade through a lateral thigh incision.[13,17,50]

This study tested the hypothesis that conventional transtibial drilling as described by Morgan et al[34] would produce reconstructions with different kinematics compared with reconstructions produced with independent drilling.

METHODS

Specimen Preparation

Ten pairs of fresh-frozen cadaveric knees were used for the tests. The specimens were from 4 female, 5 male, and 1 of unknown gender donors. The mean age was 67 years (range, 36-88 years), and the mean weight was 68.5 N (range, 42.5-102.5 N). Knees were stored at –80°C and then thawed to room temperature for 24 hours before testing. The right and left knees of a pair were tested on the same day. The femur, tibia, and fibula were cut at a minimum of 25 cm from the joint line. The knees were dissected free of soft tissues except for the extensor mechanism, joint capsule, collateral ligaments, and cruciate ligaments. A 10-mm-wide bone-patellar tendon-bone graft was harvested with patellar and tibial tubercle bone plugs (25-mm length, 10-mm width). One braided suture (No. 5 Ticron, Ethicon Inc, New Brunswick, New Jersey) was placed through a drill hole in the patellar plug, and 2 braided sutures (No. 5 Ticron, Ethicon Inc) were placed through drill holes in the tibial plug. Anteromedial and anterolateral arthrotomies were made to visualize the ACL insertions and to perform all procedures in an open manner.

Testing Protocol

Each knee underwent biomechanical tests with the ACL intact, with the ACL removed, and with the ACL

reconstructed. One knee of a pair was reconstructed with the conventional transtibial drilling technique, and the opposite knee was reconstructed with the independent drilling technique. The right/left assignment to either the conventional transtibial or the independent method was sequentially alternated between pairs of knees.

The locations of the tibial and femoral tunnels used for the reconstructions were referenced to the tibial and femoral insertions of the native ACL. This was accomplished by outlining the tibial and femoral insertions of the ACL with India ink after the ligament was resected then further dividing with India ink each insertion into thirds (anterior to posterior on the tibia and proximal to distal on the femur). The proximal to distal description of the femoral tunnels correlates with the high to low description of femoral tunnels used by Amis and Jakob.[1] The greatest portion of each tibial and femoral tunnel was identified as lying within 1 of these partitions.

For displacement tests, the femur was clamped to the vertical strut of a laboratory workstation 20 cm proximal to the joint line (Figure 1). The tibia was prepared by cementing (Palacos, Zimmer Inc, Warsaw, Indiana) a 10-cm fluted rod into the distal tibia. The tibial rod passed through the ring of a traction bow that was clamped to the rim of a laboratory workstation (Figure 1). The vertical strut was raised or lowered to set a specific knee flexion angle, whereas the knee motions of anterior-posterior translation and internal-external rotation were not constrained. Anterior displacement forces were applied to the tibia through the patellar tendon (Figure 1). A hook attached to a spring gauge (Taylor Precision Instruments, Oak Brook, Illinois) was placed through the defect in the patellar tendon to allow application of anterior displacement forces to the tibia. Internal and external torques were applied to the tibia via the fluted rod with a torque wrench (Craftsman Torque Wrench, Sears Holding Corporation, Hoffman Estates, Illinois).

Tests were performed sequentially with 156 N anterior force, 10 N·m of internal tibial torque, 10 N·m of external torque, combined 156 N anterior force + 10 N·m of internal torque, and combined 156 N anterior force + 10 N·m of external torque. Before each test, the knee was seated in a neutral position by manually applying a light posterior force (approximately 5 N) to the proximal tibia.

Image-Guided Technology

An image-guided navigation system (VectorVision, BrainLab, Munich, Germany) was used to measure motions and to direct tunnel placements for the independent drilling method.[27] The system measured knee flexion, anterior-posterior tibial translation, and internal-external tibial rotation. It has an accuracy of 0.5 mm for translation measurements and 0.5° for rotational measurements.[27,40] The system used a camera that visualized infrared reflective spheres on reference arrays attached to the femur and tibia. A computer program computed knee motions based on the relative movements of the reference arrays. The femoral and tibial reference arrays with their reflective spheres were attached to the femur and tibia with two 3-mm-diameter threaded pins.

[#]References 12, 15, 28, 34, 36, 38, 39, 45, 52.
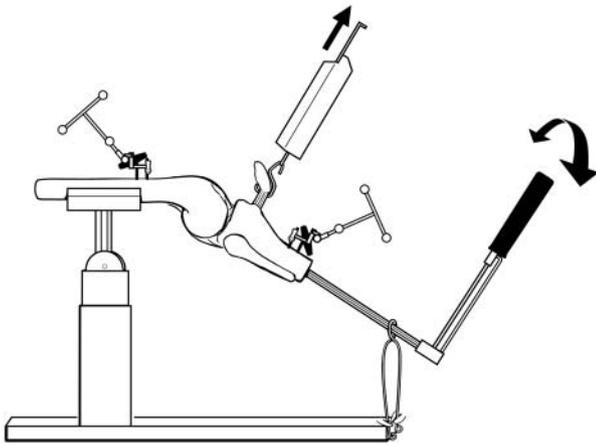[**]References 5, 8, 13, 26, 30, 34, 39, 41, 53-55.

Figure 1. Testing system. Anterior force was applied with a spring gauge through the patellar tendon at right angles to the tibia, and rotational torques were applied with a torque wrench attached to the rod in the tibia. Reprinted with permission from: 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.

Each knee underwent a registration process to record the specific anatomy of the knee. The process required a custom fluoroscopic disc attached to a C-arm fluoroscope (Ziehm 7000, Ziehm Inc, Riverside, California). The disc had infrared reflective markers around its perimeter, and it placed a grid of tungsten markers (approximately 75) on acquired fluoroscopic images. Anteroposterior and lateral fluoroscopic images were acquired to compute the specific anatomy of each knee. A pointer with infrared reflective markers was also scrolled over the intercondylar notch and the tibial plateau to acquire anatomical coordinates relevant to the ACL.

For each displacement test, anterior displacement and axial rotation were measured by the image-guided system. Displacement tests were repeated until 2 successive tests varied by less than 1 mm of translation and by less than 1° of rotation. The recorded value was the mean of the last 2 tests. No more than 3 or 4 tests were necessary for each force application.

Reconstructive Procedures

Right and left knees were sequentially alternated between conventional transtibial drilling and independent drilling. For both reconstruction methods, a tibial guide pin entered the tibia 1 cm proximal to the pes anserinus and 1.5 cm posterior to the tibial tubercle.

The method of Morgan et al[34] was used for the conventional transtibial reconstructions. A commercial tibial drill guide (Arthrex, Naples, Florida) with a 55° angle between the aiming arm and the drilling arm placed a guide pin 7 mm anterior to the PCL in the center of the intercondylar plateau. A 10-mm-diameter, full threaded reamer created the tibial tunnel. A 7-mm offset femoral drill guide (Arthrex)

introduced through the tibial tunnel was seated with its flange on the posterior wall of the intercondylar notch. The knee was flexed to the largest angle that allowed the guide to remain seated (approximately 80°), and the guide pin was drilled through the lateral cortex of the femur. A 10-mm endoscopic reamer created a femoral tunnel 35 mm in length.

For the independent drilling reconstructions, the placement of the tibial and femoral tunnels was directed by the algorithm of the surgical guidance system.[27] The software is designed to place the center of the tibial tunnel 44% medial to the medial cortex in the medial-lateral dimension and 43% posterior to the anterior cortex in the anterior-posterior dimension.[1,11,37,50] A tibial drill guide with infrared markers was positioned as directed by the targeting images of the surgical guidance system to place a guide pin. As above, a 10-mm tibial tunnel was produced.

The software placed the femoral tunnel based on the quadrant method of Bernard et al,[4] with the tunnel centered 25% inferior to Blumensaat's line and 25% anterior to the posterior femoral cortex. For guide wire placement and reaming, the knee was flexed more than 120°, and a femoral aimer with infrared markers was introduced through the anteromedial arthrotomy. The guide pin was drilled out the lateral femoral cortex using the targeting images of the guidance system, and an endoscopic reamer was used to produce a 10-mm-diameter tunnel 35 mm in length.

For both the conventional transtibial and independent drilling reconstructions, the graft passage, graft tensioning, and graft fixation techniques were identical. The patellar bone plug was positioned in the femur with its cancellous surface toward the anterior notch and its cortical surface toward the posterior notch. The bone-tendon junction was flush with the wall of the intercondylar notch. Retrograde placement of a 7 × 25-mm metal interference screw (Arthrex) provided secure femoral fixation. Before tibial fixation, 22.5 N of tension was placed on the graft via the tibial bone plug sutures with the spring gauge (Taylor Precision Instruments), and the knee was cycled from 0° to 90° ten times. The tibial bone plug was secured with a 9 × 25-mm or 9 × 20-mm interference screw while maintaining the same tension on the graft and with the knee flexed 10°. The tibial fixation was reinforced by tying the bone plug sutures to the pins of the tibial array.

Statistical Analysis

Statistical analysis was performed using StatView software (SAS Institute, Cary, North Carolina). Normal knees were compared between the 2 reconstruction groups, and no statistically significant differences were found (paired *t* tests, all *P* > .05). Similarly, ACL-deficient knees were compared between the 2 reconstruction groups, and no statistically significant differences were found (paired *t* tests, all *P* > .05). Therefore, normal knees were pooled (n = 20) and ACL-deficient knees (n = 20) were pooled for normal versus ACL-deficient analysis. Paired *t* tests were used to compare normal knees to ACL-deficient knees.

To analyze the reconstruction results, the 2 reconstruction methods were compared with the normal state within

each knee using a paired *t* test. Tunnel locations were compared using the Fisher exact test to evaluate the tibial tunnel locations, the femoral tunnel locations, and the relationship between drilling method and tunnel location.

RESULTS

Tunnel Locations

Tunnel locations were determined by direct observation of tunnel placements in relation to the tibial and femoral insertions of the ACL (Figures 2 and 3). The conventional transtibial drilling method placed 7 tibial tunnels in the posterior third of the tibial footprint and 3 tibial tunnels in the central third of the tibial footprint. On the femoral side, the conventional transtibial drilling method placed all 10 tunnels in the proximal third of the femoral footprint (Figure 2).

The independent drilling method placed 9 tibial tunnels in the anterior third of the tibial footprint and 1 tibial tunnel in the central third of the tibial footprint. For the femoral footprint, the independent drilling method placed 3 tunnels in the proximal third, 5 tunnels in the central third, and 2 tunnels in the distal third (Figure 3).

The difference in tunnel locations between the 2 methods was significant on the tibial side ($P < .001$) and on the femoral side ($P < .01$) and was related to the drilling method ($P < .001$).

Knee Kinematics

Normal versus ACL-deficient knees. Anterior translation increased after cutting the ACL with anterior force, internal torque, combined anterior force + internal torque, and combined anterior force + external torque ($P < .01$) (Table 1 and Figure 4). The changes in anterior translation were large compared with the normal state.

Internal rotation also increased after the ACL was resected but only with internal torque or combined anterior force + internal torque ($P < .01$) (Table 1 and Figure 5). The changes in internal rotation were small compared with the normal state.

Reconstructed knees versus normal knees. Conventional transtibial reconstruction reduced anterior translation but not to normal with anterior force, internal torque, and combined anterior force + internal torque ($P < .01$) (Table 2 and Figure 4). In contrast, reconstruction by the independent drilling technique restored normal anterior translation for all loading conditions (Table 2 and Figure 4).

Conventional transtibial reconstructions restored normal internal rotation with combined anterior force + internal rotation but not with internal rotation. Independent drilling reconstructions restored normal internal rotation for all loading conditions (Table 2 and Figure 5).

DISCUSSION

This study compared conventional transtibial drilling as described by Morgan et al[34] to independent drilling as

Figure 2. The average location for the tunnels drilled with the conventional transtibial method.

Figure 3. The average location for the tunnels drilled with the independent drilling method.

methods for ACL reconstruction. Tests were performed at 30° of flexion, where the greatest anterior translation occurs in ACL-deficient knees[52] and where restoration of normal motion will eliminate the pivot-shift phenomenon.[10,29,49,52]

The conventional transtibial drilling method was based on a commonly used method described by Morgan et al.** The independent drilling method was directed by an image-guided surgical guidance system (BrainLab Inc). Independent drilling of a femoral tunnel can be performed antegrade through a lateral incision or retrograde through an anteromedial portal just above the medial meniscus.[50]

The conventional transtibial technique used in this study placed the majority of tibial tunnels in the posterior tibial footprint and all the femoral tunnels in the proximal femoral footprint. The independent drilling technique placed tunnels using the image guidance system, and the average tunnels were in the anterior tibial footprint and in the central femoral footprint. Both the tibial and the femoral tunnel locations were different between the 2 drilling techniques, and the kinematic results reflect the combined effects of tibial and femoral tunnel placements. The tunnel
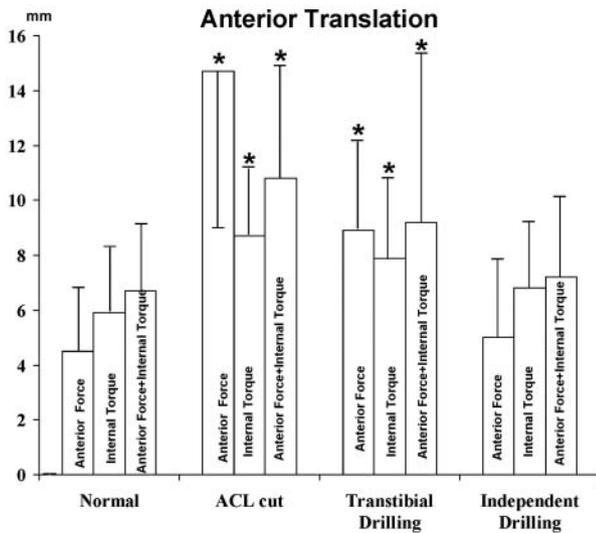
Figure 4. Mean anterior translations for normal knees (n = 20), ACL-resected knees (n = 20), and ACL-reconstructed knees (n = 10) are shown for anterior force (156 N), internal torque (10 N·m), and combined anterior force + internal torque (156 N + 10 N·m). The bars represent 1 SD. An asterisk denotes a value greater than the value in the normal knee (P < .01, paired t test).

Figure 5. Mean internal rotation in degrees for normal knees (n = 20), ACL-resected knees (n = 20), and ACL-reconstructed knees (n = 10) is shown for internal torque (10 N·m) and combined anterior force + internal torque (156 N + 10 N·m). The bars represent 1 SD. An asterisk denotes a value greater than the value in the normal knee (P < .01, paired t test).
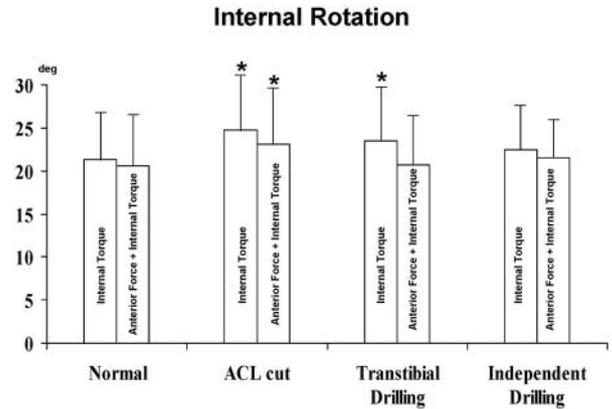
TABLE 1
Anterior Translation and Rotation in Normal Versus ACL-Deficient Knees (n = 20)[a]

	Normal		ACL Deficient	
	Mean	SD	Mean	SD
Anterior Force, 156 N				
Anterior translation, mm	4.5	2.6	14.7	5.8[b]
Rotation, deg	5.7	4.2	4.0	4.4
Internal torque, 10 N·m				
Anterior translation, mm	5.9	2.4	8.7	2.8[b]
Rotation, deg	21.3	5.5	24.8	6.3[c]
External torque, 10 N·m				
Anterior translation, mm	1.2	3.7	2.3	3.0
Rotation, deg	−18.9	7.8	−17.6	5.8
Anterior force (156 N) + internal torque (10 N·m)				
Anterior translation, mm	6.7	2.7	10.8	4.4[b]
Rotation, deg	20.6	5.8	23.1	6.5[c]
Anterior force (156 N) + external torque (10 N·m)				
Anterior translation, mm	2.6	2.0	7.4	6.7[b]
Rotation, deg	−13.1	11.1	−13.6	5.2

[a]External rotation, (−); internal rotation, (+).
[b]P < .001.
[c]P < .01.

TABLE 2
Anterior Translation and Rotation in Conventional Transtibial Drilling Versus Independent Drilling (n = 10)[a]

	Transtibial Drilling		Independent Drilling	
	Mean	SD	Mean	SD
Anterior force, 156 N				
Anterior translation, mm	8.9	3.6[b]	5.0	3.3
Rotation, deg	7.5	5.6	5.5	4.3
Internal torque, 10 N·m				
Anterior translation, mm	7.9	3.4[c]	6.6	2.8
Rotation, deg	23.5	6.1[c]	22.5	5.2
External torque, 10 N·m				
Anterior translation, mm	2.4	4.6	0.3	2.2
Rotation, deg	−18.1	6.8	−17.4	4.8
Anterior force (156 N) + internal torque (10 N·m)				
Anterior translation, mm	9.2	3.2[c]	7.2	3.3
Rotation, deg	20.7	5.7	21.5	4.5
Anterior force (156 N) + external torque (10 N·m)				
Anterior translation, mm	5.9	6.3	2.7	2.6
Rotation, deg	−13.9	10.5	−14.2	5.4

[a]External rotation, (−); internal rotation, (+).
[b]P < .001.
[c]P ≤ .01.

placements of conventional transtibial drilling produced more vertical grafts, and the tunnel placements of independent drilling produced more horizontal grafts.

The vertical grafts produced by conventional transtibial drilling decreased abnormal anterior translation but not to

normal when anterior force and/or internal torque were applied. The horizontal grafts produced by the independent drilling method restored normal anterior translation for all loading conditions. If anterior translation was normal, then internal rotation was also normal.

The problems with placing anatomical grafts using transtibial drilling have been independently documented by Arnold et al[2] and Heming et al.[19] Arnold et al used a standard femoral aimer through a tibial tunnel and found all

guide pins to be placed too superior in the notch and outside the femoral footprint.[2] Heming et al documented that transtibial drilling could center tibial and femoral tunnels in their footprints, but this required an impractical short tibial tunnel and a possible violation of the posterior femoral cortex.[19]

Howell et al have extensively studied transtibial drilling and made recommendations to avoid the method's tendency to place vertical grafts.[20-25,46] They have documented that more horizontal tibial tunnels in the coronal plane will result in knees with superior stability and better range of motion.[24] This method to improve femoral tunnel location will often require tunneling through the medial collateral ligament and under the medial tibial plateau. This practice may centralize the femoral tunnel, but the tibial tunnel will still lie posterior, and there is risk of tibial plateau articular injury and medial plateau insufficiency reactions.[3,48] Kondo et al[30] have also recommended transtibial drilling to place anatomical femoral tunnels, but this recommendation will place a tibial tunnel far posterior.

Multiple cadaveric studies have documented the poor function of vertical grafts produced by nonanatomical proximal or high femoral tunnels.[31,52-54,58] Taken collectively, the studies of Woo et al,[52] Yagi et al,[53] Loh et al,[31] and Yamamoto et al[54] support the thesis that grafts placed lower in the femoral footprint best restore normal motion at flexion angles below 60°. From another laboratory, Scopp et al[45] placed grafts with either a high or low femoral tunnel using a transtibial technique. Neither method restored normal anterior translation, but knees with lower femoral tunnels had better stability with internal rotation. Interestingly, Mae et al,[32] in a cadaveric study, placed grafts in the center of the tibial insertion and in the proximal femoral insertion with independent drilling and found normal anterior translation between 0° and 90° flexion.

Clinical data supporting the use of independent drilling come from multiple sources. Using MRIs, Chao and David (personal communication) found graft alignments to be more horizontal and anatomical and better laxity measurements with independent drilling versus transtibial drilling. Hantes et al[15] also evaluated MRIs of ACL reconstructions and found grafts placed with independent drilling to have better horizontal alignments compared to grafts placed with transtibial drilling. Paessler et al[38] attempted transtibial versus independent drilling in 77 ACL reconstructions and found that in only 3 knees could transtibial drilling place guide pins within the superior margin of the femoral footprint. With use of independent drilling, all femoral tunnels were centered in the footprints.[38] Harner et al[17] have recommended independent drilling because it allows placing the femoral tunnel correctly. Interestingly, greater femoral tunnel widening has been documented with transtibial drilling versus anteromedial tunnel drilling.[8]

The image-guided navigation system used in this study is accurate in measuring joint laxity, but some variability was observed in the tunnel placements relative to the footprints.[27,40] This may be owing to variability in the referencing process or to variability in the operator's placement of drill guides based on computer images. Also, the algorithm of the system is based on anatomical averages, and variability in knee anatomy may be a factor. It is possible that drill guides designed to center grafts in their central footprints may be more reliable than is image-guided technology in placing tunnels.

There was a clear statistical difference in tunnel locations between the 2 drilling methods. Whether it was the tibial or femoral tunnels that were more critical to the observed kinematic differences cannot be answered, but prior studies have indicated that the femoral tunnel is the more critical.[12,18,57]

The relatively more anterior tibial tunnel of the independent drilling method could predispose a graft to notch impingement.[20-22] However, the lower femoral tunnel of the independent drilling method will diminish this possibility.[24,27,36] Clinically, each reconstruction has to be carefully evaluated for graft impingement and the tibial tunnel placed to avoid this possibility.

The results of this study bear upon recent concerns with single-bundle ACL reconstructions and their ability to restore normal knee function.[3,6,32,35,58] These concerns are largely based on tests of cadaveric reconstructions and motion analyses of knees after reconstruction.[††] It is clear from these studies that many knees still function with abnormal anterior translation and rotation after reconstruction.[14,42,51] What is controversial is whether it is the placement of single-bundle grafts that needs improvement or whether 2-bundle grafts are needed.[3,6,32,33,35,55,56,58]

Whether the changes in transtibial drilling methodology suggested by Howell and Kondo can salvage the method was not evaluated in this study. Fundamentally, this study evaluated only the transtibial drilling technique described by Morgan et al,[34] and it may be possible with a more horizontal tibial tunnel to place a better functioning graft using the transtibial technique. However, horizontal tibial tunnels in the coronal plane are not without problems, and their success compared with independently drilled tunnels has not been documented.[3,24,41,44,46,50]

We suggest that tunnels in ACL reconstructions be drilled independently. The tibial tunnel should be placed anterior and medial in the footprint, provided it does not impinge the graft. The femoral tunnel should be placed in the center of the femoral footprint. These tunnel placements require drilling the femoral tunnel either through an anteromedial portal or through a lateral thigh incision.[13,17] In a cadaveric model, a single-bundle ACL construct with tunnels placed by independent drilling was very successful at restoring physiologic motion to the knee.

[††]References 6, 14, 30, 32, 35, 42, 51-55, 58.

REFERENCES

1. Amis AA, Jakob RP. Anterior cruciate ligament graft positioning, tensioning and twisting. *Knee Surg Sports Traumatol Arthrosc.* 1998;6(suppl 1):S2-S12.
2. Arnold MP, Kooloos J, van Kampen A. Single-incision technique misses the anatomical femoral anterior cruciate ligament insertion: a cadaver study. *Knee Surg Sports Traumatol Arthrosc.* 2001;9:194-199.
3. Asagumo H, Kimura M, Kobayashi Y, Taki M, Takagishi K. Anatomic reconstruction of the anterior cruciate ligament using double-bundle hamstring tendons: surgical techniques, clinical outcomes, and complications. *Arthroscopy.* 2007;23:602-609.
4. Bernard M, Hertel P, Hornung H, Cierpinski T. Femoral insertion of the ACL radiographic quadrant method. *Am J Knee Surg.* 1997;10:14-22.
5. Brown C, Sklar J. Endoscopic anterior cruciate ligament reconstruction using quadrupled hamstring tendons and EndoButton femoral fixation. *Tech Orthop.* 1998;13:281-298.
6. Cha PS, Brucker PU, West RV, et al. Arthroscopic double-bundle anterior cruciate ligament reconstruction: an anatomic approach. *Arthroscopy* 2005;21:1275e1-1275e8.
7. 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;20:328-330.
8. Chhabra A, Kline AJ, Nilles KM, Harner CD. Tunnel expansion after anterior cruciate ligament reconstruction with autogenous hamstrings: a comparison of the medial portal and transtibial techniques. *Arthroscopy.* 2006;22:1107-1112.
9. Christian C, Indelicato P. Allograft anterior cruciate ligament reconstruction with patellar tendon: an endoscopic technique. *Oper Tech Sports Med.* 1993;1:51-57.
10. Clancy WG, Nelson DA, Reider B, Narechania RG. Anterior cruciate ligament reconstruction using one-third of the patellar ligament, augmented by extra-articular tendon transfers. *J Bone Joint Surg Am.* 1982;64:352-359.
11. Colombet P, Robinson J, Christel P, et al. Morphology of anterior cruciate ligament attachments for anatomic reconstruction: a cadaveric dissection and radiographic study. *Arthroscopy.* 2006;22:984-992.
12. Cooper DE, Small J, Urrea L. Factors affecting graft excursion patterns in endoscopic anterior cruciate ligament reconstruction. *Knee Surg Sports Traumatol Arthrosc.* 1998;6(suppl 1):S20-S24.
13. Garofalo R, Mouhsine E, Chambat P, Siegrist O. Anatomic anterior cruciate ligament reconstruction: the two incision technique. *Knee Surg Sports Traumatol Arthrosc.* 2006;14:510-516.
14. Georgoulis AD, Papadonikolakis A, Papageorgiou CD, Mitsou A, Stergiiou N. Three-dimensional tibiofemoral kinematics of the anterior cruciate ligament–deficient and reconstructed knee during walking. *Am J Sports Med.* 2003;31:75-79.
15. Hantes M, Zachos V, Basdekis G, Zibis A, Dailiana Z, Malizos K. Differences in graft orientation using the transtibial and anteromedial portal technique in ACL reconstruction: an MRI prospective study. *J Bone Joint Surg Br.* 2006;88(suppl 1):93.
16. Hardin G, Bach B, Bush-Joseph C, Farr J. Endoscopic single incision anterior cruciate ligament reconstruction using patellar tendon autograft: surgical technique. *Am J Knee Surg.* 1992;5:144-155.
17. Harner CD, Honkamp NJ, Ranawat A. Anteromedial portal technique for creating the anterior cruciate ligament femoral tunnel. *Arthroscopy.* 2008;24:113-115.
18. Hefzy MS, Grood ES, Noyes FR. Factors affecting the region of most isometric femoral attachments, part II: the anterior cruciate ligament. *Am J Sports Med.* 1989;17:208-216.
19. Heming JF, Rand J, Steiner ME. Anatomic limitations of transtibial drilling in ACL reconstruction. *Am J Sports Med.* 2007;35:1708-1715.
20. Howell SM. Principles for placing the tibial tunnel and avoiding roof impingement during reconstruction of a torn anterior cruciate ligament. *Knee Surg Sports Traumatol Arthrosc.* 1998;6(suppl 1):S49-S55.
21. Howell SM, Barad SJ. Knee extension and its relationship to the slope of the intercondylar roof: implications for positioning the tibial tunnel in anterior cruciate ligament reconstructions. *Am J Sports Med.* 1995;23:288-294.
22. Howell SM, Clark JA. Tibial tunnel placement in anterior cruciate ligament reconstructions and graft impingement. *Clin Orthop Relat Res.* 1992;283:187-195.
23. Howell SM, Deutsch ML. Comparison of endoscopic and two-incision techniques for reconstructing a torn anterior cruciate ligament using hamstring tendons. *Arthroscopy.* 1999;15:594-606.
24. Howell SM, Gittins ME, Gottlieb JE, Traina SM, Zoellner TM. The relationship between the angle of the tibial tunnel in the coronal plane and loss of flexion and anterior laxity after anterior cruciate ligament reconstruction. *Am J Sports Med.* 2001;29:567-574.
25. Howell SM, Wallace MP, Hull ML, Deutsch ML. Evaluation of the single-incision arthroscopic technique for anterior cruciate ligament replacement. *Am J Sports Med.* 1999;27:284-293.
26. Jackson DW, Gasser SI. Tibial tunnel placement in ACL reconstruction. *Arthroscopy.* 1994;10:124-131.
27. Kendoff D, Meller R, Marquard S, et al. Navigated measurement of tibial translation and rotation in the ACL deficient knee. *J Bone Joint Surg Br.* 2006;88(suppl 3):445.
28. Khalfayan EE, Sharkey PF, Alexander AH, Bruckner JD, Bynum EB. The relationship between tunnel placement and clinical results after anterior cruciate ligament reconstruction. *Am J Sports Med.* 1996;24:335-341.
29. Kocher MS, Steadman JR, Briggs KK, Sterett WI, Hawkins RJ. Relationships between objective assessment of ligament stability and subjective assessment of symptoms and function after anterior cruciate ligament reconstruction. *Am J Sports Med.* 2004;32:629-634.
30. Kondo E, Yasuda K, Ichiyama H, Azuma C, Tohyama H. Radiologic evaluation of femoral and tibial tunnels created with the transtibial tunnel technique for anatomic double-bundle anterior cruciate ligament reconstruction. *Arthroscopy.* 2007;23:869-876.
31. Loh JC, Fukuda Y, Tsuda E, Steadman RJ, Fu FH, Woo SL. Knee stability and graft function following anterior cruciate ligament reconstruction: comparison between 11 o'clock and 10 o'clock femoral tunnel placement. *Arthroscopy.* 2003;19:297-304.
32. 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;17:708-716.
33. Markolf KL, Park S, Jackson SR, McAllister DR. Simulated pivot-shift testing with single- and double-bundle anterior cruciate ligament reconstructions. *J Bone Joint Surg Am.* 2008;90:1681-1690.
34. Morgan CD, Kalman KR, Grawl DM. Definitive landmarks for reproducible tibial tunnel placement in anterior cruciate ligament reconstruction. *Arthroscopy.* 1995;11:275-288.
35. Muneta T, Koga H, Morito T, Yagishita K, Sekiya I. A retrospective study of the midterm outcome of two-bundle anterior cruciate ligament reconstruction using quadrupled semitendinosus tendon in comparison with one-bundle reconstruction. *Arthroscopy.* 2006;22:252-258.
36. Muneta T, Yamamoto H, Ishibashi R, Asahina S, Murakami S, Furuya K. The effects of tibial tunnel placement and roofplasty on reconstructed anterior cruciate ligament knees. *Arthroscopy.* 1995;11:57-62.
37. Odensten M, Gillquist J. Functional anatomy of the anterior cruciate ligament and a rational for reconstruction. *J Bone Joint Surg Am.* 1985;67:257-262.
38. Paessler H, Rossis J, Mastrokalos D, Kotsovolos I. Anteromedial vs. transtibial technique for correct femoral tunnel placement during arthroscopic ACL reconstruction with hamstrings: an in vivo study. *J Bone Joint Surg Br.* 2004;suppl 3:234.
39. Panni AS, Milano G, Tartarone M, Demontis A, Fabbriciani C. Clinical radiographic results of ACL reconstruction: a 5- to 7- year follow-up study of outside-in versus inside-out reconstruction techniques. *Knee Surg Sports Traumatol Arthrosc.* 2001;9:77-85.
40. Picard F, DiGioia AM, Moody J, et al. Accuracy in tunnel placement for ACL reconstruction: comparison of traditional arthroscopic and

computer-assisted navigation techniques. *Comput Aided Surg.* 2002; 6:279-289.

41. Raffo CS, Pizzarello P, Richmond JC, Pathare N. A reproducible landmark for the tibial tunnel origin in anterior cruciate ligament reconstruction: avoiding a vertical graft in the coronal plane. *Arthroscopy.* 2008;24:843-845.

42. Ristanis S, Stergiou N, Patras K, Vasiliadis JS, Giakas G, Georgoulis AD. Excessive tibial rotation during high-demand activities is not restored by anterior cruciate ligament reconstruction. *Arthroscopy.* 2005;21:1323-1329.

43. Rosenberg TD. *Technique for Endoscopic Method of ACL Reconstruction Technical Bulletin*. Norwood, Mass: Acufex Microsurgical; 1989.

44. Rue J-P, Ghodadra N, Bach BR. Femoral tunnel placement in single-bundle anterior cruciate ligament reconstruction: a cadaveric study relating transtibial lateralized femoral tunnel position to the anteromedial and posterolateral bundle femoral origins of the anterior cruciate ligament. *Am J Sports Med.* 2008;36:73-79.

45. Scopp JM, Jasper LE, Belkoff SM, Moorman CT. The effect of oblique femoral tunnel placement on rotational constraint of the knee reconstructed using patellar tendon autografts. *Arthroscopy.* 2004;20: 294-299.

46. Simmons R, Howell S, Hull ML. Effect of the angle of the femoral and tibial tunnels in the coronal plane and incremental excision of the posterior cruciate ligament on tension of an anterior cruciate ligament graft: an in vitro study. *J Bone Joint Surg Am.* 2003;85:1018-1029.

47. Sommer C, Friederich NF, Müller W. Improperly placed anterior cruciate ligament grafts: correlation between radiological parameters and clinical results. *Knee Surg Sports Traumatol Arthrosc.* 2000;8:207-213.

48. Steiner ME. Evaluation and management of ACL injuries. In: McKeon B, Bono J, Richmond J, eds. *Knee Arthroscopy*. New York: Springer-Verlag; 2008.

49. Steiner ME, Brown C, Zarins B, Brownstein B, Koval PS, Stone P. Measurement of anterior-posterior knee displacement: comparison of instrumented devices and clinical examination. *J Bone Joint Surg Am.* 1990;72:1307-1315.

50. Steiner ME, Murray MM, Rodeo SA. Strategies to improve anterior cruciate ligament healing and graft placement. *Am J Sports Med.* 2008;36:176-189.

51. 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;32:975-983.

52. Woo SL, Kanamori A, Zeminski J, Yagi M, Papageorgiou C, Fu JG. 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: 907-914.

53. Yagi M, Wong E, Kanamori A, Debski R, Fu F, Woo S. Biomechanical analysis of an anatomic anterior cruciate ligament reconstruction. *Am J Sports Med.* 2002;30:660-666.

54. 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;32:1825-1832.

55. Yasuda K, Kondo E, Ichiyama H, et al. Anatomic reconstruction of the anteromedial and posterolateral bundles of the anterior cruciate ligament using hamstring tendon grafts. *Arthroscopy.* 2004;20: 1015-1025.

56. Zantop T, Herbort M, Raschke MJ, Fu FH, Petersen W. The role of the anteromedial and posterolateral bundles of the anterior cruciate ligament in anterior tibial translation and internal rotation. *Am J Sports Med.* 2007;35:223-227.

57. Zavras TD, Race A, Bull AMJ, Amis AA. A comparative study of "isometric" points for anterior cruciate ligament graft attachment. *Knee Surg Sports Traumatol Arthrosc.* 2001;9:28-33.

58. Zelle BA, Vidal AF, Brucker PU, Fu FH. Double-bundle reconstruction of the anterior cruciate ligament: anatomic and biomechanical rationale*. J Am Acad Orthop Surg.* 2007;15:87-96.