A Comparison of 2 Drilling Techniques on the Femoral Tunnel for Anterior Cruciate Ligament Reconstruction

Chealon D. Miller, M.D., Andrew C. Gerdeman, M.D., Joseph M. Hart, Ph.D., Chase G. Bennett, B.S., S. Raymond Golish, M.D., Christopher Gaskin, M.D., and Mark D. Miller, M.D.

Purpose: This cadaveric study was undertaken to characterize the femoral tunnel geometry resulting from commonly used drilling techniques in anterior cruciate ligament reconstruction. **Methods:** We randomized 10 matched-pair cadaveric knees (20 knees) into 2 groups with right and left matched pairs from each cadaver. Of the knees, 10 underwent transtibial femoral tunnel drilling from a far-medial starting point on the tibia (group 1) and 10 had the femoral tunnel drilled from a medial arthroscopic portal (group 2). The dimensions and size of the apertures, the volume and length of the tunnels, and the distance of the tunnels from the posterior wall and articular surface were measured by computed tomography. **Results:** The mean femoral tunnel length was 29.7 mm in group 1 and 15.7 mm in group 2. The mean volume for each tunnel was 2,401 mm^3 in group 1 and 2,071 mm^3 in group 2. The intra-articular aperture area was 94.6 mm^2 in group 1 and 98.6 mm^2 in group 2. In group 2 the intra-articular shape was more elliptical than in group 1, with the long axis averaging 13.5 ± 1.3 mm (P = .004) and short axis averaging 9.7 ± 1.0 mm (P = .002); in group 2 the long axis averaged 12.5 ± 1.7 and short axis averaged 10.3 ± 0.7 (P = .002). Group 2 was closer to the posterior wall and articular surface (6.9 ± 0.6 mm and 9.4 ± 0.6 mm, respectively) than group 1 (10.8 ± 1.0 mm and 11.8 ± 1.9 mm, respectively). **Conclusions:** We determined the length and volume of the femoral tunnel to be shorter and smaller, respectively, with a medial arthroscopic portal. In addition, the aperture shape was more of an ellipse with a medial arthroscopic portal. The medial arthroscopic portal also created a femoral tunnel that was closer to the posterior wall and articular surface of the femur. **Clinical Relevance:** Improved characterization of osseous tunnels with 3-dimensional figures will allow for improved matching of graft and incorporation.

Anterior cruciate ligament (ACL) reconstruction techniques continue to evolve; however, there continues to be concern regarding residual rotational laxity and late development of arthritis with current techniques. Anatomic tunnel positioning improves rotational laxity and may reduce the incidence of these problems.[1]

The nomenclature for placement of femoral tunnels for ACL reconstruction has, in the past, focused on sagittal plane positioning, focusing on how shallow or deep (with the knee at 90° of flexion) the tunnel began.[2-6] An emphasis on the coronal placement of the femoral tunnel has been the focus of more recently published studies on tunnel placement in ACL reconstruction, with nomenclature describing how high or low (with the knee at 90° of flexion) the femoral tunnel began.[2] Whereas anterior tibial translation can be well controlled with isometric femoral positioning and a vertical graft orientation, patients often have some rotational instability as evidenced by a pivot shift postoperatively.[1,7]

From the Department of Orthopaedic Surgery, University of Virginia, Charlottesville, Virginia, U.S.A.

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Address correspondence and reprint requests to Chealon D. Miller, M.D., Department Orthopaedic Surgery, University of Virginia, 400 Ray C Hunt Dr, Ste 330, Charlottesville, VA 22908, U.S.A. E-mail: chealonmiller@yahoo.com

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Biomechanical data have supported a more horizontal femoral tunnel position where both anterior translation and internal tibial rotation are captured.[6-8] In addition, there is a decrease in tension across the graft, increased motion, and decreased posterior cruciate ligament (PCL) impingement with a graft placed more horizontally in the coronal plane.[8,9] To achieve this position, one must drill the femoral tunnel through a medially based tibial tunnel or through a medial arthroscopic portal. Previous studies have shown that a more anatomic femoral tunnel can be achieved through medial transtibial and medial arthroscopic drilling.[10] Changing the position of the femoral tunnel has been shown to change the length of the tunnel, but it can also change the volume and shape of the intra-articular aperture. Information regarding the intra-articular aperture of the tunnel is important for graft incorporation and prevention of early graft movement within the tunnel.[11-14] Furthermore, use of available technology would allow for more detailed tunnel characterization in 3 dimensions. This information would be useful in improving on information needed to decide on the type of fixation and possibly the use of biologic scaffolds for ACL reconstruction. Because the transtibial approach and the medial arthroscopic approach for femoral tunnel drilling have become the most popular techniques, the tunnels created by these 2 techniques are important considerations. It is also important to determine how closely these 2 techniques come to re-creating the anatomic insertion of the ACL on the lateral femoral condyle.

The purpose of this study was to determine the length of the femoral tunnel created by drilling through either a transtibial tunnel or medial arthroscopic portal. In addition, we sought to determine the volume and aperture shape of a femoral tunnel when placed through a transtibial tunnel or a medial arthroscopic portal. Lastly, we determined how far the center of each tunnel was from the posterior wall of the femur and the articular surface of the femur to determine its exact position.

The hypotheses were that the tunnels created by use of the medial arthroscopic portal would be shorter in length and the tunnels resulting from the medial arthroscopic portal technique would have a lower total volume. Finally, we hypothesized that the femoral tunnel aperture would be more oval shaped when drilled transtibially and that the medial arthroscopic tunnel would create more anatomic tunnels.

METHODS

We obtained 10 matched-pair fresh-frozen cadaveric knee specimens (20 knees; age range, 73 to 89; 7 men and 3 women). Arthroscopy confirmed that none of the specimens had ACL deficiency or significant arthritis that could affect results. Each knee of a pair was randomly assigned (through a random number generator) to receive a femoral tunnel drilled from a medial location on the tibia (group 1) (transtibial) or a tunnel drilled from a medial arthroscopic portal (group 2) (anteromedial). All surgery was carried out by a sports fellowship–trained orthopaedic surgeon, with 1 year of experience with medial portal reaming.

In 1 of the limbs from each matched pair (n = 10 [5 right and 5 left]), a femoral tunnel was drilled through a transtibial approach from a medial location on the tibia, immediately anterior to the fibers of the superficial medial collateral ligament, with the knee at 90° of flexion, by use of a 55° tip-aiming tibial guide (group 1) (Fig 1). We drilled the tunnels from this location to obtain the most medial starting point without damaging any anatomic structures on the tibia. In the contralateral limb from each matched pair (n = 10 [5 right and 5 left]), a femoral tunnel was drilled from a medial arthroscopic portal (group 2) (Fig 2). A tip-aiming tibial guide (Smith & Nephew, Andover, MA) was set at 55° of rotation and used to drill the transtibial tunnels (group 1), targeting the intra-articular footprint of the ACL. To localize the tibial starting point for the transtibial tunnels, an oblique incision was made measuring 8 cm in length. A 6-mm femoral offset guide was then used to place a Beath needle through the tibial tunnel position at 90° of flexion for group 1 and through the medial arthroscopic portal at 120° of knee flexion for group 2 as far posterior and lateral in the notch as possible. After guide pin placement, a 10-mm-diameter cylindrical reamer (Smith & Nephew) was used to drill over the Beath needles.

Computed tomography (CT) (SOMATOM Definition; Siemens Medical Solutions, Erlangen, Germany) was then performed on all 20 specimens by use of the following protocol: 140 kV and 175 mA, with prospective axial reconstruction with a slice thickness of 0.6 mm at 0.3-mm intervals. Multiplanar reformatted 2-dimensional images were created at a slice thickness of 1 mm with a slice interval of 1 mm from this axial data set on a clinical workstation (Carestream PACS, Client Suite v10.2; Carestream Health, Rochester, NY). The planes of the reformatted images were cho-

FIGURE 1. Three-dimensional reconstruction of transtibial starting point: (A) coronal view and (B) sagittal view.

sen to be parallel to the intra-articular apertures to allow for accurate aperture measurements. The aperture area was calculated automatically by the Carestream PACS Client Suite by use of region-of-interest tools and freehand manual tracings (mouse and pointer) (Fig 3).

The volume was obtained by counting the number of slices (1 mm each) on the 2-dimensional reconstruction starting at the aperture until reaching the lateral cortex of the femur. The formula for volume of a cylinder is as follows: Volume $= \pi r^2 \times$ Height. The area was calculated automatically by the Carestream PACS system as mentioned previously, and the height was determined by the number of slices between the aperture and lateral cortex. Femoral tunnel length was determined by the number of 1-mm slices between the aperture opening (a complete circle on CT) and the lateral cortical wall (not including any drilling in the lateral femoral cortex). The length and the height were the same measurement.

Aperture dimensions were measured by use of standard workstation measurement and freehand (manually traced) region-of-interest tools (mouse and pointer) (Fig 4). The femoral tunnel aperture was characterized by measuring the longest and shortest tunnel diameters in relation to the lateral wall of the femoral notch. Measurements of placement of the intra-articular femoral tunnel on the femoral wall were obtained by a single investigator using custom image processing software[15] (The MathWorks, Natick, MA). Femoral tunnel aperture distances from the posterior wall of the femur and the articular surface of the femur were also calculated (Fig 5). These measurements were obtained by freehand (manually traced) region-of-interest tools (mouse and pointer). The distance from the posterior wall was measured from the center of the femoral tunnel aperture to the posterior wall of the femur by use of a 3-dimensional (3D) reconstructed figure. The distance from the articular surface was measured from the center of the femoral tunnel to the articular surface margin by use of a 3D reconstructed figure (Fig 5). All measurements were obtained independently by 1 blinded individual (a senior resident in orthopaedic surgery) who was trained by an experienced musculoskeletal radiologist who oversaw the imaging portion of the project.

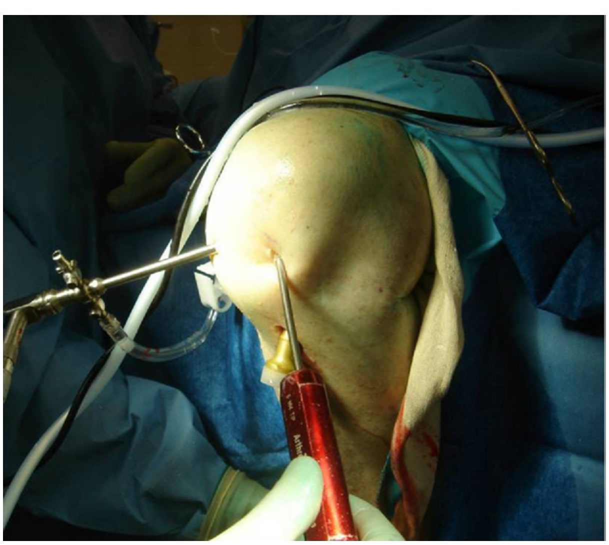

FIGURE 2. Medial arthroscopic portal used for femoral tunnel drilling.

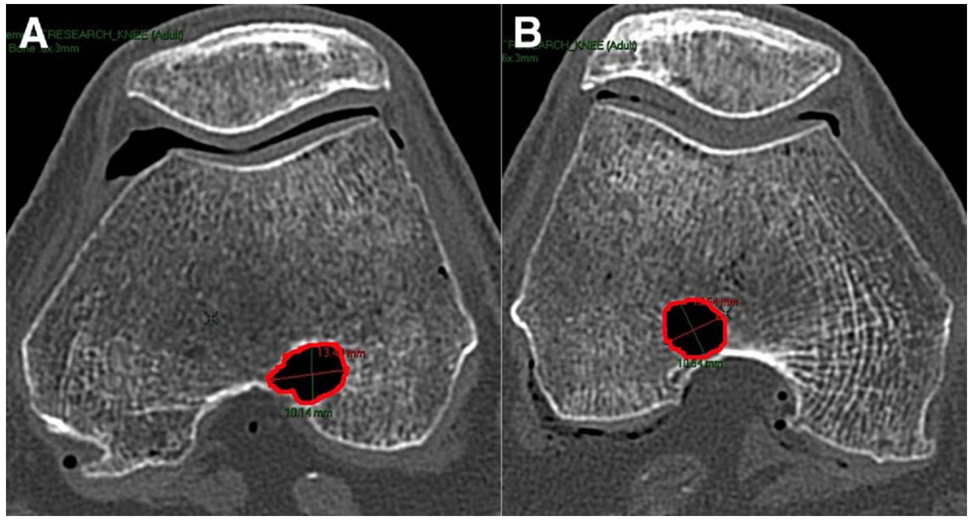

FIGURE 3. CT images of femoral tunnel aperture: (A) medial arthroscopic drilling and (B) transtibial drilling.

Statistical Analysis

We compared femoral tunnel characteristics between the 2 drilling techniques (transtibial *v* arthroscopic) with Mann-Whitney *U* tests. These nonparametric tests were selected because of the small sample size and failure of all data variables to meet the necessary assumptions (normally distributed) to justify the use of parametric statistics. Tests were considered statistically significant at $P \leq .05$. We used SPSS Statistics, version 17.0, for all comparisons (SPSS, Chicago, IL).

RESULTS

Femoral Tunnel Length

The mean femoral tunnel length in the transtibial group (group 1) (29.7 ± 6.6 mm) was significantly longer than that in the medial portal group (group 2) (15.7 ± 5.5 mm) ($P < .001$).

Femoral Intra-articular Aperture

The intra-articular aperture of the femoral tunnel in all cases formed an ellipse. The transtibial group (group 1) had a slightly smaller intra-articular area,

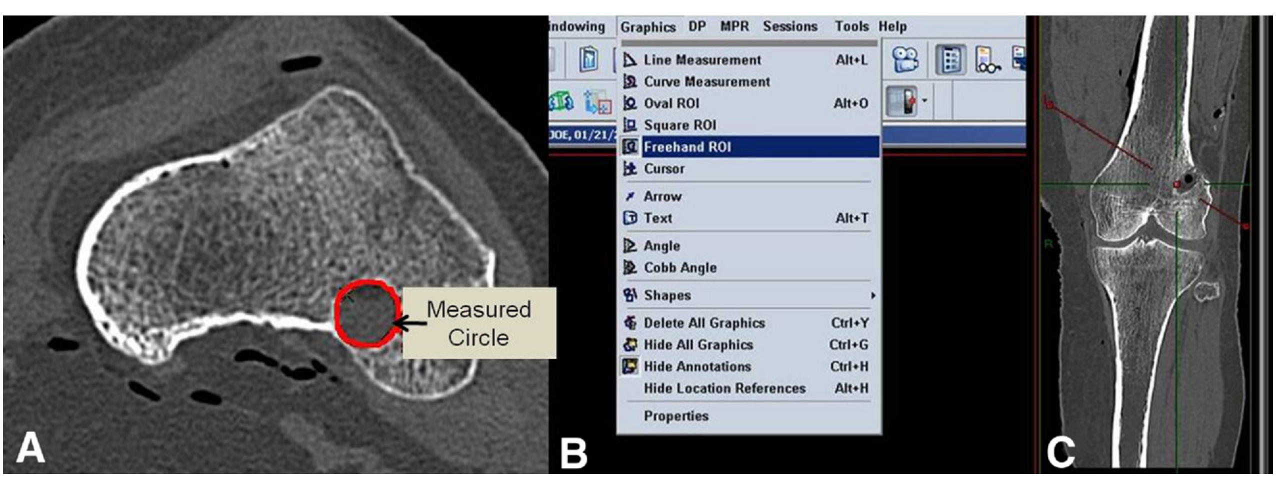

FIGURE 4. CT images of Carestream PACS system used to measure femoral tunnel. (A) Measurement of intra-articular aperture showing area obtained. (B) Toolbar with freehand region of interest (ROI) chosen for measurement. (C) The red line depicts the angle at which the tunnel length was obtained and volume was derived.

FIGURE 5. Three-dimensional reconstruction of anteromedial arthroscopic tunnel and how distance from posterior wall (green line and text) and articular margin (red line and text) was obtained.

94.6 ± 6.8 mm, in comparison to the medial arthroscopic group (group 2), 98.6 ± 13.7 mm ($P = .68$). The medial arthroscopic group (group 2) had more elliptical tunnel characteristics, with the long axis averaging 13.9 ± 1.6 mm ($P = .009$) and short axis averaging 9.4 ± 0.8 mm ($P = .002$), versus the transtibial group (group 1), with the long axis averaging 12.1 ± 0.8 mm and short axis averaging 10.6 ± 0.6 mm ($P = .002$) (Fig 3).

Femoral Tunnel Volume

The femoral tunnel volume in the transtibial group (group 1) was larger than that in the medial arthroscopic group (group 2). The mean volume of the transtibial group was 2,836.5 ± 769.5 mm^3 versus 1,635.9 ± 355.5 mm^3 ($P < .001$) for the medial arthroscopic group.

Distance From Posterior Wall and Articular Surface

The distance from the femoral tunnel to the posterior wall was significantly greater in the transtibial group (10.8 ± 1.0 mm) than in the medial arthroscopic group (6.9 ± 0.6 mm) ($P < .001$). The distance from the femoral tunnel to the articular surface was significantly greater in the transtibial group (11.8 ± 1.9 mm) than in the medial arthroscopic group (9.4 ± 0.6 mm) ($P < .001$).

DISCUSSION

The findings of this study are that (1) shorter femoral tunnel lengths are observed when drilling through a medial arthroscopic portal versus medial transtibial drilling; (2) the medial arthroscopic portal created a slightly larger and more elliptical femoral aperture, which was closer to the articular margin and the posterior wall; and (3) tunnels drilled through the tibia (transtibial group) resulted in longer and more voluminous tunnels.

To better replicate normal knee kinematics and control tibial rotation, it has been suggested that a more anatomic femoral tunnel position should be used during ACL reconstruction.[6-9] We sought to determine how more anatomic tunnel placement through 2 separate techniques would affect the size and shape of the aperture as well as the volume and length of the resultant tunnel. In a cadaveric model, Simmons et al.[9] recognized the importance of PCL impingement and noted that ACL graft tension and PCL impingement decreased when the femoral tunnel was made through a tibial tunnel that was drilled at 60° relative to the coronal plane. They noted that the position of the femoral tunnel was more important than the tibial tunnel when assessing graft tension. The actual position of the femoral tunnel relative to the anatomic position was not addressed.[9] In this study we focused on more anatomic femoral tunnel positioning through either the transtibial tunnel or anteromedial arthroscopic portal. However, our transtibial drilling was performed to re-create anatomic landmarks. This could have an effect on graft tensioning in the clinical setting.

Loh et al.[1] evaluated anterior laxity and tibial rotation relative to the intact ACL using a cadaveric model. Reconstructions were performed with the ACL in the standard 11-o'clock position and in the 10-o'clock position, and the knees were subjected to an anterior translation load as well as to a combined valgus and internal rotation torque. The authors noted that the 10-o'clock position yielded better rotational knee stability than the 11-o'clock position, supporting the use of a more horizontal and oblique graft position on the femur. In this study by Loh et al., rotational stability was examined by placing the knee in a combined rotary load of 10-Nm valgus and 5-Nm internal torque with the knee at 15° and 30° of flexion.

Zantop et al.[16] used a goat model to evaluate the structural properties and knee kinematics after soft-tissue ACL reconstruction with 15- and 25-mm graft lengths after 6 and 12 weeks. They found that reducing the tendon graft length in the femoral bone tunnel from 25 to 15 mm did not have an adverse effect in a goat model. However, they did not use human cadavers, they used an Achilles tendon graft for their study, and they reported follow-up data at only 6 and 12 weeks.[16] They also did not determine the volume of the femoral tunnel. We attempted to improve on previous characterizations of femoral tunnels by providing volumetric data and providing a human cadaveric model for bone graft fixation.

Golish et al.[10] evaluated the femoral tunnel lengths based on tibial tunnel placements in 3 locations (progressively more medial) and the medial arthroscopic portal. They found that the medial arthroscopic tunnel allowed for more horizontal tunnel placement than any transtibial tunnel but that very horizontal tunnel placement could lead to excessively short tunnels. This study found similar results with regard to tunnel length. This is expected because an anteromedial arthroscopic portal and medially based transtibial tunnel were used in their study. However, because they used plain films and not CT, they could not determine the volume of the femoral tunnel or the size and shape of the aperture. Moreover, the placement of their most medial tunnel was beyond the superficial fibers of the medial collateral ligament, which could have a significant clinical effect. We attempted to improve on characterization of the femoral tunnels by providing more anatomically friendly placement (anterior to fibers of medial collateral ligament) and improving on characterization in 3 dimensions. Bedi et al.[17] examined the relation between obliquity and femoral tunnel. This cadaveric study found that higher levels of obliquity, and thus rotational stability, are achieved when drilling the femoral tunnel independently through the anteromedial arthroscopic portal. However, drilling in this orientation led to a significantly increased risk of violation of the posterior tunnel wall. Drilling from the anteromedial portal also increased the risk of a tunnel length of less than 25 mm, which is thought to be because of the increased knee flexion used in this technique. Although their study characterized the tunnel obliquity, they did not obtain the volume or 3D characterization of the femoral tunnel aperture. Moreover, we did not find any violations of the posterior tunnel wall.

Ekdahl et al.[18] showed that anatomically placed tunnels led to superior graft incorporation versus nonanatomic tunnel placement in a goat model at 12 weeks after surgery. Each repair was examined histologically for evidence of bone-tendon healing. Macroscopically, the authors found that anatomic femoral tunnel placement led to decreased tibial tunnel enlargement with increased femoral vascularity. Three samples in each group were also examined histologically and showed that there were fewer osteoclasts at the surface of both the femoral and tibial tunnels in specimens that underwent anatomic femoral tunnel placement. Finally, specimens from each group that were not examined histologically were tested biomechanically and showed that the grafts used with nonanatomic tunnels allowed greater anterior tibial translation than those with anatomic tunnel placements. However, in this study a parapatellar arthrotomy was used and not arthroscopic reconstruction. Therefore drilling techniques used in arthroscopy and tunnel shape were not obtained. These factors could affect graft incorporation. It has been shown that a mismatch between graft diameter and intra-articular aperture may influence graft incorporation.[11,12] The mismatch between graft diameter and intra-articular aperture could also lead to decreased graft accommodation in the tunnel. L'Insalata et al.[14] showed the importance of full graft accommodation at the tunnel aperture. It was also shown that the lack of collagen at a tunnel entrance could allow a greater amount of synovial fluid into bone tunnels. This entrance of synovial fluid into the bone tunnels could allow motion of the tendinous portion of the graft inside the tunnel, leading to graft expansion. Chhabra et al.[19] examined femoral tunnel expansion with regard to transtibial versus anteromedial approaches and found significantly greater expansion in transtibial tunnels. Our study emphasizes that there could be mismatch between the aperture area and the shape of the graft, highlighting the importance of filling of the tunnel to prevent the possibility of early graft motion.

In this study our goal was to characterize the femoral tunnel using 2 common femoral tunnel drilling techniques. By use of CT with 3D reconstruction and a custom-designed computer program, this study shows that a more elliptical tunnel is achieved with a medial arthroscopic portal. A cylindrical graft through an elliptical aperture could cause problems similar to a small graft within a large aperture: decreased graft incorporation and early graft motion due to decreased cortical contact. It also shows that the size of the intra-articular aperture is comparable for a tunnel drilled from a medial arthroscopic tunnel and 1 drilled through the transtibial tunnel. We also show that a shorter tunnel is obtained through the medial arthroscopic tunnel and that the shorter tunnel resulted in a less voluminous tunnel. We made the medial starting point more anterior in this study so as to use the anterior edge of the medial collateral ligament as a consistent starting point; in contrast, in the study by Golish et al.,[10] the far medial group was drilled close to the posteromedial edge of the transtibial surface. In both groups the femoral tunnels were relatively short. We do not consider this to be related to specimen size. This is consistent with the lengths found in previous studies for a far-medial starting point for transtibial drilling and the expected short horizontal tunnel that a anteromedial arthroscopic portal would create.[10] We also showed that the anteromedial arthroscopic portal created a tunnel that was closer to the articular margin and posterior wall than the transtibial tunnel. Petersen and Zantop[2] performed cadaveric studies that characterized the anatomic footprint of the bundles of the ACL, and placement with the anteromedial arthroscopic portal seems to place the tunnel closer to the mean of the those 2 bundles.

Tunnel volume, aperture size, aperture shape, and distances from the articular surface and posterior wall were all evaluated in this study. The starting point for femoral drilling affects the placement of the aperture on the intra-articular femoral wall, which subsequently affects the shape of the intra-articular aperture and volume of tunnel created. We noted a less voluminous tunnel with a medial arthroscopic portal starting point as well as a more elliptical aperture. Tunnel length has been shown to be important in ACL reconstruction, especially with suspensory fixation. Previous studies have shown that the mean length of more horizontally placed tunnels is between 16 and 28 mm.[10] With the shortest length of some suspensory fixation devices (i.e., EndoButton tape [Smith & Nephew]) being 15 mm, this could potentially lead to an insufficient amount of graft within the tunnel. The sizes of the apertures between the 2 groups were comparable.

The mean tunnel volume for the medial arthroscopic portal was 2,071.2 mm^3. Many of the studies available give information regarding the 2-dimensional status of femoral tunnels used for ACL reconstruction. Hoser et al.[20] validated the use of CT technology for femoral positions for precise measurements. By including the volumes of the tunnels, this study attempts to include the information available from current technologies (CT with 3D reconstructions) to further improve the characterization of tunnels and how this will affect graft harvest, passage, and incorporation. Moreover, information on the 3 dimensions of tunnels provides more information regarding the possible use of biologic scaffolds by providing more detailed information for their development.

We identified several limitations to this study. The design of the study could have been focused on the ability to reach an ideal starting point on the femur. However, we believe that the intra-articular location of the tibial tunnel is most often used for femoral drilling; therefore, this study design best replicates intraoperative considerations. Taking an average of the tunnel lengths yielded small but significant differences, and this can be affected by the gender profile of the femurs used. There may be errors inherent in the measurements used and the accuracy of the freehand measurements by use of a region-of-interest tool in 2.5-mm CT sections. We attempted to correct for this by establishing a protocol with an attending radiologist. This study was carried out in a cadaveric model. Cadaveric bone osteopenia can have an effect on aperture size and tunnel characteristics. We also were not able to directly determine how well we were able to create the anatomic footprint of each cadaver. However, we used indirect methods by measuring the distance from the articular surface and the posterior wall to aid in the characterization of the placement of our tunnels.

CONCLUSIONS

We determined the length and volume of the femoral tunnel to be shorter and smaller, respectively, with a medial arthroscopic portal. In addition, the aperture shape was more of an ellipse with a medial arthroscopic portal. The medial arthroscopic portal also created a femoral tunnel that was closer to the posterior wall and articular surface of the femur.

REFERENCES

1. 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. 2002 Richard O'Connor Award paper. *Arthroscopy* 2003;19:297-304.
2. Petersen W, Zantop T. Anatomy of the anterior cruciate ligament with regard to its two bundles. *Clin Orthop Relat Res* 2007;454:35-47.
3. Boden B, Migaud H, Gougeon F, Debroucker MJ, Duquennoy A. Effect of graft position on laxity after anterior cruciate ligament reconstruction. Stress radiography in 90 knees 2 to 5 years after autograft. *Acta Orthop Belg* 1996;62:2-7.
4. 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.
5. Markolf KL, Hame S, Hunter DM, et al. Effects of femoral tunnel placement on knee laxity and forces in an anterior cruciate ligament graft. *J Orthop Res* 2002;20:1016-1024.

6. Rupp S, Muller B, Seil R. Knee laxity after ACL reconstruction with a BPTB graft. *Knee Surg Sports Traumatol Arthrosc* 2001;9:72-76.
7. Scopp JM, Jasper LE, Belkoff SM, Moorman CT III. The effect of oblique femoral tunnel placement on rotational constraint of the knee reconstructed using patellar tendon autografts. *Arthroscopy* 2004;20:294-299.
8. 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.
9. Simmons R, Howell SM, 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.
10. 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;23:1187-1192.
11. Clancy WG Jr. Intra-articular reconstruction of the anterior cruciate ligament. *Orthop Clin North Am* 1985;16:181-189.
12. Cain EL Jr, Clancy WG Jr. Anatomic endoscopic anterior cruciate ligament reconstruction with patella tendon autograft. *Orthop Clin North Am* 2002;33:717-725.
13. Hoher J, Livesay GA, Ma CB, Withrow JD, Fu FH, Woo SL. Hamstring graft motion in the femoral bone tunnel when using titanium button/polyester tape fixation. *Knee Surg Sports Traumatol Arthrosc* 1999;7:215-219.
14. L'Insalata JC, Klatt B, Fu FH, Harner CD. Tunnel expansion following anterior cruciate ligament reconstruction: A comparison of hamstring and patellar tendon autografts. *Knee Surg Sports Traumatol Arthrosc* 1997;5:234-238.
15. Yagi M, Kuroda R, Nagamune K, Yoshiya S, Kurosaka M. Double-bundle ACL reconstruction can improve rotational stability. *Clin Orthop Relat Res* 2007;454:100-107.
16. Zantop T, Ferretti M, Bell KM, Brucker PU, Gilbertson L, Fu FH. Effect of tunnel-graft length on the biomechanics of anterior cruciate ligament-reconstructed knees: Intra-articular study in a goat model. *Am J Sports Med* 2008;36:2158-2166.
17. Bedi A, Raphael B, Maderazo A, Pavlov H, Williams RJ III. Transtibial versus anteromedial portal drilling for anterior cruciate ligament reconstruction: A cadaveric study of femoral tunnel length and obliquity. *Arthroscopy* 2010;26:342-350.
18. Ekdahl M, Nozaki M, Ferretti M, Tsai A, Smolinski P, Fu FH. The effect of tunnel placement on bone-tendon healing in anterior cruciate ligament reconstruction in a goat model. *Am J Sports Med* 2009;37:1522-1530.
19. 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.
20. Hoser C, Tecklenburg K, Kuenzel KH, Fink C. Postoperative evaluation of femoral tunnel position in ACL reconstruction: Plain radiography versus computed tomography. *Knee Surg Sports Traumatol Arthrosc* 2005;13:256-262.