Optimization of Anteromedial Portal Femoral Tunnel Drilling With Flexible and Straight Reamers in Anterior Cruciate Ligament Reconstruction: A Cadaveric 3-Dimensional Computed Tomography Analysis

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Purpose: To use 3-dimensional custom CAD technology to evaluate how knee flexion angle affects femoral tunnel length and distance to the posterior wall when using curved and straight guides for drilling through the anteromedial portal (AMP). **Methods:** Six cadaveric knees were placed in an external fixator at various degrees of flexion (90°, 110°, 125°, and maximum 135° to 140°). Computed tomography scans were obtained at all flexion points for 3-dimensional point-cloud models. Using custom CAD software, surgical guides through the AMP were replicated along with virtual tunnels at each flexion angle. Distance from the posterior cortex and tunnel dimensions were collected after 8-mm and 10-mm tunnel creation. **Results:** At 90° of flexion, the average tunnel length down the posterior aspect of 8-mm tunnel was 25.0 mm (95% confidence interval [CI] 16.2-33.8) and 12.0 mm (95% CI 7.3-16.7) for curved and straight guides, respectively; 31.0 mm (95% CI 26.8-35.2) and 28.6 mm (95% CI 24.8-32.4) at 110°; 33.8 mm (95% CI 30.1-37.5) and 31.1 mm (95% CI 26.8-35.4) at 125°; and 35.0 mm (95% CI 34.1-35.9) and 35.5 mm (95% CI 34.2-36.8) with maximal flexion. Values between curved and straight guides are significantly different ($P < .001$), with straight guides breaching the posterior wall at 90° and 110° of flexion in some specimens. The average distance to the posterior wall cortex was 0.9 mm (95% CI −1.5 to 3.3) and −0.6 mm (95% CI −2.3 to 1.1) for curved and straight guides, respectively, at 90° of flexion ($P = .014$); 2.3 mm (95% CI −0.2 to 4.8) and −0.1 mm (95% CI −2.4 to 2.2) at 110° ($P = .001$); 4.4 mm (95% CI 2.8-6.0) and 3.9 mm (95% CI 1.9-5.9) at 125° ($P = .299$); and 6.7 mm (95% CI 6.2-7.2) and 8.3 mm (95% CI 6.1-10.5) at maximal flexion ($P = .184$). Posterior wall blowout was noted when using 10-mm straight guides at both 90° (2 specimens) and 110° (3 specimens). Using 10-mm curved guides posterior blowout was noted in 1 specimen at 90°. Maximum footprint coverage occurred at 110° for straight guides and 90° for curved guides. **Conclusions:** When using the AMP, flexible guides and reamers result in a greater distance of the tunnel to the femoral cortex while preserving adequate tunnel length at lower knee flexion angles. To create long femoral tunnels without breaching the posterior cortex, the knee should be flexed to at least 110° for curved reamers and 125° for straight. **Clinical Relevance:** Femoral tunnel drilling through the AMP using curved and straight reamers requires different degrees of knee flexion to achieve optimal tunnel dimensions.

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Injuries to the anterior cruciate ligament (ACL) are among the most common to the sports medicine orthopedist. As such, it has been the subject of ever increasing studies and scientific inquiry. Despite the amount of research that has been devoted to anatomic anterior cruciate ligament reconstruction, there is still considerable controversy surrounding the best way to prepare the femoral tunnel. Recent studies suggest that ACL reconstruction success depends on graft placement within the anatomic insertions of the native ACL footprint.[1-5]

Research has shown it to be difficult to place a femoral tunnel in a way that reproduces native ACL insertional anatomy through a transtibial technique.[6] In addition, this method has been known to produce unacceptable vertical tunnels high in the notch.[7] Transtibial techniques have been modified to decrease these risks and create a more anatomic femoral tunnel, with excellent long-term outcomes reported with low failure rates.[8] However, limitations still arise in regard to graft placement and tibial tunnel positioning even with these modifications.[9,10]

Many surgeons use the anteromedial approach with flexible reamers, first described by Cain and Clancy, to drill the femoral tunnel.[11] Flexible reamers are designed to limit the need of hyperflexion during tunnel placement, and allow tunnel placement to a more anterior and inferior site on the lateral condyle compared with conventional reamers. It has been shown that flexible reamers allow a more anatomic tunnel placement compared with rigid reamers when femoral tunnels are drilled through an anteromedial portal (AMP).[12,13] Flexible instrumentation creates longer tunnels that are further away from the posterior cortex. In addition, tunnel placement using a rigid reamer with the knee in hyperflexion risks creating a horizontal tunnel with elevated tunnel acuity.[14] Conversely, having the knee flexed to 90° leads to a short tunnel that may blow out the posterior cortex.

There is still controversy, however, regarding optimal knee flexion when using flexible or rigid reamers through the AMP. The objective of this study was to use 3-dimensional (3D) custom CAD technology to evaluate how knee flexion angle affects femoral tunnel length and distance to the posterior wall when using curved and straight guides for drilling through the AMP. We hypothesized that with less knee flexion, femoral tunnels drilled with curved guides would create longer tunnels with greater distance to the posterior femoral cortex compared with straight guides.

Methods

Creation of 3D CT Knee Models at Various Flexion Angles

In this cadaveric-based study, 6 fresh-frozen knees were obtained (Science Care, Phoenix, AZ) from screened individuals with no prior history of arthritis, cancer, surgery, or any ligamentous knee injury. The mean age for the collected knees was 47 years (range, 26-59 years). Each knee underwent computerized tomography (CT) images in the coronal, axial, and sagittal planes by use of 0.625-mm contiguous slices (20-cm field of view, 512 × 512 matrices) at various angles to gather cross-sectional images of the knee joint at specific flexion points. Each knee was flexed using an external fixation device to ensure consistent flexion and prevent rotation. The knees were then scanned at 90°, 110°, 125°, and 135° to 140° (maximum) of flexion. CT scans at the various flexion angles were then used to create 3D knee models at each of the 4 flexion points under investigation. CT images of the knees at various flexion angles were imported in DICOM format and segmented using 3D reconstruction software (Mimics, Materialise, Leuven, Belgium) and then 3D knee models for each flexion angle were created. The 3D CT models were further converted to point-cloud models.

Creation of 3D ACL Tunnel Models

3D models of a curved guide with 45° bend (5.0 mm in outer diameter, Stryker Corporation VersiTomic Knee Instrumentation, Kalamazoo, MI) and a straight guide with the same outer diameter used during ACL reconstruction surgery were created with identical dimensions using custom CAD software (Fig 1 A and B). The guides were oriented about the AMP. A "pivot" point was set at the tip of each guide shaft (Fig 1 B and C). Using the midpoint of the footprint and topographical landmarks in the 3D CT femur models, a single surgeon systematically identified insertion points of the ACL tunnel guide for a single bundle reconstruction to be used for both 8-mm and 10-mm tunnels (the insertion point, Fig 1D).

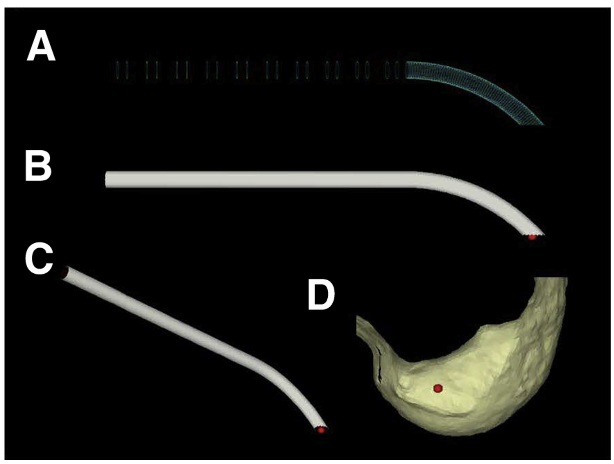

Fig 1. Curved guide and entry point. (A) Point-cloud model of the curved guide. (B, C) Three-dimensional model of the curved guide and entry point (red). (D) Lateral femoral condyle and entry point (red).

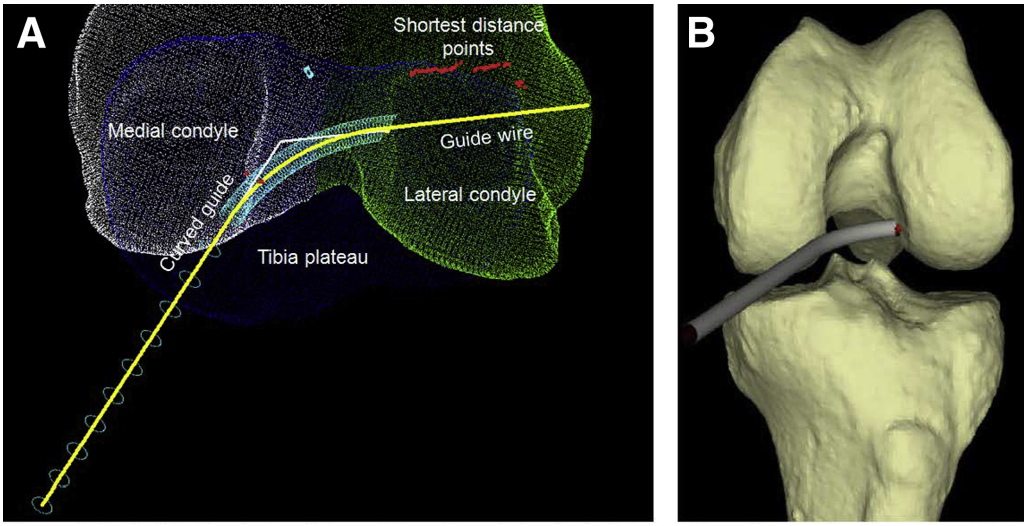

Fig 2. (A) Analysis of tunnel length and shortest distances from the guidewire using a 3-dimensional point-cloud model. The curved guide is automatically rotated around the entry point until the guide contacts the medial condyle and medial tibia plateau. (B) Three-dimensional representation of the virtual placement of the curved guide; red point is the entry point of the guidewire.

The "pivot" point of each guide shaft model was placed at the insertion point (Fig 2). Then, the guide shaft model was rotated toward medial and inferior directions about the "pivot" point until any portion of the guide shaft hit the medial condyle and medial plateau with 2 mm clearance considering cartilage thickness (Fig 2A). The angle of inclination of the curved guide shaft was kept constant at 5°. After the position of the guide was determined, a virtual guidewire was inserted into the lateral condyle aligned with the straight portion at the tip of the curved guide shaft or aligned with the straight guide shaft. The virtual guidewire was extended until it hit the lateral wall or posterior wall of the lateral condyle (the exit point). The length of the ACL tunnel was defined as the distance between the insertion point and the exit point. The distance from the guidewire to the posterior wall of the lateral condyle was calculated as the least distance in a plane perpendicular to the guidewire. The least distances to the posterior wall were calculated at 100 points along the guidewire as a function of the distance from the insertion point (as 0% at the insertion point and 100% at the exit point).

The 3D virtual guide shafts and ACL tunnel creation and 3D measurements of the tunnel length and least distance to the posterior wall of the lateral condyle were performed with a custom-written program by Visual C++ with Microsoft Foundation Class programing environment (Microsoft, Redmond, WA).

Statistical Analysis

All data were recorded in a Microsoft Excel spreadsheet (Microsoft, Redmond, WA). The data analysis for this study was performed using IBM SPSS Statistics Version 22 (SPSS, Chicago, IL). Comparisons of average tunnel lengths and average least distance to the posterior wall between straight and curved guides were performed with the use of a paired *t*-test and 2-way repeated measures analysis of variance, with a significance level $P < .05$. No power analysis was performed, so 95% confidence intervals were calculated.

Results

In our sample, there were 4 males and 3 females. Average least distances to the posterior wall of the lateral femoral condyle from the middle third of a 10-mm femoral tunnel drilled with curved and straight reamers are shown in Table 1. As the degree of knee flexion increases, the average least distance increases for both curved and straight reamers ($P < .001$). Curved reamers resulted in significantly greater least distances from the posterior wall compared with straight reamers with the knee at 90° and 110° of flexion ($P = .014$, $P = .001$). Importantly, average least distance data for straight guides at 90° and 110° of flexion were negative, indicating that the average specimen breached the posterior femoral cortex. At flexion angles of 125° and above, the least distances were not significantly different ($P = .299$ and $P = .184$). At knee flexion angles of more than 110° for curved guides and more than 125° for straight guides, the adequate distance to the posterior wall was achieved without breaching the femoral cortex.

Average tunnel lengths for 8-mm and 10-mm tunnels virtually drilled at each flexion angle with curved and straight reamers are shown in Tables 2 and 3, respectively. For both 8-mm and 10-mm straight and curved guides, increasing the knee flexion angle increased the tunnel length ($P < .001$). For both 8-mm and 10-mm tunnels, significant differences were noted between

Table 1. Average Least Distance Along the Middle Third of a 10-mm Tunnel Created With Curved and Straight Guides

	Average Least Distance, mm			
Flexion Angle	Curved	Straight	Paired *t*-Test	ANOVA
90°	0.9 ± 2.3 (−1.5 to 3.3)	−0.6 ± 1.6 (−2.3 to 1.1)	**.014**	**<.001**
110°	2.3 ± 2.4 (−0.2 to 4.8)	−0.1 ± 2.2 (−2.4 to 2.2)	**.001**	
125°	4.4 ± 1.5 (2.8-6.0)	3.9 ± 1.9 (1.9-5.9)	0.299	
Maximum	6.7 ± 0.5 (6.2-7.2)	8.3 ± 2.1 (6.1-10.5)	0.184	

NOTE. Data given as mean ± standard deviation (95% confidence interval). ANOVA: Two-way repeated measures analysis of variance. Bold numbers indicate statistical significance, $P < .05$.

curved and straight guides ($P < .001$). Using straight guides, posterior wall blowout was noted in 2 specimens at 90° and 110° of flexion to drill 8-mm tunnels. When drilling 10-mm tunnels with straight guides, posterior blowout was noted in 2 specimens at 90° and 3 specimens at 110° of flexion. Using 10-mm curved guides, posterior wall blowout was noted in one specimen at 90°. Using an 8-mm curved guide, no incidence of posterior wall blowout was noted. Both curved and straight guides are able to achieve adequate tunnel length without violating the posterior wall, though curved guides achieve this at lower knee flexion angles.

Least distance data for curved and straight guides are plotted in Figures 3 and 4, respectively, showing the distance to the posterior cortex for each flexion angle as a function of tunnel length. Increasing flexion angle consistently created tunnels with a greater distance from the posterior cortex ($P < .001$). At 90° of flexion, tunnels created using curved guides had a significantly greater distance to the posterior cortex throughout the first 50% of tunnel length. At 110°, curved guides achieved a significantly greater least distance compared with straight guides between 20% and 80% of tunnel length. At 125°, no significant differences were noted, whereas at maximum flexion, straight guides achieved a greater least distance over the final 30% of tunnel length.

Aperture data for femoral tunnels drilled to a diameter of 8 mm and 10 mm with curved and straight guides are shown in Table 4. For straight guides, the average aperture area reaches a maximum (70.6 mm^2 and 130.6 mm^2 for 8-mm and 10-mm tunnels, respectively) at 110° of flexion while decreasing at greater flexion angles. Curved guides achieved a greatest aperture area at 90° of flexion (63.0 mm^2 and 104.2 mm^2 for 8-mm and 10-mm tunnels, respectively) while decreasing with greater flexion angles. There were no significant differences between curved and straight guides for the area covered for all flexion angles.

Discussion

This study has shown that drilling the femoral tunnel through the AMP at 90° of knee flexion, with either curved or straight guides, will greatly put the posterior cortex at risk. However, at flexion angels of 125° and greater, the posterior cortex was not breached by either guide. In addition, the knee flexion angle with both the greatest aperture and the greatest least distance was 110° for curved guides and 125° and greater for straight guides. We also showed that 3D imaging software can be used to accurately model femoral tunnel placement using curved or straight guides through the AMP with knee flexion angle as the sole variable. The virtual design of this study permitted the same knees to be virtually drilled multiple times using different guides, which controlled inherent anatomic variation between the flexion angles because the same knees were drilled at each setting. The average distance to the posterior cortex along a tunnel drilled using curved and straight guides (Figs 3 and 4) shows that increasing knee flexion increases distance to the posterior cortex. Virtual tunnels of 8 mm and 10 mm were created to simulate tunnels created during routine ACL reconstruction using soft tissue and bone−tendon−bone grafts. Analyzing tunnel data (Tables 2 and 3) showed that at 90° and 110° of knee flexion, 8-mm and 10-mm femoral tunnels cannot be reliably drilled with straight guides without the risk of blowing out the posterior femoral cortex. Ten-millimeter tunnels drilled with a curved guide at 90° risks blowing out the posterior femoral cortex as well.

The use of the AMP for drilling the femoral tunnel has become increasingly more common since the advent of flexible instrumentation. Anteromedial drilling creates a more anatomic tunnel, although it does have some drawbacks including the need for hyperflexion, short tunnels, and difficulty maintaining visualization while drilling.[13,15-18] A cadaveric study by Bedi et al.[9] analyzed the obliquity and length of femoral tunnels created through transtibial versus AMP drilling. These authors concluded that anteromedial drilling allows for increased obliquity; however, there is an increased risk of critically short femoral tunnels (<25 mm). In this study, we described the adequate tunnel length as >25 mm. Recently, a study by Mariscalco et al.[19] analyzed the effect of the femoral tunnel on patient-reported outcomes in primary ACL reconstructions using hamstring grafts with cortical button fixation and anteromedial or transtibial drilling. Femoral tunnel lengths ranged from 14 mm to 35 mm, and no

Table 2. Average Tunnel Length Along the Anterior Edge, Center, and Posterior Edge of 8-mm Virtual Tunnels

	Average Tunnel Length, mm					
	8-mm Curved Guide			8-mm Straight Guide		
Flexion Angle	Anterior	Center	Posterior	Anterior	Center	Posterior
90°	34.3 ± 3.5 (33.3-35.3)	31.1 ± 4.6 (26.3-35.9)	25.0 ± 8.4 (16.2-33.8)	27.8 ± 0.9 (27.5-28.1)	18.8 ± 3.7 (14.9-22.7)	12.0 ± 4.5* (7.3-16.7)
110°	34.4 ± 1.4 (34.0-34.8)	33.5 ± 1.7 (31.7-35.3)	31.0 ± 4.0 (26.8-35.2)	34.7 ± 2.5 (34.0-35.4)	31.0 ± 2.5 (28.4-33.6)	28.6 ± 3.6* (24.8-32.4)
125°	33.0 ± 2.9 (32.1-33.9)	33.6 ± 2.2 (31.3-35.9)	33.8 ± 3.5 (30.1-37.5)	35.1 ± 1.0 (34.8-35.4)	32.6 ± 3.8 (28.6-36.6)	31.1 ± 4.1 (26.8-35.4)
Maximum	33.4 ± 3.5 (32.4-34.4)	34.1 ± 2.0 (32.0-36.2)	35.0 ± 0.9 (34.1-35.9)	37.3 ± 1.5 (36.9-37.7)	36.3 ± 0.6 (35.7-36.9)	35.5 ± 1.2 (34.2-36.8)
ANOVA	**<.001**	**<.001**	**<.001**			

NOTE. Data given as mean ± standard deviation (95% confidence interval). ANOVA: Two-way repeated measures analysis of variance. Bold numbers indicate statistical significance, $P < .05$.
*Indicates posterior wall blowout in specimens (2 at 90° and 110° with straight guides).

Table 3. Average Tunnel Length Along the Anterior Edge, Center, and Posterior Edge of 10-mm Virtual Tunnels

	Average Tunnel Length, mm					
	10-mm Curved Guide			10-mm Straight Guide		
Flexion Angle	Anterior	Center	Posterior	Anterior	Center	Posterior
90°	34.8 ± 3.4 (33.8-35.8)	31.1 ± 4.6 (26.3-35.9)	26.6 ± 3.9* (22.5-30.7)	30.1 ± 1.6 (29.6-30.6)	18.8 ± 3.7 (14.9-22.7)	11.7 ± 5.4* (6.0-17.4)
110°	34.3 ± 1.5 (33.9-34.7)	33.5 ± 1.7 (31.7-35.3)	30.6 ± 4.9 (25.5-35.7)	35.6 ± 2.3 (34.9-36.3)	31.0 ± 2.5 (28.4-33.6)	25.3 ± 1.1* (24.1-26.5)
125°	32.4 ± 3.6 (31.3-33.5)	33.6 ± 2.2 (31.3-35.9)	33.9 ± 4.1 (29.6-38.2)	36.1 ± 0.5 (36.0-36.2)	32.6 ± 3.8 (28.6-36.6)	31.0 ± 2.9 (28.0-34.0)
Maximum	33.1 ± 4.3 (31.8-34.4)	34.1 ± 2.0 (32.0-36.2)	35.1 ± 1.0 (34.1-36.1)	37.5 ± 1.9 (36.9-38.1)	36.3 ± 0.6 (35.7-36.9)	35.3 ± 1.6 (33.6-37.0)
ANOVA	**<.001**	**<.001**	**<.001**			

NOTE. Data given as mean ± standard deviation (95% confidence interval). ANOVA: Two-way repeated measures analysis of variance. Bold numbers indicate statistical significance, $P < .05$.
*Indicates posterior wall blowout in specimens (2 at 90° with curved and straight guides, 3 at 110° with straight guide).

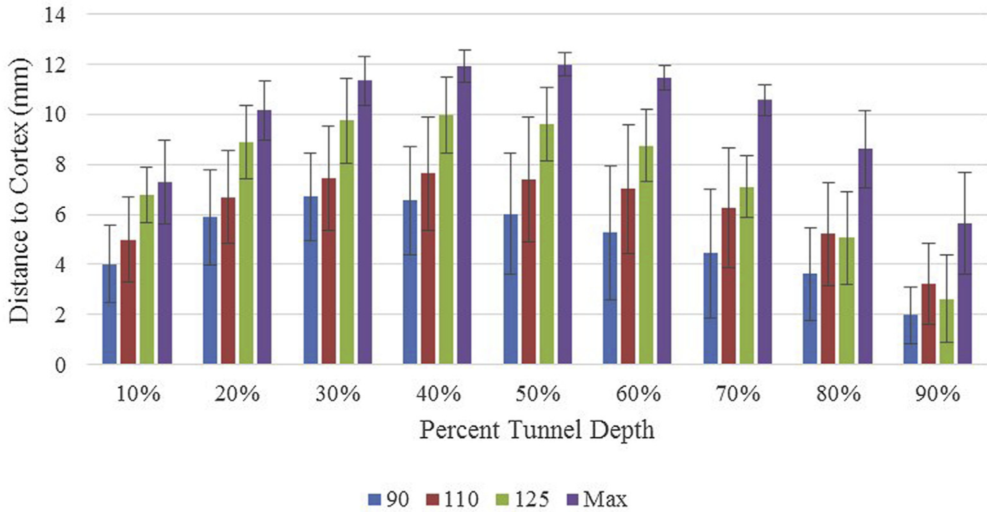

Fig 3. Least distance data along a tunnel drilled with curved guides at various flexion angles. Standard deviation is indicated by error bars.

difference in patient-reported outcomes was found at 2-year follow-up. Thus, the clinical significance of the femoral tunnel length remains unknown. Furthermore, the effect of the femoral tunnel length on revisions is also unknown. In our study, the femoral tunnel length was consistently more than 25 mm when drilling with curved reamers. With straight reamers, a 25 mm tunnel length was reached at 110° of flexion and greater. Despite no current consensus on adequate tunnel length, this study has shown the achievable tunnel lengths at multiple flexion angles for curved and straight reamers.

A study analyzing the effect of knee flexion on the femoral tunnel length during double-bundle ACL reconstruction found that lesser degrees of knee flexion produce shorter tunnel lengths using straight guides.[14] Our study analyzing single-bundle ACL reconstruction produced similar results. With both curved and straight guides, increasing knee flexion produced significantly longer tunnel lengths.

Multiple studies have analyzed the risk of posterior femoral cortex blowout when drilling the femoral tunnel. Steiner and Smart[13] analyzed the use of flexible and rigid systems for femoral tunnel drilling from the AMP versus the transtibial approach at 110° of flexion. They discovered flexible pins exited significantly further from the posterior cortex than rigid pins. In a separate study of tunnels drilled at 120° with a rigid system, findings showed that 75% of tunnels experienced posterior cortex compromise at an average of 21.3 mm.[9] Decreasing knee flexion has been shown to be a risk factor for posterior wall compromise. Our

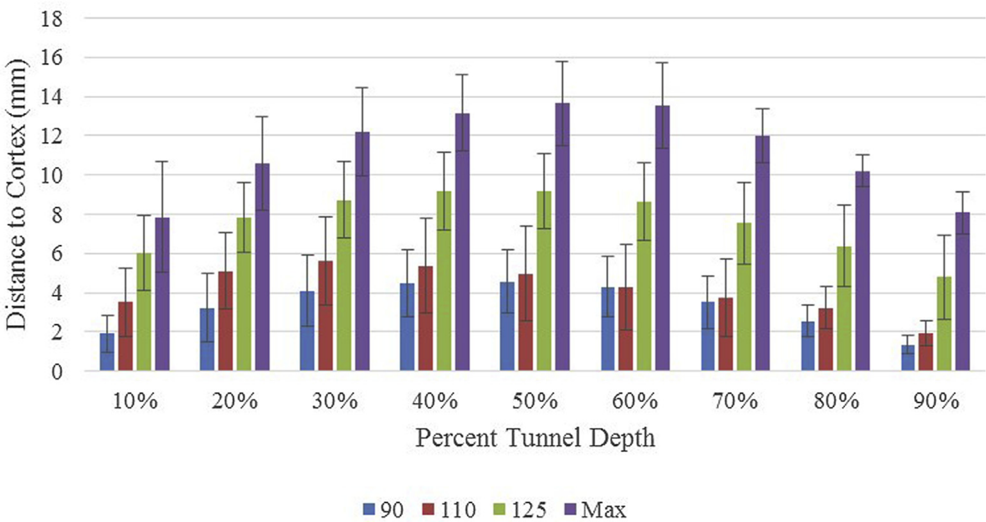

Fig 4. Least distance data along a tunnel drilled with straight guides at various flexion angles. Standard deviation is indicated by error bars.

Table 4. Average Tunnel Aperture Data for Tunnels Drilled With Curved and Straight Guides With 8 mm and 10 mm Diameter

Knee Flexion Angle	Curved Guide					
	8 mm			10 mm		
	Area, mm²	Angle, °	Max Diameter, mm	Area, mm²	Angle, °	Max Diameter, mm
90°	63.0 (51.9-74.2)	42.9 (33.8-51.9)	10.8 (8.8-12.7)	104.2 (86.7-121.8)	43.1 (33.6-52.6)	14.0 (11.4-16.6)
110°	54.2 (47.4-61.1)	33.3 (23.4-43.1)	9.0 (7.8-10.1)	93.2 (75.7-110.8)	33.2 (22.6-43.7)	12.2 (9.9-14.5)
125°	48.9 (40.8-57.1)	17.5 (8.1-26.9)	8.1 (7.0-9.1)	79.2 (69.8-88.6)	17.4 (6.6-28.2)	10.3 (9.1-11.4)
Max Flexion	47.9 (43.2-52.6)	15.9 (5.9-25.8)	7.9 (7.3-8.4)	77.5 (70.4-84.5)	15.1 (6.2-23.9)	8.3 (9.1-10.4)
	Straight Guide					
	8 mm			10 mm		
	Area, mm²	Angle, °	Max Diameter, mm	Area, mm²	Angle, °	Max Diameter, mm
90°	60.7 (43.9-77.5)	41.8 (29.5-54.0)	10.8 (7.7-13.9)	94.3 (88.2-100.3)	37.8 (31.0-44.6)	12.5 (10.0-15.0)
110°	70.6 (33.9-107.2)	38.6 (26.1-51.1)	11 (7.3-14.6)	130.6 (28.1-233.2)	38.7 (20.8-56.6)	14.5 (8.3-20.6)
125°	50.8 (38.6-62.9)	24.7 (14.2-35.1)	8.5 (7.0-10.0)	89.1 (66.0-112.2)	24.7 (13.1-36.2)	10.9 (9.2-12.6)
Max Flexion	48.9 (43.7-54.0)	19.5 (4.1-34.9)	8.3 (6.9-9.6)	79.8 (68.5-91.1)	18.6 (4.1-33.1)	10.4 (9.1-11.7)

NOTE. Data given as mean (95% confidence interval).

study confirms that increasing knee flexion significantly increases the distance to the posterior cortex with maximum flexion allowing for the greatest distance. In the same respect, Silver et al.[12] analyzed flexible and straight guide pins drilled through the AMP in knees flexed to 120° to demonstrate longer interosseous lengths using flexible pins. Although our study did not assess tunnel length at 120°, the virtual design allowed measurements throughout a range of knee flexion angles, verifying the longer tunnel provided by flexible systems. Furthermore, our virtual design enabled an 8-mm- and a 10-mm-diameter tunnel to be drilled using both curved and straight guides from the same starting point for different flexion angles, thereby permitting comparison of these permutations in the same knee. Even though this study showed that increasing flexion increased tunnel lengths, at 90° of flexion neither rigid nor flexible systems could be used without compromising the femoral cortex or creating a critically short tunnel in some specimens. In addition, at 110° of flexion, the posterior cortex was compromised when drilling a 10-mm tunnel with a straight guide.

The goal of ACL reconstruction via the AMP is to create anatomic reconstruction of the ACL, including the size of its insertion site. Hensler et al.[20] studied the effects of drill size, angle, and knee flexion on aperture morphology, discovering an average native femoral insertion site size of 136 mm^2. They discovered that with a 9-mm drill bit, a transverse angle of 40° with the knee flexed to 102° best matched the native ACL footprint. In this study, we found that with curved guides, knee flexion to 90° created the largest footprint and with straight guides, knee flexion to 110° created the largest footprint (Table 4). Increasing knee flexion past these points minimized the aperture area of the femoral tunnel. Although the aperture area is best reached at 90° for curved guides and 110° for straight guides, we have shown that risks of critically short tunnels and posterior blowout may occur at these angles. For curved and straight guides, knee flexion to 110° and 125° optimizes femoral tunnel dimensions. However, increasing knee flexion past this point diminishes the aperture area.

Limitations

There are some limitations to the present study. First, we set the thickness of the articular cartilage at 2 mm considering deformation of the articular cartilage due to compression by the guide. In a patient with the potential for a thicker cartilage, this variable may alter positioning of the guide pin as it passes adjacent to the medial condyle. Secondly, we only evaluated the bony morphology without taking into account the soft tissue. Therefore, the entry point may be slightly more medial in a surgical setting when taking into account soft tissue. The sample size is another limitation, which permitted anatomic variation as a confounding variable; although the virtual design reduced this variability by using the same knees for all flexion angles, this variability remained among each setting. Lastly, the clinical significance of tunnel length is unknown. We recognize that there is no consensus regarding adequate tunnel length, and therefore, a critically short tunnel in this study may not correspond with clinical relevance.

Conclusions

When using the AMP, flexible guides and reamers result in a greater distance of the tunnel to the femoral cortex while preserving adequate tunnel length at lower knee flexion angles. To create long femoral tunnels without breaching the posterior cortex, the knee should be flexed to at least 110° for curved reamers and 125° for straight.

References

1. Carson EW, Anisko EM, Restrepo C, Panariello RA, O'Brien SJ, Warren RF. Revision anterior cruciate ligament reconstruction: Etiology of failures and clinical results. *J Knee Surg* 2004;17:127-132.
2. Chhabra A, Starman JS, Ferretti M, Vidal AF, Zantop T, Fu FH. Anatomic, radiographic, biomechanical, and kinematic evaluation of the anterior cruciate ligament and its two functional bundles. *J Bone Joint Surg Am* 2006;88: 2-10 (suppl 4).
3. Kopf S, Forsythe B, Wong AK, et al. Nonanatomic tunnel position in traditional transtibial single-bundle anterior cruciate ligament reconstruction evaluated by three-dimensional computed tomography. *J Bone Joint Surg Am* 2010;92:1427-1431.
4. Siebold R, Ellert T, Metz S, Metz J. Femoral insertions of the anteromedial and posterolateral bundles of the anterior cruciate ligament: Morphometry and arthroscopic orientation models for double-bundle bone tunnel placement—a cadaver study. *Arthroscopy* 2008;24: 585-592.
5. Ferretti M, Ekdahl M, Shen W, Fu FH. Osseous landmarks of the femoral attachment of the anterior cruciate ligament: An anatomic study. *Arthroscopy* 2007;23: 1218-1225.
6. Forsythe B, Kopf S, Wong AK, et al. The location of femoral and tibial tunnels in anatomic double-bundle anterior cruciate ligament reconstruction analyzed by three-dimensional computed tomography models. *J Bone Joint Surg Am* 2010;92:1418-1426.
7. 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;37:1912-1919.
8. Chalmers PN, Mall NA, Cole BJ, Verma NN, Bush-Joseph CA, Bach BR Jr. Anteromedial versus transtibial tunnel drilling in anterior cruciate ligament reconstructions: A systematic review. *Arthroscopy* 2013;29: 1235-1242.
9. 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.
10. Heming JF, Rand J, Steiner ME. Anatomical limitations of transtibial drilling in anterior cruciate ligament reconstruction. *Am J Sports Med* 2007;35:1708-1715.
11. Cain EL Jr, Clancy WG Jr. Anatomic endoscopic anterior cruciate ligament reconstruction with patella tendon autograft. *Orthop Clin North Am* 2002;33:717-725.
12. Silver AG, Kaar SG, Grisell MK, Reagan JM, Farrow LD. Comparison between rigid and flexible systems for drilling the femoral tunnel through an anteromedial portal in anterior cruciate ligament reconstruction. *Arthroscopy* 2010;26:790-795.
13. Steiner ME, Smart LR. Flexible instruments outperform rigid instruments to place anatomic anterior cruciate ligament femoral tunnels without hyperflexion. *Arthroscopy* 2012;28:835-843.
14. Basdekis G, Abisafi C, Christel P. Effect of knee flexion angle on length and orientation of posterolateral femoral tunnel drilled through anteromedial portal during anatomic double-bundle anterior cruciate ligament reconstruction. *Arthroscopy* 2009;25:1108-1114.
15. Basdekis G, Abisafi C, Christel P. Influence of knee flexion angle on femoral tunnel characteristics when drilled through the anteromedial portal during anterior cruciate ligament reconstruction. *Arthroscopy* 2008;24:459-464.
16. Miller CD, Gerdeman AC, Hart JM, et al. A comparison of 2 drilling techniques on the femoral tunnel for anterior cruciate ligament reconstruction. *Arthroscopy* 2011;27:372-379.
17. Lubowitz JH, Konicek J. Anterior cruciate ligament femoral tunnel length: Cadaveric analysis comparing anteromedial portal versus outside-in technique. *Arthroscopy* 2010;26:1357-1362.
18. Chang CB, Yoo JH, Chung BJ, Seong SC, Kim TK. Oblique femoral tunnel placement can increase risks of short femoral tunnel and cross-pin protrusion in anterior cruciate ligament reconstruction. *Am J Sports Med* 2010;38: 1237-1245.
19. Mariscalco MW, Magnussen RA, Mitchell J, et al. How much hamstring graft needs to be in the femoral tunnel? A MOON cohort study. *Eur Orthop Traumatol* 2015;6:9-13.
20. Hensler D, Working ZM, Illingworth KD, Thorhauer ED, Tashman S, Fu FH. Medial portal drilling: Effects on the femoral tunnel aperture morphology during anterior cruciate ligament reconstruction. *J Bone Joint Surg Am* 2011;93:2063-2071.