Medial Portal Drilling: Effects on the Femoral Tunnel Aperture Morphology During Anterior Cruciate Ligament Reconstruction

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Background: A goal of anatomic anterior cruciate ligament (ACL) reconstruction should be to create a femoral tunnel aperture that resembles the native attachment site in terms of size and orientation. Aperture morphology varies as a function of the drill-bit diameter, the angle in the horizontal plane at which the drilled tunnel intersects the lateral notch wall (transverse drill angle), and the angle of knee flexion in the vertical plane during drilling.

Methods: A literature search was conducted to determine population-based dimensions of the femoral ACL footprint. The tunnel aperture length, width, and area associated with the use of different drill-bit diameters and transverse drill angles were calculated. The effect of the knee flexion angle on the orientation (anteroposterior and proximodistal dimension) and size of the femoral tunnel aperture relative to the native femoral insertion of the ACL were calculated with use of geometric mathematical models.

Results: The literature search revealed an average femoral insertion site size of 8.9 mm for width, 16.3 mm for length, and 136.0 mm^2 for area. The use of a 9-mm drill bit at a transverse drill angle of 40° resulted in a tunnel aperture area of 99.0 mm^2 and a tunnel aperture length of 14.0 mm. Decreasing the transverse drill angle from 60° to 20° led to an increase of 152.9% in length and of 153.1% in tunnel aperture area. When a 9-mm drill bit and a transverse drill angle of 40° were used, the aperture seemed to best match the native ACL footprint when drilling was performed at a knee flexion angle of 102°; deviations from this angle in either direction resulted in increasing tunnel area mismatch compared with the baseline aperture. Increasing the knee flexion angle to 130° decreased the proximodistal dimension of the aperture by 2.78 mm and increased the anteroposterior distance by 0.65 mm, creating a mismatched area of 13.5%.

Conclusions: The drill-bit diameter, transverse drill angle, and knee flexion angle can all affect femoral tunnel aperture morphology in medial portal drilling during ACL reconstruction. The relationship between drilling orientation and aperture morphology is critical knowledge for surgeons performing ACL reconstruction.

Clinical Relevance: This study can help the surgeon to understand how drilling parameters affect the morphology of the femoral tunnel aperture during ACL reconstruction.

Rupture of the anterior cruciate ligament (ACL) is a common ligamentous injury. The primary aim of ACL reconstruction is to restore the function of the ACL and the native kinematics of the knee[1]. Despite the widespread use and excellent short-term success of traditional arthroscopic ACL reconstruction with use of a transtibial technique, the development of late osteoarthritis of the knee has been reported[2,3]. Concerns exist that these findings are the consequence of surgically altered knee kinematics applied cyclically over time to mechanically sensitive articular cartilage chondrocytes. In the last decade, there has been an increasing interest in and focus on anatomic ACL reconstruction to more accurately restore the anatomy and biomechanics of the pre-injury ACL[4,5] through precise restoration of the osseous attachment sites and native tension patterns of the native ACL. This approach allows surgeons to individualize ACL surgery relative to the specific anatomy of every patient[6,7]. Although

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the ACL consists of two functional bundles, restoration of the ACL is most commonly performed with a single-bundle as opposed to a double-bundle reconstruction that approximates both the anteromedial and posterolateral bundles.

Restoring anatomy is a basic principle of orthopaedic surgery, and recent studies have hypothesized that ACL reconstruction with anatomic tunnel placement would provide superior stability and would reduce early degenerative changes[8]. Accurate restoration of the native ACL footprint is an essential tenet of anatomical ACL reconstruction. Thus, minimizing the mismatch between the graft tunnel and the femoral ACL insertion is theoretically a reasonable target for optimizing outcome[9]. The predominance of current studies have also shown that the commonly used transtibial technique most often fails to place the graft into the femoral ACL origin, although this remains a topic of debate[10-12]. Tibial tunnel-independent methods of femoral tunnel drilling have been developed to achieve a more anatomic femoral tunnel placement during ACL surgery, which includes the use of medial portal drilling[13,14].

In medial portal drilling, the orientation and size of the femoral tunnel aperture depend on three main parameters: (1) the drill-bit diameter, (2) the transverse drill angle, and (3) the knee flexion angle. Studies have evaluated the effect of different drilling techniques on tunnel morphology (including tunnel length) and possible complications[15,16]. Kopf et al. investigated the effect of the different drill angles on the tibial tunnel aperture morphology[9]. However, to our knowledge, no study has investigated the effects of femoral tunnel orientation or drill-bit diameter on femoral tunnel aperture with respect to restoration of the native ACL insertion morphology. The goal of the present study was to quantify the effects of these parameters on femoral tunnel aperture morphology and to provide an easy-to-use clinical reference for surgeons to evaluate the consequences of patient positioning and drilling approach.

A series of analyses were performed to accomplish this goal. First, typical dimensions for the femoral ACL footprint were determined through a literature search to establish a baseline for native ACL anatomy. Three-dimensional models of the osseous morphology of the knee and drill were then constructed to map the range of physiologically achievable drill orientations. Finally, mathematical models were developed with use of each of these components to test the effect of changing the key variables on the size and orientation of the femoral ACL footprint.

Materials and Methods

Size of Femoral ACL Insertion Site

To establish a standard for comparison, a literature search was conducted to evaluate the size of an average native femoral ACL footprint. PubMed was used to evaluate articles published through June 2010 that included the search terms "ACL," "anatomy," "size," "shape," "insertion site," and "attachment." English-language studies with measurements of the size of the femoral insertion site were included. Twelve studies that met the criteria were included[17-28]. The length, width, and area among these findings were averaged on a weighted basis as a function of the number of knees evaluated in each study. The minimum and maximum values were also averaged with use of the same weighting methodology. These averages provided a baseline footprint to compare the effects of changing parameters of drill size and orientation.

Clarification of Descriptive Terms and Coordinate System

The coordinate system that was used to evaluate the knee in the present study assumes that the patient is in the supine position with a horizontal femoral shaft axis and a knee flexion angle of 90°, similar to the arthroscopic hanging-knee

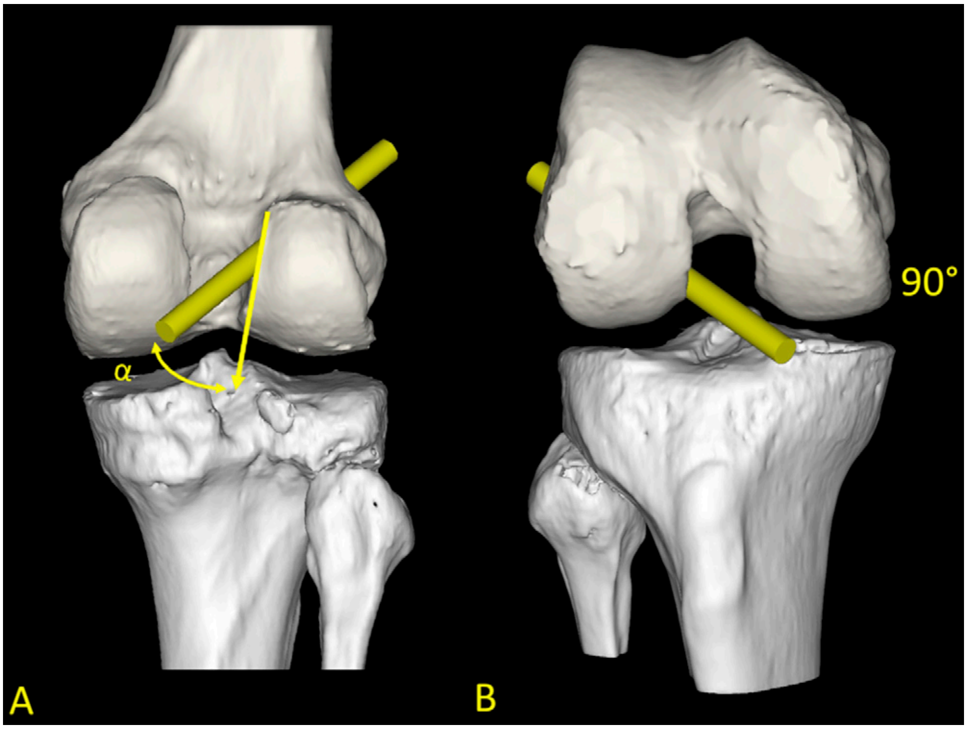

Fig. 1

Figs. 1-A and 1-B Three-dimensional model showing different transverse drill angles. α = angle at which the drill bit intersects the bone. **Fig. 1-A** Posterior view. **Fig. 1-B** Anterior view.

position. The trajectory of the drill bit can be best described by starting with a drill centered perpendicular to the notch wall and then measuring the change in the degree of tilt in the vertical plane or rotation in the horizontal plane. The ACL footprint is aligned with the horizontal plane. The angle of rotation in the horizontal plane, as shown in Figure 1, is named the "transverse drill angle" (α).

In the arthroscopic hanging-knee position, the femur can be elevated with use of various devices. According to Siebold et al.[26], the long diameter of the ACL footprint is horizontally aligned when the femoral shaft axis is elevated 12° from the horizontal plane. In this configuration, elevation of the femoral axis by 12° results in a "knee flexion angle" of 102° (90° + 12°). In the present report, all described knee flexion angles were calculated by similarly elevating the femoral axis. For illustrative purposes, the drill direction was fixed in the horizontal plane and the ACL footprint was set in the transverse plane at all flexion angles.

Three-Dimensional Computed Tomographic Model Development

The freedom of drill orientation about a joint is limited by how the surrounding structures geometrically obstruct the drill. To determine a reasonable range, the computed tomographic (CT) scans of three randomly selected patients were used to develop a composite three-dimensional model to aid in solving for the range of free drill orientation. To build these models, the CT images were processed with use of both Mimics (Materialise, Leuven, Belgium) and Geomagic Studio (Geomagic, Research Triangle Park, North Carolina) software. As the CT scans included only partial views of the bones (the middle of the tibia to the middle of the femur), the surface models from each specimen were co-registered with properly scaled male or female base models, which were each pre-aligned to an anatomic coordinate system based on the center of the femoral head and the center of the tibial malleolus (as recommended by the International Society of Biomechanics[29]). Finally, after having identified the resident's ridge and the bifurcate ridge, the centers of the anteromedial and posterolateral bundles of the ACL footprints were identified on the basis of osseous landmarks. The center of the ACL footprint was defined as the midpoint of a line connecting the two bundle centers.

Maximum Transverse Drill Angle

The maximum transverse drill angle at different knee flexion angles was defined as the maximum angle of drill rotation in the horizontal plane that was possible without coming into contact with the medial condyle. With use of a virtual 6-mm-diameter cylinder, this maximum transverse drill angle was calculated for knee flexion angles of 90°, 110°, and 130°, at which drilling of the femoral tunnel is widely performed. The range of transverse drill angles was calculated for each CT model.

Effect of Drill-Bit Diameter and Transverse Drill Angle on Tunnel Aperture Area

For purposes of mathematical simplicity, the drill bit can be modeled as a virtual cylinder. The femoral tunnel aperture can be approximated by an ellipse with a minor axis (d) and a major axis (h), representing the intersection of the drill-bit cylinder with the plane of the lateral femoral notch wall (Fig. 2). The minor axis is equal to the diameter of the drill bit, which ranged from 6 to

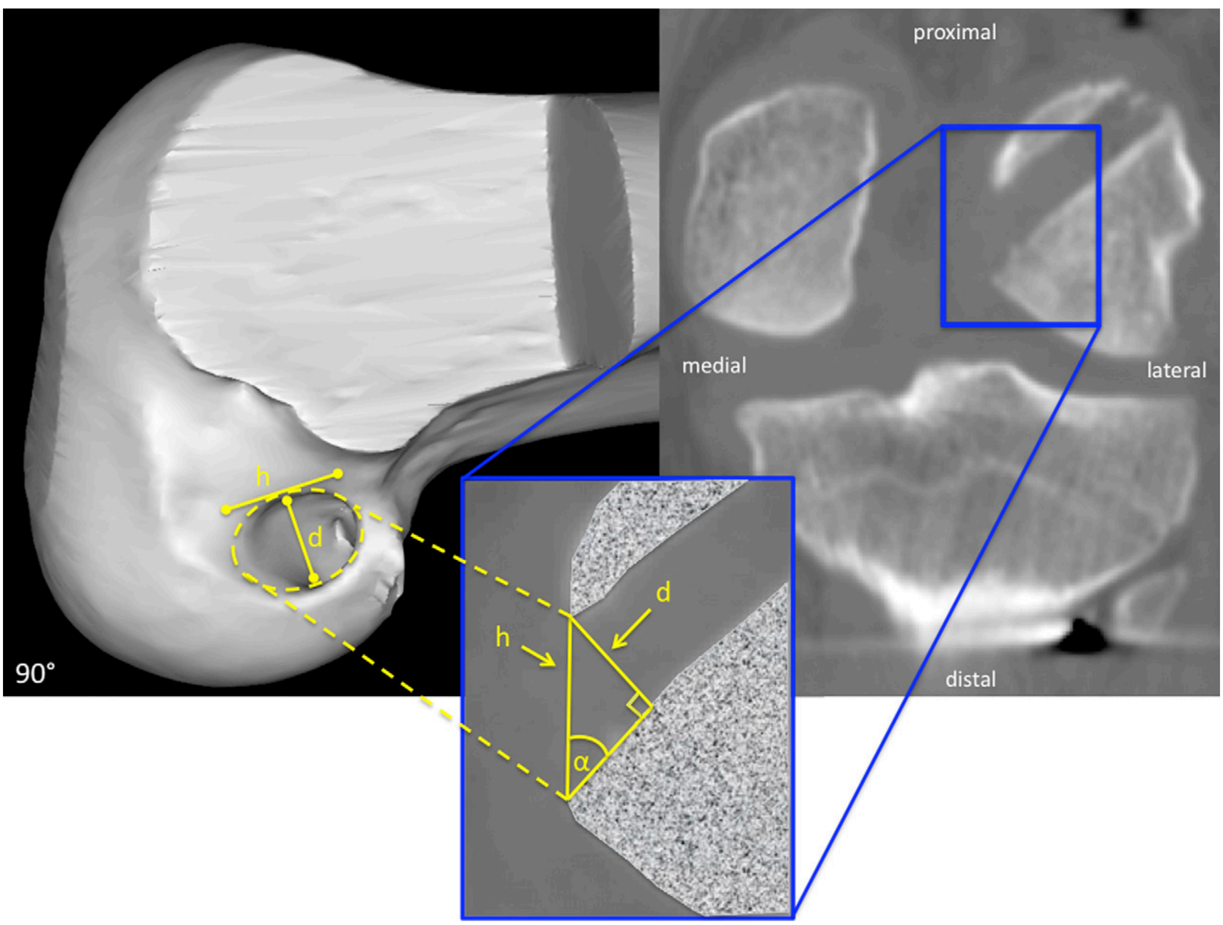

Fig. 2
Coronal computed tomography scan of the femur, showing the short axis of the oval aperture (d = drill-bit diameter) and the major axis (h = hypotenuse) and the angle at which the drill bit intersects the bone (α = transverse drill angle). For better illustration, a three-dimensional model of the CT scan is also shown and labeled.

12 mm (corresponding to the typical range of drill sizes employed for ACL reconstruction). For a 90° transverse angle, the aperture would be circular and the major axis would also equal the drill diameter. However, as the transverse angle is decreased into a physiologically achievable range, the aperture widens and the major axis lengthens. The major axis can be found by solving the following equation for the major axis h:

$$h = \frac{d}{\sin\alpha}$$

The femoral tunnel aperture area was calculated for multiple transverse drill angles and commonly used drill-bit diameters of 6 to 12 mm with use of the standard equation for the area of an ellipse:

$$A = \pi\left(\frac{d^2}{4\sin\alpha}\right)$$

We used transverse drill angles between 20° and 70°. Geometric modeling of typical femur and drill geometry suggests that drill angles outside of this range would be difficult or impossible to achieve, even with the use of a flexible drill guide.

Effect of Changing the Knee Flexion Angle

Altering the knee flexion angle in the vertical plane alters the orientation of the ellipse created by the interaction of the drill cylinder and the notch wall. The resulting ellipse rotates on a fixed axis as a function of knee flexion, which results in a mismatched aperture compared with the anatomic footprint. For calculation of the effect of changing the knee flexion angle, we used a drill-bit diameter of 9 mm and a transverse drill angle of 40° with the drill set in the horizontal direction and a baseline knee flexion angle of 102°. This combination is within the common range of clinical procedures and results in a femoral tunnel aperture with length, area, and major axis orientation similar to the native ACL footprint. Changing the knee flexion angle in either direction from the baseline value (102°) rotates the major axis away from the native horizontal alignment, creating a mismatch between the aperture and the native ACL footprint. The magnitude of this mismatch was estimated by calculating the anteroposterior and proximodistal dimensions of the modified aperture and determining the area of the native footprint ellipse no longer covered by the tunnel aperture ellipse (blue areas in inset of Figure 3), using the geometric analysis capabilities of Mathematica software (Wolfram Research, Champaign, Illinois) as described by Kopf et al.[9]. The mismatched area was calculated over a range of knee flexion angles commonly used for femoral tunnel drilling (70° to 130°).

TABLE I Effect of Different Knee Flexion Angles on Anteroposterior and Proximodistal Dimensions

Knee Flexion Angle	Proximodistal Dimension *(mm)*	Anteroposterior Dimension *(mm)*
70°	11.84	9.85
80°	12.78	9.4
90°	13.59	9.12
102°	14	9
110°	13.81	9.05
120°	13.14	9.26
130°	12.22	9.65
140°	11.29	10.21

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There was no external source of funding for this study.

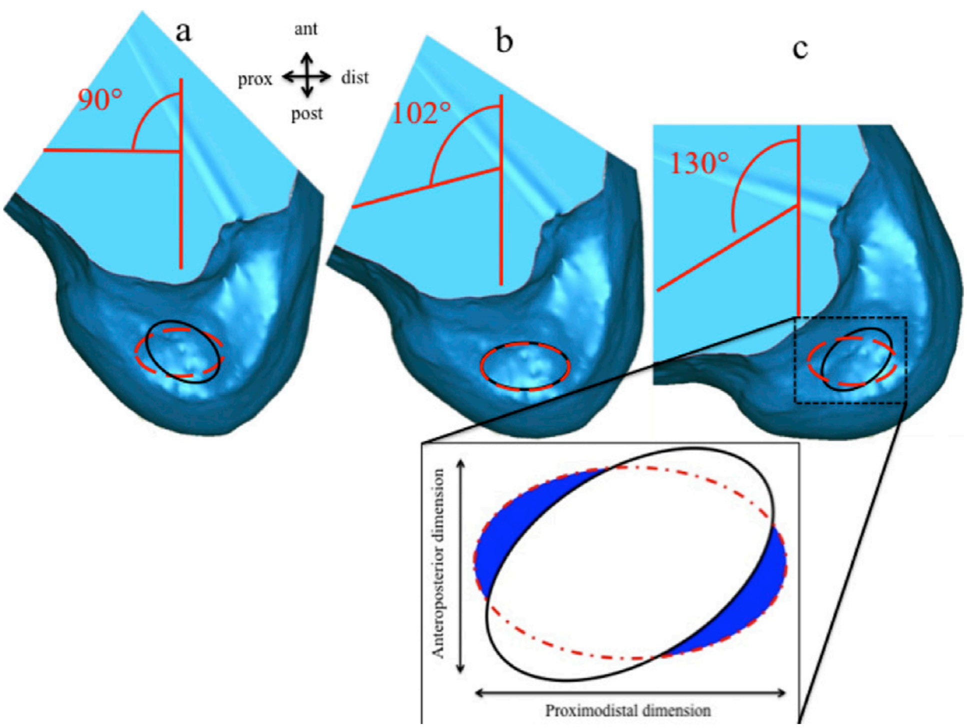

Fig. 3

Figs. 3A, 3-B, and 3-C Examples of different knee flexion angles. The ACL footprint is shown by the black oval lines, and the tunnel aperture is shown by the red dotted lines. **Fig. 3-B** Overlapping ACL footprint and tunnel aperture at a knee flexion angle of 102°. **Figs. 3-A and 3-C** Mismatch between the ACL footprint and tunnel aperture in different knee flexion angles; the inset for Figure 3-C shows the resulting non-anatomic aperture area.

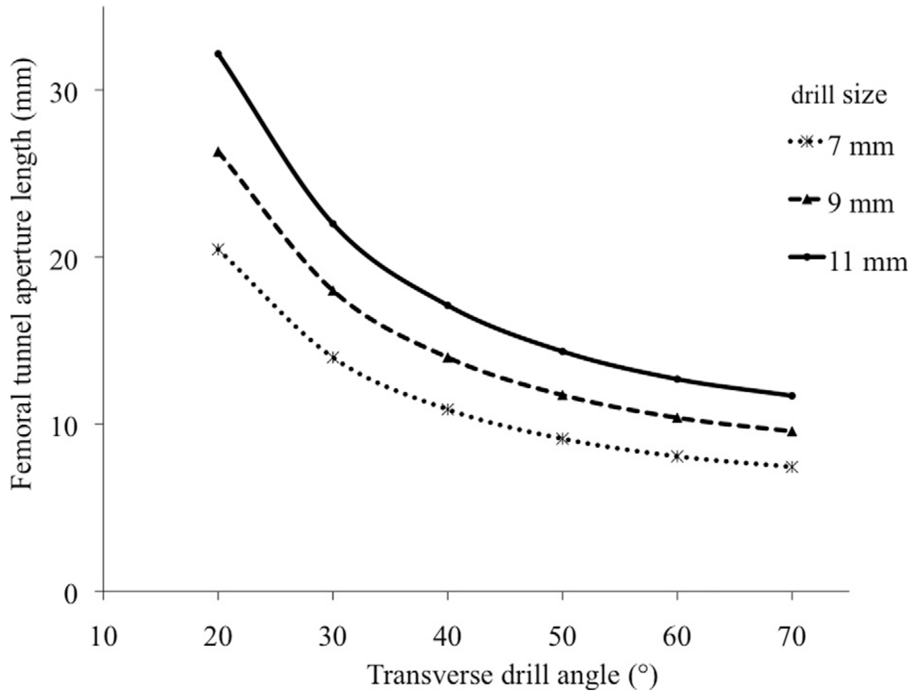

Fig. 4
Line graph demonstrating that the femoral bone tunnel aperture length is dependent on the transverse drill angle and the drill-bit diameter.

Results

The weighted average of the studies found in the literature revealed that the average femoral insertion site is 8.9 mm wide and 16.3 mm long, with an area of 136.0 mm^2 (see Appendix). The effects of varying transverse drill angles and drill-bit diameters over a clinically relevant range on the tunnel aperture length and area are listed in the Appendix and are shown in Figures 4 and 5. A typical ACL reconstruction, performed at 102° of knee flexion with use of a 9-mm drill bit at a transverse drill angle of 40°, created a tunnel aperture area

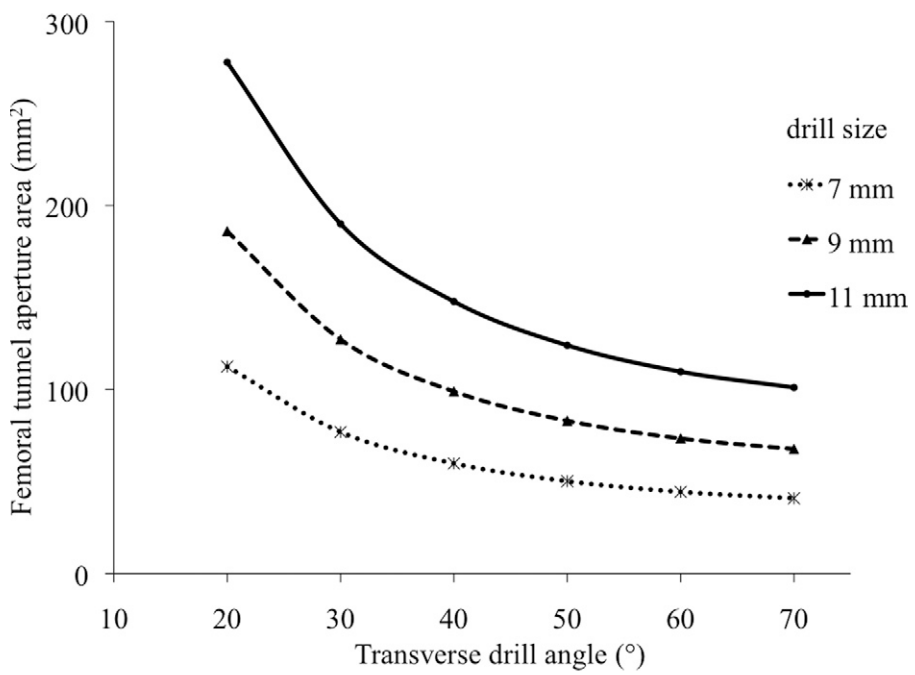

Fig. 5
Line graph demonstrating that the femoral bone tunnel aperture area is dependent on the transverse drill angle and the drill-bit diameter.

TABLE II Effect of Different Knee Flexion Angles on Mismatched Area

	70° Knee Flexion	80° Knee Flexion	90° Knee Flexion	102° Knee Flexion	110° Knee Flexion	120° Knee Flexion	130° Knee Flexion
Nonanatomic misplaced area *(mm²)*	13.3 (13.45%)	10.67 (10.77%)	5.96 (6.02%)	0 (0%)	3.99 (4.04%)	8.83 (8.92%)	13.3 (13.45%)

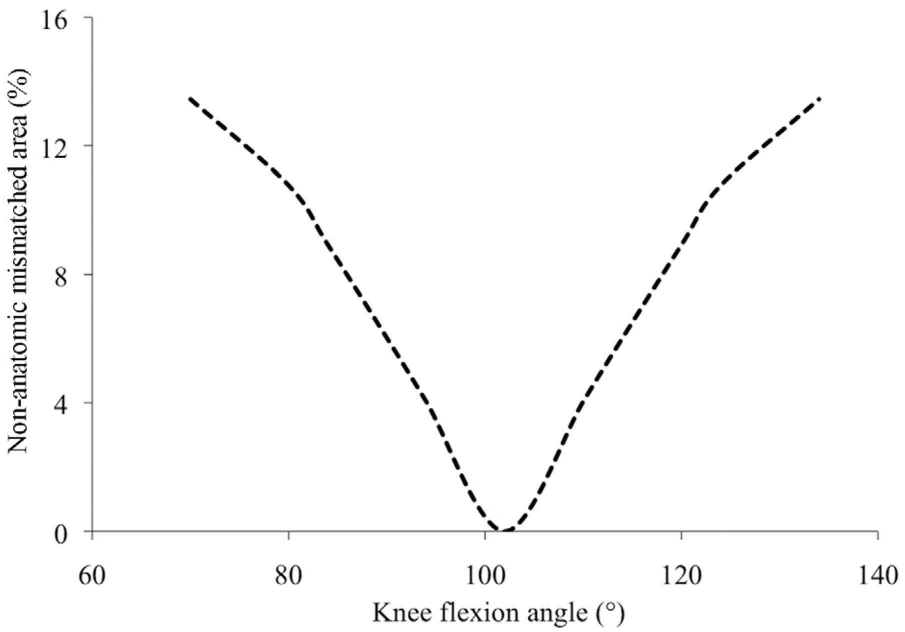

Fig. 6

Line graph showing the effect of changing the knee flexion angle on the missed area of the femoral tunnel aperture orientation relative to the native insertion site of the ACL (with use of a 9-mm drill-bit diameter at a transverse drill angle of 40°).

of 99.0 mm^2 and a tunnel aperture length of 14.0 mm. Decreasing the drill angle by only 10° resulted in an 28.5% increase in aperture area and a 28.6% increase in tunnel aperture length. The effects of different knee flexion angles on the tunnel aperture dimensions are shown in Tables I and II and are plotted in Figure 6. For example, changing knee flexion angle from the baseline of 102° to 130° decreased the proximodistal distance by 1.78 mm and increased the anteroposterior distance by 0.65 mm, creating a mismatched area of 13.5%.

Discussion

The present study demonstrates the effects of the drill-bit diameter, the transverse drill angle, and the knee flexion angle on the femoral tunnel aperture size and orientation during ACL reconstruction. The study was designed specifically to evaluate the range of tunnel options possible when employing a medial portal drilling approach and to provide the surgeon with information on how surgical parameters can alter the femoral tunnel morphology. When considering the findings of this study, it is critical to understand that alterations in tunnel aperture morphology have no impact on the shape of the drilled tunnel. The aperture is oval-shaped because the cylindrical tunnel ends at an oblique surface and not because an oval tunnel was created. A drill bit with a 9-mm diameter will create a 9-mm tunnel regardless of orientation.

In recent years, orthopaedic surgeons have shown greater interest in restoring the native ACL and its footprint[30]. Transtibial techniques are limiting in that the anatomic footprint of the ACL cannot always be reached when using this technique[11,12]. Although this is still a topic of current debate, the drive for anatomic reconstruction has facilitated a change in the surgical paradigm from traditional transtibial drilling to medial portal drilling, which allows for independent tunnel placement. In addition, this technique provides additional advantages such as individual fixation method and allows for the possibility of parallel placement of interference screw fixation through the same medial portal used for tunnel creation[31].

The goal of anatomic ACL reconstruction is to restore the physiological function of the native ACL with regard to its native dimensions, collagen orientation, graft tension, and size of the insertion sites[32]. The major principle of the anatomic concept is to individualize each ACL reconstruction by sizing the graft and positioning the tunnels to reproduce the native ACL in each patient. The wide range of femoral ACL footprint sizes makes it necessary to individualize each reconstruction[33]. Therefore, knowledge of the effects of drill-bit diameter, drill angles, and knee flexion angles on insertion site geometry, and how these variables may limit the surgeon's ability to restore the ACL femoral footprint, is essential to accurately perform anatomic ACL reconstruction and to avoid unwanted tunnel mismatch and complications such as posterior blowout and a short femoral tunnel[15,34].

The present study describes the impact that small changes in transverse drill angle and drill-bit diameter have on tunnel aperture size and morphology. For example, the commonly used 9-mm drill bit at a transverse drill angle of 50° and knee flexion angle of 102° creates a tunnel aperture length of 11.7 mm and an aperture area of 83.0 mm^2. The angle of 102° is selected because the ACL footprint is aligned horizontally in this configuration[26], matching the orientation of the drilled aperture. Hypothetically, if a patient had an ACL with average aperture length (16.3 mm) and aperture area (136.0 mm^2) as described in the literature, these drilling parameters would result in a footprint that is 71.8% as long as that of the native ACL and that covers only 61.0% of the area covered by the native ACL. Reducing the transverse drill angle to 30° (while maintaining the same drill size and knee flexion angle) would result in a femoral tunnel aperture that more closely resembles the native ACL insertion (110.4% of the native footprint length and 93.5% of the native footprint area). However, while these parameters might better restore the native footprint, the path of the drill required for a transverse angle of 30° might damage the cartilage of the posterior aspect of the lateral femoral condyle and can even lead to a posterior blowout[16], which could compromise stable fixation of the ACL graft.

A table in the Appendix and Figure 4 clarify the relationship between drill-bit diameter and transverse drill angle on the aperture length, showing the steep decrease of aperture length that can occur at high transverse drill angles. A table in the Appendix and Figure 5 show the similar decrease in aperture area as drill angle increases.

In contrast to Siebold et al.[26], who assumed that a transverse drill angle of 65° to 70° can be accomplished, our geometric modeling study suggested that transverse drill angles beyond 54° would be difficult to achieve at a knee flexion angle of 130°. The source of this discrepancy is unclear, but the difference in the findings might be due to large inter-individual variances and the small number of knees included in the current study to determine drill angle ranges. The present analysis also assumed a rigid drill bit; drill angles of 60° and 70° might be possible with use of flexible drill bits, which allow the surgeon to operate at a greater oblique angle than geometry would allow with standard tools and to reduce damage to the femoral condyles[35]. With the increased usage and knowledge of these curved drills, these angles might be realistic in the surgical setting. However, it is questionable whether a high transverse drilling angle is favorable as a 9-mm drill with a transverse drill angle of 70% only recreates 49.8% of the averaged native insertion site area and only 58.9% of its length. Excessively low transverse drill angles are also not recommended because, in addition to the risk of damage to critical structures (posterior blowout, damage to the articular cartilage of the posterior aspect of the lateral femoral condyle[16]), the resulting elongated tunnels increase the ratio between the footprint and the cross-sectional area of the graft, which might also adversely affect ACL graft function[19].

Compared with the effects of drill size and transverse drill angle, the impact of knee flexion angle on femoral tunnel aperture geometry is relatively minor, as illustrated in Figure 3. Relative to the reference position (at 102° of knee flexion, where the ACL footprint is assumed to be aligned horizontally[26] and oriented with the drilled aperture), changes of ±10° of knee flexion created an area mismatch of ≤6%, and the maximum area mismatch error (for ±30° of knee flexion) was <14%. Also, the optimum knee flexion angle to match the average native orientation (assumed to be 102° for the present study) may vary in individual patients. Certainly, the knee flexion angle affects other surgical parameters in ACL reconstruction and is often maximized in order to achieve a sufficient tunnel length for graft-bone integration. Basdekis et al.[36] studied the effect of knee flexion angle on drilled femoral tunnel angle. They noted that knee flexion angles of 90° led to a higher risk of posterior wall blowout, whereas tunnels drilled at 130° and higher resulted in graft orientations that were concerning because of increased contact pressure of the graft on the aperture rim. Basdekis et al. concluded that tunnels drilled at 110° of knee flexion led to tunnels with no significant difference in length yet avoided extreme aperture-graft angles as compared with tunnels drilled at 130°. Zantop et al.[37] showed no difference in biomechanical strength between reconstructions with tunnels that were 15 mm in length compared with tunnels that were 25 mm in length in a goat model. That study challenged the concept that tunnels needed such length, yet did so without human or in vivo validation. To date, studies have only focused on the value of replicating the location of the femoral tunnel and not on the morphologic orientation of the femoral tunnel aperture to the native footprint. Further work is necessary to determine the importance of this phenomenon. Thus, while changes in flexion angle can lead to mismatches between native footprint dimensions and tunnel aperture dimensions, other considerations may be equally or more important for selecting the optimal flexion angle for performing ACL reconstruction.

The present study had some limitations. First, the tunnel aperture area was not measured on postoperative CT scans but was calculated with use of equations. These theoretical calculations reflect idealized mathematical scenarios and do not reflect clinical realities such as surgical variability, wobbling of the drill, or the difficulty of determining an exact transverse drill angle. Second, the footprint of the ACL on the lateral notch wall was assumed to be flat and aligned with the sagittal plane, which does not reflect the true morphology of the ACL footprint. However, this assumption greatly simplifies the geometric calculations, and incorporating more precise geometry would be unlikely to substantially alter the relationships identified here. Third, our study assumed an averaged ACL morphology determined from the literature, but there is considerable variability of the ACL insertion geometry across individuals. Thus, the relationships reported here represent overall trends and may not be applied precisely for each individual. Siebold et al. showed a range of knee flexion angles (90° to 102°) at which the centers of the two bundles are horizontally aligned, suggesting that it is necessary to individualize each ACL reconstruction[26]. Fourth, larger tunnel apertures additionally may have both short-term and long-term unintended consequences that are not considered here. Larger apertures could possibly make future revisions more difficult. Finally, the present study did not consider the influence of drilling angles on many other factors of the reconstruction, such as graft fixation, tunnel widening, femoral tunnel length, and femoral tunnel placement. A fundamental assumption of the present study is that recreation of the most anatomic femoral tunnel aperture size and orientation will result in the least deleterious constraints on the graft and the most appropriate graft-fiber orientation. While we are not aware of any studies to date that have clearly demonstrated a beneficial effect of correct orientation of the tunnel aperture and restoration of the native insertion size, it has been shown that anatomical graft placement results in improved knee kinematics[6,7]. Further research and long-term outcome studies will be required to determine whether anatomic ACL graft placement positively affects clinical outcome.

In conclusion, to perform an anatomic ACL reconstruction, each surgical procedure should be individualized to account for the osseous morphology and the size of the ACL of each patient. To avoid complications such as posterior tunnel blowout or tunnel-footprint mismatches, surgeons must understand the effects of drill size and drill angle on tunnel size and orientation. The present study can be a helpful guide for the surgeon to understand the relationships between the parameters of drill-bit diameter, transverse drill angle, and knee flexion angle and the outcomes of tunnel aperture morphology and orientation.

Appendix

eA Tables showing details on the studies that were identified in the literature search as well as on femoral tunnel aperture length and femoral tunnel aperture area are available with the online version of this article as a data supplement at jbjs.org. ■

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