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John Xerogeanes, *Emory University*
Kyle Hammond, *Emory University*
Dane C. Todd, *Emory University*

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Anatomic Landmarks Utilized for Physeal-Sparing, Anatomic Anterior Cruciate Ligament Reconstruction

An MRI-Based Study

John W. Xerogeanes, MD, Kyle E. Hammond, MD, and Dane C. Todd, BS

Investigation performed at Emory Orthopaedic and Spine Center, Atlanta, Georgia

Background: Anterior cruciate ligament (ACL) injury and reconstruction in the skeletally immature patient are becoming more common. The purpose of this study was to develop a reproducible anatomic ACL reconstruction technique, based on intra-articular and extra-articular landmarks, that reliably produces a femoral tunnel of adequate length and diameter while avoiding the distal femoral physis.

Methods: Magnetic resonance images (MRIs) of one hundred and eighty-eight children (age range, six to seventeen years) were evaluated. Two extra-articular landmarks, the femoral insertion of the popliteus tendon and the lateral femoral epicondyle, and one intra-articular landmark, the central portion of the femoral footprint of the ACL, were identified. Computer software was used to plot these landmarks in all three planes and to draw lines representing two potential femoral tunnels. The first line connected the center of the ACL femoral footprint with the insertion of the popliteus tendon, and the second connected the center of the ACL femoral footprint with the lateral femoral epicondyle. The length of each tunnel, the shortest distance from the center of each tunnel to the distal femoral physis, and the height of the lateral femoral condyle from the physis to the chondral surface and to the base of the cartilage cap were calculated. A three-dimensional MRI reconstruction was used to confirm that placement of a femoral tunnel with use of the chosen landmarks would avoid the distal femoral physis.

Results: The mean distance from the center of the preferred ACL tunnel, which connected the center of the ACL femoral footprint with the insertion of the popliteus tendon, to the distal femoral physis was 12 mm, independent of sex ($p = 0.94$) or age, and the shortest distance was 8 mm. The length of this proposed tunnel averaged 30.1 mm in the boys and 27.4 mm in the girls ($p < 0.001$), and it averaged 25.4 mm at an age of six years and 29.7 mm at an age of seventeen years. The mean distance from the center of the alternative tunnel, which connected the center of the ACL femoral footprint with the lateral epicondyle, to the distal femoral physis was 8.8 mm in the boys and 8.9 mm in the girls ($p = 0.55$). The mean length of this alternative tunnel was 34.3 mm in the boys and 31.6 mm in the girls ($p < 0.001$).

Conclusions: Drilling from the center of the ACL femoral footprint to the insertion of the popliteus tendon would have resulted in a mean tunnel length of 27 to 30 mm, and it would have allowed the safe placement of a femoral tunnel at least 7 mm in diameter in a patient six to seventeen years old. The center of the ACL femoral footprint and the popliteus insertion are easily identifiable landmarks and will allow safe, reproducible, anatomic ACL reconstruction in the skeletally immature patient.

Estimates of the incidence of anterior cruciate ligament (ACL) injury continue to grow, as does the number of ACL reconstructions performed each year[1]. Prior to the 1980s, tears of the ACL in a skeletally immature individual were rarely diagnosed and were usually diagnosed and treated as a tibial spine avulsion injury[2-4]. In recent years, the diagnosis of ACL disruption, without associated tibial spine avulsion, has become more common in children with open physes. Some of

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TABLE I Age-Adjusted Distances Between Landmarks According to Sex*

Measurement†	Sex	Age-Adjusted Mean‡ *(mm)*	P Value	Regression Equation§
Length of proposed ACL tunnel			<0.001	
	M	30.1 ± 0.21		$\hat{Y} = 16.7 + 2.242X - 0.0859X^2$
	F	27.4 ± 0.23		$\hat{Y} = 14.0 + 2.242X - 0.0859X^2$
Distance from proposed ACL tunnel to physis			0.94	
	M	12.0 ± 0.18		$\hat{Y} = 7.5 + 0.78X - 0.031X^2$
	F	12.0 ± 0.20		$\hat{Y} = 7.5 + 0.78X - 0.031X^2$
Length of alternative tunnel			<0.001	
	M	34.3 ± 0.25		$\hat{Y} = 16.4 + 2.765X - 0.0966X^2$
	F	31.6 ± 0.28		$\hat{Y} = 13.7 + 2.765X - 0.0966X^2$
Distance from alternative tunnel to physis			0.55	No age adjustment necessary
	M	8.8 ± 0.12		
	F	8.9 ± 0.16		
Distance from proposed ACL tunnel to cartilage cap			0.02	
	M	9.0 ± 0.78		$\hat{Y} = 0.8 + 0.72X$
	F	8.3 ± 0.59		$\hat{Y} = 2.4 + 0.51X$
Height of lateral condyle			0.03	
	M	22.3 ± 0.22		$\hat{Y} = 10.5 + 1.64X - 0.049X^2$
	F	21.6 ± 0.25		$\hat{Y} = 9.8 + 1.64X - 0.049X^2$

*Adjustment of the data for age was performed with use of analysis of covariance (ANCOVA). Eighty-three subjects were girls and 105 were boys. †The proposed ACL tunnel connected the center of the ACL femoral footprint with the popliteus insertion, and the alternative tunnel connects the center of the ACL femoral footprint with the lateral epicondyle. ‡The values are given as the age-adjusted mean and the standard error of the mean. §X represents the age of the child.

this increase is probably due to the increased participation in cutting and pivoting sports such as soccer, basketball, and football, as well as a more intense level of training and competition among youth athletes[5-8]. Improved physical examination skills and an increase in the use of magnetic resonance images (MRIs) are also believed to be factors in the increasing diagnosis of ACL injury in children and adolescents[9,10].

Although the true incidence and prevalence of ACL tears in the pediatric population has not been established, McCarroll et al. reported that 3.3% of all ACL injuries occurred in the skeletally immature athlete[11]. In other clinical studies, estimates of the prevalence of an ACL injury in a skeletally immature patient with an acute, traumatic hemarthrosis of the knee have ranged widely, from 10% to 65%[12-15]. An analysis by Shea et al. of insurance claims involving youth soccer injuries found that ACL injuries represented 6.7% of all of the sport-related injury claims and 30.8% of the sport-related knee injury claims[16].

Controversy exists regarding the management of ACL injuries in patients with open physes. Some authors recommend activity modification, bracing, and strengthening to delay ACL reconstruction until skeletal maturity[17-22]. Although these authors have claimed outcomes that were comparable to those in adults who were treated conservatively[17,21], restricting the activity of a young, athletic patient may be difficult[23], and the majority of recent studies have contradicted their assertions. More recent studies have predicted, or have shown, that chronic instability in skeletally immature patients is associated with an increased incidence of meniscal injury, articular cartilage damage, and subsequent osteoarthritis[2,3,11,22-29]. Thus, the current literature supports the trend toward early, aggressive operative management of an unstable, ACL-deficient knee in a pediatric athlete[19,24,25,30-32].

Surgical treatment of ACL tears in skeletally immature patients has been addressed with a variety of techniques, including primary repair of the ligament[31] and partial transphyseal[32,33], physeal-sparing[34,35], and transepiphyseal reconstruction[36]. Although some success has been reported with each of these techniques, each has inadequacies. The most glaring inadequacy is that most of these techniques are nonanatomic; they do not accurately recreate the native origin and insertion of the ACL. Thus, they do not reproduce normal knee kinematics and may lead to increased rates of meniscal and chondral injury[37-40]. All four of the techniques are also technically difficult to replicate consistently.

The purpose of our study was to develop an anatomic ACL reconstruction technique that is transepiphyseal on the femoral side and utilizes a pair of easily identifiable extra-articular and intra-articular landmarks. These landmarks can be evaluated on the preoperative MRI to determine the maximum tunnel length and diameter, and again intraoperatively during creation of the femoral tunnel.

Materials and Methods

After receiving institutional review board approval, we performed a retrospective review of pediatric hospital records to identify all patients between the ages of six and seventeen years who had had a complete set of 1.5-T or 3-T MRIs of the knee during the previous seven years. These MRIs were then reviewed for evidence of ligamentous or osseous pathology, and the MRIs of 188 patients without such pathology were randomly selected after stratification by age.

The MRIs were analyzed electronically with use of eFilm Lite software (version 2.1.0; Merge Healthcare, Chicago, Illinois). Three potential anatomic landmarks for ACL reconstruction were identified: the insertion of the popliteus tendon, the lateral femoral epicondyle, and the central portion of the femoral ACL origin or "footprint." A point corresponding to each of these three anatomic landmarks was marked on the coronal, sagittal, and axial MRI images.

The coronal T1-weighted image was evaluated to find the deepest point of the popliteus insertion on the lateral femoral condyle. This insertion point was marked with use of the Ellipse Measurement Tool. The 3D Cursor Tool was then used on this image to identify and mark the identical location on the axial and the sagittal image. Once the landmark was marked in each plane, the location of the data point was captured by the software. These steps were repeated for the lateral epicondyle landmark. Finally, we evaluated the position of the ACL footprint landmark beginning with the sagittal image. The central portion of the ACL femoral footprint was marked, and this was used to locate the same point on the coronal and the axial image.

Once the position of each landmark had been captured, the Line Measurement Tool was used to connect the center of the ACL femoral footprint in the coronal image with the other two landmarks and to measure the two resulting distances. The line from the central portion of the ACL footprint to the popliteus insertion represents the femoral ACL reconstruction tunnel that we are proposing (Fig. 1). The shortest distance from the center of this proposed ACL tunnel to the distal femoral physis was also measured. The line drawn from the center of the ACL femoral footprint to the lateral epicondyle represents the alternative tunnel, and the shortest distance from this line to the femoral physis was also measured. The vertical height of the lateral femoral condyle was measured from the physis to the intra-articular chondral surface and also from the physis to the epiphyseal bone-cartilage interface (cartilage cap).

By scrolling across the coronal image, we verified that the lines connecting the ACL insertion with the other two landmarks did not enter either the distal femoral physis or the cartilage cap. If this did occur, the line was shortened until it no longer crossed the physis proximally, or the cartilaginous cap distally, and the length of the line was remeasured. The Appendix illustrates some of the steps involved in the placement of the landmarks on the images, and Figure 1 illustrates the end result.

Finally, we employed three-dimensional reconstruction of the MRIs to show that when a computer-generated 8-mm-diameter cylinder (representing a tunnel) was superimposed on the line connecting the center of the ACL femoral footprint with the insertion of the popliteus (the center of the proposed ACL tunnel), the cylinder would not encroach on the femoral physis proximally or on the cartilage cap distally (Fig. 2). These three-dimensional images represent the osseous portion of the femur (i.e., without the cartilaginous portion).

Statistical Methods

The mean and range for each measurement was determined, and an analysis of covariance (ANCOVA) was performed. A p value of 0.05 was considered significant. For each measurement, a separate quadratic regression equation was then calculated for each sex to model the effect of age, and a p value was calculated for the difference between the sexes. Finally, the age-adjusted mean and the standard error of the mean for the entire cohort were calculated by using the appropriate regression equation to adjust each measurement to the mean patient age of 11.6 years.

Source of Funding

This study received no external funding.

Results

Eighty-three of the 188 subjects whose MRIs were reviewed were girls and 105 were boys. The mean age was 11.6 years

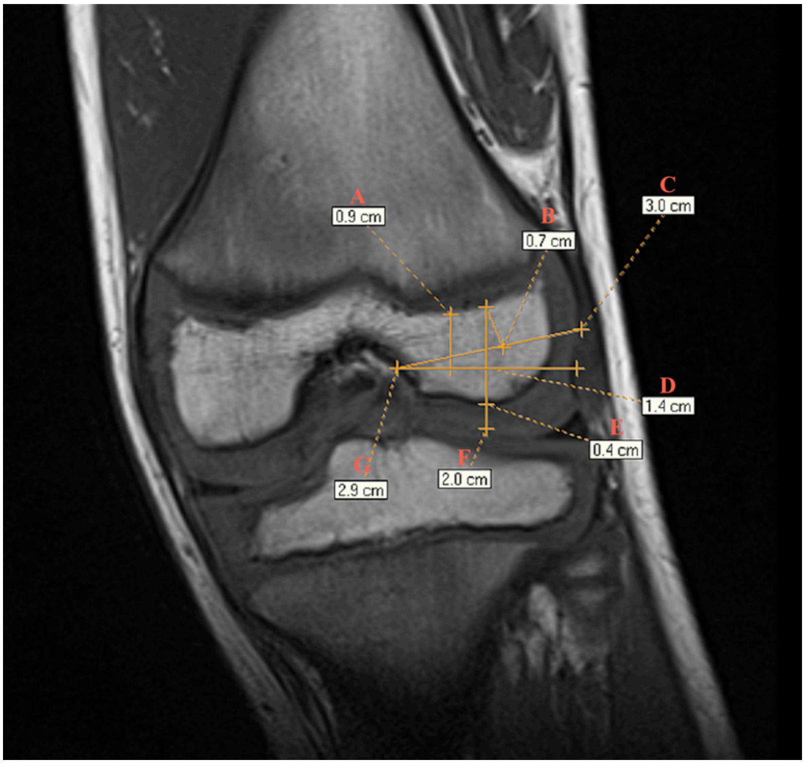

Fig. 1

T1-weighted coronal magnetic resonance image showing the position of the described data points and the resulting distance measurements in the knee of a six-year-old child. The lines beginning at point G represent the two potential femoral tunnels. The line ending at point A is the shortest distance from the center of the ACL-popliteus tunnel to the physis. The line ending at point B is the shortest distance from the center of the ACL-lateral epicondyle tunnel to the physis, and the line ending at point C is the length of this tunnel. The line extending upward from point D is the height of the epiphysis. The line from point D to point E is the distance from the center of the ACL-popliteus tunnel to the cartilage cap. The longest line beginning at point F is the distance from the articular surface to the physis. The horizontal line beginning at point G is the length of the ACL-popliteus tunnel.

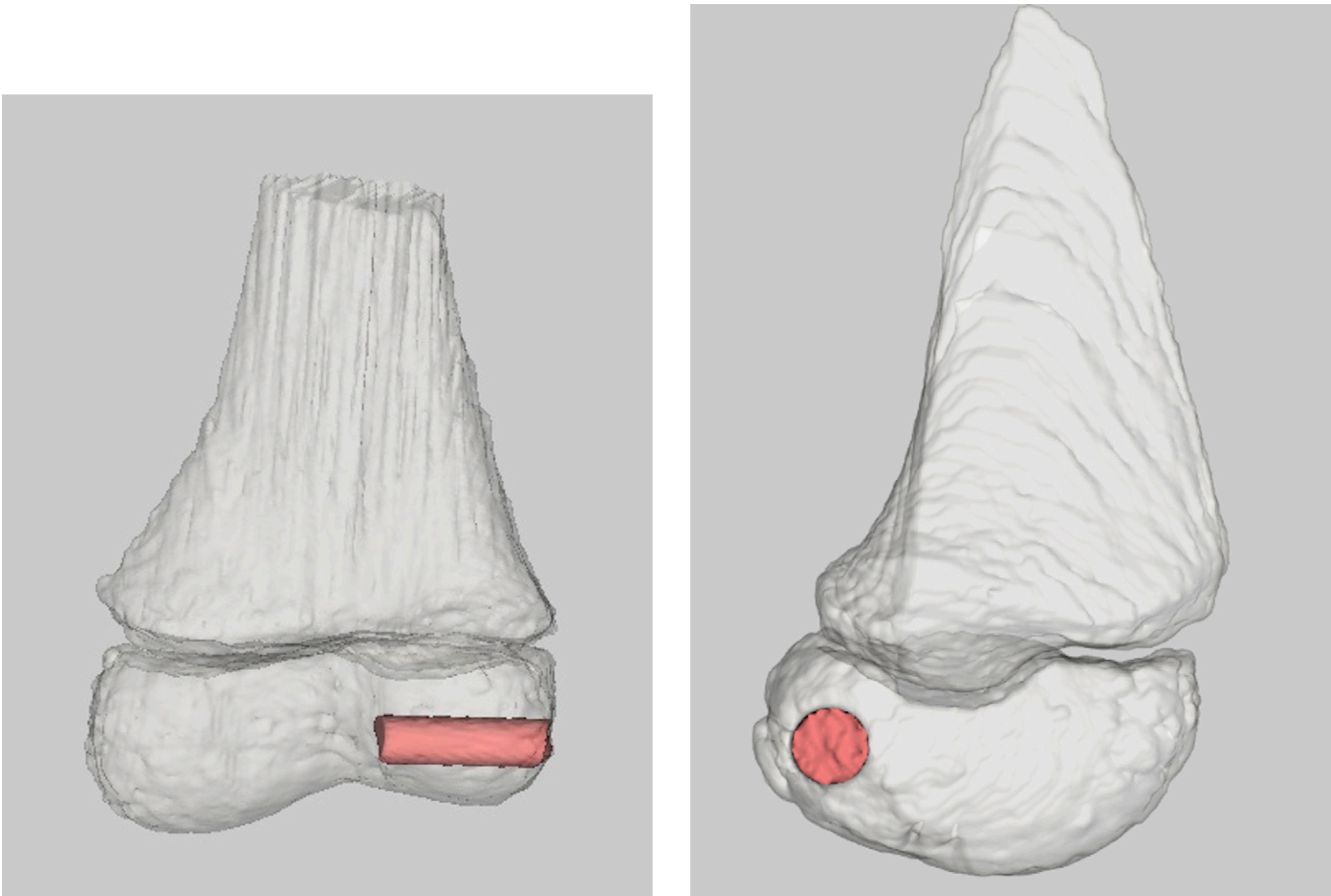

Fig. 2-A Fig. 2-B

Three-dimensional reconstruction of the knee of a ten-year-old child shown in an anterior view (**Fig. 2-A**) and a notch view of the ACL femoral footprint (**Fig. 2-B**). An 8-mm-diameter cylinder is centered over the line connecting the center of the ACL femoral footprint with the popliteus insertion on the lateral aspect of the femur. Both views of the reconstruction demonstrate that an 8-mm-diameter tunnel would not encroach on the femoral physis proximally or on the epiphyseal bone-cartilage junction (cartilage cap) distally.

(range, six to seventeen years), and the study contained at least fifteen subjects of each age between six and seventeen years. The age-adjusted mean, standard error of the mean, and p value for the difference between the sexes for each measurement are shown in Table I.

After adjustment for age, the length of the proposed ACL tunnel (between the ACL origin and the popliteus insertion) was significantly greater in the boys than in the girls, as was the length of the alternative tunnel connecting the ACL origin with the lateral femoral epicondyle ($p < 0.001$ for both). The mean age-adjusted distance from the center of either tunnel to the physis did not differ significantly according to sex. The mean age-adjusted distance from the center of the proposed ACL tunnel (connecting the ACL origin with the popliteus insertion) to the distal femoral physis was 12.0 mm in both the girls and the boys ($p = 0.94$). The mean age-adjusted distance from the center of the alternative tunnel (connecting the ACL insertion with the lateral epicondyle) to the femoral physis was 8.8 mm in the girls and 8.9 mm in the boys ($p = 0.55$).

The shortest length of the proposed ACL tunnel was 22 mm in one six-year-old subject, although the mean length in this age group was 25.38 mm. The longest tunnel length was 37 mm in one fifteen-year-old subject. The shortest distance from the center of the proposed ACL tunnel to the physis was 8 mm in one seven-year-old subject, although the mean distance in this age group was 11.20 mm. The longest distance from the center of the proposed ACL tunnel to the physis was 16 mm in ten, twelve, fourteen, and fifteen-year-old subjects. The shortest distance from the center of the proposed ACL tunnel to the epiphyseal bone-cartilage junction (cartilage cap) distally was 4 mm in three six-year-old and three seven-year-old subjects, although the mean distance in these age groups was 5.06 mm and 5.38 mm, respectively. The distance from the proposed ACL tunnel to the cartilage cap increased as the children matured, reaching 11.18 mm in the seventeen-year-old subjects. The age-adjusted mean distance from the center of the proposed ACL tunnel to the cartilage cap also differed significantly according to sex (9.03 mm in the boys compared with 8.30 mm in the girls, $p = 0.02$). Table II depicts

TABLE II Mean, Minimum, and Maximum Distances Between Landmarks According to Age*

Age *(yr)*	No.	Mean Length of Proposed ACL Tunnel (Range) *(mm)*	Mean Distance from Center of Proposed ACL Tunnel to Physis (Range) *(mm)*	Mean Length of Alternative Tunnel (Range) *(mm)*	Mean Distance from Center of Alternative Tunnel to Physis (Range) *(mm)*	Mean Distance from Center of Proposed ACL Tunnel to Cartilage Cap (Range) *(mm)*	Mean Height of Lateral Condyle (Range) *(mm)*
6	16	25.38 (22-30)	11.25 (9-14)	28.00 (25-32)	9.00 (7-15)	5.06 (4-7)	18.75 (15-23)
7	16	28.40 (27-31)	11.20 (8-14)	31.30 (29-35)	8.40 (8-9)	5.38 (4-7)	18.40 (16-21)
8	15	27.93 (25-31)	12.00 (9-15)	30.73 (27-34)	9.13 (7-12)	6.62 (5-9)	20.20 (18-22)
9	15	28.64 (25-31)	12.29 (9-15)	32.71 (29-39)	9.21 (8-11)	6.75 (5-10)	20.93 (17-25)
10	15	29.46 (25-33)	12.31 (9-16)	33.15 (28-37)	8.92 (7-12)	7.53 (5-11)	21.15 (18-25)
11	15	29.77 (25-34)	11.54 (9-13)	33.38 (30-37)	8.31 (7-10)	7.85 (7-10)	21.69 (20-25)
12	16	30.19 (25-36)	12.50 (9-16)	34.75 (28-39)	8.94 (6-12)	10.29 (8-13)	23.31 (19-29)
13	16	29.38 (24-35)	11.75 (9-15)	33.81 (25-39)	8.88 (7-12)	10.81 (7-15)	22.25 (17-25)
14	16	29.69 (25-34)	12.38 (9-16)	35.06 (30-40)	9.00 (8-14)	11.19 (9-13)	24.45 (20-28)
15	16	29.13 (26-37)	12.06 (9-16)	34.25 (29-41)	8.94 (6-11)	10.63 (7-13)	23.63 (20-26)
16	15	29.53 (26-32)	12.47 (10-14)	35.67 (31-40)	8.73 (8-11)	11.00 (9-14)	24.20 (19-30)
17	17	29.71 (25-34)	11.71 (9-14)	34.65 (29-38)	8.71 (6-10)	11.18 (9-14)	23.71 (19-27)

*The proposed ACL tunnel connected the center of the ACL femoral footprint with the popliteus insertion, and the alternative tunnel connected the center of the ACL femoral footprint with the lateral epicondyle.

the mean and range for each of the measurements in each age group.

The regression modeling demonstrated that the length of each of the potential tunnels differed significantly according to age in both the boys and the girls ($p < 0.05$ for both). However, the distance from each tunnel to the physis did not differ significantly according to age in either the boys or the girls. Most of the linear regression equations included both a positive linear and a negative quadratic term that were statistically significant, indicating that the measurement initially increased significantly as the children aged but then reached a plateau and, in the case of some measurements, decreased again. The length of the proposed ACL tunnel (connecting the center of the ACL femoral footprint with the popliteus insertion) reached a plateau at thirteen to fourteen years of age, then decreased slightly (Fig. 3); the same pattern was observed for the length of the alternative tunnel from the center of the ACL femoral footprint to the lateral epicondyle. The distance from the center of the proposed ACL tunnel (connecting the center of the ACL femoral footprint with the popliteus insertion) to the

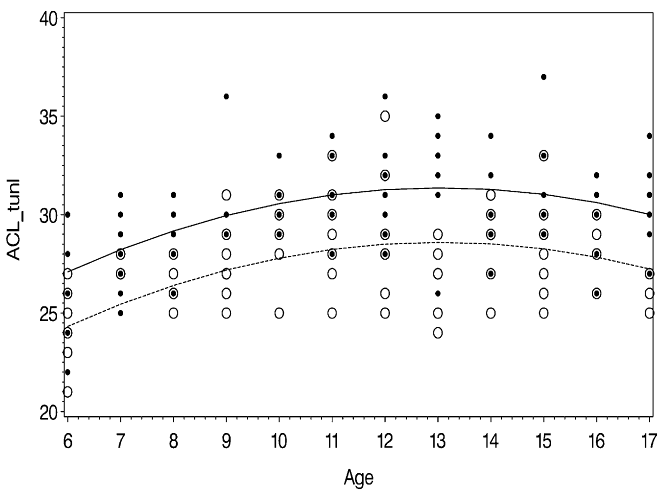

Fig. 3

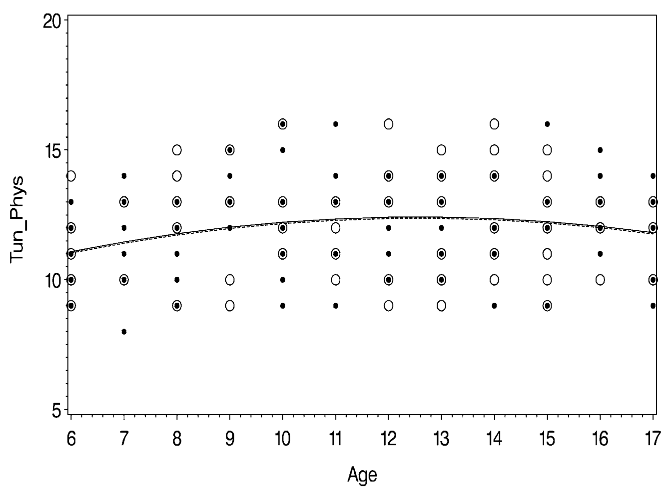

Fig. 4

Fig. 3 Length of the proposed ACL tunnel (on the vertical axis, in millimeters), which connects the center of the ACL femoral footprint with the popliteus insertion, according to age. The dots and the solid line represent the data for the boys, and the circles and the dashed line represent the data for the girls.

Fig. 4 Distance (on the vertical axis, in millimeters) from the center of the proposed ACL tunnel, which connects the center of the ACL femoral footprint with the popliteus insertion, to the physis according to age. The dots and the solid line represent the data for the boys, and the circles and the dashed line represent the data for the girls.

physis reached a plateau at approximately twelve years of age (Fig. 4), and the distance from the center of this tunnel to the distal cartilage cap reached a plateau at twelve to thirteen years of age. The height of the lateral femoral epicondyle reached a plateau at fifteen to sixteen years of age.

Discussion

Children with open physes deserve special attention because of the potential for iatrogenic injury to the physis. Injury to the physis can cause unilateral growth disturbance, resulting in a limb-length discrepancy or an angular deformity[1]. Consequently, physeal-sparing ACL reconstruction techniques are recommended in a skeletally immature patient.

Current physeal-sparing ACL reconstruction is not only technically difficult but also nonanatomic. Although the short-term functional results are promising, the long-term results and biomechanical efficacy of the reconstruction are unknown. In vivo analyses in adults have demonstrated that anatomic reconstruction of the ACL is biomechanically superior to traditional, nonanatomic, transtibial reconstruction[41-47]. Anatomic ACL reconstruction provides superior rotational control throughout the range of knee motion and improved clinical outcomes[47-50]. The force in each compartment of the knee following anatomic reconstruction is significantly less than that in a knee in which the ACL has been reconstructed in a nonanatomic fashion, and thus more similar to that in the normal knee[51]. We believe that an anatomic technique is essential for safe and viable ACL reconstruction in a skeletally immature individual.

The femoral footprint of the ACL has osseous and cartilaginous landmarks that define its borders. The intercondylar ridge lies anterior to the ACL footprint. The distal, posterior, and proximal borders of the ACL footprint include the articular cartilage. The bifurcate ridge runs perpendicular to the intercondylar ridge, dividing the anteromedial and posterolateral bundles of the ACL[52,53]. The center point of the bifurcate ridge defines the central point of the osseous and soft-tissue footprint of the ACL. Because intricate osseous anatomy is difficult to define with use of current MRI technology, we utilized the central portion of the osseous and soft-tissue attachments of the ACL for the intra-articular landmark in our study.

The intra-articular ACL footprint forms one end of the femoral tunnel and determines whether the ACL reconstruction will be anatomic. Identifying the correct extra-articular landmark will determine whether the femoral tunnel will consistently spare the distal femoral physis in all age groups. We initially chose two extra-articular points that were easily identified on MRIs, by palpation of surface anatomy, and during surgical dissection. The first point was the lateral femoral epicondyle, and the second point was the insertion of the popliteus on the lateral aspect of the femur, which lies approximately 18 mm anterior and distal to the lateral epicondyle[54]. Our study data indicated that the popliteus insertion represented the optimal point that fulfilled all of our criteria. Along with permitting an anatomic reconstruction and being easily identifiable, the popliteus insertion allowed for creation of a reproducible femoral tunnel of adequate length, diameter, and distance from both the physis and the articular cartilage.

The preoperative MRI can be used to plan the length and diameter of the tunnel that will be used for femoral fixation of the ACL. The anatomic landmarks of interest—the center of the ACL femoral footprint, the lateral epicondyle, the insertion of the popliteus on the femur, the epiphyseal bone-cartilage junction (cartilage cap), and the physis—are all easily recognizable on standard knee MRIs. With simple measurement tools and commercially available computer software, both the length of the tunnel and the maximum tunnel diameter that can be safely drilled to avoid the physis and chondral surface can be estimated.

The length of the femoral tunnel connecting the center of the ACL femoral footprint with the insertion of the popliteus ranged from 22 mm to 37 mm in the subjects in our study. Thus, each subject, regardless of age or sex, had a tunnel length that was adequate for a soft-tissue graft, and in most cases the length was also sufficient to allow use of a suspensory fixation device. Although the tunnel length generally increased as the subjects aged, ranging from 27.93 to 30.19 mm, the difference among the seven to seventeen-year-old age groups was not statistically significant. However, the mean length of 25.38 mm at six years of age was significantly shorter than the length in the older subjects. The 3.02-mm difference in mean length between the six-year-old and the seven-year-old subjects was greater than the 2.26-mm difference among the seven to seventeen-year-old age groups, although this finding may prove not to be meaningful because of the limited numbers of six-year-old subjects in our study (sixteen of 188).

The same line that was used to determine the length of the proposed femoral tunnel also represented the central portion of the tunnel. This line connecting the center of the ACL femoral footprint with the popliteus insertion was between 8 and 16 mm from the physis in every subject, regardless of age or sex. Distally, the distance from the center of the proposed ACL tunnel to the articular cartilage was at least 4 mm and this distance increased with age, reaching a plateau (10.29 mm) at approximately twelve years of age. The smallest distance of 4 mm was in six and seven-year-old subjects, but at this age we would typically safely use ACL tunnels no larger than 7 mm in diameter. The measurements of the total height of the lateral condyle indicated that the proposed femoral tunnel would also not injure the chondral surface or risk entering the knee joint. Thus, a tunnel with a diameter of 8 mm (a radius of 4 mm) could be drilled in the femur without encroaching on the physis or the articular cartilage. The majority of pediatric patients at our institution undergo ACL reconstruction with use of hamstring autograft, which tends to be narrow (7 to 8 mm in diameter), but our technique would allow an 8 to 10-mm-diameter allograft or autograft to be chosen in some patients, especially older ones, without breaching the femoral physis or the cartilage cap.

Using the lateral femoral epicondyle rather than the popliteus insertion as the extra-articular starting point produced a tunnel that was longer (range, 25 to 41 mm in length) but closer to the physis (range, 6 to 15 mm from the physis). To maintain a safer distance from the physis, we therefore use the popliteus insertion or a point just proximal to the popliteus tendon itself in our practice. Use of a starting spot between the popliteus insertion and the lateral epicondyle rather than the popliteus insertion itself will also lessen the likelihood of distal encroachment on the cartilage cap.

Current physeal-sparing techniques for ACL reconstruction utilize intraoperative fluoroscopy. The use of fluoroscopy significantly increases operative time, cost, and radiation exposure[1,36,55-57]. Use of the center of the ACL femoral footprint and the popliteus insertion as landmarks, as described in our study, may allow drilling of a consistent, physeal-sparing, anatomic ACL tunnel while eliminating or lessening the need for intraoperative fluoroscopy. We do continue to recommend the use of fluoroscopy for verification of pin placement.

Our technique involves drilling of the tibial tunnel in a transphyseal fashion. Transphyseal drilling of the tibial tunnel is less of a concern than transphyseal femoral drilling because (1) the tibial physis is breached near its center, lessening the likelihood that growth disturbance would result in an angular deformity; and (2) studies involving ACL reconstruction in animals have shown that growth disturbance is rarely seen when <7% of the physis is damaged and soft-tissue grafts rather than fixation devices or bone are placed in the tunnel[58,59], and previous work from our laboratory has shown that, on average, <3% of the physeal volume is removed by the drilling of an 8-mm-diameter tunnel[60].

There are potential concerns regarding our technique. First, a theoretical risk of osteonecrosis exists in very young patients with a small femoral condyle. However, there have been few reports of the development of osteonecrosis, which likely occurred because of the combination of the femoral drilling and the bruising of the lateral femoral condyle that is seen in association with an acute ACL injury[61,62]. The osteonecrosis risk could potentially increase if larger-diameter tunnels are drilled or if double-bundle ACL reconstruction is performed. A second potential risk of ACL reconstruction is damage to the popliteus tendon. This would be a concern if the surgeon drills from inside out. However, damage to the popliteus tendon is not a problem with our surgical technique because we drill in an outside-in manner, thus sparing the lateral femoral cortex, with a FlipCutter device (Arthrex, Naples, Florida). A third possible concern involves the epiphyseal bone-cartilage interface (cartilage cap) at the distal surface of our proposed tunnel. However, no injury to the cartilaginous cap in any subject would have resulted from a standard age-based femoral tunnel size. It would nevertheless be prudent to conduct an animal study to investigate the potential for growth disturbance resulting from damage to the cartilage cap in the distal-lateral aspect of the femur. Lastly, identification of the center of the ACL femoral footprint that forms the intra-articular starting point could pose difficulties. However, given an adequate understanding of the view through the anteromedial portal and normal anatomy of the ACL footprint, the borders of the ACL footprint and the bifurcate ridge should be easily identifiable. When the bifurcate ridge is not easily seen during arthroscopy, we often use the soft-tissue footprint, which is easily visualized from the anteromedial arthroscopic portal, and place the tunnel directly in the center of the soft-tissue footprint. The femoral tunnel position that we use is very different from the position that is traditionally used in either the transtibial or the two-incision reconstruction technique. It must be emphasized that placing the graft in what is commonly described as the “11 and 1 o’clock positions” would not only place it outside the ACL footprint but also lead to physeal damage.

Our study has several limitations. First, the measurements are based on chronological rather than physiological age, which limits the conclusions that can be drawn regarding the effect of age. Second, the number of subjects of each sex in each age group was limited. However, analyzing the sexes separately did not significantly affect the results of the statistical analyses. Third, the MRIs were acquired with use of both 1.5 and 3.0-T instruments; however, the same protocol was utilized for all examinations. Lastly, we chose six years of age as our youngest age group because the number of ACL reconstructions performed in patients less than six years old is minimal and MRIs are less readily available in this age group.

In conclusion, anatomic ACL reconstruction that spares the distal femoral physis can be safely performed utilizing the method described in this study. Preoperative MRIs can be used to determine the maximum femoral tunnel length and the maximum femoral tunnel diameter that can be employed for the reconstruction. A pair of easily identifiable extra-articular and intra-articular landmarks is used to create a reproducible femoral tunnel. These landmarks are the femoral insertion of the popliteus tendon and the central portion of the center of the ACL femoral footprint. The resulting femoral tunnel would have been of adequate length (≥25 mm) and adequate diameter (>7 mm) without violating the femoral physis or the distal cartilaginous cap, in all of our subjects. The distance from the femoral physis to the center of the proposed ACL tunnel and the calculated tunnel length would both have been fairly constant between six and seventeen years of age. Physeal-sparing, anatomic ACL reconstruction may become the preferred technique for skeletally immature patients in the future.

Appendix

eA Figures showing the labeling of landmarks on the MRIs are available with the online version of this article as a data supplement at jbjs.org. ■

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John W. Xerogeanes, MD
Emory Orthopaedic and Spine Center,
59 Executive Park South, Suite 1000, Atlanta, GA 30329.
E-mail address: john.xerogeanes@emory.edu

Kyle E. Hammond, MD
Emory Orthopaedics, 704 North Superior Avenue,
Decatur, GA 30033

Dane C. Todd, BS
Emory University, 1394 'G' Cornell Road N.E.,
Atlanta, GA 30306

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