The Influence of Femoral Technique for Graft Placement on Anterior Cruciate Ligament Reconstruction Using a Skeletally Immature Canine Model With a Rapidly Growing Physis

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Purpose: The purpose of this study was to evaluate 3 different femoral techniques of anterior cruciate ligament (ACL) reconstruction using a skeletally immature canine model. **Methods:** A soft-tissue autograft ACL reconstruction was performed in 25 ten-week-old canines via a central transphyseal tibial tunnel and 1 of 3 femoral techniques: epiphyseal, over the top, or transphyseal. The contralateral hind limbs served as controls. The canines were killed at 16 weeks postoperatively and evaluated by gross inspection, plain radiographs, photography, magnetic resonance imaging, and histomorphometry. **Results:** There were no significant differences in femoral longitudinal growth; however, tibial growth was significantly greater on the experimental side relative to controls ($P = .001$). Angular and rotational deformities were noted on the femoral side but not on the tibial side. The epiphyseal technique resulted in less angular deformity and most closely maintained the anatomic position of the ACL graft with growth; however, this technique exhibited increased femoral rotational deformity. All techniques exhibited a high rate of graft failure. Magnetic resonance imaging revealed chondral and subchondral injuries to the lateral femoral condyle, most frequently in the epiphyseal group. **Conclusions:** From the results of our study, we cannot advocate any single femoral reconstructive technique. An epiphyseal femoral technique may reduce the risk of angular deformity and allow a more optimal femoral graft position after growth as opposed to transphyseal and over-the-top techniques. However, the epiphyseal technique may possess an increased risk for rotational deformity, physeal injury, and articular surface injury. Metaphyseal fixation of ACL grafts traversing rapidly growing physes may be responsible for the observed abnormalities in graft integrity, femoral graft position, and femoral angulation and rotation. **Clinical Relevance:** ACL reconstruction in the skeletally immature individual is complicated by the presence of active physeal and epiphyseal cartilage surrounding the growing knee, the pathophysiologic consequences of injury to these developing structures, and the final effect on the anatomy and function of the graft, bone, and articular surface. Animal models can provide insight and direction as we develop and evaluate our treatment methods for this clinical problem, but these animal models have anatomic and physiologic differences that limit direct comparison to humans.

Key Words: Anterior cruciate ligament—Anterior cruciate ligament reconstruction—Skeletally immature—Epiphyseal tunnel—Physis.

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Anterior cruciate ligament (ACL) injury in the skeletally immature individual is being recognized with increasing frequency. Historically, nonoperative treatment of midsubstance ACL injuries in skeletally immature individuals has not been favorable. Many investigators report significant rates of continued instability with subsequent meniscal injury, which can lead to the development of premature degenerative changes and disability.[1-4] Despite many reports of successful ACL reconstruction, many orthopaedic surgeons are still reluctant to perform ACL reconstructive procedures in the skeletally immature individual because of clinical reports of subsequent growth abnormalities and a general lack of understanding regarding the physiologic consequences of ACL reconstruction in these patients.[5] Current clinical studies support the use of anatomic ACL reconstructive techniques via either paraphyseal, transphyseal, or epiphyseal graft positioning with either metaphyseal or epiphyseal graft fixation.[5-10] Although there is a consensus that reconstructions via fixation devices or bone grafts that traverse the physis carry a high risk for growth abnormalities and are inappropriate, it is not known which technique of ACL reconstruction provides the least risk and best restores the anatomy and function of the ACL in the growing child.[5]

The purpose of this study was to evaluate 3 different femoral techniques of ACL reconstruction in a skeletally immature canine model. We hypothesize that an anatomic ACL reconstructive technique using an epiphyseal femoral tunnel and a central transphyseal tibial tunnel can be performed without altering physeal and epiphyseal growth while maintaining the anatomic femoral position of the ACL graft better than reconstructive techniques using a femoral transphyseal tunnel or over-the-top graft positioning.

METHODS

Overview

An ACL reconstruction was performed in 25 ten-week-old, large, closed colony–bred mongrel dogs via a transphyseal tibial tunnel and 1 of 3 femoral techniques: epiphyseal, over the top, or transphyseal. The contralateral hind limbs served as controls. The animals were killed 16 weeks after surgery. Gross inspection, plain radiographs, photographs, magnetic resonance imaging (MRI), and histomorphometry were used to evaluate for physeal injury, growth disturbance, and final position of the ACL femoral origin. Our institutional animal care and use committee approved the study protocol. The animals were housed in a facility accredited by the American Association for Assessment and Accreditation of Laboratory Animal Care.

Surgical Procedure

All dogs underwent an open ACL reconstruction via a partial ipsilateral Achilles soft-tissue autograft. The partial autograft was divided from the flexor digitorum longus through a separate posterior incision and harvested, and the remaining musculotendinous unit was reinforced by repair to the flexor digitorum tendon. The cross-sectional area of the graft was similar to the native ACL in all specimens and was of sufficient length for all techniques. The native ACL was resected in its entirety to produce ACL insufficiency. Unilateral ACL reconstructions were performed via a central transphyseal tibial tunnel and 1 of 3 different femoral techniques: "over the top" (graft passed behind lateral femoral condyle), transphyseal drill tunnel, or epiphyseal drill tunnel.

The different femoral techniques were randomly assigned to an equal number of right and left stifle (knee) joints, and the contralateral hind limb served as a control. All tunnels were created with a 4.0-mm cannulated drill. We created a reproducible epiphyseal femoral tunnel using a modified outside-in guide and external landmarks on the lateral femoral condyle (entrance site just lateral to the intra-articular portion of the extensor digitorum longus and exit site in the center of the femoral ACL origin) identified before the study with the assistance of MRI and multiple trial limbs. The grafts were positioned and secured to the femur with No. 2 braided polyester sutures (Ethibond; Ethicon, Somerville, NJ) tied over a 3.5-mm bicortical screw and washer for the over-the-top and transphyseal techniques and with sutures over a button for the epiphyseal technique. All grafts were cycled, tensioned to 80 N (18 lb) of force via a tensiometer (Arthrex, Naples, FL), and secured to the tibia with sutures tied over a 3.5-mm bicortical screw and washer. Anteroposterior and lateral radiographs, standardized for rotation and magnification, were taken while the dogs were still under anesthesia.

Postoperatively, the dogs were allowed to bear weight as tolerated. They were observed daily during the first 3 postoperative weeks and again at 8 weeks. The dogs were killed after 16 weeks of growth when they reached mature skeletal size but before physeal closure. Lachman grade as defined by Torg et al.[11] was recorded immediately post mortem on the intact hind limb before any dissection.

MRI

Experimental and control hind limb specimens were imaged in a clinical 1.5-T superconducting magnet (Signa Horizon LX; GE Medical Systems, Milwaukee, WI) using a receive-only quadrature wrist coil (Quadrature Wrist; Medical Advances, Milwaukee, WI). Coronal and sagittal magnetic resonance images were obtained by use of a fast spin echo sequence validated for articular cartilage assessment[12] with a repetition time of 4,000 to 4,300 milliseconds, echo time of 31.9 milliseconds (effective), receiver bandwidth of 31.2 kHz over the entire frequency range, field of view of 9 cm, and matrix of 512×384, yielding an in-plane resolution of 176×234 μm. Slice resolution was 1.5 mm with no interslice gap. Images were obtained at 3 excitations. The magnetic resonance images were read by a musculoskeletal radiologist specializing in MRI (H.P.) to evaluate the final femoral position of the ACL graft, the graft integrity (based on signal characteristics and morphology), the condition of the subchondral bone (normal, sclerosis, edema pattern, depression), and the articular cartilage (intact, partial- or full-thickness defects), as well as violation of the physis by the bone tunnel.

We reconstructed and scanned 3 separate 10-week-old trial limbs to estimate the percent cross-sectional area of physis injured by the drilled tunnels at the time of surgery. The physes were manually segmented on an MRI workstation to measure the percent cross-sectional area of physeal signal interruption for the femoral and tibial tunnels (Advantage Windows, version 4.1; GE Medical Systems).

Gross Observation, Radiographs, and Photographs

All soft tissue except for the ACL graft was manually removed, and the specimens were then grossly inspected for graft integrity. The ACL grafts were graded as intact, attenuated, or not intact. A digital micrometer was used to measure femoral and tibial medial and lateral longitudinal lengths, distal femoral and proximal tibial dimensions, and final position of the femoral ACL graft origin (Fig 1, online only, available at www.arthroscopyjournal.org). Measurements were made on both the experimental and control limbs.

Plain radiography of the femurs and tibias was performed to evaluate for angular deformity and to compare with time-zero radiographs to determine the actual rate of growth. Radiographs were standardized for rotation and magnification by use of consistent bone positioning, consistent source-to-image distance, and radiographic size references.

Axial photographs were taken of the experimental and control femurs placed side by side with their distal femoral condyles resting on a flat table to quantify the degree of femoral rotational deformity. The angle between the axis of the femoral neck and the horizontal line parallel to the plane of the posterior surface of the femoral condyles was measured.

Histologic Analysis

For both the experimental and control limbs, a portion of the central proximal tibia and the distal femoral posterolateral hemicondyle were fixed in formalin, decalcified in 5% nitric acid, and embedded in paraffin. These sites were chosen to evaluate the physis, bone, and tunnels of the tibia and femur where the graft passed through the bone. Seven-micrometer-thick coronal sections were stained with H&E and Goldner's modified trichrome stains. The specimens were evaluated under light microscopy for changes in physeal organization, evidence of osteonecrosis, and physeal bone bridging. Computerized image analysis (SigmaScan; Jandel Scientific, San Rafael, CA) was used to measure physeal width and the thickness of bone formation across the physis ("bridging bone").

Statistical Analysis

A pre hoc power analysis was conducted with femoral varus-valgus angulation being used as a main outcome variable. We set α at 0.05 and power at 0.85. By use of previous data,[13] power calculations determined that 6 animals were needed per group to detect a 5° difference in varus-valgus angulation.

One-way repeated-measures analysis of variance was used to evaluate differences between the 3 different femoral techniques. We conservatively set statistical significance at $P = .001$ based on Bonferroni correction calculations. Statistical significance was set at $P = .05$ for secondary multiple comparison tests after significant analysis of variance tests. Spearman rank order correlation coefficients were used to identify relations between specific variables.

RESULTS

General Observations

Postoperatively, 20 of 25 dogs were fully weight-bearing by 3 weeks, and 24 of 25 dogs were fully weight-bearing with a normal gait by 8 weeks. At harvest, the Achilles donor site was inspected, and all had healed. Infection occurred in 2 of 25 dogs. One dog was diagnosed early with positive cultures and underwent irrigation and debridement, as well as antibiotic treatment. The second infection was more insidious and diagnosed late by cultures and histology after death. Careful evaluation of the data from these dogs revealed no outlying values; therefore they were included in the complete analysis.

Graft Integrity

By gross inspection, 36% (9/25) of the grafts appeared intact, 28% (7/25) were attenuated, and 36% (9/25) were not intact. Closer inspection of the specimens revealed that all of the grafts had elongated (many to failure) at their intra-articular portion, as the femoral and tibial sites of graft fixation moved away from the knee with longitudinal growth (Fig 2). In some specimens even the sutures bridging the intra-articular portion of the graft were grossly disrupted. In all specimens the proximal and distal extra-articular portion of the grafts, sutures, and knots remained intact and in continuity with secure sites of femoral and tibial fixation.

By MRI, 12% (3/25) of the grafts appeared intact, 44% (11/25) were attenuated, and 44% (11/25) were not intact. Of the grafts, 28% (7/25) were given Lachman grade 1, 32% (8/25) were given grade 2, and 40% (10/25) were given grade 3. There was no significant difference found in any measure of graft integrity between the 3 different femoral techniques.

We found no statistically significant relations between our measures of graft integrity and the other measures of growth abnormality including femoral and tibial length, angulation, rotation, ACL graft and femoral origin migration, physeal closure, and articular surface injury.

Femoral Graft Origin

In all of the transphyseal and over-the-top specimens, the ACL graft did not attach to the lateral femoral condyle. The grafts migrated from their original femoral positions according to the direction of pull from the fixation sites as they moved away from the knee with longitudinal growth (Fig 2 and Figs 3A and 3B). In the transphyseal specimens the grafts migrated completely out of the bone of the lateral femoral condyle, with interspecimen variability in the amount of graft exposed out of the posterior cortex of the femoral shaft. All of the epiphyseal specimens maintained a femoral attachment site to the lateral femoral condyle within the footprint of the native ACL origin (Fig 3C).

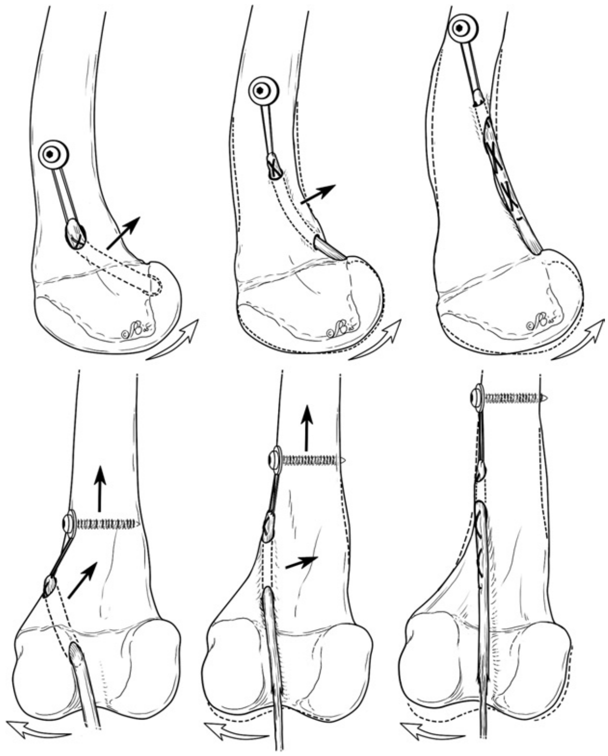


FIGURE 2. ACL graft and femoral growth abnormalities (in a transphyseal specimen) resulting from movement of femoral metaphyseal fixation site in response to physeal growth. The movement of the fixation site possibly contributed to graft migration, graft failure, and femoral coronal and sagittal deformities.

The center of the ACL femoral attachment for the epiphyseal group was, on average, 4.9 mm distal to the center of the native origin of the corresponding control ($P < .001$) (Fig 3C). We were unable to measure the proximal-distal position of the ACL femoral graft origin for the transphyseal and over-the-top groups because their ACL grafts only maintained soft-tissue connections to the posterior femur and the actual point of graft attachment was not discernable.

In the sagittal plane, relative to the control specimens, the center of the ACL graft was, on average, 2.5 mm more anterior in the transphyseal group ($P = .001$), 1.9 mm more anterior in the over-the-top group

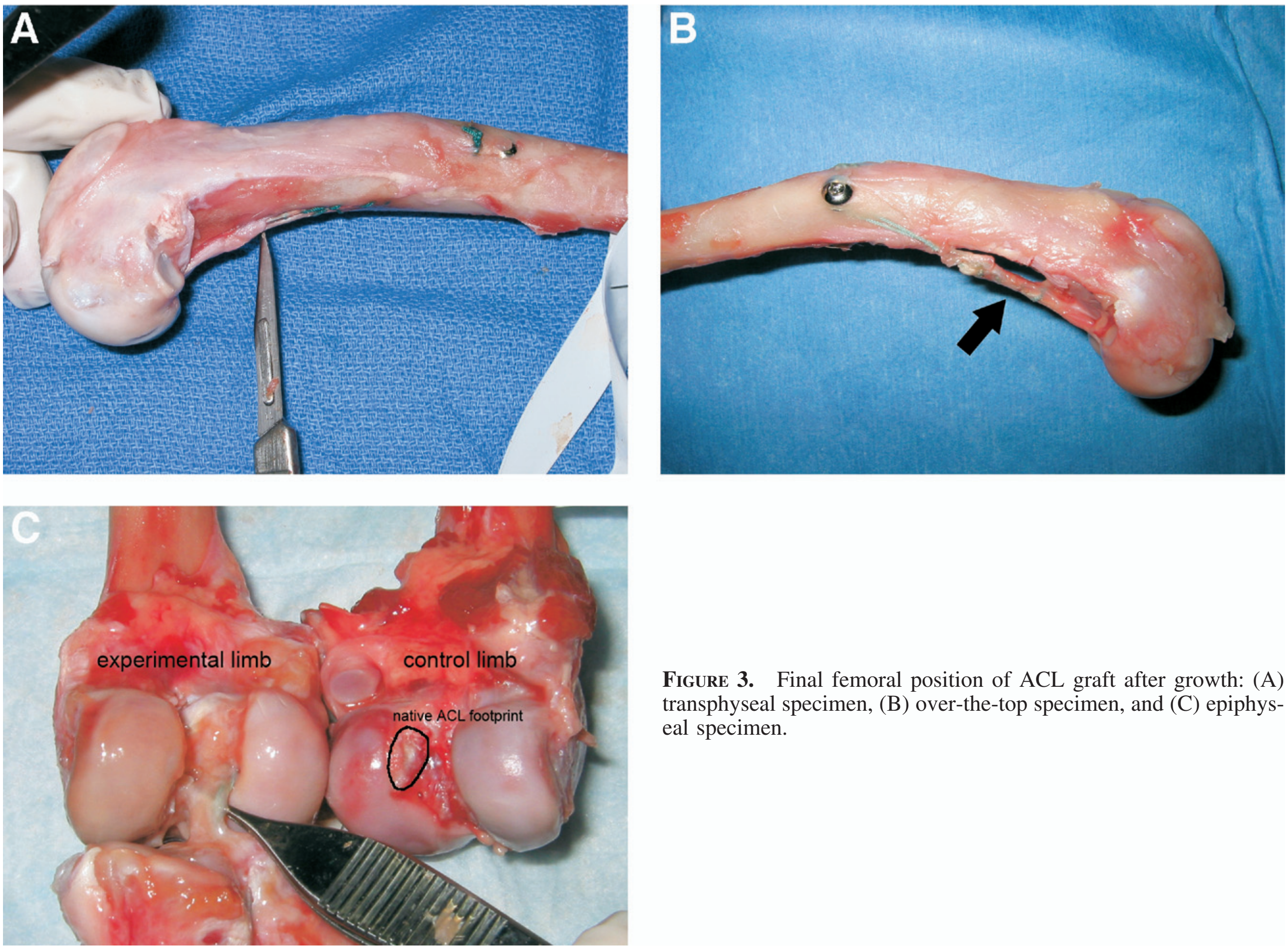


Figure 3. Final femoral position of ACL graft after growth: (A) transphyseal specimen, (B) over-the-top specimen, and (C) epiphyseal specimen.

(P = .001), and 0.8 mm more anterior in the epiphyseal group (P = .008). In the coronal plane the epiphyseal group maintained an attachment to the lateral femoral condyle. Relative to the control specimens, the center of the ACL femoral origin remained 3.6 mm more medial in the transphyseal group (P = .001) and 3.2 mm more medial in the over-the-top group (P = .001).

Physis

By MRI, physeal disruption was limited to 1.4% of the cross-sectional area of the distal femoral physis and 3.3% of the proximal tibial physis. By histology, the morphology and organization of the zones and columns of the physis were well preserved throughout. There was no evidence of osteonecrosis in the bone adjacent to the physis or between the subchondral surface and the drilled tunnel. On the femoral side (in the transphyseal groups), there was no evidence of a transphyseal tunnel or transphyseal bridge as a result of the gradual migration of the graft out of the epiphyseal bone and physeal cartilage. The femoral physis width near the posterior aspect of the lateral femoral condyle averaged 0.54 ± 0.8 mm on the experimental side and 0.54 ± 0.17 mm on the control side. There were no statistically significant differences found between the different femoral techniques (epiphyseal, 0.494 ± 0.048 mm; transphyseal, 0.643 ± 0.243 mm; and over the top, 0.496 ± 0.126 mm).

The tibial physis remained open, but we were unable to reproducibly measure its width because it invaginated into the metaphysis adjacent to the transphyseal tunnel. This invagination likely represents a relative local growth retardation surrounding the central physeal injury[14] (Fig 4). In all specimens, bone bridged the tibial physis within the tunnel with a width varying between 0.041 and 1.40 mm. Fibrous tissue rather than a mature intermediate fibrocartilage zone formed at the interface between the tendon graft and the tibial bone tunnel for its entire length.

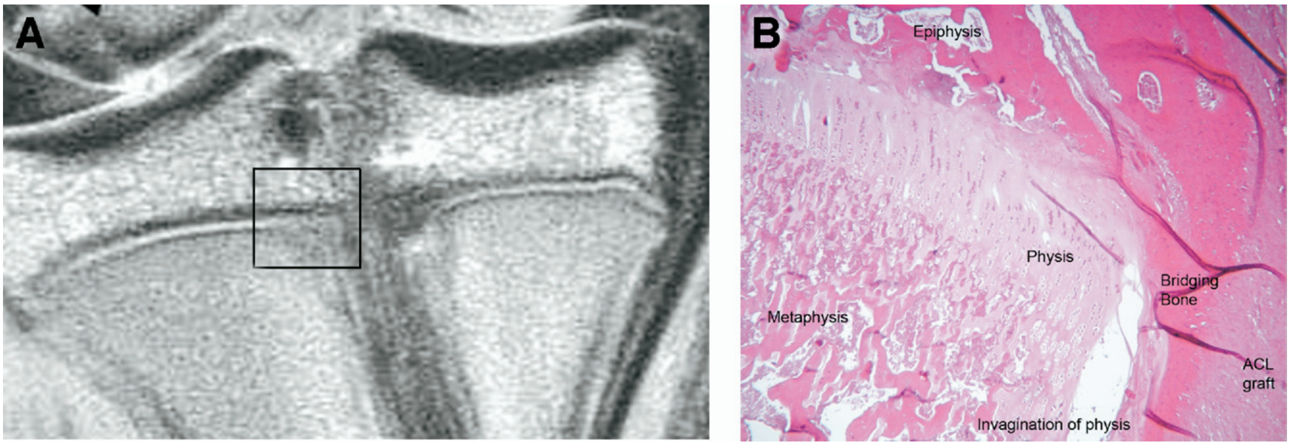


FIGURE 4. (A) Coronal magnetic resonance image of proximal tibia illustrating site of sampling for histologic section. (B) Photomicrograph of histologic section stained with H&E at 40× magnification. The section shows tibial physeal invagination and bone bridging along the transphyseal tibial tunnel.

Physeal Longitudinal Growth

There were no statistically significant differences found in the measurements of medial or lateral femoral length between the experimental and control groups or among the 3 different femoral technique groups (Fig 5A and Table 1). The medial and lateral tibial lengths were significantly longer in each of the 3 experimental technique groups relative to their control specimens ($P = .001$) (Fig 5B and Table 1), but there were no significant differences between techniques.

Epiphyseal Growth

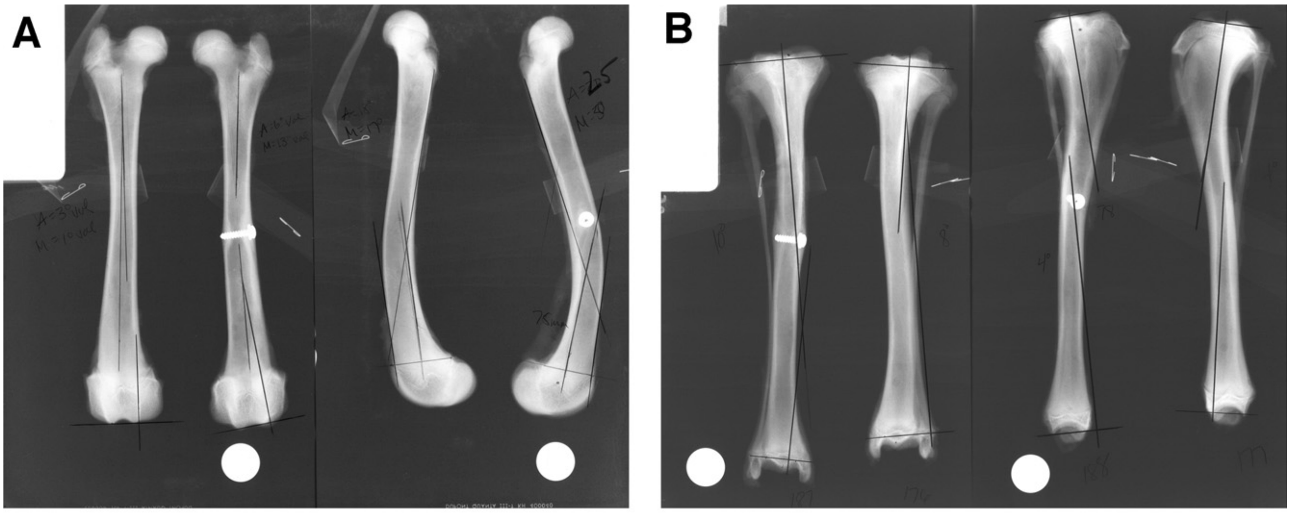
The lateral and medial femoral condylar sagittal widths and the overall distal femoral condylar coronal width revealed significant but small differences (approximately 2 mm or less) between the experimental groups and their controls and among the different femoral technique groups. The lateral femoral condylar and medial femoral condylar coronal widths were not different between experimental and control groups or among the experimental groups. The tibial epiphyseal coronal and sagittal widths showed no significant differences between the groups and their controls or among the groups.

Angular Deformity

For distal femoral coronal angulation, the transphyseal and over-the-top groups had significantly greater valgus than the epiphyseal group ($P = .022$ and $P = .010$, respectively) and all 3 experimental technique groups had significantly greater valgus than their respective controls (Table 2). For femoral sagittal diaphyseal angulation, all of the experimental technique groups had significantly greater apex anterior angulation (procurvatum) than their respective controls, but there were no significant differences seen between the 3 experimental technique groups. For the distal femoral sagittal angulation, all of the experimental technique groups had more procurvatum (flexion) than their respective controls. In addition, the transphyseal group had significantly more distal procurvatum than the epiphyseal and over-the-top groups ($P = .001$ and $P = .008$, respectively). There was no significant difference noted in the femoral coronal diaphyseal angulation between the experimental and control groups or among the experimental groups. Distal femoral angulation was always greater than diaphyseal angulation for both the coronal and sagittal planes. The tibial specimens showed no difference in coronal and sagittal angulation between experimental and control groups.

Rotational Deformity

The epiphyseal and transphyseal groups exhibited significantly increased external rotation of the distal femur relative to the proximal femur when compared with their respective controls ($P = .001$ and $P = .005$, respectively) (Fig 5C and Table 3). There was a trend in the over-the-top group toward increased rotation as well, but this did not reach statistical significance ($P = .094$). There was no statistically significant difference between the 3 experimental technique groups. We observed no rotational deformities in the tibia.



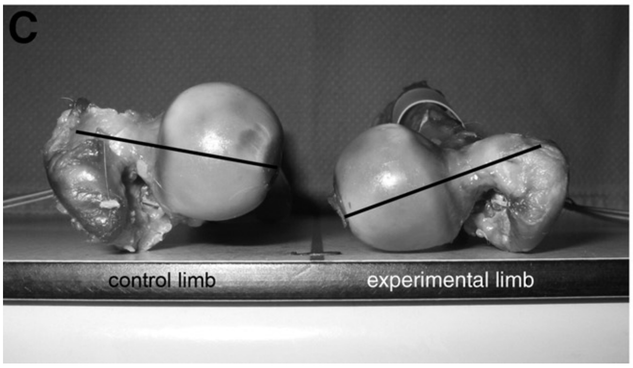


Figure 5. Growth abnormalities. (A) Radiographs showing coronal-plane deformity (valgus) and sagittal-plane deformity (procurvatum/flexion) of experimental femurs. (Experimental limbs have the fixation screw.) (B) Radiographs showing overgrowth of experimental tibias. (Experimental limb has the fixation screw.) (C) Axial photograph showing rotational deformity of experimental femur relative to its control.

Epiphyseal Technique Group

By MRI, the drilled epiphyseal tunnel did not violate the physis in 2 of 9 specimens (22%), it abutted the physis in 4 of 9 specimens (44%), and it violated the physis in 3 of 9 specimens (33%) (Fig 6A). Violation was limited to a small undulation in the femoral physis, minimal in size (producing significantly less injury to the physis than the transphyseal tunnel). Given the small number of specimens with physeal violations (n = 3), we could not show any statistical relation between physeal violation and the other measured variables of growth abnormality, including physeal closure, longitudinal growth, or femoral angulation and rotation.

Focal partial- and full-thickness chondral injuries with underlying subchondral bone depression were identified in the lateral femoral condyle in several dogs by MRI (Fig 6B). The epiphyseal group had significantly more chondral injuries than the over-the-top group (9 *v* 1 specimen, $P = .0004$) and the transphyseal group (9 *v* 4 specimens, $P = .03$). The

Table 1. *Femoral and Tibial Medial and Lateral Lengths After Growth*

Measurement	Epiphyseal	Transphyseal	Over the Top	Control	*P* Value
Medial femoral length (mm)	183.55 ± 7.99	180.60 ± 9.54	178.04 ± 10.15	177.97 ± 9.51	.010
Lateral femoral length (mm)	181.61 ± 10.74	179.54 ± 10.26	177.35 ± 9.52	179.11 ± 9.46	.484
Medial tibial length (mm)	194.97 ± 9.59*	194.84 ± 9.62*	189.52 ± 11.05*	184.81 ± 10.13	≤.001
Lateral tibial length (mm)	192.65 ± 9.92*	192.69 ± 8.46*	187.29 ± 10.26*	182.32 ± 9.73	≤.001

NOTE. Data are presented as mean ± SD.
*Statistically significant difference from respective control.

TABLE 2. *Femoral Angulation: Comparison by Procedure*

Comparison	Epiphyseal *v* Control	Transphyseal *v* Control	Over the Top *v* Control	Transphyseal *v* Epiphyseal	Over the Top *v* Epiphyseal	Transphyseal *v* Over the Top
Distal femoral angulation: Coronal						
Difference of means (°)	5.0* valgus	9.7* valgus	10.0* valgus	4.4* valgus	5.0* valgus	−0.6 valgus
Unadjusted *P* value	.001	≤.001	≤.001	.022	.010	.736
Femoral diaphyseal angulation: Sagittal						
Difference of means (°)	5.1* apex anterior	5.9* apex anterior	5.0* apex anterior	0.8 apex anterior	−0.1 apex anterior	0.9 apex anterior
Unadjusted *P* value	≤.001	≤.001	≤.001	.612	.941	.575
Distal femoral angulation: Sagittal						
Difference of means (°)	4.7* procurvatum	13.0* procurvatum	7.0* procurvatum	8.3* procurvatum	2.3 procurvatum	6.0* procurvatum
Unadjusted *P* value	.005	≤.001	≤.001	≤.001	.253	.008

*Statistically significant difference.

epiphyseal group had significantly more subchondral bone injuries than the over-the-top group (7 *v* 0 specimens, *P* = .002) and approached significance when compared with the transphyseal group (7 *v* 2 specimens, *P* = .06).

DISCUSSION

ACL reconstruction in the skeletally immature individual is not without risk for growth abnormality, and the ideal reconstructive technique is yet to be determined. We performed 25 open ACL reconstructions in a canine model and discovered that an all-epiphyseal femoral technique resulted in less angular deformity and better position of the femoral graft origin after growth when compared with transphyseal and over-the-top techniques. However, the all-epiphyseal technique may also be associated with an increased risk for femoral rotational deformity, physeal injury, and articular surface injury. In addition, metaphyseal fixation of ACL grafts eccentrically traversing rapidly growing physes may be responsible for the observed abnormalities in graft integrity, femoral graft position, and femoral angulation and rotation in our rapidly growing canine model.

We observed longitudinal overgrowth of the tibia despite bone bridging across the tibial physis. Trauma from surgery or injury has been shown to stimulate both local and distant physeal growth in the same extremity,[15] and we postulate that a similar mechanism is most likely responsible for our observations of tibial overgrowth. In addition, a previous animal study has shown how physeal growth can continue despite a complete transphyseal bone bridge.[16] The bone graft bridging the physis underwent a process similar to that of distraction histiogenesis in response to the lengthening force produced by the growing physis. Factors such as the thickness of the bone bridge and the amount of growth potential (rate and force) of the remaining physis may be competing to either arrest or allow growth. Overgrowth has also been found in clinical studies, and both Guzzanti et al.[8,9] and Anderson[6] have reported undergrowth and overgrowth in the operative limb (range, 1 to 10 mm).

After tensioning our ACL grafts at 80 N, we observed angular and rotational deformities without ev-

TABLE 3. *Comparisons of Femoral Rotation After Growth*

Femoral Rotation	Epiphyseal *v* Control	Transphyseal *v* Control	Over the Top *v* Control	Transphyseal *v* Epiphyseal	Over the Top *v* Epiphyseal	Transphyseal *v* Over the Top
Difference of means (°)	7.6* ER	6.3* ER	3.5 ER	−1.3 ER	−4.1 ER	2.8 ER
Unadjusted *P* value	≤.001	.005	.094	.607	.120	.300

Abbreviation: ER, external rotation of distal femur relative to proximal femur.
*Statistically significant difference.

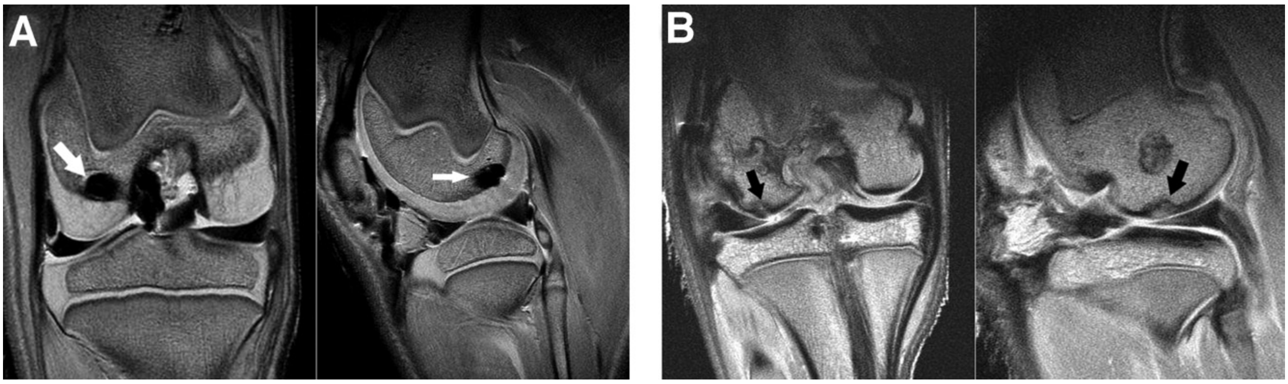


FIGURE 6. (A) Coronal and sagittal fast spin echo magnetic resonance images showing proximity of 4-mm-diameter epiphyseal femoral ACL tunnel (*arrows*) to physeal and epiphyseal cartilage. (B) Coronal and sagittal fast spin echo magnetic resonance images showing articular cartilage and subchondral bone injury (*arrows*) to lateral femoral condyle after epiphyseal technique.

idence of femoral or tibial longitudinal growth arrest. This is in direct contrast to the canine study of Edwards et al.,[13] who observed complete growth arrest of the distal lateral femoral condyle (not the tibia) after tensioning their transphyseal (tibia and femur) grafts to 80 N. Edwards et al. drilled 4-mm transphyseal tunnels, as we did, but they used a much smaller beagle canine model. The higher percentage of eccentric femoral physeal destruction combined with the smaller magnitude of physeal growth potential (rate and force) in this smaller canine model may have contributed and may explain the differences in our observations. In addition, soft-tissue grafts used during ACL reconstruction are viscoelastic structures that do not maintain their initial tension,[17] and therefore high initial graft tension alone is unlikely to result in a complete growth arrest. However, graft tension may be maintained when ACL grafts with metaphyseal fixation traverse rapidly growing physes.

Metaphyseal fixation of the ACL graft traversing the rapidly growing physis of our model may be responsible for the observed growth abnormalities of graft integrity, femoral graft position, and femoral angulation and rotation. As the metaphyseal fixation sites of the graft migrated away from the knee with physeal growth, the grafts were observed to elongate by approximately 100% (69.6 ± 8.6 mm) of their original length (65 mm) in the transphyseal group and over-the-top groups and approximately 50% (33.6 ± 3.8 mm) in the epiphyseal group (Fig 2). The grafts elongated (many to failure) at their most mechanically disadvantageous site, the unsheltered intra-articular portion. Our study cannot completely rule out other mechanical sources that may have contributed to graft failure; however, it is likely that graft elongation and failure were, in part, a result of the inability of the tendon graft to accommodate the large and rapid amount of growth. Because of our gross observations and because we could not find a correlation between degree of graft integrity and the observed growth abnormalities, we believe that the grafts did not fail early and maintained sufficient tension to result in femoral graft origin migration and femoral angulation and rotation, deformities that are best explained by the effects of persistent tension in the graft. These conclusions are further supported by the findings of Stadelmaier et al.,[18] who also used the same 10-week-old canine model. In half of their dogs, they placed an untensioned graft in 4-mm transphyseal tunnels with minimal fixation (simple interrupted sutures to the periosteum) to merely hold the graft in place, and they left the tunnels empty in the other half. At 4 months postoperatively, they found intact viable grafts in all of the grafted dogs and no growth abnormalities in either group of dogs.

Metaphyseal fixation of the graft eccentrically traversing the rapidly growing femoral physis in the transphyseal and over-the-top groups resulted in migration of the femoral graft origin to a nonanatomic position. The ACL graft migrated according to the relative pull of the moving fixation site such that neither the transphyseal group nor the over-the-top group maintained an ACL graft attachment to the lateral femoral condyle (Fig 2 and Fig 3). Femoral graft origin migration with growth holds significant potential consequences with regard to the function of the ACL graft.

We observed femoral rather than tibial angular and rotational deformities, illustrating the significance of an eccentric rather than central physeal insult in cre-

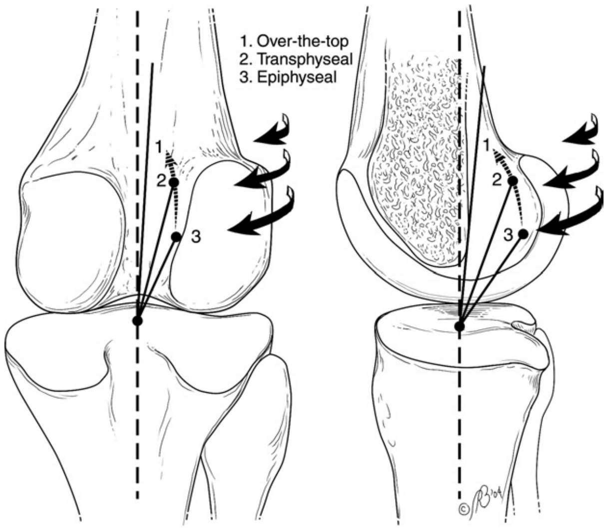


FIGURE 7. Eccentricity of femoral origin by procedure (1, over the top; 2, transphyseal; 3, epiphyseal) and relative magnitude of rotational deforming forces (solid curved black arrows). The femoral origin of the transphyseal graft (2) migrated (segmented arrow) with growth from an initial position equivalent to that of the epiphyseal technique (3) to a final position more similar to that of the over-the-top graft (1). It is hypothesized that the rotational deformity results from graft tethering through the eccentric femoral position.

ating unbalanced deformities. As tension was generated or maintained in the graft by metaphyseal fixation and physeal growth, the growth of the distal femur was asymmetrically restricted, resulting in the observed valgus and procurvatum (flexion) femoral deformities (Fig 2). The most angular deformity was exhibited by the transphyseal and over-the-top groups possibly because the ACL graft traversed both the proximal tibial and distal femoral physes.

Tension in the ACL graft may have also been sufficient to externally rotate (rotationally tether) the distal femur by its eccentric posterolateral graft attachment around the central pivot point of the tibial tunnel. The magnitude of rotational deformity was directly related to the degree of eccentric graft attachment of the ACL—that is, the further the femoral graft attachment from the central axis of the femur, the more eccentric the vector of the deforming force and, therefore, the larger the rotational deformity (Fig 7) (epiphyseal > transphyseal > over the top). In addition, sagittal growth of the lateral femoral epiphysis may have also contributed to the graft tension that tethered and rotated the distal femur in the epiphyseal group.

The prevalence of physeal violation (33%) and the increased rate of subchondral and chondral injuries seen with the epiphyseal technique show the potential consequences of attempting to drill in the developing epiphysis. With our open drilling technique, we were able to clearly view and avoid injury to the articular surface of the joint. However, the bony window available in which to place an epiphyseal femoral tunnel between the developing physeal and epiphyseal cartilage was extremely narrow in these immature 10-week-old dogs (Fig 6A). Our need to drill close to the epiphyseal bone–articular cartilage interface (still remote from the actual articular surface) to avoid the physis may have injured the developing subchondral bone and epiphyseal cartilage and may also explain the increased incidence of cartilage and subchondral bone injury in the epiphyseal group (Fig 6B).

This study has limitations inherent to the use of an animal model, with rapid growth rates and knee and gait biomechanics different from humans. Differences between our animal model and humans, particularly in the rate of physeal growth, make direct application of our findings to clinical practice difficult. The actual amount of longitudinal growth remaining is similar between our 10-week-old canine model and skeletally immature humans of ages susceptible to ACL injury (girls aged 9 to 10 years and boys aged 11 to 12 years based on the data of Anderson et al.[19]). However, because the physeal growth rate in humans is much slower (10-fold) than that of this canine model, metaphyseal fixation of an ACL graft traversing a human physis may not produce as much graft tension and may allow for epiphyseal incorporation of the ACL graft. Both of these factors may reduce the human risk for the growth abnormalities of femoral graft position, graft integrity, and femoral angulation and rotation observed in this more rapidly growing canine model. Despite this limitation, our study still provides important insight into the potential pathophysiologic consequences associated with performing ACL reconstruction in the presence of open physes; however, animal models such as this canine model have obvious anatomic and physiologic differences that limit direct comparison to humans.

CONCLUSIONS

From the results of our study, we cannot advocate any single femoral reconstructive technique. An epiphyseal femoral technique may reduce the risk of angular deformity and allow a more optimal femoral graft position after growth as opposed to transphyseal and over-the-top techniques. However, the epiphyseal technique may possess an increased risk for rotational deformity, physeal injury, and articular surface injury. Metaphyseal fixation of ACL grafts traversing rapidly growing physes may be responsible for the observed abnormalities in graft integrity, femoral graft position, and femoral angulation and rotation.

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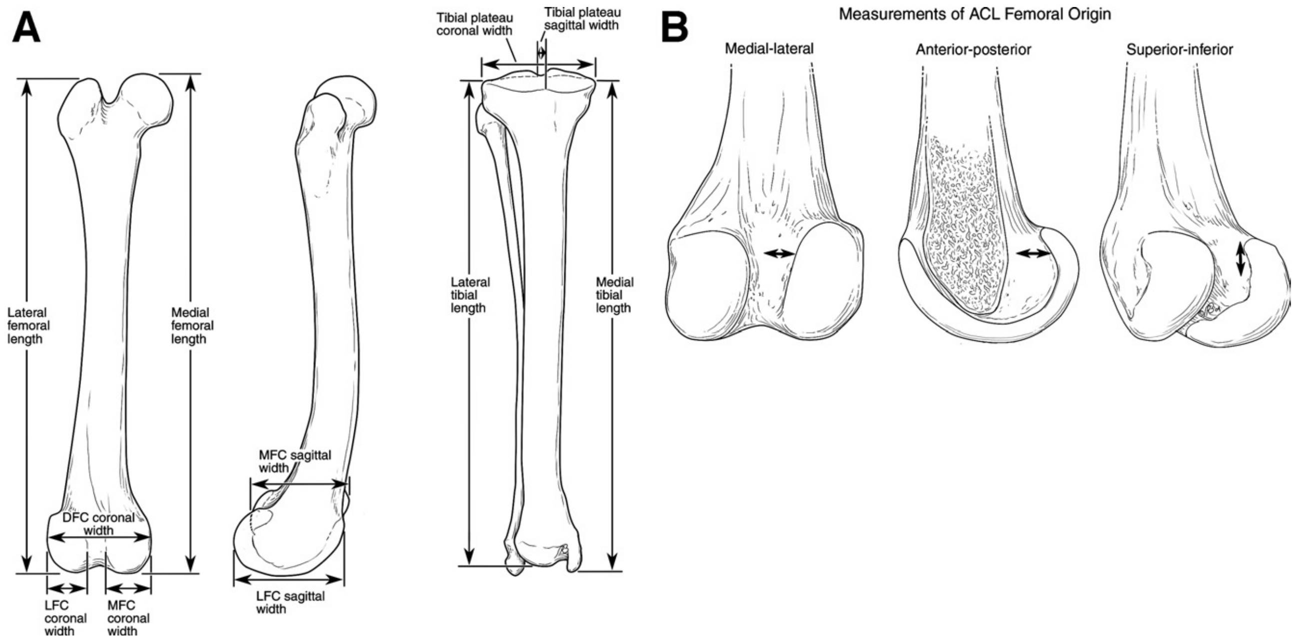

FIGURE 1. Gross measurements of specimen. (A) Femoral and tibial gross measurements made by digital micrometer. (LFC, lateral femoral condyle; MFC, medial femoral condyle.) (B) Measurements of center of femoral ACL origin relative to reproducible landmarks on lateral femoral condyle.