Volumetric Injury of the Physis During Single-Bundle Anterior Cruciate Ligament Reconstruction in Children: A 3-Dimensional Study Using Magnetic Resonance Imaging

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Purpose: To determine the volume of injury to the physis during anterior cruciate ligament (ACL) reconstruction in pediatric patients. **Methods:** Magnetic resonance imaging scans of 10 pediatric knees were converted into 3-dimensional models. Computer-aided design/computer-aided manufacturing software placed drill holes (6, 7, 8, and 9 mm in diameter) in these models, simulating tunnels used for ACL reconstruction. The software was used to calculate total physeal volume and volume of physis removed by the tunnel. The ratio of physeal volume removed to the total physeal volume was determined. **Results:** For 6-, 7-, 8-, and 9-mm-diameter drill holes, the mean percent of physeal volume removed/total physeal volume was 1.6%, 2.2%, 2.9%, and 3.8%, respectively, for the tibia and 2.4%, 3.2%, 4.2%, and 5.4%, respectively, for the femur. For all subjects, the volume removed was less than 7.0% for the tibia and 9.0% for the femur by use of drill holes from 6 to 9 mm. The tibial drill hole was centrally placed in all cases compared with a more peripheral drill hole placement of the femur. **Conclusions:** Drill hole placement during ACL reconstruction produces a zone of physeal injury. The overall volume of injury is relatively low, which reduces the risk of physeal arrest. With careful drill hole placement, the region of injury is central on the tibia, and the total volume of injury can be less than 5.0% of the physeal volume. For the femur, the total volume can be less than 5.0% as well. However, the region of injury is peripheral, which carries a higher risk of physeal arrest. **Clinical Relevance:** A better understanding of the relation between the ACL and physis may guide the placement of drill holes, which have a lower risk of producing physeal arrest.
Key Words: Anterior cruciate ligament—Anatomy—Pediatric—Adolescent—Physis—Knee injury—Skeletally immature.

The incidence of midsubstance anterior cruciate ligament (ACL) tears in children is unknown, although studies have provided evidence that this injury is now recognized more frequently in children and adolescents.[1-4] Historically, ACL reconstruction in children has not been recommended because of concerns about potential physeal injuries from placement of transphyseal drill holes. These physeal injuries can lead to premature physeal closure with subsequent leg length discrepancy and/or angular deformity.[5,6]

Recent studies of skeletally immature patients with ACL tears have shown that nonoperative treatment results in poor outcomes, especially in children who return to sports.[1,7,8] Because of the poor outcomes after ACL injury in young patients, some authors have advocated physeal-sparing techniques. These techniques may result in nonanatomic graft placement, and the long-term function of these grafts is unknown.[9-11]

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The authors report no conflict of interest.
Received September 2, 2008; accepted June 22, 2009.
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0749-8063/09/2512-8508$36.00/0
doi:10.1016/j.arthro.2009.06.023

Recent studies have developed algorithms for treating ACL injury in skeletally immature patients, which include surgical reconstruction in carefully selected patients.[3,10,12-15] Some of these studies have advocated the placement of standard ACL reconstruction drill holes in the tibia and femur, even in patients with open physes.[3,10]

Studies have suggested that the placement of drill holes across the physis can cause physeal arrest, although smaller drill holes and those in certain locations may have a lower risk of producing physeal injury.[16-18] Epidemiologic studies have also shown that ACL injury in children, though more common above age 12 years, also occurs in patients aged as young as 5 years.[4]

The purpose of this study was to use 3-dimensional (3D) computer models to drill tunnels simulating ACL reconstruction in skeletally immature subjects and assess the volume of physeal injury during drill hole placement on the proximal tibia and distal femur. We hypothesized that the quantified volume of physis removed during such repairs would be below 7% to 9%—the amount identified in the literature as the accepted threshold for physeal arrest.

METHODS

Institutional review board approval for the study was obtained. Ten knee magnetic resonance imaging (MRI) sequences of skeletally immature subjects were obtained for the study. Four of the subjects were male, with a mean age of 9.25 years, and six were female, with a mean age of 7.30 years. The total tibial and femoral physeal volume values, corresponding to each subject, ranged from 3,960 mm^3 to 11,290 mm^3 and are shown in Tables 1 and 2.

TABLE 1. *Subject, Age, Sex, and Total Tibial Physeal Volume*

Subject No.	Age (yr)	Sex	Total Tibial Physeal Volume
1	9	M	7,311 mm^3
2	8	F	7,633 mm^3
3	5	F	3,960 mm^3
4	10	M	8,445 mm^3
5	7	F	4,833 mm^3
6	8	F	6,035 mm^3
7	9	M	8,826 mm^3
8	6	F	2,615 mm^3
9	9	M	6,177 mm^3
10	10	F	11,290 mm^3

TABLE 2. *Subject, Age, Sex, and Total Femoral Physeal Volume*

Subject No.	Age (yr)	Sex	Total Femoral Physeal Volume
1	9	M	7,149 mm^3
2	8	F	8,702 mm^3
3	5	F	4,448 mm^3
4	10	M	7,279 mm^3
5	7	F	4,898 mm^3
6	8	F	6,978 mm^3
7	9	M	10,364 mm^3
8	6	F	3,087 mm^3
9	9	M	6,818 mm^3
10	10	F	11,126 mm^3

Patients were scanned on either a GE Signa LX 1.5-T scanner (GE Medical Systems, Milwaukee, WI), a Siemens Symphony 1.5-T scanner (Siemens AG, Erlangen, Germany), or an Hitachi Aries II 0.3-T scanner (Hitachi, Tokyo, Japan). All of these magnets allowed for adequate model generation to be used for the creation of 3D knee models with the physis. All of the images were obtained with the patient in the supine position with the knee in full extension and externally rotated at approximately 15°. T1-weighted spin-echo sagittal images (repetition time range, 400 to 800 milliseconds; echo time range, 7 to 20 milliseconds) were obtained in all patients. Proton-density and T2-weighted spin-echo or fast spin-echo images were also obtained in each patient. These images had a repetition time ranging from 3,000 to 6,000 milliseconds and echo time from 30 to 100 milliseconds. The slice thickness was 3.0 to 4.0 mm, and the gap width was 0.5 to 1.0 mm. The matrix size was 256 × 256. The T1-weighted and T2-weighted sagittal images were preferred for anatomic measurements. The images were downloaded to an independent workstation for analysis, and the sagittal sequences were digitized by use of photo capture software. The obtained *.dicom (Digital Imaging and Communications in Medicine) image files were imported into the imaging software Mimics, version 9.11 (Materialise, Ann Arbor, MI). Mimics allows the user to segregate different bone and soft tissue, based on separate luminosity thresholds, and create a 3D model. The low resolution of MRI scans often causes ambiguous boundaries between soft tissue and bone. The user must edit and manually segregate such tissues, especially those around the growth plate. This requires magnification to better see the contrasting tissues. The user must then individually color in the different tissues pixel by