Physeal Sparing Reconstruction of the Anterior Cruciate Ligament in Skeletally Immature Prepubescent Children and Adolescents

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Background: The management of anterior cruciate ligament injuries in skeletally immature patients is controversial. Conventional adult reconstruction techniques risk potential iatrogenic growth disturbance due to physeal damage. The purpose of this study was to evaluate the results of a physeal sparing, combined intra-articular and extra-articular reconstruction technique in prepubescent skeletally immature children.

Methods: Between 1980 and 2002, forty-four skeletally immature prepubescent children and adolescents who were in Tanner stage 1 or 2 (with a mean chronological age of 10.3 years) underwent physeal sparing, combined intra-articular and extra-articular reconstruction of the anterior cruciate ligament with use of an autogenous iliotibial band graft. Twenty-seven patients had additional meniscal surgery. Functional outcome, graft survival, radiographic outcome, and growth disturbance were evaluated at a mean of 5.3 years after surgery.

Results: Two patients underwent a revision reconstruction for graft failure at 4.7 and 8.3 years postoperatively. In the remaining forty-two patients, the mean International Knee Documentation subjective knee score (and standard deviation) was 96.7 ± 6.0 points, and the mean Lysholm knee score was 95.7 ± 6.7 points. The results of the Lachman examination for anterior cruciate ligament integrity was normal for twenty-three patients, nearly normal for eighteen patients, and abnormal for one patient. The results of the pivot-shift examination were normal for thirty-one patients and nearly normal for eleven patients. Four of the twenty-three patients who underwent concurrent meniscal repair had a repeat arthroscopic meniscal repair or partial meniscectomy. The mean growth in total height from the time of surgery to the final follow-up evaluation was 21.5 cm. No patient had an angular deformity measured radiographically or a discrepancy in the length of the lower extremities measured clinically.

Conclusions: Physeal sparing, combined intra-articular and extra-articular reconstruction of the anterior cruciate ligament with use of an autogenous iliotibial band graft in skeletally immature prepubescent children and adolescents provides excellent functional outcome with a low revision rate and a minimal risk of growth disturbance.

Levels of Evidence: Therapeutic Level IV. See Instructions to Authors for a complete description of levels of evidence.

Intrasubstance injuries of the anterior cruciate ligament in children and adolescents were once thought to be rare, with avulsion fractures of the tibial eminence considered to be the pediatric equivalent of an anterior cruciate ligament injury[1-4]. However, intrasubstance injuries of the anterior cruciate ligament in children and adolescents are being seen with greater frequency and have received increased attention. In clinical series of pediatric patients with acute traumatic hemarthrosis of the knee, anterior cruciate ligament injury has been reported to occur in 10% to 65% of such patients[5-10].

Controversy exists with regard to the management of anterior cruciate ligament injuries in patients with open physes. Nonoperative management of complete tears generally has a poor prognosis, with instability leading to further meniscal and chondral injury[11-17]. Conventional surgical reconstruction tech-

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niques risk iatrogenic growth disturbance because of physeal damage to the distal femoral physis or the proximal tibial physis, or both[18-23]. Surgical techniques to address anterior cruciate ligament insufficiency in skeletally immature patients include primary repair, extra-articular tenodesis, transphyseal reconstruction, partial transphyseal reconstruction, and physeal sparing reconstruction[10-12,14,24-46].

The management of these injuries in prepubescent children and adolescents is particularly vexing, given the poor prognosis with nonoperative management, the substantial amount of growth remaining, and the consequences of potential growth disturbance. The purpose of this study was to evaluate the results of a physeal sparing, combined intra-articular and extra-articular reconstruction technique in skeletally immature prepubescent children and adolescents. Our hypothesis was that this technique would yield a good functional outcome with minimal risk of growth disturbance.

Materials and Methods

Institutional review board approval and informed patient consent were obtained for this study. The study design is a retrospective case series. Patients returned for follow-up outcome analysis.

Between 1980 and 2002, fifty skeletally immature prepubescent patients underwent physeal sparing, combined intra-articular and extra-articular reconstruction of the anterior cruciate ligament with use of an autogenous iliotibial band graft performed by two surgeons (M.S.K. and L.J.M.). Six patients were unable to be located for follow-up, but forty-four (88%) had complete follow-up. Thus, the study population included forty-four patients (forty-four knees) who had reconstruction of the anterior cruciate ligament. The six patients lost to follow-up were similar to the study population in terms of age, gender, mechanism of injury, and associated injuries.

The study population included twenty-eight boys (64%) and sixteen girls (36%). The mean chronological age at the time of surgery was 10.3 years (range, 3.6 to 14.0 years). According to age-group, three patients were three to six years old, twenty-four were seven to ten years old, and seventeen were eleven to fourteen years old. A 3.6-year-old boy underwent anterior cruciate ligament reconstruction because of symptomatic knee instability due to congenital absence of the anterior cruciate ligament associated with proximal femoral focal deficiency. Skeletal age was determined by pediatric radiologists on an anteroposterior radiograph of the left hand and wrist with use of the atlas of Greulich and Pyle[47]. Despite the potential increased variance in the determination of skeletal age in young children, we believed that it was necessary to assess skeletal age to allow for comparisons with other studies. The mean skeletal age at the time of surgery was 10.1 years (range, 3.5 to 14.0 years). Biological age was determined according to the method of Tanner and Whitehouse (see Appendix)[48]. The Tanner stage was assessed by the patients and families on a questionnaire completed preoperatively and was confirmed by the surgeon at the time of surgery after the patient was placed under general anesthesia. Thirty-one patients were in Tanner stage 1, and thirteen patients were in Tanner stage 2. No patient in this study was in Tanner stage 3 or 4.

The mechanisms of injury included accidents that occurred during soccer (eight patients), football (seven), basketball (five), gymnastics (four), bicycling (four), free play (three), jumping on a trampoline (three), and during a dance, wrestling, lacrosse, field hockey, baseball, martial arts, and a fall from stairs (one patient each). The mean time-interval from the injury to surgery was 11.1 months (range, three to forty months). Five patients had undergone arthroscopic surgery prior to anterior cruciate ligament reconstruction for a partial lateral meniscectomy (two patients), lateral meniscal repair (one patient), and diagnostic arthroscopy (two patients). Three patients did not have a specific injury, but they had congenital absence of the anterior cruciate ligament associated with proximal femoral focal deficiency (two patients) or with fibular hemimelia (one patient). Two of those patients underwent anterior cruciate ligament reconstruction after limb-lengthening procedures, and one patient underwent reconstruction prior to limb-lengthening.

Patients were managed surgically if they had an associated meniscal injury requiring repair or if they had had failure of prior nonreconstructive management consisting of rehabilitation and functional bracing with recurrent episodes of instability and limited function. The duration of nonoperative management prior to reconstruction and the compliance with nonoperative management were not reliably recorded. Twenty-seven patients had an associated meniscal injury at the time of anterior cruciate ligament reconstruction involving the lateral meniscus (twenty-three patients) or the medial meniscus (four patients). Meniscal injury was treated with meniscal repair in twenty-three patients and with partial meniscectomy in four patients.

Functional outcome was assessed with use of questionnaires completed by the patients to determine the International Knee Documentation Committee (IKDC) subjective knee score[49] and the Lysholm knee score[50]. The IKDC subjective knee form is a validated region-specific outcome measure that consists of eighteen questions in the domains of symptoms, function during activities of daily living and sports, current function of the knee, and participation in work and/or sports[49]. An overall score of 0 to 100 points is calculated. The Lysholm knee scale is a condition-specific outcome measure that contains eight domains: limp, locking, pain, stair-climbing, support, instability, swelling, and squatting[50]. An overall score of 0 to 100 points is calculated, with 95 to 100 points indicating an excellent result; 84 to 94 points, a good result; 65 to 83 points, a fair result; and <65 points, a poor result. The objective examination included a comprehensive physical evaluation of the knee, with stability assessed with use of the Lachman and pivot-shift examinations as graded according to the IKDC criteria by two of the authors (M.S.K. and L.J.M.). Radiographic examination of the knee included weight-bearing anteroposterior, notch, lateral, and Merchant radiographs. Radiographic evidence of a growth disturbance

Fig. 1-A

Figs. 1-A through 1-H The technique of physeal sparing, combined intra-articular and extra-articular reconstruction of the anterior cruciate ligament with use of an autogenous iliotibial band graft. **Fig. 1-A** The iliotibial band is harvested through an oblique lateral knee incision.

was evaluated by a single observer and was assessed according to the integrity of the physes and the symmetry of the Harris lines. A radiographically important angular growth disturbance was considered to be any anatomic varus and/or valgus change of >5° from the findings on the preoperative radiographs. Clinically, growth disturbance was assessed with use of blocks to level the top of the iliac crests with the patient standing with the knees extended and with measurement of the true lower-extremity length from the anterior superior iliac spine to the medial malleolus. A clinically important

Fig. 1-B

The iliotibial band graft is detached proximally, left attached distally, and dissected free from the lateral patellar retinaculum.

Fig. 1-C

The iliotibial band graft is brought through the knee with use of a full-length clamp placed from the anteromedial portal through the over-the-top position into the lateral incision.

limb-length discrepancy was considered to be >2 cm, as measured with either method.

Surgical Technique

The surgical technique consists of arthroscopically assisted, physeal sparing, combined intra-articular and extra-articular reconstruction of the anterior cruciate ligament with use of an autogenous iliotibial band graft. This procedure is a modification of the combined intra-articular and extra-articular reconstruction described by MacIntosh and Darby[51]. Modifications include application in skeletally immature patients, arthroscopic assistance, graft fixation, and accelerated rehabilitation.

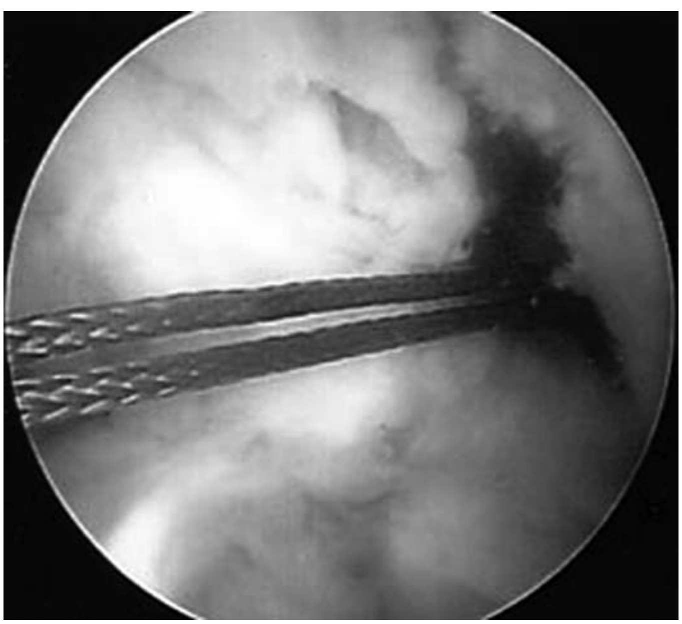

Fig. 1-D

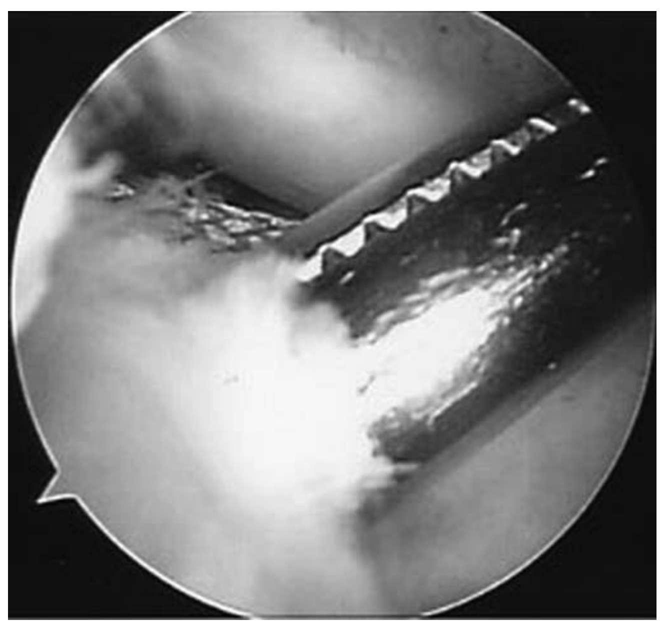

Fig. 1-E

Fig. 1-D The graft is then brought through the over-the-top position. **Fig. 1-E** A clamp is placed from the proximal medial incision in the leg under the intermeniscal ligament, and a groove is made in the anteromedial tibial epiphysis with use of a rasp.

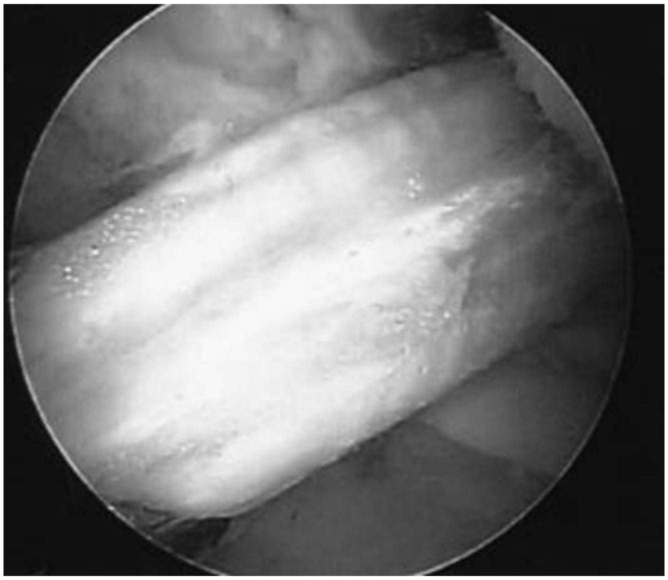

Fig. 1-F
The graft is brought through the knee in the over-the-top position and under the intermeniscal ligament.

The procedure is performed with the patient under general anesthesia as an overnight observation procedure. The child is positioned supine on the operating table with a pneumatic tourniquet about the proximal aspect of the thigh, which is used routinely. With the patient under anesthesia, he or she is examined to confirm anterior cruciate ligament insufficiency. An incision of approximately 6 cm is made obliquely from the lateral joint line to the superior border of the iliotibial band (Fig. 1-A). Proximally, the iliotibial band is separated from the subcutaneous tissue with use of a periosteal elevator under the skin of the lateral part of the thigh. The anterior and posterior borders of the iliotibial band are incised, and the incisions are carried proximally under the skin with use of a curved meniscotome. The iliotibial band is detached proximally under the skin with use of a curved meniscotome or an open tendon stripper. The iliotibial band is left attached distally at Gerdy's tubercle. Dissection is performed distally to separate the iliotibial band from the joint capsule and from the lateral patellar retinaculum (Fig. 1-B). The free proximal end of the iliotibial band is then tubularized with use of a whipstitch with a number-5 Ethibond suture (Ethicon, Johnson and Johnson, Somerville, New Jersey). Arthroscopy of the knee is then performed through standard anterolateral and anteromedial portals. Management of meniscal injury or chondral injury is performed, if present. The anterior cruciate ligament remnant is excised. The over-the-top position on the femur and the over-the-front position under the intermeniscal ligament are identified. A minimal notchplasty is performed to avoid iatrogenic injury to the perichondrial ring of the distal femoral physis, which is in close proximity to the over-the-top position[52]. The free end of the iliotibial band graft is brought through the over-the-top position with use of a full-length clamp (Figs. 1-C and 1-D) or a two-incision rear-entry guide and out the anteromedial portal. A second incision of approximately 4.5 cm is made over the proximal medial aspect of the

Fig. 1-G
The graft is brought out of the proximal medial incision in the leg. It is sutured to the intermuscular septum and periosteum of the lateral femoral condyle through the lateral knee incision and it is sutured in a trough to the periosteum of the proximal medial tibial metaphysis.

tibia in the region of the pes anserinus. Dissection is carried through the subcutaneous tissue to the periosteum. A curved clamp is placed from this incision into the joint under the intermeniscal ligament (Fig. 1-E). A small groove is made in the anteromedial aspect of the proximal tibial epiphysis under the intermeniscal ligament with use of a curved rat-tail rasp to bring the tibial graft placement more posterior. The free end of the graft is then brought through the joint (Fig. 1-F), under the intermeniscal ligament in the anteromedial epiphyseal groove, and out the medial tibial incision (Fig. 1-G). The graft is fixed on the femoral side through the lateral incision with the knee at 90° of flexion and 15° of external rotation with use of mattress sutures to the lateral femoral condyle at the insertion of the lateral intermuscular septum to effect an extra-articular reconstruction. The tibial side is then fixed through the medial incision with the knee flexed 20° and tension applied to the graft. A periosteal incision is made distal to the proximal tibial physis as checked with fluoroscopic imaging. A trough is made in the proximal medial tibial metaphyseal cortex, and the graft is sutured to the periosteum at the rough margins with mattress sutures (Fig. 1-H).

Postoperatively, the patient is maintained with touch-down weight-bearing for six weeks. Immediate mobilization is performed, from 0° to 90° for the first two weeks, followed by progression to a full range of motion. Continuous passive motion from 0° to 90° is used for the first two weeks postoperatively to initiate motion and overcome the anxiety associated with postoperative movement in these young children. A protective hinged knee brace is used for six weeks postoperatively with motion limits of 0° to 90° for the first two weeks. Progressive rehabilitation consists of range-of motion exercises, patellar mobilization, electrical stimulation, pool therapy (if available), proprioception exercises, and closed-chain strengthening exercises during the first three months postoperatively followed by straight-line jogging, plyometric exercises, sport cord exercises, and sport-specific exercises. Return to full activity, including sports that involve cutting, is usually allowed at six months postoperatively. A custom-made functional knee brace is used routinely during cutting and pivoting activities for the first two years after the return to sports. Compliance with bracing was not formally assessed.

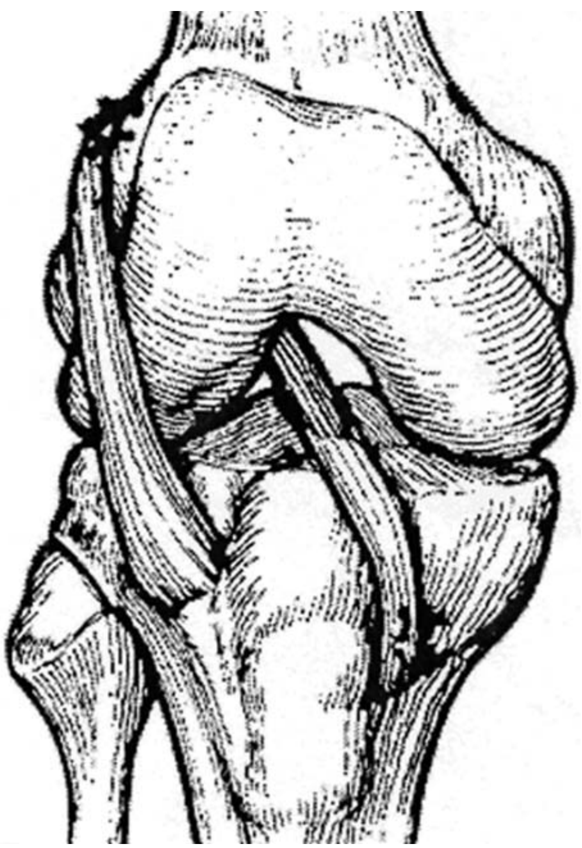

Fig. 1-H
Schematic appearance of a combined intra-articular and extra-articular reconstruction.

Results

The mean postoperative duration of follow-up was 5.3 years (range, 2.0 to 15.1 years). The mean duration of the operation was 101 minutes (range, sixty to 140 minutes), and the mean tourniquet time was seventy-two minutes (range, forty-three to 109 minutes). There were no surgical complications, such as infection, failure of graft harvest, or arthrofibrosis. Two patients (4.5%) underwent a revision anterior cruciate ligament reconstruction for graft failure at 4.7 and 8.3 years postoperatively. Both patients had a reinjury and were participating in cutting and pivoting sports. Both had midsubstance rupture of the iliotibial band graft. The grafts appeared well incorporated at the femoral and tibial insertions. Four patients who underwent concurrent meniscal repair during anterior cruciate ligament reconstruction had repeat arthroscopic meniscal repair or partial meniscectomy.

For the remaining forty-two patients without revision anterior cruciate ligament repair, the mean IKDC subjective knee score (and standard deviation) was 96.7 ± 6.0 points (range, 88.5 to 100 points) and the mean Lysholm knee score was 95.7 ± 6.7 points (range, 74 to 100 points). All patients, other than the three patients with congenital limb deficiencies, had returned to cutting or pivoting sports. According to the IKDC criteria, the findings of the Lachman examination were normal for twenty-three patients, nearly normal for eighteen patients, and abnormal for one patient. The results of the pivot-shift examination were normal for thirty-one patients and nearly normal for eleven patients. The mean growth in total height from the time of surgery to the final follow-up examination was 21.5 cm (range, 9.5 to 118.5 cm). It should be noted that total height is a combination of trunk and lower extremity lengths. No patient had a substantial angular deformity measured radiographically. No patient had a substantial limb-length discrepancy measured clinically.

Discussion

There is controversy regarding the management of anterior cruciate ligament injuries in patients with open physes. Nonoperative management, consisting of rehabilitation, bracing, and activity restriction, is often recommended in order to temporize for later conventional reconstruction near skeletal maturity. Nonoperative management of partial tears may be successful in patients with a lower-grade partial tear, in younger children, and in patients with a tear that predominantly involves the anteromedial bundle[53]. However, nonoperative management of complete tears generally has a poor prognosis, with recurrent instability leading to further meniscal and chondral injury[11-17]. Graf et al.[12], Janarv et al.[13], and Mizuta et al.[16] reported instability symptoms, subsequent meniscal tears, a decreased activity level, and a need for anterior cruciate ligament reconstruction in skeletally immature patients treated nonoperatively. Similarly, when comparing the results of operative and nonoperative management of complete anterior cruciate ligament injuries in adolescents, McCarroll et al.[14] and Pressman et al.[17] found that those managed with anterior cruciate ligament reconstruction had less instability, higher levels of activity and return to sports, and lower rates of subsequent reinjury and meniscal tears. These subsequent meniscal and chondral injuries have important implications in terms of the long-term prognosis for the knee and the risk of degenerative joint disease. In addition, compliance with activity restriction is often problematic in the pediatric athlete and is unappealing to the patient's family.

Conventional surgical reconstruction techniques risk potential iatrogenic growth disturbance due to physeal damage. Cases of growth disturbance have been reported in animal models[18-20]. Animal models have demonstrated mixed results regarding growth disturbances from soft-tissue grafts across the physes. In a canine model with iliotibial band grafts through 0.16-in (4-mm) tunnels, Stadelmaier et al. found no evidence of growth arrest in four animals with a soft-tissue graft across the physis, whereas four animals with drill-holes and no graft demonstrated physeal arrest[54]. In a rabbit model with use of a semitendinosus graft through 2-mm tunnels, Guzzanti et al. noted cases of growth disturbance; however, they were not common[18]. Examining the effect of a tensioned soft-tissue graft across the physis, Edwards et al. found a substantial rate of deformity[19]. In a canine model with an iliotibial band graft tensioned to 80 N, those investigators found increases, compared with the nonoperatively treated control limb, in distal femoral valgus deformity and proximal tibial varus deformity despite no evidence of an osseous bar. Similarly, Houle et al. reported growth disturbance after use of a tensioned tendon graft in a bone tunnel across the rabbit physis[20]. However, the tension applied to the graft in the studies by Edwards et al. and Houle et al. may have been correspondingly excessive for their animal models, thus resulting in growth disturbance.

Clinical reports of growth deformity after anterior cruciate ligament reconstruction are unusual. In a series of twenty-four skeletally immature patients who had reconstruction with transphyseal semitendinosis and gracilis grafts, Lipscomb and Anderson described one patient who had 20 mm of shortening[21]. This was associated with staple fixation of a graft across the physis. Koman and Sanders reported the case of a patient who had a distal femoral valgus deformity requiring an osteotomy and contralateral epiphyseodesis after transphyseal reconstruction with a doubled semitendinosus graft[22]. This deformity was also associated with fixation across the distal femoral physis. In a study based on a survey of experts in the management of anterior cruciate ligament injuries in pediatric patients, Kocher et al. reported the cases of an additional fifteen patients who had growth disturbances, including eight patients who had a distal femoral valgus deformity with an arrest of the lateral distal femoral physis; three patients who had tibial recurvatum with an arrest of the tibial tubercle apophysis; two patients who had genu valgum, without arrest, due to a lateral extra-articular tether; and two patients who had a leg-length discrepancy (one who had shortening and one who had overgrowth)[23]. Associated factors included fixation hardware across the lateral distal femoral physis in three patients, bone plugs of a patellar tendon graft across the distal femoral physis in three patients, large (12-mm) tunnels in two patients, lateral extra-articular tenodesis in two patients, fixation hardware across the tibial tubercle apophysis in two patients, and suturing near the tibial tubercle apophysis in one patient.

Surgical techniques to address anterior cruciate ligament insufficiency in skeletally immature patients include primary repair, extra-articular tenodesis, transphyseal reconstruction, partial transphyseal reconstruction, and physeal sparing reconstruction. Primary ligament repair[24,25] and extra-articular tenodesis alone[12,14] in children and adolescents have had poor results, similar to the outcomes seen in adults. Transphyseal reconstructions with tunnels that violate both the distal femoral and proximal tibial physes have been performed with hamstrings autograft, patellar tendon autograft, and allograft tissue[11,14,26-35]. Partial transphyseal reconstructions damage only one physis with a tunnel through the proximal tibial physis and over-the-top positioning on the femur or with a tunnel through the distal femoral physis with an epiphyseal tunnel in the tibia[36,37,39,40]. A variety of physeal sparing reconstructions to avoid tunnels across either the distal femoral physis or the proximal tibial physis have been described[10,38,41-46].

The management of anterior cruciate ligament injuries in prepubescent children and adolescents is particularly vexing, given the large amount of growth remaining. Most clinical series of skeletally immature patients with anterior cruciate ligament injuries have involved adolescent patients, not prepubescent patients. The consequences of growth disturbance in the prepubescent age-group are substantial, requiring major limb reconstruction with osteotomy and/or limb-lengthening. However, anterior cruciate ligament insufficiency must be adequately corrected with reconstructive techniques in order to avoid subsequent meniscal and chondral injuries, which also have substantial consequences. Case reports or small clinical series of patients in this age-group managed with physeal sparing techniques to provide a stable knee while avoiding violation of the physes have been described. DeLee and Curtis[43] used a portion of the patellar tendon without drill-holes. Brief[42] and Parker et al.[46] used hamstrings tendons, left at-

Fig. 2
A STIR (short-tau-inversion-recovery) sagittal magnetic resonance imaging scan of an iliotibial band graft at 3.4 years after reconstruction.

tached distally, that were brought through the knee under the intermeniscal ligament on the tibial side and the over-the-top position on the femoral side. More recently, physeal sparing reconstruction techniques with use of hamstrings tendon in prepubescent patients were described by Guzzanti et al.[38], who used an epiphyseal tibial tunnel with distal femoral epiphyseal fixation, and by Anderson[41], who used epiphyseal tibial and femoral tunnels.

In the present study, we report the results of a physeal sparing, combined intra-articular and extra-articular reconstruction technique with use of an autogenous iliotibial band graft in prepubescent, skeletally immature children (Fig. 2). In forty-four children who were followed for a mean of 5.3 years, this technique provided excellent functional outcome with a low revision rate and no growth disturbance. Our rationale for the utilization of this technique is to provide knee stability and improve function while avoiding the risk of iatrogenic growth disturbance in prepubescent, skeletally immature patients with complete intrasubstance injuries of the anterior cruciate ligament who have repairable meniscal tears or who have had failure of nonoperative treatment. This series included three prepubescent patients with congenital insufficiency of the anterior cruciate ligament associated with longitudinal deficiency of the lower extremities. Our indications for reconstruction of the anterior cruciate ligament in a child with congenital deficiency of a limb are symptomatic instability that substantially limits function and is uncontrolled by bracing. In older, skeletally immature adolescents (Tanner stage 3 and 4) with an anterior cruciate ligament injury, we perform transphyseal reconstruction with a quadrupled hamstrings tendon graft with fixation away from the physes. However, in our opinion, the consequences of potential iatrogenic growth disturbance caused by transphyseal reconstruction in prepubescent children are prohibitive and, therefore, we perform the physeal sparing reconstruction. This procedure is nonanatomic as the graft is in the over-the-top position on the femur and under the intermeniscal ligament on the tibia. Although nonanatomic, it provided for a stable knee with excellent function in children who returned to sports that involved cutting and pivoting. We counsel parents that this may be a temporizing procedure for later conventional reconstruction near skeletal maturity; however, this technique has functioned as the definitive reconstruction for most of our patients.

Appendix

eA A table showing the Tanner staging system is available with the electronic versions of this article, on our web site at jbjs.org (go to the article citation and click on "Supplementary Material") and on our quarterly CD-ROM (call our subscription department, at 781-449-9780, to order the CD-ROM). ■

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References

1. Kocher MS, Micheli LJ, Gerbino P, Hresko MT. Tibial eminence fractures in children: prevalence of meniscal entrapment. Am J Sports Med. 2003;31:404-7.

2. Rang M. Children's fractures. 2nd ed. Philadelphia: Lippincott; 1983.

3. Kocher MS, Foreman ES, Micheli LJ. Laxity and functional outcome after arthroscopic reduction and internal fixation of displaced tibial spine fractures in children. Arthroscopy. 2003;19:1085-90.

4. Kocher MS, Mandiga R, Klingele K, Bley L, Micheli LJ. Anterior cruciate ligament injury versus tibial spine fracture in the skeletally immature knee: a comparison of skeletal maturation and notch width index. J Pediatr Orthop. 2004;24:185-8.

5. Eiskjaer S, Larsen ST, Schmidt MB. The significance of hemarthrosis of the knee in children. Arch Orthop Trauma Surg. 1988;107:96-8.

6. Kloeppel-Wirth S, Koltai JL, Dittmer H. Significance of arthroscopy in children with knee joint injuries. Eur J Pediatr Surg. 1992;2:169-72.

7. Kocher MS, DiCanzio J, Zurakowski D, Micheli LJ. Diagnostic performance of clinical examination and selective magnetic resonance imaging in the evaluation of intraarticular knee disorders in children and adolescents. Am J Sports Med. 2001;29:292-6.

8. Luhmann SJ. Acute traumatic knee effusions in children and adolescents. J Pediatr Orthop. 2003;23:199-202.

9. Stanitski CL, Harvell JC, Fu F. Observations on acute knee hemarthrosis in children and adolescents. J Pediatr Orthop. 1993;13:506-10.

10. Vahasarja V, Kinnuen P, Serlo W. Arthroscopy of the acute traumatic knee in children. Prospective study of 138 cases. Acta Orthop Scand. 1993;64:580-2.

11. Aichroth PM, Patel DV, Zorrilla P. The natural history and treatment of rupture of the anterior cruciate ligament in children and adolescents. A prospective review. J Bone Joint Surg Br. 2002;84:38-41.

12. Graf BK, Lange RH, Fujisaki CK, Landry GL, Saluja RK. Anterior cruciate ligament tears in skeletally immature patients: meniscal pathology at presentation and after attempted conservative treatment. Arthroscopy. 1992;8:229-33.

13. Janarv PM, Nystrom A, Werner S, Hirsch G. Anterior cruciate ligament injuries in skeletally immature patients. J Pediatr Orthop. 1996;16:673-7.

14. McCarroll JR, Rettig AC, Shelbourne KD. Anterior cruciate ligament injuries in the young athlete with open physes. Am J Sports Med. 1988;16:44-7.

15. Millett PJ, Willis AA, Warren RF. Associated injuries in pediatric and adolescent anterior cruciate ligament tears: does a delay in treatment increase the risk of meniscal tear? Arthroscopy. 2002;18:955-9.

16. Mizuta H, Kubota K, Shiraishi M, Otsuka Y, Nagamoto N, Takagi K. The conservative treatment of complete tears of the anterior cruciate ligament in skeletally immature patients. J Bone Joint Surg Br. 1995;77:890-4.

17. Pressman AE, Letts RM, Jarvis JG. Anterior cruciate ligament tears in children: an analysis of operative versus nonoperative treatment. J Pediatr Orthop. 1997;17:505-11.

18. Guzzanti V, Falciglia F, Gigante A, Fabbriciani C. The effect of intra-articular ACL reconstruction on the growth plates of rabbits. J Bone Joint Surg Br. 1994;76:960-3.

19. Edwards TB, Greene CC, Baratta RV, Zieske A, Willis RB. The effect of placing a tensioned graft across open growth plates. A gross and histologic analysis. J Bone Joint Surg Am. 2001;83:725-34.

20. Houle JB, Letts M, Yang J. Effects of a tensioned tendon graft in a bone tunnel across the rabbit physis. Clin Orthop Relat Res. 2001;391:275-81.

21. Lipscomb AB, Anderson AF. Tears of the anterior cruciate ligament in adolescents. J Bone Joint Surg Am. 1986;68:19-28.

22. Koman JD, Sanders JO. Valgus deformity after reconstruction of the anterior cruciate ligament in a skeletally immature patient. A case report. J Bone Joint Surg Am. 1999;81:711-5.

23. Kocher MS, Saxon HS, Hovis WD, Hawkins RJ. Management and complications of anterior cruciate ligament injuries in skeletally immature patients: survey of the Herodicus Society and The ACL Study Group. J Pediatr Orthop. 2002;22:452-7.

24. Clanton TO, DeLee JC, Sanders B, Neidre A. Knee ligament injuries in children. J Bone Joint Surg Am. 1979;61:1195-201.

25. Engebretsen L, Svenningsen S, Benum P. Poor results of anterior cruciate ligament repair in adolescence. Acta Orthop Scand. 1988;59:684-6.

26. Angel KR, Hall DJ. Anterior cruciate ligament injury in children and adolescents. Arthroscopy. 1989;5:197-200.

27. Aronowitz ER, Ganley TJ, Goode JR, Gregg JR, Meyer JS. Anterior cruciate ligament reconstruction in adolescents with open physes. Am J Sports Med. 2000;28:168-75.

28. Edwards PH, Grana WA. Anterior cruciate ligament reconstruction in the immature athlete: long-term results of intra-articular reconstruction. Am J Knee Surg. 2001;14:232-7.

29. Fuchs R, Wheatley W, Uribe JW, Hechtman KS, Zvijac JE, Schurhoff MR. Intra-articular anterior cruciate ligament reconstruction using patellar tendon allograft in the skeletally immature patient. Arthroscopy. 2002;18:824-8.

30. Matava MJ, Siegel MG. Arthroscopic reconstruction of the ACL with semitendinosis-gracilis autograft in skeletally immature adolescent patients. Am J Knee Surg. 1997;10:60-9.

31. McCarroll JR, Shelbourne KD, Porter DA, Rettig AC, Murray S. Patellar tendon graft reconstruction for midsubstance anterior cruciate ligament rupture in junior high school athletes. An algorithm for management. Am J Sports Med. 1994; 22:478-84.

32. Shelbourne KD, Gray T, Wiley BV. Results of transphyseal anterior cruciate ligament reconstruction using patellar tendon autograft in tanner stage 3 or 4 adolescents with clearly open growth plates. Am J Sports Med. 2004;32:1218-22.

33. Simonian PT, Metcalf MH, Larson RV. Anterior cruciate ligament injuries in the skeletally immature patient. Am J Orthop. 1999;28:624-8.

34. Stanitski CL. Anterior cruciate ligament injury in the skeletally immature patient: diagnosis and treatment. J Am Acad Orthop Surg. 1995;3:146-58.

35. Volpi P, Galli M, Bait C, Pozzoni R. Surgical treatment of anterior cruciate ligament injuries in adolescents using double-looped semitendinosis and gracilis tendons: supraepiphysary femoral and tibial fixation. Arthroscopy. 2004; 20:447-9.

36. Andrews M, Noyes FR, Barber-Westin SD. Anterior cruciate ligament allograft reconstruction in the skeletally immature athlete. Am J Sports Med. 1994;22:48-54.

37. Bisson LJ, Wickiewicz T, Levinson M, Warren R. ACL reconstruction in children with open physes. Orthopedics. 1998;21:659-63.

38. Guzzanti V, Falciglia F, Stanitski CL. Physeal-sparing intraarticular anterior cruciate ligament reconstruction in preadolescents. Am J Sports Med. 2003;31: 949-53.

39. Guzzanti V, Falciglia F, Stanitski CL. Preoperative evaluation and anterior cruciate ligament reconstruction technique for skeletally immature patients in Tanner stages 2 and 3. Am J Sports Med. 2003;31:941-8.

40. Lo IK, Kirkley A, Fowler PJ, Miniaci A. The outcome of operatively treated anterior cruciate ligament disruptions in the skeletally immature child. Arthroscopy. 1997;13:627-34.

41. Anderson AF. Transepiphyseal replacement of the anterior cruciate ligament in skeletally immature patients. A preliminary report. J Bone Joint Surg Am. 2003;85:1255-63.

42. Brief LP. Anterior cruciate ligament reconstruction without drill holes. Arthroscopy. 1991;7:350-7.

43. DeLee JC, Curtis R. Anterior cruciate ligament insufficiency in children. Clin Orthop Relat Res. 1983;172:112-8.

44. Kim SH, Ha KI, Ahn JH, Chang DK. Anterior cruciate ligament reconstruction in the young patient without violation of the epiphyseal plate. Arthroscopy. 1999; 15:792-5.

45. Micheli LJ, Rask B, Gerberg L. Anterior cruciate ligament reconstruction in patients who are prepubescent. Clin Orthop Relat Res. 1999;364:40-7.

46. Parker AW, Drez D Jr, Cooper JL. Anterior cruciate ligament injuries in patients with open physes. Am J Sports Med. 1994;22:44-7.

47. Greulich WW, Pyle SI. Radiographic atlas of skeletal development of the hand and wrist. 2nd ed. Stanford: Stanford University Press; 1959.

48. Tanner JM, Whitehouse RH. Clinical longitudinal standards for height, weight, height velocity, and stages of puberty. Arch Dis Child. 1976;51:170-9.

49. Irrgang JJ, Anderson AF, Boland AL, Harner CD, Kurosaka M, Neyret P, Richmond JC, Shelborne KD. Development and validation of the international knee documentation committee subjective knee form. Am J Sports Med. 2001;29:600-13.

50. Lysholm J, Gillquist J. Evaluation of knee ligament surgery results with special emphasis on use of a scoring scale. Am J Sports Med. 1982;10:150-4.

51. MacIntosh DL, Darby TA. Lateral substitution reconstruction [abstract]. In: Proceedings and reports of universities, colleges, councils and associations. J Bone Joint Surg Br. 1976;58:142.

52. Behr CT, Potter HG, Paletta GA Jr. The relationship of the femoral origin of the anterior cruciate ligament and the distal femoral physeal plate in the skeletally immature knee. An anatomic study. Am J Sports Med. 2001;29:781-7.

53. Kocher MS, Micheli LJ, Zurakowski D, Luke A. Partial tears of the anterior cruciate ligament in children and adolescents. Am J Sports Med. 2002;30:697-703.

54. Stadelmaier DM, Arnoczky SP, Dodds J, Ross H. The effect of drilling and soft tissue grafting across open growth plates. A histologic study. Am J Sports Med. 1995;23:431-5.