Transphyseal Anterior Cruciate Ligament Reconstruction in Skeletally Immature Pubescent Adolescents

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Background: Management of anterior cruciate ligament injuries in skeletally immature patients is controversial. Conventional surgical reconstruction techniques for adults can cause iatrogenic growth disturbance due to physeal damage in children. The purpose of this study was to evaluate the results of a transphyseal reconstruction technique in pubescent but skeletally immature adolescents.

Methods: Between 1996 and 2004, sixty-one knees in fifty-nine skeletally immature pubescent adolescents (Tanner stage 3) with a mean chronological age of 14.7 years (range, 11.6 to 16.9 years) underwent transphyseal reconstruction of the anterior cruciate ligament with use of an autogenous quadrupled hamstrings-tendon graft and metaphyseal fixation. Thirty-one knees had additional meniscal surgery. The functional outcome, graft survival, radiographic outcome, and any growth disturbance were evaluated at a mean of 3.6 years (range, 2.0 to 10.2 years) after the surgery.

Results: Two patients (3%) underwent revision anterior cruciate ligament reconstruction because of graft failure at fourteen and twenty-one months postoperatively. For the remaining fifty-nine knees, the mean International Knee Documentation Committee subjective knee score (and standard deviation) was 89.5 ± 10.2 points and the mean Lysholm knee score was 91.2 ± 10.7 points. The result of the Lachman examination was normal in fifty-one knees and nearly normal in eight; it was not abnormal or severely abnormal in any knee. The result of the pivot-shift examination was normal in fifty-six knees and nearly normal in three knees; it also was not abnormal or severely abnormal in any knee. The mean increase in total height was 8.2 cm (range, 1.2 to 25.4 cm) from the time of surgery to the time of final follow-up. No angular deformities of the lower extremity were measured radiographically, and no lower-extremity length discrepancies were measured clinically. Complications included three cases of avulsion requiring manipulation with the patient under anesthesia.

Conclusions: Transphyseal reconstruction of the anterior cruciate ligament with use of an autogenous quadrupled hamstrings-tendon graft and metaphyseal fixation in skeletally immature pubescent adolescents provides an excellent functional outcome with a low revision rate and a minimal risk of growth disturbance.

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

Intrasubstance anterior cruciate ligament injuries in children and adolescents were once thought to be rare, with tibial eminence avulsion fractures considered to be the pediatric equivalent of an anterior cruciate ligament injury. However, intrasubstance anterior cruciate ligament injuries in children and adolescents are being seen with more frequency and have recently received increased attention. In clinical series of immature patients with acute traumatic hemarthrosis of the knee, the prevalence of anterior cruciate ligament injury was reported to be 10% to 65%.

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There is controversy regarding the management of anterior cruciate ligament injuries in patients with open physes. Nonoperative management of complete tears generally has a poor result, with instability leading to further meniscal and chondral injury\(^1\). Conventional surgical reconstruction techniques used in adults can cause iatrogenic growth disturbance due to damage to the distal femoral physe and/or the proximal tibial physe in children\(^2\). Surgical techniques to address anterior cruciate ligament insufficiency in skeletally immature patients include primary ligament repair, extra-articular tenodesis, transphyseal reconstruction, partial transphyseal reconstruction, and physeal-sparing reconstruction\(^3\).

The purpose of this study was to evaluate the results of a transphyseal technique for reconstruction of the anterior cruciate ligament in skeletally immature pubescent adolescents. Our hypothesis was that this technique would yield a good functional outcome with minimal risk of growth disturbance because the reconstruction is anatomic, the graft traversing the physe consists of soft tissue, and the fixation is distant from the physe.

Materials and Methods

The approval of our institutional review board and informed consent from the patients were obtained for this study. The study design is a retrospective case series. Patients returned for a follow-up outcome analysis.

Between 1996 and 2004, two surgeons (M.S.K. and L.J.M.) performed transphyseal reconstruction of the anterior cruciate ligament with use of an autogenous quadrupled hamstrings-tendon graft with metaphyseal fixation in eighty-seven knees in eighty-five skeletally immature pubescent patients. Twenty-two patients could not be located for follow-up, and four patients refused to participate in the study. Thus, the study population included fifty-nine patients treated with a total of sixty-one anterior cruciate ligament reconstructions (a follow-up rate of 70%). The twenty-six patients who were 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-three boys (35%) and thirty-six girls (65%). The mean chronological age at the time of surgery was 14.7 years (range, 11.6 to 16.9 years). Five knees were in patients between eleven and twelve years of age, thirty-five were in patients between thirteen and fourteen years of age, and twenty-one were in patients between fifteen and seventeen years of age. Skeletal age was determined by pediatric radiologists from an anteroposterior radiograph of the left hand and wrist with use of the Greulich and Pyle atlas\(^4\). The mean skeletal age at the time of surgery was 14.4 years (range, 12.0 to 15.5 years). The biological age was determined with the method of Tanner and Whitehouse\(^5\) (see Appendix). The patients and families self-reported the patient’s Tanner stage on a questionnaire preoperatively, and the Tanner stage was confirmed by the surgeon at the time of surgery, after induction of general anesthesia. All fifty-nine patients included in this study were in Tanner stage 3 according to their own assessment, whereas fifty-seven were in Tanner stage 3 and two were in Tanner stage 4 according to the surgeon’s assessment (agreement, 97%). No patients who, according to their own assessment, were prepubescent (Tanner stage 1 or 2), an older adolescent (Tanner stage 4), or a skeletally mature adolescent (Tanner stage 5) were included in this study.

The activities in which the patients were participating at the time of injury included soccer (twenty-two knees), football (eight), skiing (six), basketball (five), free play (four), jumping on a trampoline (three), track and field (two), lacrosse (two), ballet (two), cheerleading (two), volleyball (one), baseball (one), softball (one), wrestling (one), and water tubing (one). The mean time-interval from the injury to the surgery was 3.8 months (range, one-half to twenty-four months). Prior to the reconstruction of the anterior cruciate ligament, three patients had undergone arthroscopic surgery, for repair of medial and lateral meniscal tears (one patient), repair of a medial meniscal tear (one), or diagnosis only (one). At the time of the reconstruction of the anterior cruciate ligament, thirty-one knees had an associated meniscal injury, which involved the lateral meniscus (twenty-one knees), the medial meniscus (six), or both the lateral and the medial meniscus (four). The meniscal injury was treated with a meniscal repair in seventeen knees and with a partial meniscectomy in fourteen knees.

The functional outcome was assessed with use of the International Knee Documentation Committee (IKDC) subjective knee score\(^6\) and Lysholm knee score\(^7\) questionnaires, which were completed by the patients. 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\(^8\). 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, use of supports, instability, swelling, and squatting\(^9\). An overall score of 0 to 100 points is calculated, with 95 to 100 points graded as an excellent result; 84 to 94 points, a good result; 65 to 83 points, a fair result; and <65 points, a poor result. Objective examination included a comprehensive physical examination of the knee, with knee stability assessed with use of the Lachman and pivot-shift examinations and graded according to the IKDC criteria by two of us (M.S.K. and L.J.M.).

Weight-bearing anteroposterior, notch, lateral, and Merchant radiographs of the knee were made. Growth disturbance was evaluated radiographically by a single observer (B.J.Z.) according to the integrity of the physes and the symmetry of the Harris lines. A relevant angular growth disturbance, as seen radiographically, was considered to be any anatomic varus or valgus change of >5° compared with the measurement on preoperative radiographs. Clinical limb-length growth disturbance was assessed with use of blocks to level the tops of the iliac crests with the patient standing with the knees extended and by measurement of the true length of the lower extremities from the anterior superior iliac spine to the medial malleolus. A clinically relevant limb-length
discrepancy was considered to be >2 cm as measured with either method.

**Surgical Technique**
The surgical technique consisted of arthroscopically assisted transphyseal reconstruction of the anterior cruciate ligament with use of an autogenous quadrupled hamstrings-tendon graft with metaphyseal fixation.

The procedure is performed with the patient under general anesthesia. The patient is positioned supine on the operating table with a pneumatic tourniquet about the proximal aspect of the thigh. After induction of the anesthesia, he or she is examined to confirm the insufficiency of the anterior cruciate ligament. An incision of approximately 2 to 3 cm is made under tourniquet control over the proximal-medial aspect of the tibia (Fig. 1-A). Dissection is carried through the skin, subcutaneous tissue, and sartorius fascia to identify the gracilis and semitendinosus tendons. These hamstrings tendons are dissected free distally, cleared of any adhesions proximally, and then harvested with a closed tendon-stripper. The tendons are prepared by removing excess muscle, whip-stitching the proximal ends, and placing the graft over a 15-mm continuous-loop (or tied-loop) EndoButton (Smith and Nephew Endoscopy, Andover, Massachusetts) under tension.

The leg is then elevated, and the tourniquet is inflated. Standard arthroscopic anterolateral and anteromedial portals are made, and a meniscal or chondral injury, if present, is managed. The intercondylar notch is visualized, and the stump of the anterior cruciate ligament, if present, is debrided. The notch is assessed to determine whether its width is adequate (with a notchplasty performed if necessary), and the over-the-top position is debrided. A tibial tunnel is placed in the posterior aspect of the footprint of the anterior cruciate ligament with use of a tibial guide at 55°. The tibial tunnel isreamed according to the diameter of the graft. The diameter of the quadrupled graft was 7 mm in one knee, 8 mm in sixteen knees, 9 mm in twenty-nine knees, and 10 mm in fifteen knees. The arthroscopic is placed up the tibial tunnel to the visible ring of the proximal tibial physis to confirm a minimum 25-mm tibial tunnel length distal to the physis for placement of the metaphyseal interference screw fixation. All sixty-one knees in this study and all eighty-seven knees that were eligible for this study had a minimum tibial tunnel length of 25 mm distal to the tibial physis and had fixation with use of this interference screw. The free edge of the tibial tunnel is debrided, and a stainless-steel offset guide is positioned to leave a 2 to 2-mm back wall is hooked in the over-the-top position (Fig. 1-B). A guidewire is placed and then overreamed with an EndoButton reamer. The depth of the femoral tunnel is measured with use of a depth gauge, and the guidewire is replaced to allow reaming of the femoral tunnel to the appropriate depth. The EndoButton and graft are brought through the femoral tunnel across the joint and through the femoral tunnel (Fig. 1-C). The EndoButton is then flipped, and tension is applied to the graft to assess its stability, after which the knee is extended fully to assess notch impingement. The knee is cycled, and the tibial fixation is performed with a metal or bioabsorbable interference screw of the same diameter as the tibial tunnel and of 25 mm in length. The screw is placed with tension on the graft with the knee at 30° of flexion. The stability of the graft is then evaluated and graded with the Lachman examination.

Postoperatively, the patient is allowed only touch-down weight-bearing for two weeks. Immediate mobilization, from 0° to 90°, is allowed for the first two weeks, and this is followed by progression to a full range of motion. Continuous passive motion from 0° to 90° is used for the first two postoperative weeks to initiate motion and to overcome the patient’s anxiety about postoperative movement. A protective hinge knee brace is used for six weeks postoperatively with motion limits of 0° to 90° for the first two-week period. If a meniscal repair was performed, the rehabilitation protocol may be modified to increase the duration of touch-down weight-bearing to four to six weeks and delay progression to full motion until six weeks postoperatively. Progressive rehabilitation consists of knee range-of-motion exercises, patellar mobilization, electrical stimulation, pool therapy (if available), proprioception
Fig. 1-B
The transtibial over-the-top offset guide is used to drill the femoral tunnel.

Fig. 1-C
The hamstring graft after fixation.
exercises, and closed-chain strengthening exercises during the first three postoperative months, followed by straight-line jogging, plyometric exercises, sport-cord exercises, and sport-specific exercises. Routine radiographs are made at three months postoperatively (Figs. 2-A and 2-B). Return to full activity, including sports that involve cutting, is usually allowed at six months postoperatively. A custom 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.

Results

The mean duration of postoperative follow-up was 3.6 years (range, 2.0 to 10.2 years). The mean operating time was 103 minutes (range, fifty-one to 140 minutes), and the mean tourniquet time was sixty-six minutes (range, thirty-two to 117 minutes). Surgical complications included three cases of arthrofibrosis, which required manipulation with the patient under anesthesia with arthroscopic lysis of adhesions at eleven to sixteen weeks postoperatively. In addition, one patient required removal of the tibial interference screw remnant because of pain at six months postoperatively, and one patient received oral antibiotics for a stitch abscess, which resolved.

Two patients had graft failure and underwent revision anterior cruciate ligament reconstruction at fourteen and twenty-one months postoperatively; thus the revision rate was 3%. Both patients had a reinjury (a midsubstance rupture of the graft) while participating in cutting and pivoting sports. Two patients who had undergone concurrent meniscal repair had a subsequent arthroscopic meniscectomy because the repair had failed to heal.

For the fifty-nine knees that did not undergo a revision anterior cruciate ligament reconstruction, the mean IKDC subjective knee score (and standard deviation) was 89.5 ± 10.2 points and the mean Lysholm knee score was 91.2 ± 10.7 points. All patients had returned to cutting or pivoting sports. According to IKDC criteria, the result of the Lachman examination was normal in fifty-one knees, was nearly normal in eight knees, and was not abnormal or severely abnormal in any knee. The result of the pivot-shift examination was normal in fifty-six knees, was nearly normal in three knees, and was not abnormal or severely abnormal in any knee. There was no significant difference in the mean IKDC subjective knee score between the boys and the girls or between the patients who were younger than fourteen years of age and those who were fourteen years of age or older (p > 0.05).
The mean increase in total height (trunk plus lower extremity) from the time of the surgery to the time of final follow-up was 8.2 cm (range, 1.2 to 25.4 cm). The radiographic assessment demonstrated no cases of angular deformity (>5° change in alignment between the preoperative and postoperative radiographs). The mean postoperative femorotibial angle was 4.3° ± 3.1° of valgus (range, 1.0° of varus to 11° of valgus), the mean distal femoral angle was 8.2° ± 2.8° of valgus (range, 2.0° to 16° of valgus), and the mean proximal tibial angle was 2.9° ± 2.1° of varus (range, 10.0° of varus to 0°). No lower-extremity length discrepancies were 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 temporarily delay reconstruction until skeletal maturity can be reached. Nonoperative management of a partial tear of the anterior cruciate ligament may be successful in patients with a lower-grade partial tear, in younger children, and in those in whom the tear predominantly involves the anteromedial bundle. However, nonoperative management of complete tears of the anterior cruciate ligament generally has a poor outcome, with recurrent instability leading to further meniscal and chondral injury. Graf et al., Mizuta et al., and Janarv et al. reported instability symptoms with subsequent meniscal tears, decreased activity levels, and the need for later anterior cruciate ligament reconstruction in skeletally immature patients who had been treated nonoperatively. Similarly, when comparing the results of operative and nonoperative management of complete injuries of the anterior cruciate ligament in adolescents, McCarroll et al. and Pressman et al. found that those treated early with reconstruction of the anterior cruciate ligament had less instability, a return to higher levels of activity and sports participation, and lower rates of subsequent re-injury and meniscal tears. Subsequent meniscal and chondral injuries have important implications in terms of the long-term prognosis of the knee and the risk of degenerative joint disease. In addition, compliance with activity restriction is often difficult for children who are athletes and is appealing to their families.

Conventional surgical techniques for reconstruction of the anterior cruciate ligament in adults can cause iatrogenic growth disturbance due to physial damage in immature patients. Cases of growth disturbance have been reported in animal models of anterior cruciate ligament reconstruction. Animal models have demonstrated mixed results regarding growth disturbances associated with soft-tissue grafts placed across the physes. In a study in which iliotibial band grafts were placed through 5/32-in (4-mm) tunnels in a canine model, Stadlermaier et al. found no evidence of growth arrest in four animals in which the soft-tissue graft crossed the physes, whereas four animals with drill holes and no graft demonstrated physial arrest. Guzzanti et al. did report cases of growth disturbance in a rabbit model with a semitendinosus graft through 2-mm tunnels, although these disturbances were not common. In a canine model with an iliotibial band graft tensioned to 80 N, Edwards et al. found increases in distal femoral varus deformity and proximal tibial varus deformity, compared with the findings in untreated control limbs, despite no evidence of an osseous bar. Similarly, Houle et al. reported growth disturbances after tensioning of a tendon graft in a bone tunnel across rabbit physes. However, the tension applied to the graft in the studies by Edwards et al. and Houle et al. may have been excessive for the corresponding animal models, so it is possible that the tension and not the use of the physial tunnel led to the growth disturbance.

Clinical reports of growth deformity after anterior cruciate ligament reconstruction are unusual. Lipscomb and Anderson reported that, in a series of twenty-four skeletally immature patients who had reconstruction with transphysseal semitendinosus and gracilis grafts, one patient had 20 mm of leg shortening; this case was associated with staple fixation across the physes. Koman and Sanders reported that a distal femoral valgus deformity requiring osteotomy and contralateral epiphysiolysis developed in a patient treated with transphysseal reconstruction with a doubled semitendinosus graft. This case was also associated with fixation across the distal femoral physes. With use of a questionnaire on expert experience, one of us (M.S.K.) and colleagues identified an additional fifteen cases of growth disturbance, including eight cases of distal femoral valgus deformity with an arrest of the lateral aspect of the distal femoral physes, three cases of tibial recurvatum with an arrest of the tibial tubercle apophysis, two cases of genu valgum without arrest due to a lateral extra-articular tether, and two cases of leg-length discrepancy (one of shortening and one of overgrowth). Associated factors included fixation hardware across the lateral aspect of the distal femoral physes in three cases, bone plugs of a patellar tendon graft across the distal femoral physes in three cases, large (12-mm) tunnels in two cases, lateral extra-articular tenodesis in two cases, fixation hardware across the tibial tubercle apophysis in two cases, creation of the over-the-top femoral position in one case, and suturing near the tibial tubercle apophysis in one case.

Surgical techniques to address anterior cruciate ligament insufficiency in skeletally immature patients include primary ligament repair, extra-articular tenodesis, transphysseal reconstruction, partial transphysseal reconstruction, and physiologically surgical reconstruction. Primary repair of the anterior cruciate ligament and extra-articular tenodesis alone have had poor results in children and adolescents, as they have in adults. Transphysseal reconstructions with tunnels that violate both the distal femoral and the proximal tibial physes have been performed with a hamstrings autograft, a patellar tendon autograft, and allograft tissues. Partial transphysseal reconstructions violate only one physes, with a tunnel through the proximal tibial physes and over-the-top positioning on the femur or with a tunnel through the distal femoral physes and an epiphysseal tunnel in the tibia. A variety of physiologically reconstructions have been described to avoid the use of tunnels across either the distal femoral or the proximal tibial physes.
We advocate a treatment algorithm for anterior cruciate ligament insufficiency in skeletally immature patients based on the amount of growth remaining, which can be evaluated most accurately with an assessment of physiological age, skeletal age, growth velocity, and the growth of other family members. Chronological age alone may be a poor guide to the amount of growth remaining because of large variations in skeletal and physiological maturity. In older adolescents approaching skeletal maturity with minimal growth remaining (Tanner stage 4), adult-type reconstruction of the anterior cruciate ligament with a variety of grafts (autogenous hamstrings, autogenous patellar tendon, or allograft) and a variety of fixation methods (interference screws, transfixation pins, or cortical fixation) are likely acceptable. Since, with minimal growth remaining, the consequences of an iatrogenic growth disturbance are minimal. In prepubescent children with a large amount of growth remaining (Tanner stage 1 or 2), we perform a previously described physeal-sparing combined intra-articular and extra-articular reconstruction with an autogenous iliotibial band, since this minimizes the risk of an iatrogenic growth disturbance, which would have major consequences in these very young children. In pubescent adolescents with growth remaining (Tanner stage 3), we perform the technique described in this study.

In this study, we report the results of transphyseal reconstruction of the anterior cruciate ligament with use of an autogenous quadrupled hamstrings graft with metaphyseal fixation in sixty-one knees in fifty-nine skeletally immature pubescent adolescents. There was a low revision rate (3%), with excellent functional outcomes, few complications, and no cases of growth disturbance. Limitations of this study include the duration of follow-up, the lack of radiographic assessment of limb-length inequality, the follow-up rate, the method of assessment of physiological maturity, and the absence of a control group treated with another type of anterior cruciate ligament reconstruction for comparison. Although the patients were followed for a minimum of two years and a mean of 3.6 years, longer follow-up until all patients reach skeletal maturity is required to rule out any late-occurring growth disturbances. In addition, long-term follow-up is necessary to evaluate the risk of degenerative articular cartilage changes developing in these young patients. Lower-limb-length inequality was assessed in this study with a clinical examination; routine scagograms were not performed to minimize radiation exposure. Small limb-length differences may therefore have been missed, although these are usually not clinically relevant. The follow-up rate in this study was 70%. Twenty-two patients could not be located despite extensive efforts, and four patients refused to participate in the study. The physiological stage was estimated with use of the Tanner system, both by the patients themselves and by the surgeons at the time of the operation. In general, there was good agreement between the patients' and surgeons' assessments (97%). However, the surgeons involved in this study, and orthopaedic surgeons in general, are not typically trained to perform this assessment. Therefore, more accurate staging of physiological maturity may be performed by a pediatrician or an adolescent medicine specialist who is formally trained to perform this assessment. In addition, age at menarche, an important biological marker of pubescence, was not routinely recorded. Finally, skeletal age was assessed with use of the conventional method based on the Greulich and Pyle atlas. Because of intrinsic variability and the dated nature of these standards, inaccuracies may occur even with use of this method of assessment of skeletal age.

In conclusion, we advocate a treatment algorithm for skeletally immature patients with anterior cruciate ligament insufficiency based on the amount of growth remaining, as determined according to three categories: prepubescent children with substantial growth remaining, pubescent adolescents with a variable amount of growth remaining, and older adolescents approaching skeletal maturity with minimal growth remaining. On the basis of our findings, we believe that transphyseal reconstruction of the anterior cruciate ligament with use of an autogenous quadrupled hamstrings-tendon graft with metaphyseal fixation is a reasonable treatment option for skeletally immature pubescent patients with a variable degree of growth remaining.

Appendix
A table showing the Tanner staging classification 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).

References


