Transepiphyseal Replacement of the Anterior Cruciate Ligament in Skeletally Immature Patients

A PRELIMINARY REPORT

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Background: Fear of iatrogenic growth disturbance has prevented the routine use, in children, of anatomic methods of anterior cruciate ligament replacement that have proven successful in adults. To minimize the risk of growth disturbance, extra-articular or modified physeal sparing procedures have been performed to stabilize the knee, but these procedures do not provide isometry. This study was performed to evaluate the results of a transepiphyseal replacement of the anterior cruciate ligament in skeletally immature athletes.

Methods: From 1993 to 1999, twelve patients with a mean age (and standard deviation) of 13.3 ± 1.4 years underwent replacement of the anterior cruciate ligament with a quadruple hamstring tendon graft performed with an arthroscopic technique and intraoperative fluoroscopic imaging for precise tunnel placement. The femoral and tibial tunnels went through the epiphyses but avoided the physes. Eight of the twelve patients also had a meniscal repair. All patients returned for follow-up, at a mean of 4.1 ± 1.9 years (range, two to 8.2 years) after surgery.

Results: The mean amount of growth from the time of surgery to the time of follow-up was 16.5 ± 10.0 cm (range, 8 to 38 cm). The difference between the lengths of the lower limbs, as measured on orthoradiographs, was not clinically relevant. The mean score on the International Knee Documentation Committee (IKDC) subjective knee form was 96.5 ± 4.4 points (range, 86 to 100 points). Ligament laxity testing with a KT-1000 arthrometer revealed a mean side-to-side difference of 1.5 ± 1.1 mm. The rating according to the criteria of the objective 2001 IKDC knee form was normal for seven patients and nearly normal for five.

Conclusions: Transepiphyseal replacement of the anterior cruciate ligament, a technically demanding procedure with a small margin of error, should be attempted only by accomplished knee surgeons. The preliminary results in this small series, however, demonstrate that this surgical technique can be performed in prepubescent patients with efficacy and relative safety.

Level of Evidence: Therapeutic study, Level IV (case series [no, or historical, control group]). See Instructions to Authors for a complete description of levels of evidence.

Intrasubstance tears of the anterior cruciate ligament, once considered rare in children and adolescents with open physes[1], are now being reported with increasing frequency[2-6]. An increase in the number of children participating in sports combined with improved clinical examination and diagnostic methods has contributed to a greater awareness of this injury. When a child or adolescent sustains a tear of the anterior cruciate ligament, the physician is faced with a treatment dilemma.

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The natural history of complete tears of the anterior cruciate ligament is generally poor in skeletally immature patients[4,7-9]. Even so, many surgeons still advocate a nonoperative approach in younger patients because of the risk of iatrogenic bone-growth disturbance caused by surgical intervention[5,10-12]. Other authors have recommended operative procedures that are nonanatomic and physeal sparing as a means of minimizing the risk of growth disturbance[3,10,13-17].

The purposes of this study were to describe a surgical technique that follows the generally accepted principles of anterior cruciate ligament replacement in adults but theoretically minimizes the risk of physeal injury by not transgressing either the tibial or the femoral physis and to determine the results of this technique when used for replacement of the anterior cruciate ligament with a quadruple hamstring graft in children and adolescents.

Materials and Methods

In the period between 1993 and 1999, 453 patients with a torn anterior cruciate ligament were treated operatively. Twelve patients, children or adolescents who had open physes of the distal part of the femur and the proximal part of the tibia, were evaluated.

The study population included ten boys and two girls. The mean age (and standard deviation at the time of injury to the anterior cruciate ligament was 12.9 ± 1.5 years (range, 10.0 to 14.6 years), and the mean age at the time of surgery was 13.3 ± 1.4 years (range, 11.1 to 15.9 years). The oldest patient, a boy who was 15.9 years of age, was included in the study because his biological age was younger than his chronological age. The mean age at the time of surgery was 11.5 years for the girls and 13.4 years for the boys. The mean height of the patients preoperatively was 156 ± 13.7 cm (range, 135 to 178 cm). The tear of the anterior cruciate ligament was acute (treated less than two weeks after injury) in two patients, subacute (treated two weeks to three months after injury) in eight, and chronic in two. Five patients were injured while participating in football; two, while playing basketball; two, in a bicycle accident; one, while performing gymnastics; one, while playing soccer; and one, while wrestling.

A history was recorded to determine the goals of the patient and the parents and whether the patient had started an adolescent growth spurt. The patient's height was compared with that of the parent of the same sex. Physical examination was used to assess pathologic laxity, to look for meniscal tears, and to perform growth staging. Anteroposterior, lateral, and Merchant radiographs were made to rule out fractures or other pathological changes of bone and to assess skeletal maturity.

Determining the patient's biological age and potential for growth is important when treating adolescents who have a torn anterior cruciate ligament. The criteria for staging biological age described by Tanner and Whitehouse were used to classify maturity[18]. Skeletally immature patients are divided into prepubescent (Tanner stages I and II) and pubescent (Tanner stages III and IV) groups. The Tanner staging was performed by examining the genitalia, axillary hair, and breasts prior to surgery but after induction of anesthesia. Three of the patients in this series were in Tanner stage I, four were in Tanner stage II, and five were in Tanner stage III.

Adolescents who had an injury to the anterior cruciate ligament were excluded from this study when anteroposterior and lateral radiographs of the knee demonstrated that the physes were open but approaching closure, the patient had already experienced an adolescent growth spurt, the patient was within 10 cm of the height of the parent of the same sex, or the patient had reached Tanner stage IV. Bone-age radiographs are not necessary to determine skeletal maturity if these criteria are used to assess biological age[5,19].

Nine patients had at least one associated procedure in addition to the replacement of the anterior cruciate ligament. In eight patients, a tear in the lateral meniscus was observed during the index procedure, and the meniscus was repaired in six of these patients. In one patient, the torn lateral meniscus was not severe enough to require repair and was left untreated. In another, approximately 10% of the lateral meniscus was excised because of a small radial tear. One of the patients who had a torn lateral meniscus also had repairs of acute tears of the biceps tendon, fibular collateral ligament, and posterolateral aspect of the capsule. In addition, two medial menisci were repaired.

Postoperative Rehabilitation

Each patient's knee was placed in a hinged brace postoperatively. Phase I of rehabilitation was started as soon as the patient awakened after surgery. The patient was encouraged to perform quadriceps muscle contraction and straight-leg raises. Cryotherapy was used for five to ten minutes every hour. Range-of-motion exercises and hamstring muscle stretches while the patient was prone were started the day after surgery. The patients who had not had a meniscal repair were allowed to walk with crutches with weight-bearing as tolerated. The patients who had had a meniscal repair were allowed only toe-touch weight-bearing for six weeks.

At one week after surgery, the goal was a range of motion from 0° of extension to 90° of flexion. Phase II of rehabilitation, the strengthening phase, lasted from two to eleven weeks postoperatively. Active range-of-motion exercises along with patellar mobilization and electrical muscle stimulation were begun. Patients progressed through the exercises at their own pace. They were fitted with a functional knee brace two weeks after surgery, and full weight-bearing was encouraged. Exercises, introduced into the rehabilitation program in order of increasing difficulty, included hamstring and quadriceps muscle stretching and strengthening, proprioception exercises, functional strengthening, and strengthening exercises while in a pool. The goal was a full range of motion equal to that of the contralateral, normal knee at six weeks after surgery.

Phase III of rehabilitation lasted from twelve to twenty weeks postoperatively. This phase included functional strengthening, straight-line jogging, plyometric exercises, sport cord exercises for jogging, lateral movement, and foot agility exercises. At sixteen to twenty weeks postoperatively, patients were permitted to perform functional activities, including full-speed running, while wearing the brace. They were allowed to advance to full activity, including competitive sports, twenty-eight weeks after surgery.

Postoperative Evaluation

Postoperative evaluation included subjective assessment and objective examination. The subjective assessment was performed with the International Knee Documentation Committee (IKDC) subjective knee form[20], which the patient completed

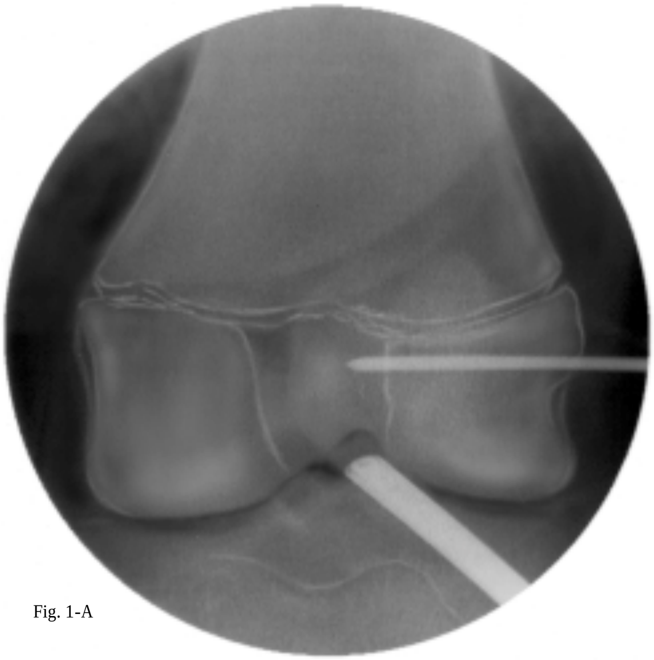

Fig. 1-A

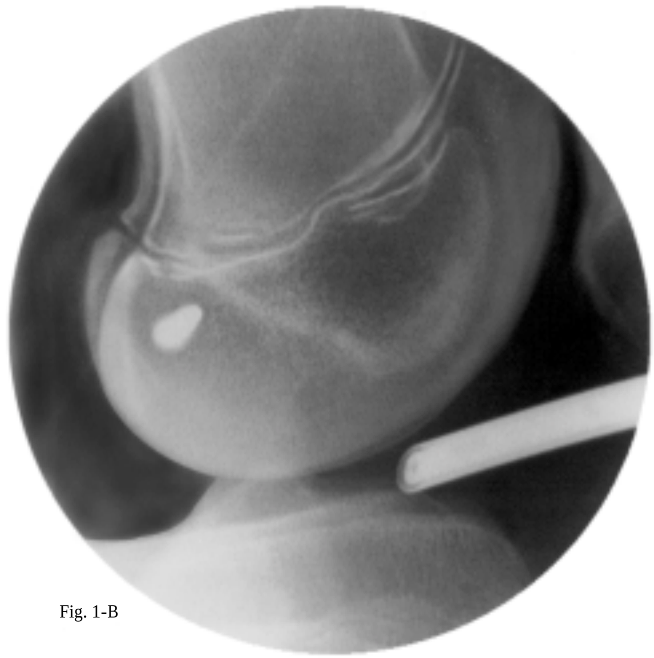

Fig. 1-B

Anteroposterior (Fig. 1-A) and lateral (Fig. 1-B) views shown on a fluoroscopic monitor, demonstrating the position of the guide wire in the femoral epiphysis.

in privacy. This form includes assessment of symptoms (pain, swelling, locking, and giving-way) and activity level. The form has a scoring algorithm that provides a final total score, with 100 points indicating the highest level of function without symptoms.

The objective examination included a comprehensive physical examination of the knee, laxity testing with the KT-1000 arthrometer (MEDmetric, San Diego, California)[21,22], and radiographs. The KT-1000 arthrometer was used to measure anterior-posterior displacement of the tibia on the femur. A force of 134 N was applied, and the difference between the involved and uninvolved knees was recorded in millimeters. The results of the objective examinations were used to complete the 2001 IKDC knee form[23,24]. The patient's height was recorded in centimeters before surgery and at the time of follow-up.

Anteroposterior, lateral, and Merchant radiographs were made to assess degenerative changes or signs of growth disturbance at the time of follow-up. Bilateral standing long-leg radiographs with a radiographic ruler were also made to assess tibial and femoral length.

Surgical Technique

The injured lower limb is placed in an arthroscopic leg holder with the hip flexed 20° to elevate the knee for c-arm (portable fluoroscopy) visualization in the lateral plane. The c-arm is brought in from the side of the table opposite the injured knee, and the monitor is placed at the head of the table. The tibial

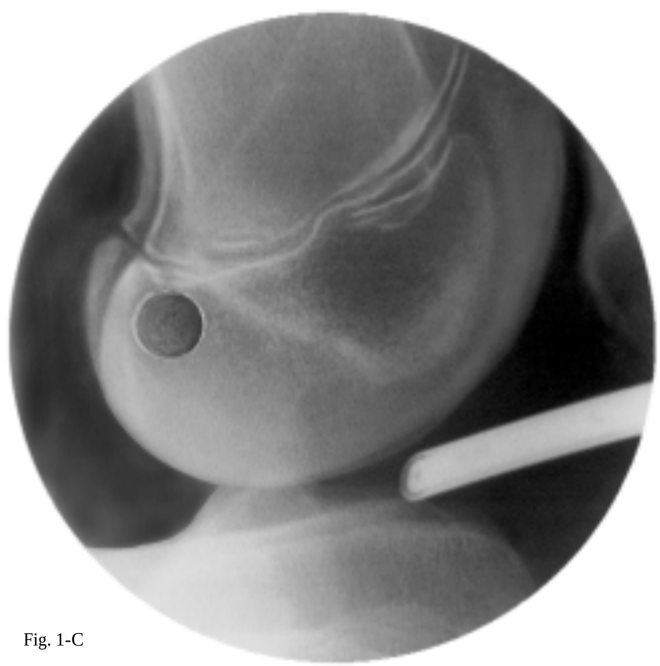

Fig. 1-C

Graphically enhanced lateral view from the fluoroscopic monitor after drilling of the femoral hole.

Fig. 2

Lateral view of the tibia, demonstrating the position of the tibial guide wire. Although it appears to enter the tibial tubercle in this picture, the guide wire actually enters the epiphysis medial to the tibial tubercle.

and femoral growth plates are visualized, in both the anteroposterior and the lateral plane. When the distal part of the femur is viewed, the c-arm is adjusted so that the medial and lateral femoral condyles line up perfectly in the lateral plane. The c-arm is then rotated to visualize the extension of the tibial physis into the tibial tubercle on the lateral view of the tibia.

An oblique 4-cm incision is made over the semitendinosus and gracilis tendons, which are dissected free and transected at the musculotendinous junction with use of a standard tendon stripper. The tendons are then doubled, and a number-5 Ethibond suture (Ethicon, Johnson and Johnson, Somerville, New Jersey) is placed in the ends of the tendons with a whip-stitch. The doubled tendons are then placed under 4.5 kg (10 lb) of tension on the back table with use of the Graft Master device (Acufex-Smith Nephew, Andover, Massachusetts). The arthroscope is inserted into the anterolateral portal, and a probe is inserted through the anteromedial portal. Intra-articular examination is systematically performed in the usual manner. Any debris in the intercondylar notch is removed, and a minimal notchplasty is performed. If a substantial meniscal tear is found, it is repaired.

With the c-arm in the lateral position, a guide wire is used to identify the site for a 2-cm lateral incision. The lateral incision is then made, the iliotibial tract is incised longitudinally, and the periosteum is stripped from a small area of the lateral femoral condyle. The c-arm is used to visualize the entry point of the guide wire in both the anteroposterior and the lateral plane. With a freehand technique, the guide wire is introduced into the femoral epiphysis with care taken to avoid the physis (Figs. 1-A, 1-B, and 1-C). Entrance of the guide wire into the intercondylar notch is then visualized arthroscopically. The guide wire should enter the joint 1 mm posterior and superior to the center of the anatomic footprint of the anterior cruciate ligament on the femur. The femoral guide wire is left in place, and a second guide wire is then inserted into the anteromedial aspect of the tibia through the epiphysis. The c-arm is used again to avoid the tibial physis (Fig. 2). The tibial guide wire enters the joint at the level of the free edge of the lateral meniscus and in the posterior footprint of the anterior cruciate ligament on the tibia. Tendon-sizers are used to measure the diameter of the quadruple tendon graft (range, 6 to 8 mm). A tight fit is important; consequently, the smallest appropriate drill should be used to ream over the guide wires. The edge of the femoral hole is chamfered intra-articularly, and the width of the lateral femoral condyle is measured. The appropriate Endobutton continuous loop (Acufex-Smith Nephew) (2 to 3 cm) is chosen so that at least 2 cm of the quadruple hamstring tendon graft remains within the lateral femoral condyle. The Endobutton continuous loop is then passed around the middle of the doubled tendons and is looped inside of itself to secure the tendons proximally (Fig. 3). Alternatively, the tendons can be placed through the continuous loop before the tendon ends are sutured together. However, that would require drilling and measuring the length of the femoral hole prior to graft preparation. Otherwise, it would be difficult to determine the appropriate length of Endobutton continuous loop necessary to

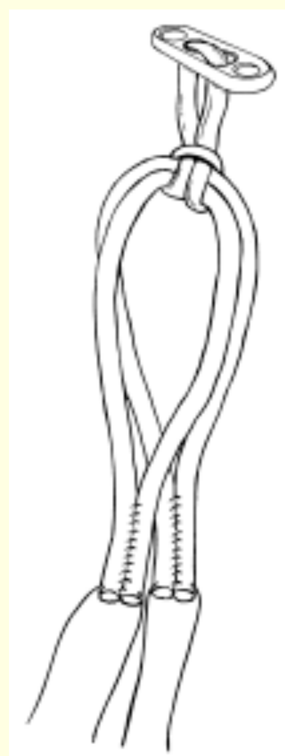

Fig. 3

The Endobutton continuous loop is passed around the middle of the doubled tendons and is looped on itself.

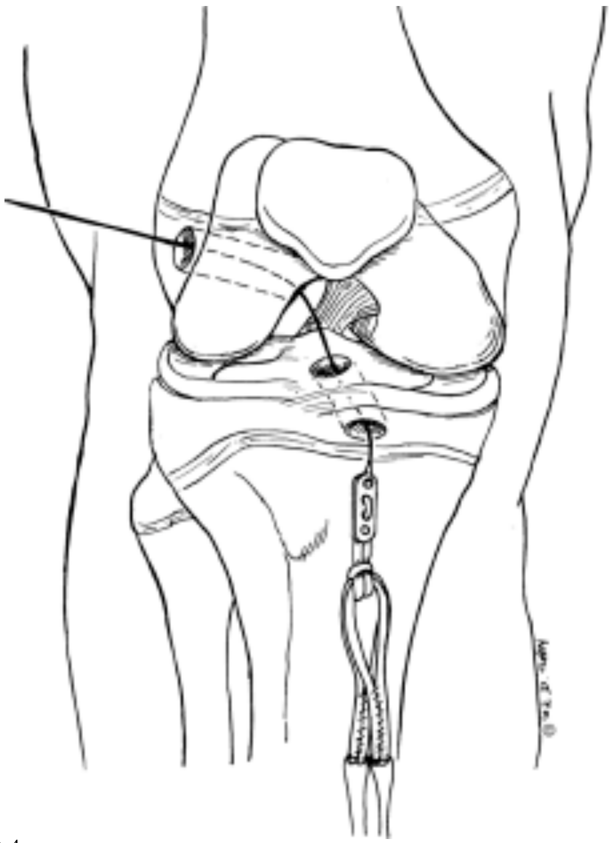

Fig. 4

The semitendinosus and gracilis tendons are pulled up through the tibia and out the lateral femoral condyle with use of number-5 suture in the Endobutton.

leave 2 cm of the tendon graft within the lateral femoral condyle.

A number-5 Ethibond suture is placed in one end of the Endobutton, and a guide wire is used to pass the suture from anterior to posterior up through the tibia and out the lateral femoral condyle (Fig. 4). The Endobutton and tendons are then pulled up through the tibia and out the femoral hole with use of the number-5 suture. An Endobutton washer is placed over the Endobutton and tension is applied to the tendons distally, pulling the Endobutton and washer to the surface of the lateral femoral condyle (Fig. 5). The washer is necessary to anchor the graft proximally because the hole in the lateral femoral condyle is larger than the Endobutton. The knee is then extended to evaluate graft impingement on the intercondylar notch. With the knee in 10° of flexion, the quadruple hamstring graft is secured distally by tying the number-5 Ethibond sutures over a tibial screw and post that is placed medial to the tibial tubercle apophysis and distal to the proximal tibial physis (Figs. 6 and 7). If the tendon graft extends through the tibial drill hole, it is also secured to the periosteum of the anterior aspect of the tibia with multiple number-0 Ethibond sutures and use of figure-of-eight stitches (Fig. 6). The subcutaneous tissue and the skin are closed in a routine fashion, and a hinged brace is applied.

Results

All twelve patients were reexamined at a minimum of two years (mean, 4.1 ± 1.9 years; range, two to 8.2 years) after replacement of the anterior cruciate ligament.

Subjective Assessment

Before the injury to the anterior cruciate ligament, all patients had normal knee function without pain. After surgery, according to the criteria of the IKDC subjective form, eleven patients participated in very strenuous activities and the other patient participated in strenuous activities on a regular basis. Eight patients were able to perform very strenuous activities without pain, and four were able to perform strenuous activities without pain. Eleven had no swelling with very strenuous activities, and one had no swelling with strenuous activities. Ten patients had no giving-way, and two had giving-way only with the most strenuous activities. When asked to rate the function of the involved knee on a scale of 0 to 10, with 10 being normal excellent function, eleven patients rated it as 10 and one patient rated it as 9. The mean IKDC subjective score was 96.5 ± 4.4 points (range, 86 to 100 points). The patient with the lowest score also had had a torn lateral meniscus, avulsions of the fibular collateral ligament and biceps tendon, and a tear of the posterolateral aspect of the capsule.

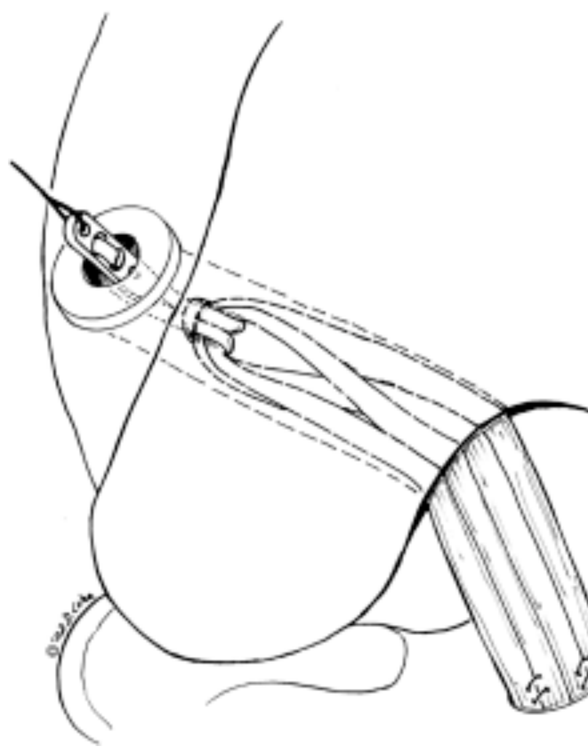

Fig. 5

The Endobutton washer is placed over the Endobutton, and the washer is pulled back to the surface of the lateral femoral condyle.

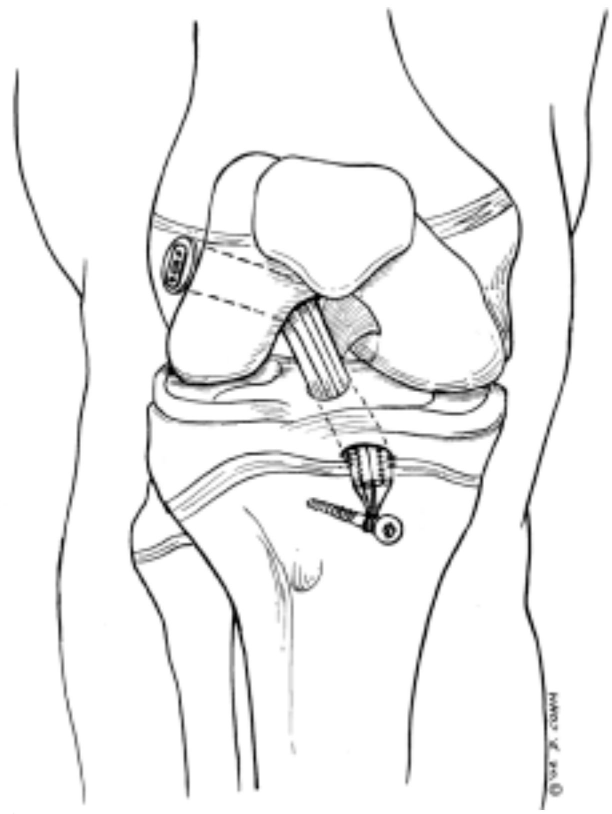

Fig. 6

The quadruple hamstring graft is secured distally by tying the number-5 Ethibond sutures over a tibial screw and post.

Objective Evaluation

Examination of the range of motion revealed no deficits of knee extension. Five patients had a deficit of knee flexion (mean, 3°) compared with that of the contralateral knee; no patient had a flexion deficit of >8°. No patient had an effusion or patellofemoral crepitation. Knee laxity was evaluated with the Lachman test, pivot-shift test, and KT-1000 arthrometer. The Lachman test was negative in ten patients and <1+ (3 mm) in two patients. The pivot-shift test was negative in all patients. Ligament laxity testing with the KT-1000 arthrometer revealed a mean side-to-side difference of 1.5 ± 1.1 mm (range, 0 to 3.75 mm) at the 134-N force. Only one patient had a side-to-side difference of >2.5 mm. Radiographic evaluation revealed that all of the knees were normal according to the IKDC criteria, meaning that they had no sclerosis or flattening of the femoral condyle, no joint-space narrowing, and no osteophytes. There was also no radiographic evidence of varus or valgus angular deformity.

The mean amount of growth from the time of surgery to the time of follow-up was 16.5 ± 10.0 cm (range, 8 to 38 cm). The oldest boy, whose age was 15.9 years at the time of surgery, grew 18 cm. At the time of follow-up, the physes had closed in ten patients. The remaining two patients had grown 17.5 and 33 cm, without evidence of growth disturbance.

Orthoradiographs revealed that four patients had a difference in the lengths of the lower limbs. The involved limb was longer (2, 9, and 10 mm longer) in three patients and 3 mm shorter in one patient. The patient who had the 10-mm limb-length discrepancy had sustained an ipsilateral femoral fracture several years prior to the index procedure; he had no difference in tibial lengths but had 10 mm of femoral overgrowth. Orthoradiographs were not made preoperatively, so it is impossible to determine if the difference in limb length was preexisting or caused by the surgery. In any event, the limb-length difference in all patients was within normal limits[25-27]. The degree of femoral-tibial valgus angulation was equal in the two limbs of all patients. According to the criteria of the objective 2001 IKDC knee examination form, seven patients were given a rating of normal and five, of nearly normal.

Complications

A superficial infection at the site of the lateral incision developed in one patient, and it resolved with antibiotic treatment. There was no deep venous thrombosis, nerve injury, or other perioperative complication in this series. There were no reinjuries or subsequent surgical procedures.

Discussion

Historically, nonoperative treatment consisting of physical therapy, bracing, and modification of activity has been recommended for skeletally immature athletes with a torn anterior cruciate ligament. Although the natural history of these injuries is still not well defined, a growing body of evidence indicates that nonoperative treatment of midsubstance tears of the anterior cruciate ligament in skeletally immature patients has a poor outcome. Angel and Hall[2] retrospectively reviewed the results of nonoperative treatment of twenty-seven

Fig. 7

Radiographs made four months after surgery, revealing transepiphyseal tibial and femoral holes.

children and adolescents who had a documented acute injury of the anterior cruciate ligament. At the time of follow-up, most patients reported giving-way, pain, and limitations of activity. Eleven of twelve patients under the age of fourteen years were disabled because of the decreased knee function. Graf et al.[7] reported that, during a mean follow-up period of fifteen months, seven of eight patients treated nonoperatively sustained a new meniscal tear secondary to recurrent episodes of instability. Mizuta et al.[28], in 1995, described the results of nonoperative treatment of complete midsubstance tears of the anterior cruciate ligament in adolescents. Degenerative changes were found in eleven of eighteen patients at fifty-one months after injury. The authors concluded that the results of nonoperative treatment of anterior cruciate ligament injuries in this age group are "poor and not acceptable." In my experience, the natural history of anterior cruciate ligament injuries is worse in children than it is in adults[4]. Consequently, the primary goals of surgical treatment in adults—restoration of the function of the anterior cruciate ligament and meniscal preservation—are even more important in children.

Despite the problems associated with nonoperative treatment, many authors still did not advocate surgery for this injury[5,10,11,29]. Case reports[4,9,11] and animal studies[30] showing iatrogenic growth disturbance after intra-articular transphyseal replacement have prevented clinicians from routinely applying proven methods of anterior cruciate ligament reconstruction for adults to skeletally immature patients. To avoid growth disturbance, some surgeons have performed primary repair[31,32] or extra-articular replacement[7,9] in this age group. Unfortunately, these procedures have been found to be no more successful in children than they are in adults.

Modified physeal-sparing intra-articular replacements have also been advocated to minimize the risk of physeal injury. Parker et al.[17] reconstructed the anterior cruciate ligament by passing the hamstring tendons through a groove in the anterior aspect of the tibia and over the top of the lateral femoral condyle. Micheli et al.[15] passed the iliotibial band around the outside of the lateral femoral condyle and through the intercondylar notch and then sutured it to the periosteum of the proximal part of the tibia. Others have passed an autograft[13,14] or allograft[10] through a transphyseal tibial drill hole and secured it in the over-the-top femoral position. Although these physeal-sparing procedures have not caused growth disturbances, they do not provide isometry. Odensten and Gillquist[33] demonstrated that the femoral over-the-top position resulted in an average of 10 mm of graft elongation as the knee approached extension.

Anterior cruciate ligament replacement procedures with intra-articular transphyseal placement of the graft remain controversial because of the potential for physeal injuries. Clinical studies documenting the safety of transphyseal replacement primarily have involved postmenarchal female adolescents or postpubescent male adolescents with physes that were near closure[5,10,34,35]. Pressman et al.[12] performed an intra-articular replacement in eighteen patients, only seven of whom had open physes and eleven of whom had closed or closing physes. Andrews et al.[10] and McCarroll et al.[5] also performed intra-articular replacements, but postoperatively their patients gained a mean of only 4.5 and 2.3 cm of height, respectively. The potential for limb-length discrepancy and angular deformity was relatively low in those cohorts. In contrast, the patients in this study were biologically younger, as demonstrated by the mean gain in height of 16.5 cm. Surgical treatment of patients who are thirteen years old or younger and are in Tanner stage I or II presents a greater risk for growth disturbance resulting in limb-length discrepancy or angular deformity. Only a few patients who were that immature were included in the previous clinical reports on transphyseal replacement. Consequently, the safety of transphyseal procedures for preadolescent children has not been substantiated in the clinical literature, and basic-science studies have also failed to clearly demonstrate the safety of transphyseal drilling[36] or of placement of a soft-tissue graft across the physis[30,37].

The success of any anterior cruciate ligament replacement depends on many factors, including graft selection, method of fixation, and surgical technique. Autologous semitendinosus and gracilis tendons were used as grafts in the present series because of the distinct advantages of using hamstring grafts in prepubescent patients. Quadruple hamstring grafts are high-strength grafts that, in contradistinction to patellar tendon grafts, can be harvested with low donor-site morbidity in patients with open physes. The quadruple hamstring grafts are also relatively long and composed entirely of soft tissue. If the physis is inadvertently broached during surgery, filling the hole with soft tissue will reduce the risk of growth disturbance. Furthermore, the efficacy of quadruple hamstring grafts has been proven in the literature[38-40].

Initially, the weakest link in anterior cruciate ligament replacement is fixation of the graft. This is most important in the early phase of healing, when failure of fixation can lead to instability. The tensile loads on the anterior cruciate ligament during daily activities are, at most, 20% of its failure capacity, or approximately 450 N[41]. Fear of growth plate injury in preadolescents precludes the use of fixation that provides the greatest stiffness and highest loads to failure of soft-tissue grafts. The load to failure of the femoral fixation (1345 N) and tibial fixation (830 N) used in this study exceeds the normal tensile loads on the anterior cruciate ligament. The greatest disadvantages of the graft fixation used in this study are decreased stiffness and slippage that are associated with suture-post fixation[42]. Although the fixation was not optimal in this series, it is reasonable to conclude that the mechanical properties of the graft construct were adequate to withstand the strains encountered during the early postoperative period. No patient had a positive pivot-shift test, and only one patient had a side-to-side difference of >2.5 mm (3.75 mm) on testing with the KT-1000 arthrometer. Furthermore, complications that have been associated with this type of fixation, including pain, tenderness, or radiographic widening of the tunnel[29], were not identified in this series.

Previous studies of postpubescent adolescent athletes have demonstrated the feasibility of an all-epiphyseal femoral hole of adequate size accommodating a quadruple hamstring graft[4]. The recent study by Behr et al.[43], however, showed that the margin of error is small. They found that the distance between the superior margin of the anterior cruciate ligament and the femoral physis was only 3 mm in children and adolescents. Although the guide wires were inserted carefully under direct c-arm visualization in the present study, there was still concern that the operative trauma might cause a growth disturbance of the knee. The results of this study demonstrated, however, that the limb-length difference in all patients was within normal limits[25-27], which should allay those fears.

The importance of the menisci in maintaining stability and preventing degenerative changes of the knee has been documented[44-49]. All of the menisci that were repaired in this series were presumed to have healed because the patients resumed normal activity without symptoms and there were no degenerative changes after a mean duration of follow-up of 4.1 years. The success with meniscal repair and surgical stabilization, without evidence of growth disturbance, in the present study supports a recommendation for aggressive treatment, with use of the described surgical technique, of patients with an anterior cruciate ligament injury who are in Tanner stage I or II of development. ■

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