Children and adolescent athletes constitute the largest demographic of patients who sustain anterior cruciate ligament (ACL) tears, and the frequency is increasing.

In ACL-deficient children and adolescents, continued symptoms of instability can result in progressive meniscal and cartilage damage as well as arthritic changes.

Growth disturbance can occur after ACL surgery in children, and includes tibial recurvatum due to tibial tubercle apophyseal arrest as well as limb-length discrepancy and/or angular deformity due to physeal arrest or overgrowth.

Several “physeal sparing” and “physeal respecting” ACL reconstruction techniques have been developed for use in skeletally immature patients to minimize the risk of growth disturbance, with favorable clinical outcomes.

ACL injury prevention strategies include neuromuscular conditioning and may be performed to prevent both initial ACL injury as well as reinjury and injury of the contralateral ACL after reconstruction.
More recent case reports and imaging studies have demonstrated the potential for varying amounts of growth disturbance after transphyseal ACL reconstruction\(^{11,13,23}\), physeal sparing all-epiphyseal ACL reconstruction\(^{24,26}\), and partial transphyseal reconstruction\(^{24,27}\). These include recurvatum that is due to tibial tubercle apophyseal arrest as well as limb-length discrepancy and/or angular deformity resulting from physeal arrest, retardation, tethering, or overgrowth. One small study noted that 3 of 4 patients with a limb deformity after reconstruction required surgery for correction, including guided growth and epiphysiodysis\(^1\). All patients returned to sports. Another case report of postreconstruction growth arrest described limb lengthening and deformity correction with an external fixator for more severe deformity\(^2\).

**Risk Factors for ACL Injury in Youth Athletes**

Characterizing the “at-risk” youth athlete requires an understanding and assessment of several intrinsic and extrinsic risk factors. Intrinsic risk factors include biomechanical, hormonal, and anatomical considerations. Biomechanical risk factors are introduced with pivoting, deceleration, and landing maneuvers and are affected by posture, alignment, and increased quadriceps activation. Girls are more frequently “quadriceps-dominant,” with higher quadriceps-hamstring activation ratios, compared with boys, which may predispose girls to ACL injuries\(^3\). This has led to the development of strength and neuromuscular conditioning programs targeted at ACL tear prevention, which have been shown to be cost-effective when universally implemented\(^{30-33}\). Despite this, 1 systematic review noted that the heterogeneity of currently published randomized controlled trials on injury prevention programs have placed restraints on quantifying intervention efficacy\(^3\). With regard to hormonal risk factors, several studies have discovered sex hormone receptors within the ACL\(^{36-39}\). These include estrogen, testosterone, and relaxin\(^39\), which may alter the biomechanical properties of the ACL, although the precise mechanism is not completely understood\(^40,44\).

Anatomical risk factors include increased anterior pelvic tilt, increased femoral anteversion, increased quadriceps angle, decreased intercondylar notch width or volume, and increased posterior tibial slope\(^{42-46}\). Females tend to exhibit several of these anatomical characteristics more frequently than males, possibly increasing noncontact ACL injury risk\(^{37,42-49}\). Although epidemiological studies have indicated that the total frequency of ACL tears is greater in males than in females, females have an injury rate per athletic exposure that is 2 to 8 times that of their male counterparts\(^{30-52}\).

Extrinsic risk factors include variables such as the sport\(^41\), weather conditions, and footwear-surface interaction\(^{52-55}\). Weather conditions contribute to poor playing surfaces, as low rainfall and high evaporation during summer months may result in harder playing surfaces, an increased coefficient of friction, and a resultant increased strain on the ACL\(^{55-59}\). Likewise, studies have demonstrated that cleat configuration (specifically at the lateral peripheral margin of the foot) increases ACL strain\(^6\). The choice of sports and activities is also modifiable and closely related to ACL injury risk. In a recent meta-analysis, Gornizky et al.\(^{52}\) identified high and low-risk sports on the basis of the ACL injury risk per high school season. For girls, soccer, basketball, and lacrosse were highest risk (1.11%, 0.88%, and 0.53% per season, respectively); for boys, football, lacrosse, and soccer were highest risk (0.80%, 0.44%, and 0.30% per season, respectively).

**Clinical Evaluation and Diagnosis**

Each encounter should begin with a thorough history and physical examination, as well as ruling out concomitant injury. ACL injuries are present in up to 65% of adolescents with acute traumatic hemarthrosis on physical examination\(^3\), and they are seen in 20% to 40% of those on magnetic resonance imaging (MRI), depending on patient age\(^3\). Lachman, anterior drawer, and pivot-shift tests are used to detect ACL insufficiency. Pain and swelling, however, can affect patient compliance and the accuracy of these tests; the pivot-shift has been shown to be up to 98% positive in anesthetized patients compared with as low as 35% in awake patients\(^{36,38}\). It is important to evaluate for baseline clinical malalignment and leg-length discrepancy. This is typically measured using blocks under the clinically short leg to correct pelvic obliquity and measure functional limb-length discrepancy, but may also be quantified radiographically. Because children often have more physiologic laxity than adults, examination of the contralateral, uninjured knee is important to determine normal findings, including a physiologic pivot-shift or glide\(^4\).

MRI is the principal imaging modality used to evaluate the ACL and is 95% sensitive and 88% specific for ACL tears in children\(^5\), also allowing further evaluation for concomitant injury and internal derangement. Meniscal and cartilage injury has been observed in over half of high school athletes with ACL injuries\(^6\). In addition to the standard radiographic evaluation (anteroposterior, lateral, notch, and Merchant views), surgeons can quantify baseline leg-length discrepancy and angular deformity using 51-inch (1.3-m) standing anteroposterior hip-to-ankle radiographs\(^3,6\). Skeletal age should be determined for children and adolescents with open physes, and it is most frequently assessed using a posteroanterior radiograph of the left hand\(^\text{6,7,8,46}^\text{6,7,8,46}\); however, alternative methods based on pelvic, elbow, and calcaneal radiographs have also been described\(^6\). The timing of peak growth velocity may be ascertained from Tanner staging, as well as the age at menarche\(^7\). Characterization of preexisting length and angular deformities as well as remaining growth allows the surgeon to both document preexisting deformity and consider realignment using an osteotomy or implant-mediated guided growth in extreme cases.

**Nonoperative and Delayed Operative Treatment**

Nonoperative management was historically appealing, given the overall increased healing potential of children and the risk of physeal damage with operative reconstruction\(^7\). However, subsequent reports have indicated that this treatment strategy leads to sport dropout (up to 94% of 18 children were unable to participate at the preinjury level of activity and up to 56% of 16 children were unable to participate at all) because of recurrent buckling and giving-way\(^5,7,8,46\). Furthermore, continued instability events can result in progressive meniscal and cartilage damage, as
well as arthritic changes\(^5,74,77,78\), which in 1 study occurred in 61% of 18 knees\(^74\). This is particularly true in children and adolescents who are frequently disinterested in modifying activity levels after injury. Several studies have shown increasing frequency of cartilage and meniscal damage with instability episodes\(^6\) and treatment delay\(^9,30-82\), and higher risk for graft failure and reoperation\(^6\). Anderson and Anderson\(^1\) noted that the odds of lateral and medial meniscal injury were increased 2.2 times and 3.5 times, respectively, with a treatment delay of >12 weeks. Lawrence et al\(^2\) reported that the odds of medial and lateral compartment chondral injuries increased 5.6 times and 11.3 times, respectively, and there was an increased risk of irreparable meniscal tears, with a treatment delay of >12 weeks. Vavken et al\(^3\) confirmed these results, reporting an increase in meniscal or chondral injury of 6% per month of surgical delay. Moksnes et al\(^2\) performed a large, prospective MRI-based study that advocated a strict nonoperative rehabilitation protocol and active surveillance rather than routine reconstruction of ACL tears in skeletally immature patients. However, during the 4 years after injury, 33% of the 41 knees required ACL reconstruction for persistent symptoms of instability and 20% sustained new meniscal pathology requiring treatment. Meta-analyses have shown that early stabilization decreases pathological laxity and improves rates of return to activity\(^4,44\).

**Treatment of Partial Tears and ACL Sprains**
Partial ACL tears, in which there is not a complete disruption of all ACL fibers, occur more frequently in children than in adults, and nonoperative treatment has been successful in select patients. In 1 large series of 45 patients (mean age, 13.9 years), 31% of children with partial ACL tears who were treated nonoperatively with a hinged knee brace, partial weight-bearing for 6 to 8 weeks, and a progressive ACL rehabilitation protocol ultimately required surgical reconstruction for persistent symptoms of instability\(^39\). Nonoperative management had greater success in children and adolescents in that cohort who sustained tears that were less than half of the ACL thickness, had tears of the anteromedial bundle only, had a grade-A pivot-shift, and had a skeletal age of ≤14 years. It may be reasonable to consider a trial of nonoperative treatment in patients who meet all of these criteria, with the mutual understanding that recurrent symptoms of instability may inevitably require ACL reconstruction.

**Complete ACL Tears: Operative Treatment and Techniques**
Given the perils of nonoperative treatment of complete ACL tears in children and the necessity of respecting growing physes, contemporary surgical techniques and instrumentation offer a variety of reconstruction options. These may be broadly categorized as physeal sparing (extraphyseal\(^18,86-87\) and all-epiphyseal\(^25,26,88-90\)), partial transphyseal\(^97\), and transphyseal\(^98,99\). A summary of clinical outcomes for each technique is displayed in Table I; a recent large, heterogeneous, retrospective study of youth athletes found revision rates of 9.6% and injury rates of the contralateral ACL of 8%\(^44\), although studies of individual techniques have noted various re-injury rates. As no technique has shown universal superiority, multiple instrumentation sets and fixation options are available, depending on surgeon preference. Biomechanical studies have indicated restoration of many kinematic parameters\(^45,90\), but we are aware of no long-term comparative outcomes studies. Careful attention during tunnel drilling is crucial to avoid substantial physeal damage and resultant limb deformity. Additionally, the use of autograft tissue for primary ACL reconstruction in youth athletes is preferred\(^79,80\) as large multicenter studies have shown 4 times higher rates of failure after allograft ACL reconstruction in patients 10 to 19 years old\(^89\).

**Physseal Sparing: Extraphyseal Iliotibial Band Autograft Reconstruction**
In prepubescent children (Tanner stage 1 or 2; a skeletal age of ≤11 years for girls and ≤12 years for boys), a modified MacIntosh combined intra-articular and extra-articular iliotibial (IT) band reconstruction, described by Micheli et al\(^86\) and further characterized by Kocher et al\(^80\), may be performed (Video 1, Fig. 1). In this reconstruction, the central portion of the IT band is harvested proximally and left attached to Gerdy’s tubercle distally. The graft is brought through the knee in an over-the-top-position posteriorly and is passed under the intermeniscal ligament anteriorly within an epiphyseal groove on the tibia. The graft is fixed with suture to the intermuscular septum and periosteum on the femur and on the periosteum on the tibia. This technique has the advantages of avoiding the physis, improving the ease of revision surgery (no previous tunnels and all other autograft sources remain intact), and providing an additional extra-articular reconstruction limb analogous to the anterolateral ligament\(^86,100-102\).

Some proponents of this technique cite its nonanatomical configuration; however, biomechanical studies have shown restoration of kinematic constraint\(^89\).

Outcomes after ACL reconstruction using this technique have been excellent. The retear rate was 4.5% in a cohort of 44 patients (with a mean age of 10.3 years and a mean follow-up of 5.3 years); for the remaining patients, the mean scores (and standard deviation) were 96.7 ± 6.0 points on the International Knee Documentation Committee (IKDC) subjective knee-scoring system and 95.7 ± 6.7 points on the Lysholm knee-scoring system\(^86\). All patients, except 3 with congenital limb anomalies, returned to cutting and pivoting sports. There were no clinical or radiographic growth disturbances. These results have been maintained in the longer term as well with a subsequent study of 237 patients, at a mean of 6.2 years postoperatively, who had a 5.8% rate of revision, 2.1% rate of arthrofibrosis, 0.4% rate of septic arthritis, and no limb-length or angular deformities\(^103\). Pedi-IKDC (Pediatric IKDC) and Lysholm scores averaged 93 points each. Clinical success has been replicated in other series as well\(^104,105\). Twenty-two knees at a mean follow-up of 3.0 years had mean Pedi-IKDC and Lysholm scores of 96.5 and 95 points, respectively, with high patient satisfaction, no limb-length or angular deformities, and 3 knees (14%) that required revision ACL surgery\(^106\).

**Physseal Sparing: All-Epiphyseal Technique**
Another option for ACL reconstruction in prepubescent children is an all-epiphyseal technique originally described by Anderson\(^26\),...
## TABLE I Review of Clinical Outcomes Following ACL Reconstruction in Children and Adolescents (Limited to Previous 20 Years)*

| Technique and Study | No. of Subjects | Mean Age (yr) | Mean Follow-up (yr) | Graft | Recurrent Instability and/or Reinjury | Return to Preinjury Activity Level | Mean Angular Deformity | Mean LLD | Complications, Other than Rerupture or Growth-Related |
|---------------------|----------------|---------------|---------------------|-------|---------------------------------------|-----------------------------------|------------------------|ucht|--------------------------------------------------|
| Extraphyseal, combined intra- and/or extra-articular ITB  | | | | | | | | | |
| Kocher et al.86 (2005) | 44 | 10.3 | 5.3 | ITB | 4.5% | 93% | None | None | None |
| Willimon et al.105 (2015) | 21 | 11.8 | 3.0 | ITB | 14% | 95% | None | None | None |
| Fanelli and Hennrikus104 (in press) | 13 | 12.2 | 2.0 | ITB | 0% | 77% | None | None | None |
| Kocher et al.103 (unpublished data) | 237 | 11.2 | 6.2 | ITB | 5.8% | 97% any return; 84% same or higher level | None | None | None |
| All-epiphyseal  | | | | | | | | | |
| Guzzanti et al.132 (2003) | 8 | 11.2 | 5.8 | HS | None | NR | None | None | NR |
| Anderson26 (2004) | 12 | 13.3 | 4.1 | HS | 17% | NR | None | <1 cm in 4 subjects | None |
| Cassard et al.108 (2014) | 28 | 12.8 | 2.8 | HS | 7.1% | 100% | None | None | None |
| Cruz et al.26 (2015) | 103 | 12.1 | 1.8 | HS/HS allograft | 10.7% | NR | None | <1 cm in 1 subject | None |
| Koch et al.24 (2016) | 12 | 12.0 | 4.5 | HS | 15.4% | NR | 5° varus in 1 subject | 1.9 cm in 2 subjects; <1 cm in 4 subjects | None |
| Cordasco et al.109 (2016) | 23 | 11.3 | NR, >2.0 | HS | 4.3% | 96% any return | None | None | None |
| Partial transphyseal  | | | | | | | | | |
| Lo et al.27 (1997) | 5 | 12.9 | 7.4 | HS/quad. | None | 80% | None | <1 cm | Non-ACL knee reinjury (20%) |
| Demange and Camanho21 (2014) | 12 | 10.7 | 18.3 | HS | 25% | 83% | None | None | None |
| Transphyseal with soft-tissue graft  | | | | | | | | | |
| Aronowitz et al.118 (2000) | 15 | 3.8 | 2.1 | Achilles allograft | NR | 84% | None | None | None |
| Seon et al.231 (2005) | 11 | 14.7 | 6.5 | HS | None | 90.1% | 0.6° valgus | <1 cm | None |
| McIntosh et al.117 (2006) | 16 | 13.5 | 3.4 | HS | 12.5% | 88% | None | <1 cm | None |

*continued*
and modified by others, which employs hamstring autograft and all-epiphyseal sockets with epiphyseal fixation (Fig. 2). This technique may be used as a primary reconstruction, or in skeletally immature patients who require revision reconstruction. Grafts prepared with subsequent pretensioning and circumferential compression may minimize bone removal in small

<table>
<thead>
<tr>
<th>Technique and Study</th>
<th>No. of Subjects</th>
<th>Mean Age (yr)</th>
<th>Mean Follow-up (yr)</th>
<th>Graft</th>
<th>Recurrent Instability and/or Reinjury</th>
<th>Return to Preinjury Activity Level</th>
<th>Mean Angular Deformity</th>
<th>Mean LLD</th>
<th>Complications, Other than Rerupture or Growth-Related</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kocher et al. (2007)</td>
<td>59</td>
<td>14.7</td>
<td>3.6</td>
<td>HS</td>
<td>8.5%</td>
<td>100% (of those not revised)</td>
<td>None</td>
<td>None</td>
<td>Arthrofibrosis (5.1%), superficial infection (1.7%), and painful hardware (1.7%)</td>
</tr>
<tr>
<td>Liddle et al. (2008)</td>
<td>17</td>
<td>12.0</td>
<td>3.7</td>
<td>HS</td>
<td>5.9%</td>
<td>NR</td>
<td>None</td>
<td>None</td>
<td>Superficial infection (5.9%)</td>
</tr>
<tr>
<td>Sankar et al. (2008)</td>
<td>247</td>
<td>15.4</td>
<td>6.3</td>
<td>Achilles allograft</td>
<td>6.9%</td>
<td>NR</td>
<td>NR NR</td>
<td>None</td>
<td>Wound dehiscence (3.8%)</td>
</tr>
<tr>
<td>Cohen et al. (2009)</td>
<td>26</td>
<td>13.3</td>
<td>3.8</td>
<td>HS</td>
<td>6.7%</td>
<td>89%</td>
<td>0.5° valgus in 1 subject</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td>Nikoletou et al. (2011)</td>
<td>94</td>
<td>13.7</td>
<td>3.2</td>
<td>HS</td>
<td>4.3%</td>
<td>90%</td>
<td>None</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td>Couvrasier et al. (2011)</td>
<td>37</td>
<td>14.0</td>
<td>3.0 (median)</td>
<td>HS</td>
<td>8.1%</td>
<td>100%</td>
<td>NR NR</td>
<td>None</td>
<td>Hematoma (8.1%)</td>
</tr>
<tr>
<td>Hu et al. (2012)</td>
<td>16</td>
<td>12.0</td>
<td>2.0</td>
<td>HS</td>
<td>None</td>
<td>100%</td>
<td>None</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td>Redier et al. (2012)</td>
<td>18</td>
<td>14.2</td>
<td>3.0</td>
<td>HS</td>
<td>None</td>
<td>100%</td>
<td>None</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td>Goddard et al. (2013)</td>
<td>32</td>
<td>13.0</td>
<td>NR, &gt;2.0</td>
<td>HS living related donor</td>
<td>6.3%</td>
<td>100%</td>
<td>NR NR</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td>Kumar et al. (2013)</td>
<td>32</td>
<td>11.3</td>
<td>6.0</td>
<td>HS</td>
<td>5.1%</td>
<td>100%</td>
<td>6° valgus in 1 subject</td>
<td>&lt;1 cm</td>
<td>Suture abscess (3.1%) and incisional numbness (3.1%)</td>
</tr>
<tr>
<td>Kohli et al. (2014)</td>
<td>15</td>
<td>12.8</td>
<td>4.1</td>
<td>Quad.</td>
<td>None</td>
<td>NR</td>
<td>6° valgus in 1 subject</td>
<td>&lt;1 cm (range, –2 to +0.9 cm)</td>
<td>NR</td>
</tr>
<tr>
<td>Schmaler et al. (2014)</td>
<td>29</td>
<td>14.0</td>
<td>4.0</td>
<td>HS/TB allograft</td>
<td>13.8%</td>
<td>41%</td>
<td>None</td>
<td>None</td>
<td>Arthrofibrosis (13.8%) and painful hardware (10.3%)</td>
</tr>
<tr>
<td>Calvo et al. (2015)</td>
<td>27</td>
<td>13.0</td>
<td>10.6</td>
<td>HS</td>
<td>14.8%</td>
<td>89%</td>
<td>None</td>
<td>None</td>
<td>Subsequent meniscal and/or chondral surgery (11.1%)</td>
</tr>
<tr>
<td>Revision ACL reconstruction</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Symptomatic hardware (4.4%), superficial infection (3.4%), deep infection (1.1%), arthrofibrosis (2.2%), wound drainage (2.2%), and saphenous nerve injury (1.1%)</td>
</tr>
<tr>
<td>Christino et al. (unpublished data)</td>
<td>88</td>
<td>16.6</td>
<td>5.1</td>
<td>BTB, HS, ITB, and allograft</td>
<td>20%</td>
<td>69% any return; 55% same or higher level</td>
<td>None</td>
<td>None</td>
<td>None</td>
</tr>
</tbody>
</table>

*LLD = limb-length discrepancy, ITB = iliotibial band, HS = hamstring, NR = not reported, TA = tibialis anterior, and BTB = bone-patellar tendon-bone. All grafts are autograft unless specified otherwise.
In his original series, Anderson reported on 12 prepubescent patients (mean age, 13.3 years) with a mean IKDC score of 96.5 points and a mean side-to-side difference on the KT-1000 arthrometer (MEDmetric) of 1.5 mm at a mean follow-up of 4.1 years without any significant length or angular limb deformity. Cassard et al., in a series of 28 subjects at a mean follow-up of 2.8 years, noted a 100% return to activities; however, as far as we know, this outcome was not reported in other studies. Complications have been reported in the orthopaedic literature; in small and short-term series, graft rupture rates of 4% to 17% have been noted. An MRI-based investigation noted physeal compromise in 10 of 15 tibias and 1 (4%) of 23 femora, without clinical growth disturbances at 1 year. There have, however, been reports of limb-length and angular deformity after epiphyseal-only tunnel drilling, with few cases requiring surgical correction.

**Partial Transphyseal Reconstruction**

In studies of borderline pubescent children who were skeletally immature but had limited remaining growth (e.g., Tanner stage 3), a partial transphyseal reconstruction has been described. In this technique, a physis-avoiding over-the-top position or all-epiphyseal femoral tunnel is used in conjunction with a transphyseal, vertical, centrally located tibial tunnel. This technique has the theoretical advantage of avoiding the lateral distal femoral physis and resultant angular deformity while using traditional tibial drilling techniques. Few small series have demonstrated clinical outcomes using this technique, with no clinically relevant length or angular deformity but with graft rupture and subsequent cartilage and/or meniscal injury rates of 20% to 25%.

**Transphyseal Reconstruction**

In older children and adolescents with some growth remaining (a Tanner stage of ≥3 and a skeletal age of ≥12 years in girls and ≥13 years in boys), so-called physial-respecting transphyseal reconstruction may be performed by removing an acceptable amount of physeal tissue and utilizing soft-tissue grafts with metaphyseal fixation (Fig. 3). While the precise amount...
of acceptable physeal violation in humans is unknown, animal studies have indicated that removing >7% of the area of the physeal plate is associated with an increased risk of growth disturbance. Recent clinical data have suggested that transtibial ACL tunnel-drilling techniques may remove less physeal tissue than independent drilling. However, this may also be accomplished with independent tunnel-drilling techniques with a vertical trajectory. Regardless, the clinical impact of the drilling technique in humans in the setting of soft-tissue grafts and metaphyseal fixation is not yet known. Meticulous attention to developmental and skeletal age allows the surgeon to select the appropriate approach and to know when the amount of growth remaining will not lead to length or angular limb deformity with transphyseal techniques. In patients with

Fig. 2


Fig. 2-A Drawing of the technique. Fig. 2-B A quadrupled hamstring autograft is prepared with suspensory fixation on both ends. Fig. 2-C The femoral footprint is localized with a guide pin. Fig. 2-D The femoral socket is prepared using an inside-out retrograde reamer. Fig. 2-E Fluoroscopy may be used to ensure adequate distance from the physis prior to reaming. Fig. 2-F Similarly, the tibial socket is prepared. Fig. 2-G The socket may also be checked with fluoroscopy prior to reaming. Fig. 2-H The graft is passed via the anteromedial portal and is docked in the femoral socket (shown here) and tibial socket. Fig. 2-I The graft is sequentially tightened to ensure adequate graft tension.
considerable growth remaining, bone-patellar tendon-bone (BTB) autograft reconstructions are not recommended as they can cause premature physeal arrest with bone plug healing around the physis.

Kocher et al. reported that the use of transphyseal ACL reconstruction in 61 knees in skeletally immature, pubescent (Tanner stage-3) adolescents who were evaluated at a mean of 3.6 years postoperatively resulted in a 3% revision rate; for the patients who did not have a revision, the mean IKDC subjective knee score was 90 points and the mean Lysholm knee score was 91 points. No limb length or angular deformities arose. This is in line with other reports of transphyseal ACL reconstructions. Limb-length discrepancy has been reported, and is frequently <1 cm; however, in some studies, it has occurred in up to 30% of the patients. At a mean follow-up of 2 to 4 years, mean IKDC and Lysholm scores in the 90s have been reported, with durable results as long as 6 to 10 years postoperatively. Arthrofibrosis and superficial infections are rare complications, but may occur in up to 5% of patients. There is typically a low rate of revision surgery (0% to 14%), which is often due to reinjury after return to full sports participation.

Treatment of Associated Intra-Articular Pathology

As is true for adult patients, the treatment of concomitant pathology is essential to successful management of ACL reconstruction in youth athletes. Vavken et al. reported that more than half of their 208 patients under 18 years old who underwent ACL surgery had a concurrent meniscal or chondral injury. In that series, 32% and 35% had medial and lateral meniscal tears, respectively, and 5% had chondral lesions requiring treatment. These findings confirmed previous reports of high school athletes with ACL injuries and meniscal and cartilage injury rates of 57% and 20%, respectively.

Understanding the clinical outcomes after repair of concomitant injuries allows surgeons to counsel a patient appropriately. Krych et al. reported a 74% rate of healing after meniscal repairs (84% for simple tears) at 8 years postoperatively in 99 patients under 18 years old. Complex and bucket-handle tears had significantly lower healing rates of approximately 60%. Patients with open physes at the time of surgery demonstrated increased failure rates; however, this was potentially due to the children’s increased activity levels in the postoperative period.

For youth athletes presenting with combined ACL and medial collateral ligament (MCL) injuries, the current literature supports early bracing, protected weight-bearing, and delayed...
ACL reconstruction without repair of grade-II and III MCL tears. In a cohort of 12 adolescent patients (mean age, 15.6 years) with combined MCL and ACL injuries, patients were braced immediately, with a mean surgical delay to ACL reconstruction of 33 days, which resulted in 100% return to sports and a mean Lysholm score of 96 points.

### TABLE II Grades of Recommendation for Diagnosis and Management of ACL Injury in Children and Adolescents

<table>
<thead>
<tr>
<th>No.</th>
<th>Recommendation</th>
<th>Grade*</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>MRI should be acquired to evaluate for ACL injury and concomitant internal derangement if clinical suspicion exists after a thorough history and physical examination.</td>
<td>A</td>
</tr>
<tr>
<td>2</td>
<td>A trial of nonoperative treatment consisting of bracing, protected weight-bearing, and a progressive ACL rehabilitation protocol may be considered for younger patients (skeletal age of ≤14 years) with partial ACL injury (≤50% disrupted fibers, particularly of the anteromedial bundle only) and a grade-A pivot-shift.</td>
<td>C</td>
</tr>
<tr>
<td>3</td>
<td>Complete ACL tears in skeletally immature patients should be treated with reconstruction to prevent continued knee instability, sport dropout, and progressive irreversible chondral and meniscal damage.</td>
<td>B</td>
</tr>
<tr>
<td>4</td>
<td>Primary ACL reconstruction in skeletally immature patients should be performed with autograft tissue.</td>
<td>A</td>
</tr>
<tr>
<td>5</td>
<td>Physeal-sparing ACL reconstruction techniques provide surgical options for prepubescent patients (Tanner stage 1 to 2) with complete ACL tears and substantial growth remaining.</td>
<td>C</td>
</tr>
<tr>
<td>6</td>
<td>Transphyseal ACL reconstruction using soft-tissue autograft and metaphyseal fixation is a surgical option for adolescents (Tanner stage ≥3) with complete ACL tears and limited growth remaining.</td>
<td>C</td>
</tr>
<tr>
<td>7</td>
<td>ACL injury prevention and neuromuscular training protocols may be used to prevent ACL injury as well as assess youth athletes for return to sports and activities.</td>
<td>B</td>
</tr>
</tbody>
</table>

*Grade A indicates consensus agreement or Level-I studies with consistent findings for or against recommending intervention; Grade B, fair evidence with Level-II or III studies with consistent findings; Grade C, poor-quality evidence (Level-IV or V studies with consistent findings) for or against intervention; and Grade I, insufficient evidence to make a recommendation.
Revision ACL Reconstruction in Youth Athletes

Little has been published to date on revision ACL reconstruction in youth athletes. Christino et al. analyzed the cases of 88 youth athletes (mean age, 16.6 years) who underwent revision ACL reconstruction using a variety of grafts and techniques and who were followed for an average of 5.1 years. Of that cohort, 69% went on to participate in sports and 20% experienced a recurrent sense of instability. Complications included symptomatic implants (4.4%), superficial infection (3.4%), deep infection (1.1%), arthrofibrosis (2.2%), wound drainage (2.2%), and saphenous nerve injury (1.1%).

Rehabilitation

Currently, few youth-specific ACL rehabilitation protocols have been described, and many have been designed on the basis of a combination of the adult literature and clinical expertise. Despite differences in published protocols regarding postoperative weight-bearing, strengthening regimens, and return to play, the general principles indicate that ACL rehabilitation should include an initial phase of pain and edema control and restoration of range of motion, followed by strengthening, nonimpact activities, then straight-line running, cardiovascular exercise and/or plyometrics, and a return to sports at 6 to 12 months postoperatively. In our practice, patients who undergo extraphyseal IT band autograft ACL reconstruction (which utilizes suture graft fixation) and/or meniscal repair are prescribed protected (touch-down) weight-bearing for 6 weeks to allow for soft-tissue healing. ACL injury prevention programs can be used as part of a milestone-based return-to-play readiness training, and may reduce the risk of reinjury as well as injury of the contralateral ACL. Because of the lack of a clear benefit of bracing in a recent systematic review, use of a functional ACL brace is variable; however, in our practice, it is generally recommended until graft maturity at 1 to 2 years after return to play. Two years after surgery, bracing becomes optional but is frequently encouraged for younger prepubescent patients and those who compete in high-risk sports and activities. In order to further decrease the risk of retear, focused hamstring strengthening during postoperative rehabilitation, and as part of ongoing athletic training, may decrease the risk of an ACL tear.

Otherwise, redirection to lower-risk sports and activities is an option.

Overview

While ACL tears were historically considered a rare injury in skeletally immature athletes, they are now observed with increasing frequency because of a dramatic rise in competitive athletic activity among youths, early sport specialization, and year-round training and competition. Recent epidemiological data have shown that the greatest number of ACL reconstructions per capita are being performed in adolescents and teenagers, including skeletally immature patients. In light of the increasing frequency and awareness of ACL injuries in children, diagnostic and treatment strategies have evolved and now cater to the unique anatomy of the skeletally immature patient. Current literature supports the trend toward early operative treatment to restore knee stability and prevent progressive meniscal and/or chondral damage, while a small subset of patients may attempt structured nonoperative management with reasonable success (Fig. 4, Table II). Future research should focus on widespread implementation of ACL injury prevention programs and optimizing surgical technique and postoperative rehabilitation protocols in multicenter prospective registry studies utilizing youth-validated patient-reported outcomes.

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