Current Concepts Review

Management of ACL Injuries in Children and Adolescents

Peter D. Fabricant, MD, MPH, and Mininder S. Kocher, MD, MPH

Investigation performed at Boston Children's Hospital, Boston, Massachusetts

- ➤ 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.

Peer Review: This article was reviewed by the Editor-in-Chief and one Deputy Editor, and it underwent blinded review by two or more outside experts. The Deputy Editor reviewed each revision of the article, and it underwent a final review by the Editor-in-Chief prior to publication. Final corrections and clarifications occurred during one or more exchanges between the author(s) and copyeditors.

Anterior cruciate ligament (ACL) tears, which were once considered rare in skeletally immature athletes, are now observed with increasing frequency[1-3]. A dramatic rise in competitive athletic activity among children and adolescents, early sport specialization, increased awareness of these injuries in children, and year-round training and competition may contribute to a commensurate increase in the frequency of diagnosis of pediatric ACL tears. Epidemiological analysis has indicated that the rate of ACL reconstruction in children under the age of 20 years increased nearly threefold between 1990 and 2009 in the United States, and that adolescents and teenagers represent the largest per capita demographic of patients having ACL reconstructions[1]. Furthermore, ambulatory ACL procedures in patients <15 years old increased 924% from 1994 to 2006[2,3].

Historically, nonoperative management until skeletal maturity followed by traditional ACL reconstruction was a popular treatment strategy. However, the recent understanding of the perils of nonoperative and delayed surgical treatment have supported a trend toward early surgery[4-9]. In light of this, surgical techniques and instrumentation have evolved in order to accommodate the unique anatomy of skeletally immature patients.

Minimal growth (<1 cm in each limb segment) remains around the knee after the age of 12 to 13 years in girls (i.e., 1 year after menarche) and 14 years in boys[10]. Until this time, reconstruction strategies must respect growing physes. Only in small case series has growth disturbance after ACL reconstruction been reported[11-17], so the true rate is not entirely known and is likely greater than what has been reported in the literature. Experienced ACL surgeons from the Herodicus Society and The ACL Study Group identified the cases of 15 patients with postoperative deformity due to physeal injury, including genu valgum (femoral), tibial recurvatum, and leg-length discrepancy[18].

Disclosure: No internal or external funding was provided for this project. On the **Disclosure of Potential Conflicts of Interest** forms, *which are provided with the online version of the article*, one or more of the authors checked "yes" to indicate that the author had a relevant financial relationship in the biomedical arena outside the submitted work (http://links.lww.com/JBJS/B603).

More recent case reports and imaging studies have demonstrated the potential for varying amounts of growth disturbance after transphyseal ACL reconstruction[11,19-23], physeal sparing all-epiphyseal ACL reconstruction[24-26], and partial transphyseal reconstruction[16,27]. 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 epiphysiodesis[11]. 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[28].

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[29]. 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[30-35]. 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[36]. With regard to hormonal risk factors, several studies have discovered sex hormone receptors within the ACL, including those for estrogen[37,38], testosterone, and relaxin[39], which may alter the biomechanical properties of the ACL, although the precise mechanism is not completely understood[40,41]. 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[42-48]. Females tend to exhibit several of these anatomical characteristics more frequently than males, possibly increasing noncontact ACL injury risk[39,42,49]. 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[50-52].

Extrinsic risk factors include variables such as the sport[52], weather conditions, and footwear-surface interaction[53-55]. 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[53-55]. Likewise, studies have demonstrated that cleat configuration (specifically at the lateral peripheral margin of the foot) increases ACL strain[53]. The choice of sports and activities is also modifiable and closely related to ACL injury risk. In a recent meta-analysis, Gornitzky 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[56], and they are seen in 20% to 40% of those on magnetic resonance imaging (MRI), depending on patient age[57]. 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[56,58]. 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[59].

MRI is the principal imaging modality used to evaluate the ACL and is 95% sensitive and 88% specific for ACL tears in children[60], 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[61,62]. 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[11,63]. 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[64-66]; however, alternative methods based on pelvic, elbow, and calcaneal radiographs have also been described[67-70]. The timing of peak growth velocity may be ascertained from Tanner staging, as well as the age at menarche[71]. 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[72]. 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[73-76]. 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[79] and treatment delay[6-9,80-82], and higher risk for graft failure and reoperation[83]. Anderson and Anderson[7] 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.[8] 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 medial meniscal tears, with a treatment delay of >12 weeks. Vavken et al.[62] confirmed these results, reporting an increase in meniscal or chondral injury of 6% per month of surgical delay. Moksnes et al.[75] 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[4,84].

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[85]. 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[86,87] and all-epiphyseal[25,26,88-90]), partial transphyseal[27,91], and transphyseal[20,92,93]. 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%[94], although studies of individual techniques have noted various reinjury 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[95,96], 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[97,98], as large multicenter studies have shown 4 times higher rates of failure after allograft ACL reconstruction in patients 10 to 19 years old[99].

Physeal 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.[87] and further characterized by Kocher et al.[86], 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 to the periosteum on the tibia. This technique has the advantages of avoiding the physes, 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 opponents of this technique cite its nonanatomical configuration; however, biomechanical studies have shown restoration of kinematic constraint[95].

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[105].

Physeal 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
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	Subsequent meniscal surgery (14.3%)
Fanelli and Hennrikus[104] (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	Arthrofibrosis (2.1%), septic arthritis (0.4%), wound dehiscence (0.4%), subsequent meniscal/chondral surgery (5.8%)
All-epiphyseal									
Guzzanti et al.[132] (2003)	8	11.2	5.8	HS	None	NR	None	None	NR
Anderson[26] (2004)	12	13.3	4.1	HS	17%	NR	None	<1 cm in 4 subjects	Superficial infection (8.3%)
Cassard et al.[108] (2014)	28	12.8	2.8	HS	7.1%	100%	None	None	None
Cruz et al.[25] (2015)	103	12.1	1.8	HS/HS allograft	10.7%	NR	None	<1 cm in 1 subject	Arthrofibrosis (1.9%)
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	Subsequent bucket-handle meniscal tear (7.7%)
Cordasco et al.[109] (2016)	23	11.3	NR, ≥2.0	HS	4.3%	96% any return	None	6 patients with LLD of >5 mm (range, 6-18 mm)	Meniscectomy for medial meniscal retear (4.3%), and contralateral ACL tear (4.3%)
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 Camanho[91] (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	Painful hardware (13.3%)
Seon et al.[121] (2005)	11	14.7	6.5	HS	None	90.1%	0.6° valgus	<1 cm	NR
McIntosh et al.[117] (2006)	16	13.5	3.4	HS	12.5%	88%	None	<1 cm	Painful hardware (18.8%), and failed meniscal repair (18.8%)

continued

TABLE I (*continued*)

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
Kocher et al.[93] (2007)	59	14.7	3.6	HS	8.5%	100% (of those not revised)	None	None	Arthrofibrosis (5.1%), superficial infection (1.7%), and painful hardware (1.7%)
Liddle et al.[23] (2008)	17	12.0	3.7	HS	5.9%	NR	5° valgus in 1 subject	None	Superficial infection (5.9%)
Sankar et al.[133] (2008)	247	15.4	6.3	Achilles allograft	6.9%	NR	NR	NR	NR
Cohen et al.[20] (2009)	26	13.3	3.8	HS	6.7%	89%	0.5° valgus	<1 cm in 13 patients	Wound dehiscence (3.8%)
Nikolaou et al.[134] (2011)	94	13.7	3.2	HS	4.3%	90%	None	None	None
Courvoisier et al.[116] (2011)	37	14.0	3.0 (median)	HS	8.1%	100%	NR	NR	Hematoma (8.1%)
Hui et al.[119] (2012)	16	12.0	2.0	HS	None	100%	None	None	None
Redler et al.[135] (2012)	18	14.2	3.6	HS	None	100%	None	None	None
Goddard et al.[136] (2013)	32	13.0	NR, ≥2.0	HS living related donor	6.3%	100%	NR	NR	None
Kumar et al.[22] (2013)	32	11.3	6.0	HS	3.1%	NR	6.2° valgus in 1 subject	<1 cm	Suture abscess (3.1%) and incisional numbness (3.1%)
Kohl et al.[21] (2014)	15	12.8	4.1	Quad.	None	NR	6° valgus in 1 subject	<1 cm (range, −2 to +0.9 cm)	NR
Schmale et al.[137] (2014)	29	14.0	4.0	HS/TA allograft	13.8%	41%	None	None	Arthrofibrosis (13.8%) and painful hardware (10.3%)
Calvo et al.[120] (2015)	27	13.0	10.6	HS	14.8%	89%	None	None	Subsequent meniscal and/or chondral surgery (11.1%)
Revision ACL reconstruction									
Christino et al.[125] (unpublished data)	88	16.6	5.1	BTB, HS, ITB, and allograft	20%	69% any return; 55% same or higher level	None	None	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%)

*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.

and modified by others[25,26,88-90], 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[106]. Grafts prepared with subsequent pretensioning and circumferential compression may minimize bone removal in small

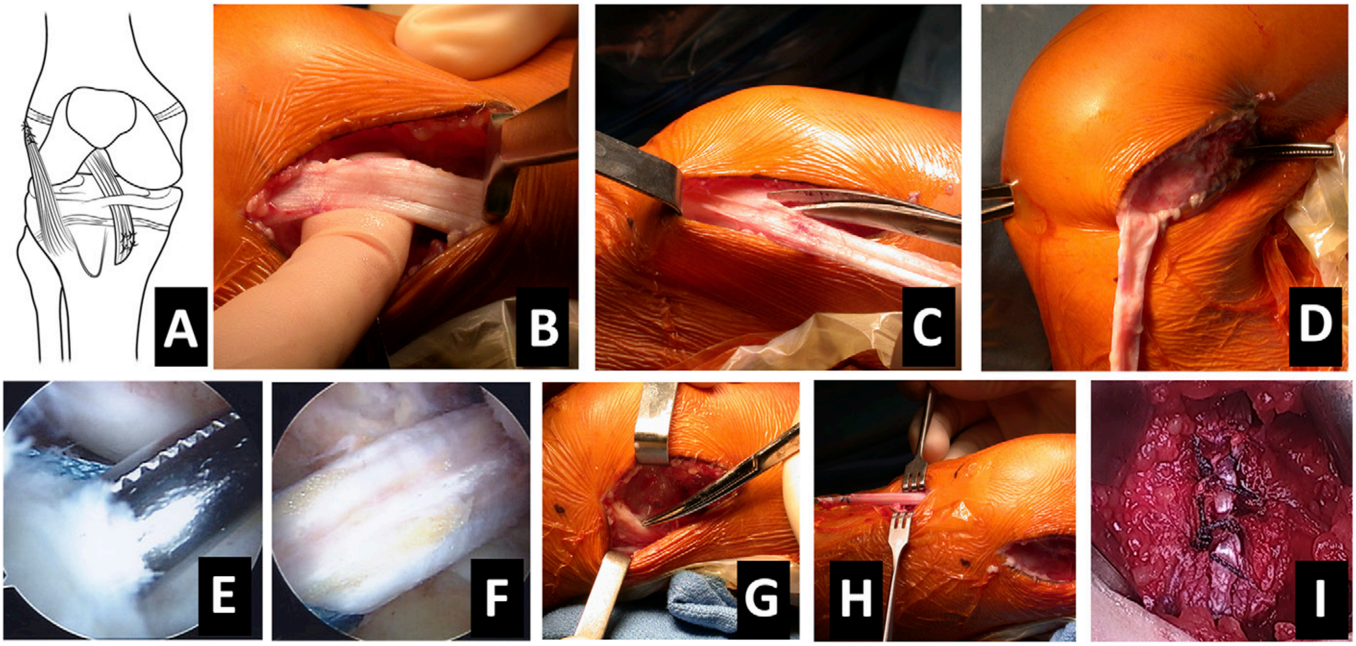

Fig. 1

Figs. 1-A through 1-I The technique for physeal sparing, combined intra-articular and extra-articular iliotibial (IT) band autograft reconstruction, as previously described in detail[86,87]. (Figure 1-A is reproduced, with modification, from: Fabricant PD, Jones KJ, Delos D, Cordasco FA, Marx RG, Pearle AD, Warren RF, Green DW. Reconstruction of the anterior cruciate ligament in the skeletally immature athlete: a review of current concepts: AAOS exhibit selection. J Bone Joint Surg Am. 2013;95:e28. Figures 1-B through 1-F and 1-H are reproduced from: Kocher MS, Garg S, Micheli LJ. Physeal sparing reconstruction of the anterior cruciate ligament in skeletally immature prepubescent children and adolescents. J Bone Joint Surg Am. 2005;87:2371-2379.) **Fig. 1-A** Drawing of the technique. **Fig. 1-B** IT band graft harvest is performed first by isolating the midportion of the IT band and detaching it proximally for 15 cm. **Fig. 1-C** The distal aspect of the graft is freed in line with the IT band fibers toward Gerdy's tubercle. The graft is then tubularized proximally with sutures that are used to pass the graft. **Fig. 1-D** Graft passage is then accomplished by using a curved clamp in the over-the-top position, with passage of the sutures intra-articularly. **Figs. 1-E and 1-F** Subsequent passage of the graft under the intermeniscal ligament is done after preparation of the tibial epiphysis with a rasp in the ACL footprint. **Fig. 1-G** The graft is then pulled out from the tibial incision and is tensioned with the knee flexed to 90° while the extra-articular limb is sewn into the periosteum of the lateral femoral condyle and the intermuscular septum (identified with clamp) with a heavy nonabsorbable suture using at least 2 figure-of-8 stitches. **Fig. 1-H** The knee is then brought into full extension. **Fig. 1-I** With tension on the graft, it is laid into a decorticated trough in the tibial metaphysis and is oversewn to the periosteum with nonabsorbable suture.

knees[107]. In his original series, Anderson[26] 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.[108], 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[24-26,108,109]. An MRI-based investigation noted physeal compromise in 10 of 15 tibiae and 1 (4%) of 23 femora, without clinical growth disturbances at 1 year[110]. There have, however, been reports of limb-length[24-26] and angular[16,24] deformity after epiphyseal-only tunnel drilling, with few cases requiring surgical correction[24].

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[27,91]. 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%[27,91].

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 physeal-respecting transphyseal reconstruction may be performed by removing an acceptable amount of physeal tissue and utilizing soft-tissue grafts with metaphyseal fixation (Fig. 3)[63,93,111]. While the precise amount

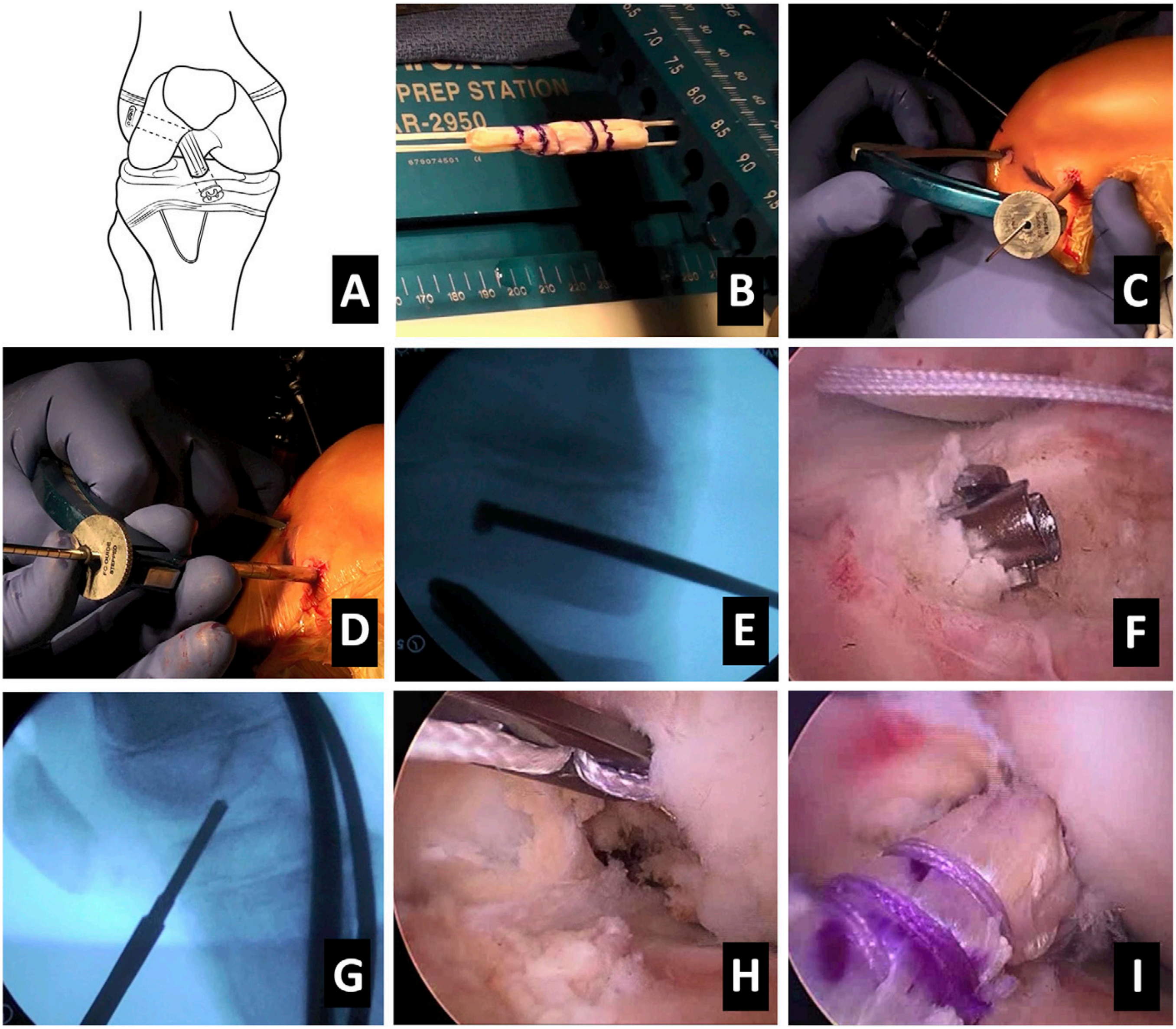

Fig. 2

Figs. 2-A through 2-I The technique for physeal sparing all-epiphyseal ACL reconstruction with hamstring autograft, as previously described in detail[88-90,139]. (Reproduced, with modification, from: Fabricant PD, Jones KJ, Delos D, Cordasco FA, Marx RG, Pearle AD, Warren RF, Green DW. Reconstruction of the anterior cruciate ligament in the skeletally immature athlete: a review of current concepts: AAOS exhibit selection. J Bone Joint Surg Am. 2013;95:e28.) **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.

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[112-114]. 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[115]. 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

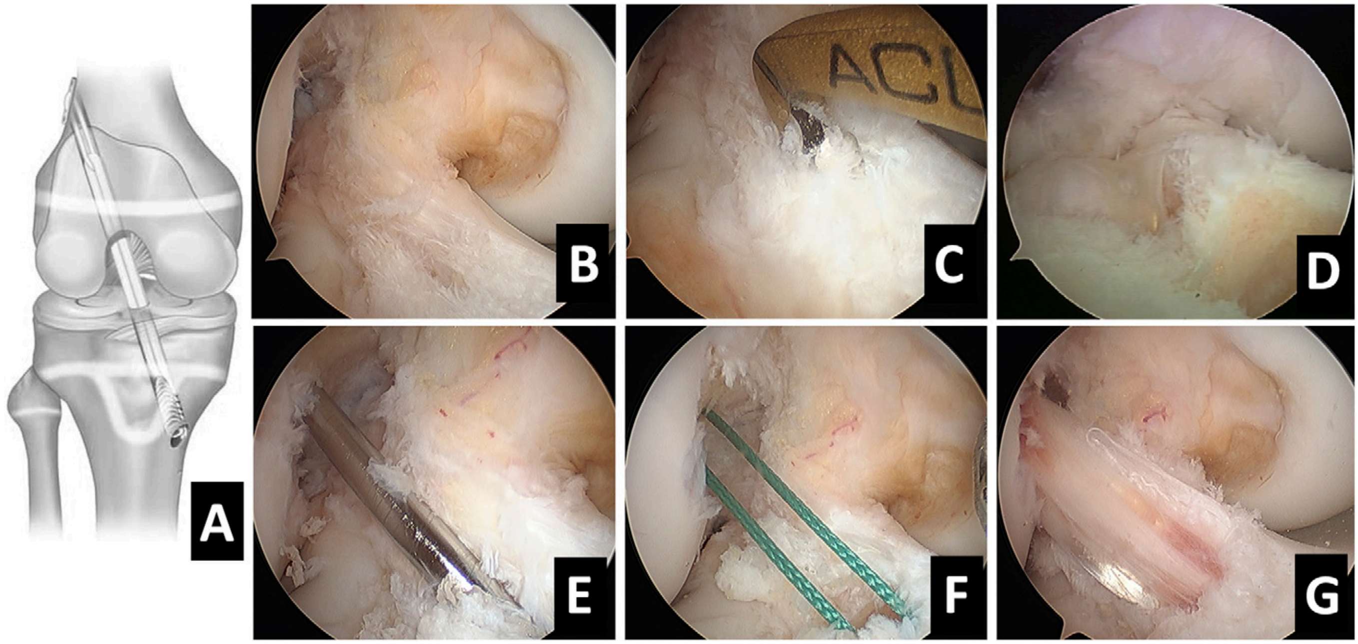

Fig. 3

Figs. 3-A through 3-G Technique for transphyseal ACL reconstruction with hamstring autograft and metaphyseal fixation as previously described in detail[93]. **Fig. 3-A** Drawing of the technique. **Figs. 3-B, 3-C, and 3-D** After debridement of the ACL remnant (**Fig. 3-B**), a guide pin is placed in the posterior portion of the tibial ACL footprint to allow easy access to the over-the-top position (**Fig. 3-C**) and the tibial tunnel is drilled (**Fig. 3-D**). **Fig. 3-E** An appropriate transtibial femoral offset guide is selected, and the femoral guide pin is drilled. Independent femoral tunnel drilling may also be performed using an anteromedial portal or an outside-in technique based upon surgeon preference. **Fig. 3-F** After reaming over the guide pin with a suspensory fixation cortical reamer and measuring with a depth gauge, the femoral tunnel is drilled to the appropriate depth and passing sutures are placed. **Fig. 3-G** The graft is then passed and secured to the lateral femoral cortex with the suspensory button, and a nonmetal metaphyseal tibial interference screw is applied with the knee in extension. The final graft position is anatomical. In hamstring ACL reconstruction, the harvested tendons tend to offer an appropriately sized graft for the patient's anatomy; however, we consider augmenting with allograft for the grafts that are <7 mm in size.

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[93]. No limb length or angular deformities arose. This is in line with other reports of transphyseal ACL reconstructions[12,20,22,23,93,116-120]. 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[12,20-22,117,121]. At a mean follow-up of 2 to 4 years, mean IKDC and Lysholm scores in the 90s have been reported[20,23,93,117,118], with durable results as long as 6 to 10 years postoperatively[22,120]. Arthrofibrosis[93,122] and superficial infections[23] 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[22,23,92,93,119,120].

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.[62] 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[61].

Understanding the clinical outcomes after repair of concomitant injuries allows surgeons to counsel a patient appropriately. Krych et al.[123] 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

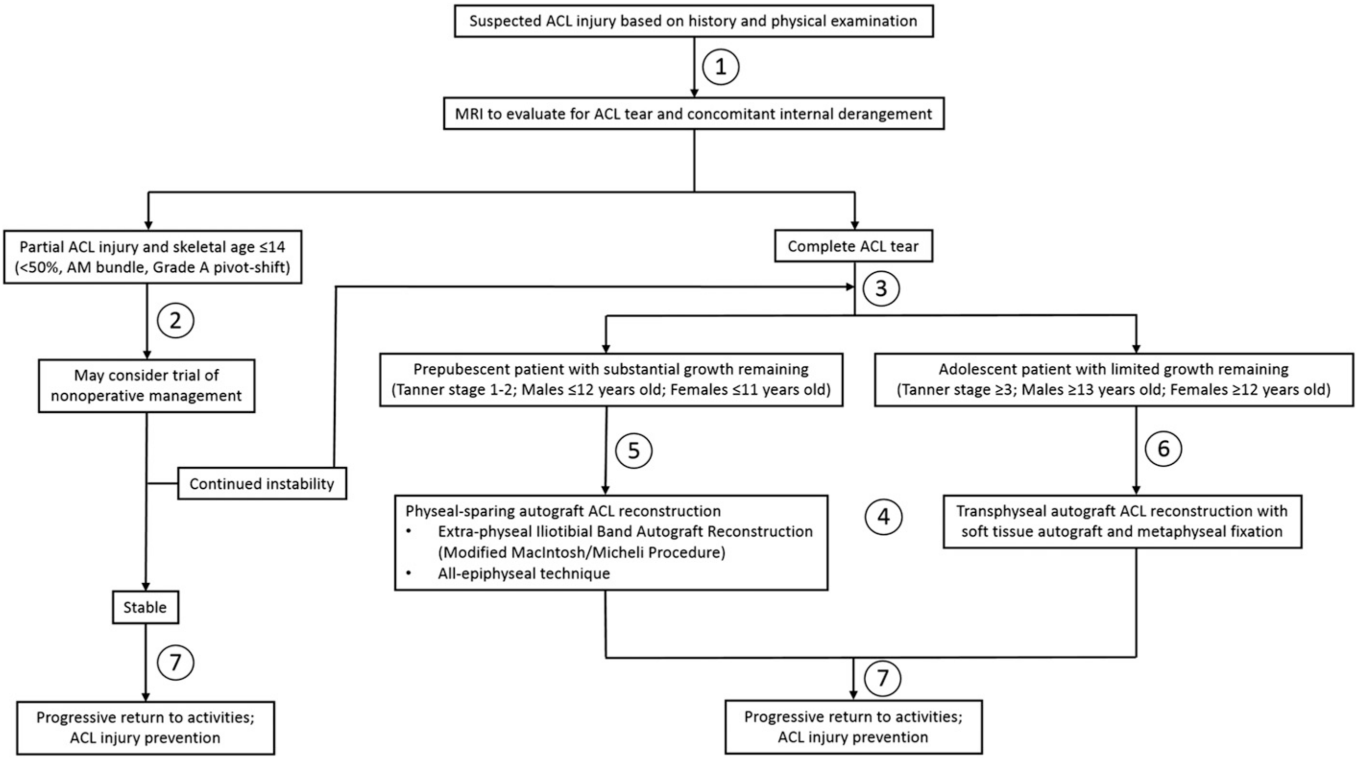

Fig. 4

Diagnostic and treatment flowchart for the management of ACL injury in children and adolescents. Numbers in circles represent the grades of recommendation outlined in **Table II**.

ACL reconstruction without repair of grade-II and III MCL tears[124]. 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[124].

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

No.	Recommendation	Grade*
1	MRI should be acquired to evaluate for ACL injury and concomitant internal derangement if clinical suspicion exists after a thorough history and physical examination.	A
2	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.	C
3	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.	B
4	Primary ACL reconstruction in skeletally immature patients should be performed with autograft tissue.	A
5	Physeal-sparing ACL reconstruction techniques provide surgical options for prepubescent patients (Tanner stage 1 to 2) with complete ACL tears and substantial growth remaining.	C
6	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.	C
7	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.	B

*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[138].

Revision ACL Reconstruction in Youth Athletes

Little has been published to date on revision ACL reconstruction in youth athletes. Christino et al.[125] 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[63,88,90,126-128]. 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[32-35]. Because of the lack of a clear benefit of bracing in a recent systematic review[129], 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[29]. Otherwise, redirection to lower-risk sports and activities is an option[52].

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[130,131]. ■

Peter D. Fabricant, MD, MPH[1]
Mininder S. Kocher, MD, MPH[2,3]

[1]Pediatric Orthopaedic Surgery Service, Hospital for Special Surgery, Weill Cornell Medical College, New York, NY

[2]Division of Sports Medicine, Department of Orthopedic Surgery, Boston Children's Hospital, Boston, Massachusetts

[3]Harvard Medical School, Boston, Massachusetts

E-mail address for P.D. Fabricant: fabricantp@hss.edu
E-mail address for M.S. Kocher: mininder.kocher@childrens.harvard.edu

References

1. Dodwell ER, Lamont LE, Green DW, Pan TJ, Marx RG, Lyman S. 20 years of pediatric anterior cruciate ligament reconstruction in New York State. Am J Sports Med. 2014 Mar;42(3):675-80. Epub 2014 Jan 29.

2. Buller LT, Best MJ, Baraga MG, Kaplan LD. Trends in anterior cruciate ligament reconstruction in the United States. Orthop J Sports Med. 2014 Dec 26;3(1):2325967114563664.

3. Werner BC, Yang S, Looney AM, Gwathmey FW Jr. Trends in pediatric and adolescent anterior cruciate ligament injury and reconstruction. J Pediatr Orthop. 2016 Jul-Aug;36(5):447-52.

4. Fabricant PD, Lakomkin N, Cruz AI, Spitzer E, Marx RG. ACL reconstruction in youth athletes results in an improved rate of return to athletic activity when compared with non-operative treatment: a systematic review of the literature. J ISAKOS. 2016;1:62-9.

5. Fabricant PD, Lakomkin N, Cruz AI, Spitzer E, Lawrence JT, Marx RG. Early ACL reconstruction in children leads to less meniscal and articular cartilage damage when compared with conservative or delayed treatment. J ISAKOS. 2016;1:10-5.

6. Newman JT, Carry PM, Terhune EB, Spruiell MD, Heare A, Mayo M, Vidal AF. Factors predictive of concomitant injuries among children and adolescents undergoing anterior cruciate ligament surgery. Am J Sports Med. 2015 Feb;43(2):282-8. Epub 2014 Dec 23.

7. Anderson AF, Anderson CN. Correlation of meniscal and articular cartilage injuries in children and adolescents with timing of anterior cruciate ligament reconstruction. Am J Sports Med. 2015 Feb;43(2):275-81. Epub 2014 Dec 12.

8. Lawrence JT, Argawal N, Ganley TJ. Degeneration of the knee joint in skeletally immature patients with a diagnosis of an anterior cruciate ligament tear: is there harm in delay of treatment? Am J Sports Med. 2011 Dec;39(12):2582-7. Epub 2011 Sep 14.

9. Dumont GD, Hogue GD, Padalecki JR, Okoro N, Wilson PL. Meniscal and chondral injuries associated with pediatric anterior cruciate ligament tears: relationship of treatment time and patient-specific factors. Am J Sports Med. 2012 Sep;40(9):2128-33. Epub 2012 Jun 22.

10. Kelly PM, Diméglio A. Lower-limb growth: how predictable are predictions? J Child Orthop. 2008 Dec;2(6):407-15. Epub 2008 Aug 29.

11. Shifflett GD, Green DW, Widmann RF, Marx RG. Growth arrest following ACL reconstruction with hamstring autograft in skeletally immature patients: a review of 4 cases. J Pediatr Orthop. 2016 Jun;36(4):355-61.
12. Lipscomb AB, Anderson AF. Tears of the anterior cruciate ligament in adolescents. J Bone Joint Surg Am. 1986 Jan;68(1):19-28.
13. Chotel F, Henry J, Seil R, Chouteau J, Moyen B, Bérard J. Growth disturbances without growth arrest after ACL reconstruction in children. Knee Surg Sports Traumatol Arthrosc. 2010 Nov;18(11):1496-500. Epub 2010 Feb 25.
14. Higuchi T, Hara K, Tsuji Y, Kubo T. Transepiphyseal reconstruction of the anterior cruciate ligament in skeletally immature athletes: an MRI evaluation for epiphyseal narrowing. J Pediatr Orthop B. 2009 Nov;18(6):330-4.
15. Koman JD, Sanders JO. Valgus deformity after reconstruction of the anterior cruciate ligament in a skeletally immature patient. A case report. J Bone Joint Surg Am. 1999 May;81(5):711-5.
16. Lawrence JT, West RL, Garrett WE. Growth disturbance following ACL reconstruction with use of an epiphyseal femoral tunnel: a case report. J Bone Joint Surg Am. 2011 Apr 20;93(8):e39.
17. Robert HE, Casin C. Valgus and flexion deformity after reconstruction of the anterior cruciate ligament in a skeletally immature patient. Knee Surg Sports Traumatol Arthrosc. 2010 Oct;18(10):1369-73. Epub 2009 Nov 28.
18. Kocher MS, Saxon HS, Hovis WD, Hawkins RJ. Management and complications of anterior cruciate ligament injuries in skeletally immature patients: survey of the Herodicus Society and The ACL Study Group. J Pediatr Orthop. 2002 Jul-Aug;22 (4):452-7.
19. Yoo WJ, Kocher MS, Micheli LJ. Growth plate disturbance after transphyseal reconstruction of the anterior cruciate ligament in skeletally immature adolescent patients: an MR imaging study. J Pediatr Orthop. 2011 Sep;31(6):691-6.
20. Cohen M, Ferretti M, Quarteiro M, Marcondes FB, de Hollanda JP, Amaro JT, Abdalla RJ. Transphyseal anterior cruciate ligament reconstruction in patients with open physes. Arthroscopy. 2009 Aug;25(8):831-8.
21. Kohl S, Stutz C, Decker S, Ziebarth K, Slongo T, Ahmad SS, Kohlhof H, Eggli S, Zumstein M, Evangelopoulos DS. Mid-term results of transphyseal anterior cruciate ligament reconstruction in children and adolescents. Knee. 2014 Jan;21(1):80-5. Epub 2013 Aug 21.
22. Kumar S, Ahearne D, Hunt DM. Transphyseal anterior cruciate ligament reconstruction in the skeletally immature: follow-up to a minimum of sixteen years of age. J Bone Joint Surg Am. 2013 Jan 02;95(1):e1.
23. Liddle AD, Imbuldeniya AM, Hunt DM. Transphyseal reconstruction of the anterior cruciate ligament in prepubescent children. J Bone Joint Surg Br. 2008 Oct;90 (10):1317-22.
24. Koch PP, Fucentese SF, Blatter SC. Complications after epiphyseal reconstruction of the anterior cruciate ligament in prepubescent children. Knee Surg Sports Traumatol Arthrosc. 2016 Sep;24(9):2736-40. Epub 2014 Oct 26.
25. Cruz AI Jr, Fabricant PD, McGraw M, Rozell JC, Ganley TJ, Wells L. All-epiphyseal ACL reconstruction in children: review of safety and early complications. J Pediatr Orthop. 2015 Jul 17. Epub 2015 Jul 17.
26. Anderson AF. Transepiphyseal replacement of the anterior cruciate ligament using quadruple hamstring grafts in skeletally immature patients. J Bone Joint Surg Am. 2004 Sep;86(Pt 2)(Suppl 1):201-9.
27. Lo IK, Kirkley A, Fowler PJ, Miniaci A. The outcome of operatively treated anterior cruciate ligament disruptions in the skeletally immature child. Arthroscopy. 1997 Oct;13(5):627-34.
28. Rozbruch SR, Fryman C, Schachter LF, Bigman D, Marx RG. Growth arrest of the tibia after anterior cruciate ligament reconstruction: lengthening and deformity correction with the Taylor Spatial Frame. Am J Sports Med. 2013 Jul;41(7):1636-41. Epub 2013 Apr 25.
29. Myer GD, Ford KR, Barber Foss KD, Liu C, Nick TG, Hewett TE. The relationship of hamstrings and quadriceps strength to anterior cruciate ligament injury in female athletes. Clin J Sport Med. 2009 Jan;19(1):3-8.
30. Gilchrist J, Mandelbaum BR, Melancon H, Ryan GW, Silvers HJ, Griffin LY, Watanabe DS, Dick RW, Dvorak J. A randomized controlled trial to prevent noncontact anterior cruciate ligament injury in female collegiate soccer players. Am J Sports Med. 2008 Aug;36(8):1476-83.
31. Sugimoto D, Myer GD, Foss KD, Hewett TE. Specific exercise effects of preventive neuromuscular training intervention on anterior cruciate ligament injury risk reduction in young females: meta-analysis and subgroup analysis. Br J Sports Med. 2015 Mar;49(5):282-9. Epub 2014 Dec 1.
32. Swart E, Redler L, Fabricant PD, Mandelbaum BR, Ahmad CS, Wang YC. Prevention and screening programs for anterior cruciate ligament injuries in young athletes: a cost-effectiveness analysis. J Bone Joint Surg Am. 2014 May 07;96 (9):705-11.
33. Hewett TE, Myer GD, Ford KR, Heidt RS Jr, Colosimo AJ, McLean SG, van den Bogert AJ, Paterno MV, Succop P. Biomechanical measures of neuromuscular control and valgus loading of the knee predict anterior cruciate ligament injury risk in female athletes: a prospective study. Am J Sports Med. 2005 Apr;33(4):492-501. Epub 2005 Feb 8.
34. Mandelbaum BR, Silvers HJ, Watanabe DS, Knarr JF, Thomas SD, Griffin LY, Kirkendall DT, Garrett W Jr. Effectiveness of a neuromuscular and proprioceptive training program in preventing anterior cruciate ligament injuries in female athletes: 2-year follow-up. Am J Sports Med. 2005 Jul;33(7):1003-10. Epub 2005 May 11.
35. Hewett TE, Ford KR, Myer GD. Anterior cruciate ligament injuries in female athletes: part 2, a meta-analysis of neuromuscular interventions aimed at injury prevention. Am J Sports Med. 2006 Mar;34(3):490-8. Epub 2005 Dec 28.
36. Grimm NL, Shea KG, Leaver RW, Aoki SK, Carey JL. Efficacy and degree of bias in knee injury prevention studies: a systematic review of RCTs. Clin Orthop Relat Res. 2013 Jan;471(1):308-16. Epub 2012 Sep 8.
37. Hattori K, Sano H, Komatsuda T, Saijo Y, Sugita T, Itoi E. Effect of estrogen on tissue elasticity of the ligament proper in rabbit anterior cruciate ligament: measurements using scanning acoustic microscopy. J Orthop Sci. 2010 Jul;15(4):584-8. Epub 2010 Aug 19.
38. Komatsuda T, Sugita T, Sano H, Kusakabe T, Watanuki M, Yoshizumi Y, Murakami T, Hashimoto M, Kokubun S. Does estrogen alter the mechanical properties of the anterior cruciate ligament? An experimental study in rabbits. Acta Orthop. 2006 Dec;77(6):973-80.
39. Dragoo JL, Padrez K, Workman R, Lindsey DP. The effect of relaxin on the female anterior cruciate ligament: analysis of mechanical properties in an animal model. Knee. 2009 Jan;16(1):69-72. Epub 2008 Oct 28.
40. Park SK, Stefanyshyn DJ, Loitz-Ramage B, Hart DA, Ronsky JL. Changing hormone levels during the menstrual cycle affect knee laxity and stiffness in healthy female subjects. Am J Sports Med. 2009 Mar;37(3):588-98. Epub 2009 Jan 27.
41. Zazulak BT, Paterno M, Myer GD, Romani WA, Hewett TE. The effects of the menstrual cycle on anterior knee laxity: a systematic review. Sports Med. 2006;36 (10):847-62.
42. Alentorn-Geli E, Myer GD, Silvers HJ, Samitier G, Romero D, Lázaro-Haro C, Cugat R. Prevention of non-contact anterior cruciate ligament injuries in soccer players. Part 1: mechanisms of injury and underlying risk factors. Knee Surg Sports Traumatol Arthrosc. 2009 Jul;17(7):705-29. Epub 2009 May 19.
43. Dare DM, Fabricant PD, McCarthy MM, Rebolledo BJ, Green DW, Cordasco FA, Jones KJ. Increased lateral tibial slope is a risk factor for pediatric anterior cruciate ligament injury: An MRI-based case-control study of 152 patients. Am J Sports Med. 2015 Jul;43(7):1632-9.
44. Shaw KA, Dunoski B, Mardis N, Pacicca D. Knee morphometric risk factors for acute anterior cruciate ligament injury in skeletally immature patients. J Child Orthop. 2015 Apr;9(2):161-8. Epub 2015 Mar 28.
45. O'Malley MP, Milewski MD, Solomito MJ, Erwteman AS, Nissen CW. The association of tibial slope and anterior cruciate ligament rupture in skeletally immature patients. Arthroscopy. 2015 Jan;31(1):77-82. Epub 2014 Sep 16.
46. Swami VG, Mabee M, Hui C, Jaremko JL. Three-dimensional intercondylar notch volumes in a skeletally immature pediatric population: a magnetic resonance imaging-based anatomic comparison of knees with torn and intact anterior cruciate ligaments. Arthroscopy. 2013 Dec;29(12):1954-62.
47. Christensen JJ, Krych AJ, Engasser WM, Vanhees MK, Collins MS, Dahm DL. Lateral tibial posterior slope is increased in patients with early graft failure after anterior cruciate ligament reconstruction. Am J Sports Med. 2015 Oct;43(10):2510-4. Epub 2015 Aug 28.
48. Vyas S, van Eck CF, Vyas N, Fu FH, Otsuka NY. Increased medial tibial slope in teenage pediatric population with open physes and anterior cruciate ligament injuries. Knee Surg Sports Traumatol Arthrosc. 2011 Mar;19(3):372-7. Epub 2010 Jul 30.
49. Harmon KG, Ireland ML. Gender differences in noncontact anterior cruciate ligament injuries. Clin Sports Med. 2000 Apr;19(2):287-302.
50. LaBella CR, Hennrikus W, Hewett TE; Council on Sports Medicine and Fitness, and Section on Orthopaedics. Anterior cruciate ligament injuries: diagnosis, treatment, and prevention. Pediatrics. 2014 May;133(5):e1437-50.
51. Toth AP, Cordasco FA. Anterior cruciate ligament injuries in the female athlete. J Gend Specif Med. 2001;4(4):25-34.
52. Gornitzky AL, Lott A, Yellin JL, Fabricant PD, Lawrence JT, Ganley TJ. Sport-specific yearly risk and incidence of anterior cruciate ligament tears in high school athletes: a systematic review and meta-analysis. Am J Sports Med. 2016 Oct;44 (10):2716-23. Epub 2015 Dec 11.
53. Drakos MC, Hillstrom H, Voos JE, Miller AN, Kraszewski AP, Wickiewicz TL, Warren RF, Allen AA, O'Brien SJ. The effect of the shoe-surface interface in the development of anterior cruciate ligament strain. J Biomech Eng. 2010 Jan;132 (1):011003.
54. Taylor SA, Fabricant PD, Khair MM, Haleem AM, Drakos MC. A review of synthetic playing surfaces, the shoe-surface interface, and lower extremity injuries in athletes. Phys Sportsmed. 2012 Nov;40(4):66-72.
55. Drakos MC, Taylor SA, Fabricant PD, Haleem AM. Synthetic playing surfaces and athlete health. J Am Acad Orthop Surg. 2013 May;21(5):293-302.
56. Stanitski CL, Harvell JC, Fu F. Observations on acute knee hemarthrosis in children and adolescents. J Pediatr Orthop. 1993 Jul-Aug;13(4):506-10.

57. Abbasi D, May MM, Wall EJ, Chan G, Parikh SN. MRI findings in adolescent patients with acute traumatic knee hemarthrosis. J Pediatr Orthop. 2012 Dec;32(8):760-4.

58. Leblanc MC, Kowalczuk M, Andruszkiewicz N, Simunovic N, Farrokhyar F, Turnbull TL, Debski RE, Ayeni OR. Diagnostic accuracy of physical examination for anterior knee instability: a systematic review. Knee Surg Sports Traumatol Arthrosc. 2015 Oct;23(10):2805-13. Epub 2015 Mar 13.

59. Baxter MP. Assessment of normal pediatric knee ligament laxity using the Genucom. J Pediatr Orthop. 1988 Sep-Oct;8(5):546-50.

60. Lee K, Siegel MJ, Lau DM, Hildebolt CF, Matava MJ. Anterior cruciate ligament tears: MR imaging-based diagnosis in a pediatric population. Radiology. 1999 Dec;213(3):697-704.

61. Piasecki DP, Spindler KP, Warren TA, Andrish JT, Parker RD. Intraarticular injuries associated with anterior cruciate ligament tear: findings at ligament reconstruction in high school and recreational athletes. An analysis of sex-based differences. Am J Sports Med. 2003 Jul-Aug;31(4):601-5.

62. Vavken P, Tepolt FA, Kocher MS. Concurrent meniscal and chondral injuries in pediatric and adolescent patients undergoing ACL reconstruction. J Pediatr Orthop. 2016 May 12. Epub 2016 May 12.

63. Fabricant PD, Jones KJ, Delos D, Cordasco FA, Marx RG, Pearle AD, Warren RF, Green DW. Reconstruction of the anterior cruciate ligament in the skeletally immature athlete: a review of current concepts: AAOS exhibit selection. J Bone Joint Surg Am. 2013 Mar 06;95(5):e28.

64. Zerin JM, Hernandez RJ. Approach to skeletal maturation. Hand Clin. 1991 Feb;7(1):53-62.

65. Acheson RM, Fowler G, Fry EI, Janes M, Koski K, Urbano P, Werfftenboschjj VA. Studies in the reliability of assessing skeletal maturity from X-rays. I. Greulich-Pyle atlas. Hum Biol. 1963 Sep;35:317-49.

66. Heyworth BE, Osei DA, Fabricant PD, Schneider R, Doyle SM, Green DW, Widmann RF, Lyman S, Burke SW, Scher DM. The shorthand bone age assessment: a simpler alternative to current methods. J Pediatr Orthop. 2013 Jul-Aug;33(5):569-74.

67. Diméglio A, Charles YP, Daures JP, de Rosa V, Kaboré B. Accuracy of the Sauvegrain method in determining skeletal age during puberty. J Bone Joint Surg Am. 2005 Aug;87(8):1689-96.

68. Hans SD, Sanders JO, Cooperman DR. Using the Sauvegrain method to predict peak height velocity in boys and girls. J Pediatr Orthop. 2008 Dec;28(8):836-9.

69. Nicholson AD, Liu RW, Sanders JO, Cooperman DR. Relationship of calcaneal and iliac apophyseal ossification to peak height velocity timing in children. J Bone Joint Surg Am. 2015 Jan 21;97(2):147-54.

70. Sitoula P, Verma K, Holmes L Jr, Gabos PG, Sanders JO, Yorgova P, Neiss G, Rogers K, Shah SA. Prediction of curve progression in idiopathic scoliosis: validation of the Sanders skeletal maturity staging system. Spine (Phila Pa 1976). 2015 Jul 01;40(13):1006-13.

71. Granados A, Gebremariam A, Lee JM. Relationship between timing of peak height velocity and pubertal staging in boys and girls. J Clin Res Pediatr Endocrinol. 2015 Sep;7(3):235-7.

72. Woods GW, O'Connor DP. Delayed anterior cruciate ligament reconstruction in adolescents with open physes. Am J Sports Med. 2004 Jan-Feb;32(1):201-10.

73. McCarroll JR, Rettig AC, Shelbourne KD. Anterior cruciate ligament injuries in the young athlete with open physes. Am J Sports Med. 1988 Jan-Feb;16(1):44-7.

74. Mizuta H, Kubota K, Shiraishi M, Otsuka Y, Nagamoto N, Takagi K. The conservative treatment of complete tears of the anterior cruciate ligament in skeletally immature patients. J Bone Joint Surg Br. 1995 Nov;77(6):890-4.

75. Moksnes H, Engebretsen L, Risberg MA. Prevalence and incidence of new meniscus and cartilage injuries after a nonoperative treatment algorithm for ACL tears in skeletally immature children: a prospective MRI study. Am J Sports Med. 2013 Aug;41(8):1771-9. Epub 2013 Jun 14.

76. Fabricant PD, Lakomkin N, Sugimoto D, Tepolt FA, Stracciolini A, Kocher MS. Youth sports specialization and musculoskeletal injury: a systematic review of the literature. Phys Sportsmed. 2016 Sep;44(3):257-62. Epub 2016 May 3.

77. Graf BK, Lange RH, Fujisaki CK, Landry GL, Saluja RK. Anterior cruciate ligament tears in skeletally immature patients: meniscal pathology at presentation and after attempted conservative treatment. Arthroscopy. 1992;8(2):229-33.

78. Aichroth PM, Patel DV, Zorrilla P. The natural history and treatment of rupture of the anterior cruciate ligament in children and adolescents. A prospective review. J Bone Joint Surg Br. 2002 Jan;84(1):38-41.

79. Funahashi KM, Moksnes H, Maletis GB, Csintalan RP, Inacio MC, Funahashi TT. Anterior cruciate ligament injuries in adolescents with open physis: effect of recurrent injury and surgical delay on meniscal and cartilage injuries. Am J Sports Med. 2014 May;42(5):1068-73. Epub 2014 Mar 14.

80. Henry J, Chotel F, Chouteau J, Fessy MH, Bérard J, Moyen B. Rupture of the anterior cruciate ligament in children: early reconstruction with open physes or delayed reconstruction to skeletal maturity? Knee Surg Sports Traumatol Arthrosc. 2009 Jul;17(7):748-55. Epub 2009 Feb 28.

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

82. Vavken P, Murray MM. Treating anterior cruciate ligament tears in skeletally immature patients. Arthroscopy. 2011 May;27(5):704-16.

83. Reid D, Leigh W, Wilkins S, Willis R, Twaddle B, Walsh S. A 10-year retrospective review of functional outcomes of adolescent anterior cruciate ligament reconstruction. J Pediatr Orthop. 2015 Jul 09. [Epub ahead of print].

84. Ramski DE, Kanj WW, Franklin CC, Baldwin KD, Ganley TJ. Anterior cruciate ligament tears in children and adolescents: a meta-analysis of nonoperative versus operative treatment. Am J Sports Med. 2014 Nov;42(11):2769-76. Epub 2013 Dec 4.

85. Kocher MS, Micheli LJ, Zurakowski D, Luke A. Partial tears of the anterior cruciate ligament in children and adolescents. Am J Sports Med. 2002 Sep-Oct;30(5):697-703.

86. Kocher MS, Garg S, Micheli LJ. Physeal sparing reconstruction of the anterior cruciate ligament in skeletally immature prepubescent children and adolescents. J Bone Joint Surg Am. 2005 Nov;87(11):2371-9.

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

88. Fabricant PD, McCarthy MM, Cordasco FA, Green DW. All-inside, all-epiphyseal autograft reconstruction of the anterior cruciate ligament in the skeletally immature athlete. JBJS Essent Surg Tech. 2013 May 8;3(2):e9.

89. Lawrence JT, Bowers AL, Belding J, Cody SR, Ganley TJ. All-epiphyseal anterior cruciate ligament reconstruction in skeletally immature patients. Clin Orthop Relat Res. 2010 Jul;468(7):1971-7. Epub 2010 Feb 20.

90. McCarthy MM, Graziano J, Green DW, Cordasco FA. All-epiphyseal, all-inside anterior cruciate ligament reconstruction technique for skeletally immature patients. Arthrosc Tech. 2012 Nov 22;1(2):e231-9.

91. Demange MK, Camanho GL. Nonanatomic anterior cruciate ligament reconstruction with double-stranded semitendinosus grafts in children with open physes: minimum 15-year follow-up. Am J Sports Med. 2014 Dec;42(12):2926-32. Epub 2014 Oct 1.

92. Lemaitre G, Salle de Chou E, Pineau V, Rochcongar G, Delforge S, Bronfen C, Haumont T, Hulet C. ACL reconstruction in children: a transphyseal technique. Orthop Traumatol Surg Res. 2014 Jun;100(4)(Suppl):S261-5. Epub 2014 Apr 4.

93. Kocher MS, Smith JT, Zoric BJ, Lee B, Micheli LJ. Transphyseal anterior cruciate ligament reconstruction in skeletally immature pubescent adolescents. J Bone Joint Surg Am. 2007 Dec;89(12):2632-9.

94. Ho B, Edmonds EW, Chambers HG, Bastrom TP, Pennock AT. Risk factors for early ACL reconstruction failure in pediatric and adolescent patients: a review of 561 cases. J Pediatr Orthop. 2016 Jul 2. [Epub ahead of print].

95. Kennedy A, Coughlin DG, Metzger MF, Tang R, Pearle AD, Lotz JC, Feeley BT. Biomechanical evaluation of pediatric anterior cruciate ligament reconstruction techniques. Am J Sports Med. 2011 May;39(5):964-71. Epub 2011 Jan 21.

96. McCarthy MM, Tucker S, Nguyen JT, Green DW, Imhauser CW, Cordasco FA. Contact stress and kinematic analysis of all-epiphyseal and over-the-top pediatric reconstruction techniques for the anterior cruciate ligament. Am J Sports Med. 2013 Jun;41(6):1330-9. Epub 2013 Apr 23.

97. Engelman GH, Carry PM, Hitt KG, Polousky JD, Vidal AF. Comparison of allograft versus autograft anterior cruciate ligament reconstruction graft survival in an active adolescent cohort. Am J Sports Med. 2014 Oct;42(10):2311-8. Epub 2014 Jul 31.

98. Ellis HB, Matheny LM, Briggs KK, Pennock AT, Steadman JR. Outcomes and revision rate after bone-patellar tendon-bone allograft versus autograft anterior cruciate ligament reconstruction in patients aged 18 years or younger with closed physes. Arthroscopy. 2012 Dec;28(12):1819-25. Epub 2012 Oct 24.

99. Kaeding CC, Aros B, Pedroza A, Pifel E, Amendola A, Andrish JT, Dunn WR, Marx RG, McCarty EC, Parker RD, Wright RW, Spindler KP. Allograft versus autograft anterior cruciate ligament reconstruction: predictors of failure from a MOON prospective longitudinal cohort. Sports Health. 2011 Jan;3(1):73-81.

100. Vincent JP, Magnussen RA, Gezmez F, Uguen A, Jacobi M, Weppe F, Al-Saati MF, Lustig S, Demey G, Servien E, Neyret P. The anterolateral ligament of the human knee: an anatomic and histologic study. Knee Surg Sports Traumatol Arthrosc. 2012 Jan;20(1):147-52. Epub 2011 Jun 30.

101. Parsons EM, Gee AO, Spiekerman C, Cavanagh PR. The biomechanical function of the anterolateral ligament of the knee. Am J Sports Med. 2015 Mar;43(3):669-74. Epub 2015 Jan 2.

102. Claes S, Vereecke E, Maes M, Victor J, Verdonk P, Bellemans J. Anatomy of the anterolateral ligament of the knee. J Anat. 2013 Oct;223(4):321-8. Epub 2013 Aug 1.

103. Kocher MS, Heyworth BE, Tepolt F, Fabricant PD, Micheli LJ. Outcomes of physeal sparing ACL reconstruction with IT band in skeletally immature children. Unpublished data.

104. Fanelli D, Hennrikus W. Pediatric ACL reconstruction with iliotibial band autograft. J Knee Surg. [In press].

105. Willimon SC, Jones CR, Herzog MM, May KH, Leake MJ, Busch MT. Micheli anterior cruciate ligament reconstruction in skeletally immature youths: a retrospective case series with a mean 3-year follow-up. Am J Sports Med. 2015 Dec;43(12):2974-81. Epub 2015 Oct 23.

106. Erdman MK, Warnick DE. Revision pediatric anterior cruciate ligament reconstruction after failure of iliotibial band technique treated with all-epiphyseal technique in a prepubescent with Ehlers-Danlos syndrome: a case report. J Pediatr Orthop B. 2016 Mar 16. Epub 2016 Mar 16.

107. Cruz AI Jr, Fabricant PD, Seeley MA, Ganley TJ, Lawrence JT. Change in size of hamstring grafts during preparation for ACL reconstruction: effect of tension and circumferential compression on graft diameter. J Bone Joint Surg Am. 2016 Mar 16;98(6):484-9.

108. Cassard X, Cavaignac E, Maubisson L, Bowen M. Anterior cruciate ligament reconstruction in children with a quadrupled semitendinosus graft: preliminary results with minimum 2 years of follow-up. J Pediatr Orthop. 2014 Jan;34(1):70-7.

109. Cordasco FA, Mayer SW, Green DW. All-inside, all-epiphyseal anterior cruciate ligament reconstruction in skeletally immature athletes. Am J Sports Med. 2016 Dec 1. [Epub ahead of print].

110. Nawabi DH, Jones KJ, Lurie B, Potter HG, Green DW, Cordasco FA. All-inside, physeal-sparing anterior cruciate ligament reconstruction does not significantly compromise the physis in skeletally immature athletes: a postoperative physeal magnetic resonance imaging analysis. Am J Sports Med. 2014 Dec;42(12):2933-40. Epub 2014 Oct 16.

111. Gausden EB, Calcei JG, Fabricant PD, Green DW. Surgical options for anterior cruciate ligament reconstruction in the young child. Curr Opin Pediatr. 2015 Feb;27(1):82-91.

112. Mäkelä EA, Vainionpää S, Vihtonen K, Mero M, Rokkanen P. The effect of trauma to the lower femoral epiphyseal plate. An experimental study in rabbits. J Bone Joint Surg Br. 1988 Mar;70(2):187-91.

113. Janarv PM, Wikström B, Hirsch G. The influence of transphyseal drilling and tendon grafting on bone growth: an experimental study in the rabbit. J Pediatr Orthop. 1998 Mar-Apr;18(2):149-54.

114. Stadelmaier DM, Arnoczky SP, Dodds J, Ross H. The effect of drilling and soft tissue grafting across open growth plates. A histologic study. Am J Sports Med. 1995 Jul-Aug;23(4):431-5.

115. Cruz AI Jr, Lakomkin N, Fabricant PD, Lawrence JT. Transphyseal ACL reconstruction in skeletally immature patients: does independent femoral tunnel drilling place the physis at greater risk compared with transtibial drilling? Orthop J Sports Med. 2016 Jun 7;4(6):2325967116650432.

116. Courvoisier A, Grimaldi M, Plaweski S. Good surgical outcome of transphyseal ACL reconstruction in skeletally immature patients using four-strand hamstring graft. Knee Surg Sports Traumatol Arthrosc. 2011 Apr;19(4):588-91. Epub 2010 Oct 2.

117. McIntosh AL, Dahm DL, Stuart MJ. Anterior cruciate ligament reconstruction in the skeletally immature patient. Arthroscopy. 2006 Dec;22(12):1325-30.

118. Aronowitz ER, Ganley TJ, Goode JR, Gregg JR, Meyer JS. Anterior cruciate ligament reconstruction in adolescents with open physes. Am J Sports Med. 2000 Mar-Apr;28(2):168-75.

119. Hui C, Roe J, Ferguson D, Waller A, Salmon L, Pinczewski L. Outcome of anatomic transphyseal anterior cruciate ligament reconstruction in Tanner stage 1 and 2 patients with open physes. Am J Sports Med. 2012 May;40(5):1093-8. Epub 2012 Mar 5.

120. Calvo R, Figueroa D, Gili F, Vaisman A, Mocoçain P, Espinosa M, León A, Arellano S. Transphyseal anterior cruciate ligament reconstruction in patients with open physes: 10-year follow-up study. Am J Sports Med. 2015 Feb;43(2):289-94. Epub 2014 Nov 17.

121. Seon JK, Song EK, Yoon TR, Park SJ. Transphyseal reconstruction of the anterior cruciate ligament using hamstring autograft in skeletally immature adolescents. J Korean Med Sci. 2005 Dec;20(6):1034-8.

122. Nwachukwu BU, McFeely ED, Nasreddine A, Udall JH, Finlayson C, Shearer DW, Micheli LJ, Kocher MS. Arthrofibrosis after anterior cruciate ligament reconstruction in children and adolescents. J Pediatr Orthop. 2011 Dec;31(8):811-7.

123. Krych AJ, Pitts RT, Dajani KA, Stuart MJ, Levy BA, Dahm DL. Surgical repair of meniscal tears with concomitant anterior cruciate ligament reconstruction in patients 18 years and younger. Am J Sports Med. 2010 May;38(5):976-82. Epub 2010 Mar 18.

124. Sankar WN, Wells L, Sennett BJ, Wiesel BB, Ganley TJ. Combined anterior cruciate ligament and medial collateral ligament injuries in adolescents. J Pediatr Orthop. 2006 Nov-Dec;26(6):733-6.

125. Christino MA, Tepolt FA, Sugimoto D, Micheli LJ, Kocher MS. Revision ACL reconstruction in children and adolescents. Unpublished data.

126. Akinleye SD, Sewick A, Wells L. All-epiphyseal ACL reconstruction: a three-year follow-up. Int J Sports Phys Ther. 2013 Jun;8(3):300-10.

127. Greenberg EM, Albaugh J, Ganley TJ, Lawrence JT. Rehabilitation considerations for all epiphyseal ACL reconstruction. Int J Sports Phys Ther. 2012 Apr;7(2):185-96.

128. Yellin JL, Fabricant PD, Gornitzky A, Greenberg EM, Conrad S, Dyke JA, Ganley TJ. Rehabilitation following anterior cruciate ligament tears in children: a systematic review. JBJS Rev. 2016 Jan 19;4(1):e4.

129. Kruse LM, Gray B, Wright RW. Rehabilitation after anterior cruciate ligament reconstruction: a systematic review. J Bone Joint Surg Am. 2012 Oct 03;94(19):1737-48.

130. Fabricant PD, Robles A, Downey-Zayas T, Do HT, Marx RG, Widmann RF, Green DW. Development and validation of a pediatric sports activity rating scale: the Hospital for Special Surgery pediatric functional activity brief scale (HSS pedi-FABS). Am J Sports Med. 2013 Oct;41(10):2421-9. Epub 2013 Jul 26.

131. Kocher MS, Smith JT, Iversen MD, Brustowicz K, Ogunwole O, Andersen J, Yoo WJ, McFeely ED, Anderson AF, Zurakowski D. Reliability, validity, and responsiveness of a modified International Knee Documentation Committee Subjective Knee Form (Pedi-IKDC) in children with knee disorders. Am J Sports Med. 2011 May;39(5):933-9. Epub 2010 Nov 10.

132. Guzzanti V, Falciglia F, Stanitski CL. Physeal-sparing intraarticular anterior cruciate ligament reconstruction in preadolescents. Am J Sports Med. 2003 Nov-Dec;31(6):949-53.

133. Sankar WN, Carrigan RB, Gregg JR, Ganley TJ. Anterior cruciate ligament reconstruction in adolescents: a survivorship analysis. Am J Orthop (Belle Mead NJ). 2008 Jan;37(1):47-9.

134. Nikolaou P, Kalliakmanis A, Bousgas D, Zourntos S. Intraarticular stabilization following anterior cruciate ligament injury in children and adolescents. Knee Surg Sports Traumatol Arthrosc. 2011 May;19(5):801-5. Epub 2011 Feb 3.

135. Redler LH, Brafman RT, Trentacosta N, Ahmad CS. Anterior cruciate ligament reconstruction in skeletally immature patients with transphyseal tunnels. Arthroscopy. 2012 Nov;28(11):1710-7. Epub 2012 Aug 27.

136. Goddard M, Bowman N, Salmon LJ, Waller A, Roe JP, Pinczewski LA. Endoscopic anterior cruciate ligament reconstruction in children using living donor hamstring tendon allografts. Am J Sports Med. 2013 Mar;41(3):567-74. Epub 2013 Jan 31.

137. Schmale GA, Kweon C, Larson RV, Bompadre V. High satisfaction yet decreased activity 4 years after transphyseal ACL reconstruction. Clin Orthop Relat Res. 2014 Jul;472(7):2168-74. Epub 2014 Mar 15.

138. Wright JG. Revised grades of recommendation for summaries or reviews of orthopaedic surgical studies. J Bone Joint Surg Am. 2006 May;88(5):1161-2.

139. Anderson AF. Transepiphyseal replacement of the anterior cruciate ligament in skeletally immature patients. A preliminary report. J Bone Joint Surg Am. 2003 Jul;85(7):1255-63.