Comparing Outcomes Between the Over-the-Top and All-Epiphyseal Techniques for Physeal-Sparing ACL Reconstruction

A Narrative Review

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A variety of techniques are used for physeal-sparing anterior cruciate ligament (ACL) reconstruction; however, there is no clear consensus on the ideal surgical technique, the frequency of complications, and how to best avoid growth disturbance. The purpose of this study was to compare outcomes and complications between over-the-top and all-epiphyseal ACL reconstruction techniques. The hypothesis was that both physeal-sparing reconstruction techniques are efficacious, with similar risk of growth disturbance and complications. The Embase and PubMed databases were queried for studies on ACL ruptures in the skeletally immature population from 1985 to 2018. Full-text English studies were included (N = 160). Studies reporting rerupture and/or complications after physeal-sparing ACL reconstruction, specifically growth disturbance, were included (n = 10). Studies were separated into 2 groups: an all-epiphyseal group with femoral and tibial fixation points within the epiphysis and a group that had over-the-top femoral and tibial physeal-sparing reconstruction. Complications not specific to the pediatric population were excluded. Demographics, evaluation of skeletal maturity, surgical technique, growth disturbance, rerupture, and patient-reported outcome scores were collected. Data were analyzed in aggregate. The 10 studies included 482 knees. The mean age was 12.0 years; 81% of patients were male; and mean follow-up was 47.7 months. A total of 178 patients underwent all-epiphyseal reconstruction, and 298 had the femoral graft placed over the top. The rerupture rate was 9.0% (16 of 178) in the all-epiphyseal group and 7.2% (14 of 195) in the over-the-top group, of which 82% required revision reconstruction. Six patients had overgrowth in the all-epiphyseal group (mean, 1.8 cm) and 1 patient in the over-the-top group (1.5 cm). Three angular deformities occurred, all of which were in the over-the-top group. Both physeal-sparing ACL reconstruction techniques are successful. Overgrowth was more common in the all-epiphyseal group and angular deformity in the over-the-top group. Rerupture rates were similar between the groups. The authors recommend standardization of skeletal age assessment and baseline lower extremity alignment films.

Keywords: anterior cruciate ligament; ACL; pediatric sports medicine; physeal sparing; skeletally immature

The incidence of anterior cruciate ligament (ACL) injuries has been increasing among young patients in recent years.[3,40] Swenson et al[38] found that ACL injuries accounted for one-fourth of all high school knee injuries. Increased participation in youth competitive sports, early specialization, year-round training, and improved recognition of ACL injuries contribute to the increase in incidence of ACL injuries among children and adolescents. With this increase of ACL injuries, there has been a concomitant increase in surgical intervention. Between 1994 and 2006, the rate of ACL reconstruction increased among young patients.[6,23] Christino et al[7] described a 924% increase among those aged <15 years.

Early operative intervention for pediatric ACL ruptures is often advocated owing to concerns about recurrent

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instability and meniscal and chondral injury, potentially contributing to early osteoarthritis with nonoperative treatment or delayed reconstruction after skeletal maturity.[12,14] Surgical techniques for pediatric ACL reconstruction are varied and include physeal sparing, partial transphyseal, and complete transphyseal.[1,2,12,21] While the rate of ACL reconstruction increases, there is no consensus on the ideal technique.

In the pediatric population, with significant growth remaining, concerns regarding potential growth disturbance play a large role in determining which ACL reconstruction technique is utilized. Various techniques have been described for ACL reconstruction among skeletally immature patients, with the focus on physeal-sparing approaches for those with the most potential growth remaining. Physeal-sparing techniques include combined intra- and extra-articular reconstruction with an iliotibial (IT) band autograft placed in an over-the-top position on the femur, as described by Micheli et al.[24] The all-epiphyseal technique allows for anatomic reconstruction by placing the tunnels within the femoral and tibial epiphyses, without violation of the physes.

IT band autograft reconstruction as described by Micheli et al,[24] also known as the modified MacIntosh procedure, involves a combined intra- and extra-articular reconstruction where a strip of IT band is detached proximally and left attached to the Gerdy tubercle distally. The distal IT band is freed from the lateral patellar retinaculum and tubularized with suture. Standard knee arthroscopy is then performed with meniscal and chondral pathology addressed as needed. An over-the-top position on the femur and an over-the-front position under the intermeniscal ligament are then identified. The free end of the IT band autograft is then passed over the top of the lateral femoral condyle and then into the joint and under the intermeniscal ligament. A small trough is made in the anterior tibial epiphysis, and the graft is secured to the proximal tibial periosteum. Similar techniques include the Clocheville procedure,[5] with a groove created within the tibial epiphysis and the graft placed in a similar over-the-top position on the femur. These reconstructions are most commonly indicated for Tanner stage 1 or 2. There is a relatively long-term follow-up available for the modified MacIntosh procedure.[19] One potential disadvantage of this reconstruction is the nonanatomic graft position on the femur and concerns about rotational control and isometry of the graft.

The other physeal-sparing technique—described as all-epiphyseal, all-inside, or transepiphyseal[1]—involves femoral and tibial tunnel placement within the epiphyses. Anderson[1] described this technique using a doubled semitendinosus and gracilis tendon autograft on a button device. Following the hamstring harvest, standard knee arthroscopy is performed with meniscal and chondral pathology addressed as needed. A C-arm is used intraoperatively to locate the femoral tunnel within the femoral epiphysis on anteroposterior and lateral views. A guide wire is drilled outside-in within the femoral epiphysis, with care to avoid the distal femoral physis and with arthroscopic confirmation of the location of the guide wire: 1 mm posterior and superior to the center of the anatomic footprint ACL on the femur. A second guide wire is inserted through the anteromedial aspect of the tibia within the epiphysis. Again, a C-arm is used to confirm that this wire is within the epiphysis and not violating the physis. The hamstring autograft is sized, and tunnels are drilled over the guide wires as appropriate. A passing suture is used to pass the graft up through the tibia and out the lateral femoral condyle. The graft is fixed to the lateral femoral condyle over a washer with the button, and the tibial-side fixation is a screw and post. This technique allows for anatomic tunnel reconstruction but requires high precision to avoid physeal injury. Multiple studies have described the risks of drilling in ACL reconstruction and the risk of physeal injury.[9,32,33] Anderson[1] noted that it was a "technically demanding procedure with a small margin of error (and) should be attempted only by accomplished knee surgeons."

As the majority of studies on pediatric ACL reconstruction are small case series without comparison groups, there is limited evidence for the ideal surgical technique for skeletally immature patients with significant remaining growth. Data on surgical outcomes, including complications such as growth disturbance and rerupture, are limited. Thus, we performed a review to compare outcomes and complications between the over-the-top and all-epiphyseal ACL reconstruction techniques. For skeletally immature patients, does all-epiphyseal reconstruction result in lower rates of growth disturbance in comparison with femoral over-the-top reconstruction? Our hypothesis was that both physeal-sparing reconstruction techniques are efficacious, with a similar risk of growth disturbance and complications.

METHODS

The PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) checklist was completed for this narrative review.[30] The PubMed and Embase databases were searched for studies from 1985 to 2018 on ACL ruptures among skeletally immature patients. The following search terms were used: "ACL" or "anterior cruciate ligament" AND "pediatric" OR "immature" OR "young" or "children" or "child." Studies were included if they were full-text studies in English and if they discussed operative intervention among skeletally immature patients with ACL ruptures (Figure 1). The references from each study were reviewed to ensure that no studies were missed. The literature search was performed independently by 2 authors (S.K.W. and N.K.P.) to ensure agreement of study inclusion. A total of 160 studies were identified. Of these, 10 studies that reported rerupture or complications with physeal-sparing ACL reconstruction—specifically, growth disturbance—were included in a secondary analysis. The MINORS tool[34] (Methodological Index for Nonrandomized Studies) was used to evaluate the risk of bias of the included studies (Table 1).

Studies were separated into 2 groups: an all-epiphyseal group with femoral and tibial fixation points within the epiphysis and a group that had over-the-top femoral and

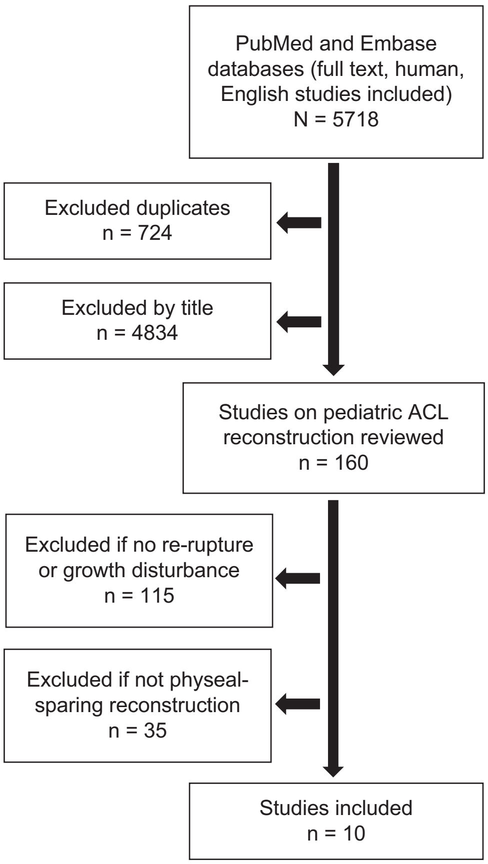

Figure 1. Flowchart of study design. PubMed and Embase databases were searched for clinical studies on physeal-sparing anterior cruciate ligament (ACL) ruptures in skeletally immature patients from 1985 to 2018.

tibial physeal-sparing reconstruction. All graft types were included. Studies were excluded if the inclusion criteria were not met, if the studies discussed complications not specific to the pediatric population (eg, infection or knee stiffness), or if they were animal studies, basic science studies, or surgeon survey studies.

The 10 studies meeting the inclusion criteria were analyzed (Table 2). The threshold values for growth disturbance were described in previous studies on complications following ACL reconstruction. The threshold used for limb-length discrepancy was >1 cm based on a study showing that 77% of patients had a discrepancy ≤7 mm.[28] Angular deformity >3° between the operative and nonoperative extremities was used as the threshold in this study.[29] All data were analyzed in aggregate.

RESULTS

A total of 482 knees among 478 skeletally immature patients underwent physeal-sparing ACL reconstruction. In the group that had the femoral graft placed in an over-the-top position, the mean age was 12.3 years, as compared with 11.6 years for the all-epiphyseal group. Among all patients, 81% were male, and the mean postoperative follow-up was 47.7 months. There were 178 knees that underwent all-epiphyseal reconstruction and 298 knees that underwent ACL reconstruction with the femoral graft placed in an over-the-top position. In the all-epiphyseal group, the majority of the grafts were hamstring autograft (156 of 178, 87.6%). The remaining grafts in that group were allograft or hybrid autograft/allograft. In the over-the-top femoral reconstruction group (n = 298), patellar tendon autograft was used in 19.1% (57 of 298), IT band autograft in 80.5% (240 of 298), and hamstring autograft in 0.3% (1 of 298). Five studies reported Lysholm scores, and 6 reported International Knee Documentation Committee (IKDC) scores.

The rerupture rate was 7.9% (30 of 379). Of note, Kocher et al[20] reported rerupture data on 137 of 240 patients. The rate was 7.0% (14 of 201) in the over-the-top group and 9.0% (16 of 178) in the all-epiphyseal group. The majority of reruptures occurred after traumatic injury or during sports. Reinjury occurred as early as 6 weeks postoperatively and as late as 3 years after initial ACL reconstruction. Fourteen of 17 (82%) patients underwent revision ACL reconstruction from studies that specified treatment for

TABLE 1
MINORS Tool to Evaluate the Risk of Bias of the Included Studies[a]

Study	Year	Study Design	Prospective or Retrospective?	Comparison Group Present?	Adjusting for Confounding Variables?	MINORS Score
Bisson[4]	1998	Case series	Prospective	No	No	12
Bonnard[5]	2011	Case series	Retrospective	No	Yes	12
Cordasco[10]	2017	Case series	Prospective	No	No	13
Cruz[11]	2017	Case series	Retrospective	No	No	14
Koch[18]	2016	Case series	Retrospective	No	No	12
Kocher[20]	2018	Case series	Retrospective	No	No	11
Koizumi[22]	2013	Case series	Retrospective	Yes	No	17
Nathan[25]	2013	Case report	Retrospective	No	No	10
Nawabi[26]	2014	Case series	Prospective	No	No	12
Robert[27]	2010	Case report	Retrospective	No	No	9

[a]The maximum score is 16 for noncomparative studies and 24 for comparative studies. MINORS, Methodological Index for Nonrandomized Studies.

TABLE 2
Individual Studies[a]

Study	Patients (Knees), n	Male, %	Mean Age, y	Mean Follow-up, mo	Technique	Type of Physeal Sparing Reconstruction	Growth Disturbance	Reruptures, n	IKDC Score; Grade	Mean Lysholm Score
Bisson[4]	7 (7)	100	13.0	39	Partial transphyseal and physeal sparing	Over-the-top femur, intraepiphyseal tibia (1)	0	2	–	99
Bonnard[5]	56 (56)	77	12.2	66	Physeal sparing	Clocheville (over-the-top femur, groove in tibial epiphysis)	1.5-cm overgrowth, 4° valgus, 4° varus	3	95% A or B	–
Cordasco[10]	23 (23)	74	12.2	32.1	Physeal sparing	All-epiphyseal	1.6- and 1.8-cm overgrowth	1	94.6	97.9
Cruz[11]	103 (103)	77	12.1	21	Physeal sparing	All-epiphyseal	0	11		
Koch[18]	12 (13)		12.1	54[b]	Physeal sparing	All-epiphyseal	2.1- and 1.6-cm overgrowth	2	88.5[b]; A (5), B (6), C (2)	93[b]
Kocher[20]	237 (240)	86	11.2	74.4	Physeal sparing	IT band (modified MacIntosh)	0	2	89.5	91.2
Koizumi[22]	15 (15)	53	14.0	38[b]	Physeal sparing	Double bundle (AM bundle over the top, PM bundle intraepiphyseal femur, intraepiphyseal on tibia)	0	2	96.7	99
Nathan[25]	1 (1)	100	9	32	Physeal sparing	All-epiphyseal	2.7-cm overgrowth	0	–	–
Nawabi[26]	23 (23)	65	12.6	18.5	Physeal sparing (15), partial transphyseal (8)	All-epiphyseal	1.1-cm overgrowth	0	–	–
Robert[27]	1 (1)	100	14.5	90	Physeal sparing	Clocheville (over-the-top femur, groove in tibial epiphysis)	13° valgus, 9° flexion contracture, 1.0-cm shortening	0	100; B (1)	–

[a]Dashes indicate data not provided. AM, anteromedial; IKDC, International Knee Documentation Committee; IT, iliotibial; PM, posteromedial.
[b]Median.

reconstruction. The grafts used in the revision reconstruction varied and included allograft and autograft (bone–patellar tendon–bone and contralateral hamstring autograft). The timing of revision ACL reconstruction was variable between acute revision and delayed reconstruction as an adult. Eleven additional patients had graft failure; however, their treatment was not specified.

In the 10 reviewed studies, were 7 total limb-length discrepancies reported, 1 of which occurred in the over-the-top femoral group and 6 in the all-epiphyseal group. Specifically, all were overgrowth (a mean 1.8 cm in the all-epiphyseal group; 1.5 cm for the patient in the over-the-top femoral group). There was no shortening limb-length discrepancy described in the included studies. Two patients from the all-epiphyseal group had >2 cm of overgrowth and required epiphysiodesis (28.6%). Five patients were observed and did not undergo surgical intervention.

There were 3 total angular deformities. One patient developed 4° of valgus at the knee, and 1 developed 4° of varus deformity at the knee; neither patient required surgical intervention.[5] No knees developed angular deformity in the all-epiphyseal group.

One patient developed a multiplanar flexion-valgus deformity after ACL reconstruction with an over-the-top femoral/Clocheville technique.[27] The Clocheville technique is a physeal-sparing technique that involves taking the central one-third of the patellar tendon (periosteum-ligament-periosteum) and securing it in a groove in the tibial epiphysis and lateral in the distal femoral metaphysis. The patient was 14.5 years old (bone age, 13.9 years) and sustained an ACL injury while playing soccer. Postoperatively, he developed knee deformity over the course of 3 to 18 months, which culminated in a valgus deformity of 13°, a 9° knee flexion contracture, and 1 cm of shortening. This deformity was attributed to drilling the outside-in femoral tunnel (above the distal femoral physis) within 1 cm of the distal femoral physis laterally, causing a posterolateral distal femoral epiphysiodesis. He required distal femoral osteotomy for correction. At follow-up at age 22 years, his knee was asymptomatic, although he no longer participated in sports.

About half of the studies reported patient-reported outcomes after physeal-sparing ACL reconstruction. Of the included studies, the overall outcomes were good to excellent. Five studies reported excellent Lysholm scores (mean, 95.7). Five studies reported IKDC scores (range, 88.5-100; 93% grade A or B). One study[27] was excluded from IKDC score calculations, as the score reported was after corrective osteotomy for multiplanar deformity.

In 60% of the studies, posteroanterior hand radiographs were used to assess preoperative skeletal maturity. Three studies used Tanner staging: 2 used Tanner staging with posteroanterior hand radiographs; only 1 study used Tanner staging alone. Two studies did not conduct objective assessment of skeletal maturity. The majority of studies (50%) did not assess for baseline limb-length inequality or angular deformity: 30% performed routine hips-to-ankles bilateral lower extremity radiographs, and 20% assessed baseline limb-length discrepancy/angular deformity with clinical examination. Postoperatively, 50% of studies obtained routine hips-to-ankles lower extremity radiographs; 30% obtained postoperative alignment imaging only if there was clinical suspicion of growth disturbance.

DISCUSSION

The objective of this study was to review the outcomes after physeal-sparing ACL reconstruction—specifically, complications related to growth. Both over-the-top and all-epiphyseal reconstruction techniques were successful, with good to excellent Lysholm and IKDC scores. Overall growth disturbance was uncommon. The most common growth disturbance was overgrowth, which was seen more often in the all-epiphyseal group and treated with epiphysiodesis in a minority of patients. No patients developed shortening of the operative limb. Angular deformity occurred in the over-the-top group only, was uncommon and mild, and did not require surgical intervention. One patient who developed a multiplanar deformity after over-the-top ACL reconstruction required osteotomy for realignment.

Rerupture of the ACL graft is an unfortunate complication. Out of the 10 studies reviewed, the rerupture rate was 7.9% (30 of 379). The majority of patients with rerupture required revision reconstruction (82%), as opposed to a much lower percentage of patients requiring intervention for growth disturbance (30%; 2 epiphysiodesis for overgrowth and 1 osteotomy for multiplanar deformity). In this young and highly active population, reruptures predictably occurred during sporting activity or because of traumatic injury. Revision ACL reconstruction is widely associated with inferior outcomes. In the pediatric population, revision ACL surgery is associated with lower patient-reported outcome scores, high rates of complication (subsequent surgical procedures after revision, 25%; graft retear, 20%), and low return-to-sports rates, as compared with first-time ACL reconstruction.[7] Any relationship between graft type and rerupture is difficult to assess, given variation in reporting of the initial graft type used among those who sustained ACL graft injuries.

Despite the focus on growth disturbance as a unique complication of ACL reconstruction in the skeletally immature population, operative intervention to correct deformity is performed infrequently. Compared with the majority of patients requiring revision surgery after ACL rerupture, only 30% of patients in our study underwent a second surgical procedure for growth disturbance. Growth disturbance about the physis can occur in the coronal plane, causing angular deformity, shortening or lengthening of the limb, or both. Angular deformity was described for just 2 patients undergoing physeal-sparing reconstruction: 1 had 4° of varus and 1 had 4° of valgus when compared with their contralateral extremities, which was narrowly past our angular deformity threshold of >3°. Interestingly, both cases occurred in the over-the-top group. Placement of the femoral graft in the over-the-top position potentially tethers the distal lateral femoral physis, thus explaining the development of a valgus deformity; however, it does not provide a clear explanation for the varus deformity.

The case report by Robert and Casin[27] described a multiplanar deformity that occurred in a skeletally immature patient after an over-the-top femoral/Clocheville ACL reconstruction. This flexion, valgus, and shortening deformity was attributed to technical complications, including drilling too close to the proximal aspect of the distal femoral physis (within 1 cm). This deformity ultimately required osteotomy for correction—a much larger surgical procedure than typical epiphysiodesis or guided growth procedures, which can often be used to correct isolated angular deformity or isolated limb-length discrepancy. This case report highlights some key points. Thorough preoperative risk counseling and close attention to detail are essential, as physeal injury can occur despite the use of "physeal sparing" reconstruction. Despite the use of intraoperative fluoroscopy and avoidance of direct drill penetration of the physis, physeal damage can occur indirectly from the heat created by the drill, as illustrated by this case report. Furthermore, while some techniques that place the femoral tunnel over the top avoid drilling tunnels entirely (eg, modified MacIntosh), others involve drilling a femoral tunnel in the femoral metaphysis (eg, Clocheville).

Overgrowth of a limb was first described by Truesdell in 1921 in pediatric femoral fractures.[39] Since then, it has been a commonly described pediatric phenomenon, often associated with femoral shaft fractures.[2,16,31] Theories explaining overgrowth include hyperemia and increased vascularity in the physis[2,8] and a compensatory mechanism[36] after an injury or insult to a long bone, such as fracture, injury, or infection. Overgrowth has also been described after ACL reconstruction in the skeletally immature population,[34] including the patients in our study. In our review of the literature, all limb-length discrepancies were overgrowth (no isolated shortening was described). The phenomenon of overgrowth is commonly described among younger, skeletally immature patients. There were more occurrences of overgrowth in the all-epiphyseal group, which may correlate with the younger mean age of that group versus the over-the-top group (11.6 vs 12.3 years). The patients who required intervention for overgrowth (epiphysiodesis) had >2 cm of overgrowth, while those who had 1 to 2 cm of overgrowth were simply observed. While the threshold of limb-length discrepancy in this study was 1 cm based on several studies,[28,29,41] other literature suggests that limb-length discrepancy does not reach clinical significance until the difference is >2 cm.[13,15,17,35,37]

To accurately monitor for growth disturbance after ACL reconstruction, it is essential to have a preoperative baseline measure, as side-to-side differences may exist. Only about half the studies included assessed baseline alignment and limb lengths with clinical examination or imaging studies. Only 30% of studies utilized full-length alignment imaging of the bilateral lower extremities. Furthermore, postoperative assessment of growth disturbance was limited: in one-third of studies, imaging was obtained only if clinical suspicion for growth disturbance existed. Overall, evaluation of growth disturbance was limited in this group of studies owing to the lack of standardized pre- and postoperative assessment.

Objective determination of skeletal maturity is crucial in this group of patients; however, this is not standardized for pediatric ACL reconstruction. While all of the studies we reviewed reported chronologic age (the easiest objective measure of age), studies variably reported their assessment of skeletal age (posteroanterior hand radiographs) and physiologic age (Tanner staging). In the 2 studies that reported overgrowth requiring surgical intervention,[18,25] there was no preoperative assessment of skeletal age. While preoperative determination of skeletal age may not have prevented overgrowth, it would have provided important information to families and surgeons alike to allow for informed discussion regarding risks of ACL reconstruction. Uniformity in pre- and postoperative hips-to-ankles alignment radiographs and standardization of skeletal age measurement would facilitate research in this area.

Limitations

Limitations of this study include those inherent to a review. Our study compiled data from multiple case reports and case series on skeletally immature patients; therefore, our data analysis was limited by the data compiled from the individual studies. The studies were heterogeneous in their design and collection of data, including follow-up, graft type, evaluation of skeletal maturity, assessment of growth disturbance, and details of patients who sustained rerupture and subsequent treatment. It is possible that the rates of growth disturbance were underestimated given the lack of standardization of measurements; however, the majority of growth disturbances were mild and treated with observation. The specific surgical techniques varied within the 2 surgical groups—for example, the type of graft as well as choice of fixation. Despite these limitations, we believe that our review provides important information comparing physeal-sparing ACL reconstruction techniques.

CONCLUSION

Growth disturbance after physeal-sparing ACL reconstruction was overall uncommon and mild; however, it can occur despite the common belief that physeal-sparing reconstruction lessens this risk. The phenomenon of overgrowth was likely common because of the younger patients receiving physeal-sparing procedures. Overgrowth was more common in the all-epiphyseal group and angular deformity in the over-the-top group. Rerupture rates were similar between the groups. Evaluation of preoperative skeletal maturity and comparison of baseline and postoperative growth disturbance were limited by a lack of routine imaging assessment. We recommend routine posteroanterior hand radiographs and pre- and postoperative hips-to-ankles alignment radiographs of all skeletally immature patients prior to ACL reconstruction.

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