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Anterior cruciate ligament reconstruction in skeletally immature patients is effective: A systematic review

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Abstract

Purpose: The present study evaluated the outcomes of anterior cruciate ligament (ACL) reconstruction in children with open physes. The outcomes of interest were to compare the increase in joint laxity and PROMs from baseline to the last follow-up, the rate and features of the return to sport and the rate of complications.

Methods: This study was conducted according to the 2020 PRISMA guidelines. In October 2023, the following databases were accessed: PubMed, Web of Science, Google Scholar and Embase. All the clinical studies investigating ACL reconstruction in skeletally immature patients were accessed. Only articles which clearly stated that surgeries were conducted in children with open physis were eligible.

Results: Data from 53 studies (1691 procedures) were collected. 35% (597 out of 1691 patients) were women. The mean length of the follow-up was 44.7 ± 31.3 months. The mean age of the patients was 12.7 ± 1.1 years old. All PROMs significantly improved from the baseline values to those at the last follow-up. The mean time to return to sport was 8.3 ± 1.9 months. 89% (690 out of 771 patients) returned to sports, 15% (109 out of 721 patients) reduced their level of sports activity or league, and 84% (651 out of 771 patients) returned to their previous level of sport. 9% (112 out of 1213) of patients experienced re-tear of the reconstructed ACL, and 11% (75 out of 660) of patients underwent a further ACL reoperation. No patients (0 out of 83) demonstrated increased laxity at the last follow-up, and persistent sensation of instability was reported by 5% (11 out of 235) of patients.

Conclusion: ACL reconstruction in skeletally immature patients is effective and safe, and is associated with fast recovery and a high rate of return to sport.

Level of Evidence: Level IV.

KEYWORDS

ACL, anterior cruciate ligament, children, skeletally immature

Abbreviations: ACL, anterior cruciate ligament; CI, confidence interval; CMS, Coleman Methodology Score; FU, follow-up; IKDC, International Knee Documentation Committee; MCID, minimum clinically important difference; MD, mean difference; PROMS, patient-reported outcome measures; SE, standard error.

INTRODUCTION

The prevalence of anterior cruciate ligament (ACL) tears in children and adolescents with open physes is raising [1, 2]. Consequently, the number of ACL reconstructions in this population has also increased in the last decades [3, 4]. Traditionally, ACL tears in skeletally immature patients were treated conservatively with bracing and physiotherapy, as ACL reconstruction techniques could damage the growing epiphyseal plates, potentially leading to growth disturbances, including leg-length discrepancy or angular deformities [5, 6]. However, instability sensation might persist and soft tissue injuries might occur following conservative management [7, 8]. Different surgical techniques for ACL reconstruction to avoid epiphyseal plate injuries have been described [9, 10]. These techniques improve knee function and decrease the risk of meniscal tears and/or chondral lesions [11, 12]. However, the evidence on ACL reconstruction in children with open physis is still limited. Moreover, although several clinical investigations are available, the rate of return to sport in skeletally immature patients following ACL reconstruction is still unclear [13, 14].

Despite several studies on ACL reconstruction in skeletally immature patients have been published, a comprehensive and updated systematic review which summarises outcomes, return to sport and complications is missing. The present study evaluated the outcomes of ACL reconstruction in children with open physis. The outcomes of interest were to compare the clinical improvement in joint laxity and patient-reported outcome measures (PROMs) from baseline to the last follow-up, the rate and features of return to sport, and the rate of complications. It was hypothesised that ACL reconstruction in skeletally immature patients is effective and safe, and is associated with fast recovery and a high rate of return to sport.

MATERIAL AND METHODS

Eligibility criteria

All the clinical studies investigating ACL reconstruction in skeletally immature patients were accessed. Only studies published in peer-reviewed journals were considered. According to the language capabilities of the authors, articles in English, German, Italian, French and Spanish were eligible. Only studies with levels I–III of evidence, according to the Oxford Centre of Evidence-Based Medicine [15], were considered. Reviews, opinions, letters and editorials were not considered. Animals, in vitro, biomechanics, computational and cadaveric studies were not eligible. Only articles with a minimum of 6-month follow-up were included. Only articles which clearly stated that surgeries were conducted in children with open physis were eligible. Missing quantitative data under the outcomes of interests warranted the exclusion of the study.

Search strategy

This study was conducted according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses: the 2020 PRISMA statement [16]. The following algorithm was established:

- Problem: ACL tears in children.
- Intervention: ACL reconstruction.
- Outcomes: laxity, PROMs, return to sport, complications.
- Timing: minimum 6-month follow-up.

In October 2023, the following databases were accessed: PubMed, Web of Science, Google Scholar and Embase. No time constraint was set for the search. The medical subject headings used for the database search are described in the supplementary material. No additional filters were used in the database search.

Selection and data collection

Two authors (R.G. and L.S.) independently performed the database search. All the resulting titles were screened by hand and, if suitable, the abstract was accessed. The full text of the abstracts which matched the topic was accessed. If the full text was not accessible or available, the article was not considered for inclusion. A cross reference of the bibliography of the full-text articles was also performed for inclusion. Disagreements were debated and mutually solved by the two authors above. In case of further disagreements, a third senior author (N.M.) took the final decision.

Data items

Two authors (R.G. and L.S.) independently performed data extraction. The following data at baseline were extracted: author, year of publication and journal, length of follow-up, number of procedures and mean age of the patients. To investigate knee laxity, data on Pivot shift and Lachman tests were extracted. Data concerning the following PROMs were collected at baseline and last follow-up: Tegner Activity Scale [17], Lysholm Knee Scoring Scale [18], and International Knee Documentation Committee (IKDC) [19]. The minimum clinically important difference (MCID) for the VAS was 2.7/10, 10/100 for the Lysholm score, 15/100 for the IKDC, and 0.5/10 for the Tegner score [20–22]. To evaluate the return to sport, the following data were extracted: mean return to sport, rate of patients unable to return to sport, rate of return to sport, rate of patients who had reduced their league or level of sports activity, rate of patients who had returned to their previous league or level of sports activity. Data on the following complications were collected: re-tear, reoperation, increased laxity and persistent instability sensation. Data were entered in Microsoft Office Excel version 16.72 (Microsoft Corporation).

Assessment of the risk of bias

Methodological quality assessment was performed using the Coleman Methodology Score (CMS) [23]. Two authors (R.G. and L.S.) independently evaluated the included studies, and discrepancies were resolved by consensus. The CMS is a reliable and validated tool to evaluate the methodological quality of articles included in systematic reviews and meta-analyses. In addition to study design and methodology, Coleman's criteria also assess the quality of outcome reports. The criteria evaluated are the population size, length of follow-up, surgical approach used, study design, description of diagnosis, surgical technique, and rehabilitation, as well as outcome criteria assessment and the subject selection process. Subscores for each domain were added for a total possible score of 100. The quality of the studies is scored between 0 (poor) and 100 (excellent). A mean value greater than 60 points was considered satisfactory.

Synthesis methods

The statistical analyses were performed by the main author (F.M.) following the recommendations of the Cochrane Handbook for Systematic Reviews of Interventions [24]. The software IBM SPSS version 25 was used. For descriptive statistics, mean and standard deviation or the observed frequency (number of cases divided by the number of included patients) were used. The mean difference (MD) effect measure was calculated to assess the improvement of PROMs and laxity from the baseline to the last follow-up. Standard deviation and standard error (SE) were also evaluated. The confidence interval (CI) was set at 95%. The t test was performed, with values of $p < 0.05$ considered statistically significant.

RESULTS

Study selection

The literature search resulted in 1203 articles. Of these, 879 were excluded because they were duplicates. A further 261 articles were excluded because they did not match eligibility criteria: study design ($N = 156$), articles which did not clearly state that surgeries were conducted in children with open physis (N = 42), poor level of evidence ($N = 37$), language limitations ($N = 14$), follow-up time less than 6 months ($N = 12$). A further 10 investigations were excluded because of a lack of quantitative data on the outcomes of interest. This left 53 investigations for inclusion: two prospective and 51 retrospective clinical studies. The results of the literature search are shown in Figure 1.

Methodological quality assessment

According to the CMS, the follow-up was adequate in most of the articles reviewed. The surgical approach, diagnosis, and rehabilitation protocols were generally well described. Limitations identified by the CMS score included the limited number of patients enrolled in 21% (11 out of 53) of the studies assessed and the retrospective design in 96% (51 out of 53) of the included studies. Outcome measures and the assessment process were frequently confounded and had poor descriptions, leading to fair reliability. Concluding, the CMS resulted in 61.4 ± 6.8 points, attesting to the present study a fair quality of the methodology. The CMS for each included study is shown in Table 1.

Study characteristics and results of individual studies

Data from 1691 procedures were collected. 35% (597 out of 1691 patients) were female. The mean length of follow-up was 44.7 ± 31.3 months. The mean age of the patients was 12.7 ± 1.1 years old. The generalities and demographics of the included studies are shown in Table 1.

Joint laxity and PROMs

All endpoints significantly improved from the baseline values to those at the last follow-up (Table 2): positive pivot shift test (MD 85.1; 95% CI 86.18–84.01; $p < 0.0001$), positive Lachman test (MD 71.3; 95% CI 72.93–69.66; $p < 0.0001$), IKDC (MD 39.4; 95% CI 38.80–39.99; $p < 0.0001$), Lysholm (MD 30.7; 95% CI 29.80–31.59; $p < 0.0001$) and Tegner Score (MD 1.1; 95% CI 1.00–1.19; $p < 0.0001$).

Return to sport

The mean time to return to sport was 8.3 ± 1.9 months. 89% (690 out of 771 patients) returned to sport, 15% (109 out of 721 patients) reduced their level of sport activity or league and 84% (651 out of 771 patients) returned to their previous level of sport (Table 3).

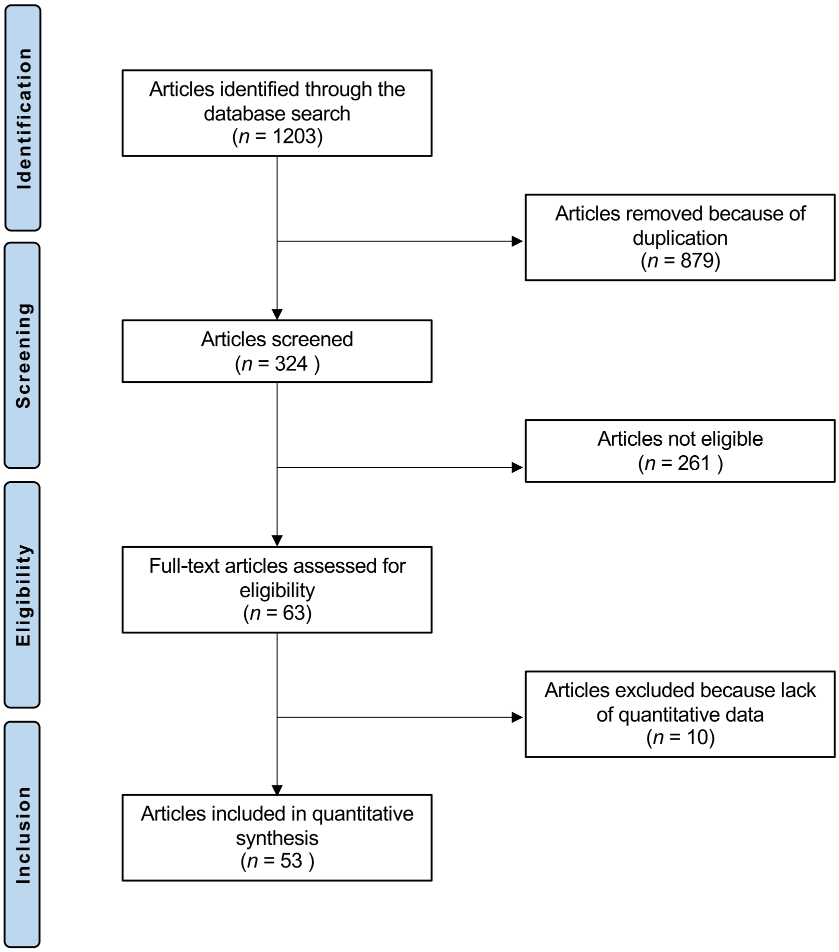

FIGURE 1 PRISMA flow chart of the literature search.

Complications

Within the period of follow-up, 9% (112 out of 1213) of patients experienced a re-tear of the ACL and 11% (75 out of 660) of patients underwent a further ACL operation. No patients (0 out of 83) demonstrated postoperative signs of increased laxity at the last follow-up, and persistent instability sensation was reported by 5% (11 out of 235) of patients.

DISCUSSION

According to the main findings of the present systematic review, ACL reconstruction in skeletally immature patients is effective in reducing laxity and improving PROMs at approximately 4 years of follow-up. 89% (690 out of 771 patients) of children returned to their sport at a mean of eight months, mostly at their previous level or league. The rate of re-tear and reoperation was 9% (112 out of 1213) and 11% (75 out of 660), respectively, which is a concern. However, few articles reported data on complications, which might underestimate the real rate of complications.

The results of the present study are in accordance with previously published evidence. Kay et al. [77] conducted a meta-analysis including 20 studies (1156 patients) and a follow-up of 6.5 years. Similarly, 92% (809 out of 852 patients) of children returned to practise sporting activity after ACL reconstruction, 81% (816 out of 1008 patients) at their pre-injury level [77]. The rate of graft rupture was relatively high at 13% (93 out of 717 knees), as was the rate of injury to the contralateral ACL, reported at 14% (91 out of 652 knees) [77]. Growth impairment was reported in 2.7% of children, which is higher compared with 2% reported in previous meta-analyses [77, 78]. Children who had undergone transphyseal ACL reconstruction using hamstring tendon autografts had a lower rate of growth disturbances, but a higher rate of graft re-rupture compared to those who had undergone epiphyseal-sparing technique using bone-patellar tendon-bone tendon autograft [77]. In another meta-analysis including 935 patients with a median follow-up of 40 months, 84.2% (187 out of 224) of the patients reported excellent or good postoperative knee function (International Knee Documentation Committee grade A or B) [78]. The

TABLE 1 Generalities and patient baseline of the included studies.

Author et al., year	Journal	Design	CMS	Follow-up (months)	Procedure	Knees (s)	Type of graft	Mean age	Female (*n*)
Aichroth et al., 2002 [25]	*J Bone Joint Surg Br*	Prospective	77	49.0	Trans-Epiphyseal	45	Hamstring	13.0	13
Akinleye et al., 2013 [26]	*Int J Sports Phys Ther*	Retrospective	48	36.0	All-Epiphyseal	2	Hamstring	10.0	1
Andrews et al., 1994 [27]	*Am J Sports Med*	Retrospective	60	58.0	Trans-Epiphyseal	8	Fascia lata, Achilles	13.0	0
Arbes et al., 2007 [28]	*Int Orthop*	Retrospective	54	64.8	Trans-Epiphyseal	4	Patellar	13.9	13
Aronowitz et al., 2000 [29]	*Am J Sports Med*	Retrospective	68	25.0	Trans-Epiphyseal	19	Achilles	13.4	10
Asai et al., 2021 [30]	*Sci Rep*	Retrospective	66	23.0	Trans-Epiphyseal	27	Hamstring	13.9	16
Bigoni et al., 2017 [31]	*Knee*	Retrospective	61	43.4	All-Epiphyseal (suture)	5		9.2	1
Bonnard et al., 2011 [32]	*J Bone Joint Surg Br*	Retrospective	72	66.0	All-Epiphyseal	56	Patellar	12.2	13
Calvo et al., 2015 [33]	*Am J Sports Med*	Retrospective	64	127.2	Trans-Epiphyseal	27	Hamstring	13.0	11
Cassard et al., 2014 [34]	*J Pediatr Orthop*	Retrospective	66	33.6	All-Epiphyseal	28	Hamstring	13.0	8
Cohen et al., 2009 [35]	*Arthroscopy*	Retrospective	63	45.0	Trans-Epiphyseal	26	Hamstring	13.3	15
Courvoisier et al., 2011 [36]	*Knee Surg Sports Traumatol Arthrosc*	Retrospective	69	36.0	Trans-Epiphyseal	37	Hamstring	14.0	20
Cordasco et al., 2017 [37]	*Am J Sports Med*	Retrospective	60	32.1	All-Epiphyseal	23	Hamstring	12.2	6
Cruz et al., 2015 [38]	*J Pediatr Orthop*	Retrospective	56	21.0	All-Epiphyseal	103	Hamstring	12.1	24
Demange et al., 2014 [39]	*Am J Sports Med*	Prospective	58	219.6	Trans-Epiphyseal	12	Semitendinosus	10.7	5
Foissey et al., 2022 [40]	*Arthrosc Sports Med Rehabil*	Retrospective	62	57.0	Trans-Epiphyseal	40		13.8	8
				57.0	Trans-Epiphyseal	20	Hamstring	13.6	6
				57.0	Trans-Epiphyseal	20	Semitendinosus, fascia lata	14.0	2
Fuchs et al., 2002 [41]	*Arthroscopy*	Retrospective	62	40.0	Trans-Epiphyseal	10	Patellar	13.2	4

(Continues)

TABLE 1 (Continued)

Author et al., year	Journal	Design	CMS	Follow-up (months)	Procedure	Knees (s)	Type of graft	Mean age	Female (*n*)
Gebhard et al., 2006 [42]	*Knee Surg Sports Traumatol Arthrosc*	Retrospective	63	32.0	Trans-Epiphyseal	68			
				33.0	Trans-Epiphyseal	40	Hamstring	11.9	19
				40.0	Trans-Epiphyseal	28	Patellar, hamstring	15.3	14
Goddard et al., 2013 [43]	*Am J Sports Med*	Retrospective	55	24.0	Trans-Epiphyseal	32	Hamstring	13.0	11
Greenberg et al., 2014 [44]	*Sports Health*	Retrospective	69	15.4	All-Epiphyseal	16	Hamstring	12.3	
Guzzanti et al., 2003 [45]	*Am J Sports Med*	Retrospective	52	69.2	All-Epiphyseal	8	Hamstring	11.4	0
Hoshikawa et al., 2020 [46]	*Orthop J Sports Med*	Retrospective	55	52.7	All-Epiphyseal	3	Hamstring	13.0	1
Hui et al., 2012 [47]	*Am J Sports Med*	Retrospective	54	25.0	Trans-Epiphyseal	16	Hamstring	12.0	4
Koch et al., 2014 [48]	*Knee Surg Sports Traumatol Arthrosc*	Retrospective	60	54.0	All-Epiphyseal	13	Hamstring	12.1	2
Kocher et al., 2005 [49]	*J Bone Joint Surg Am*	Retrospective	61	63.6	All-Epiphyseal	44	Ilotibial band	10.3	
Kohl et al., 2014 [50]	*Knee*	Retrospective	58	49.2	Trans-Epiphyseal	15	Quadriceps	12.8	3
Kumar et al., 2013 [51]	*J Bone Joint Surg Am*	Retrospective	55	72.3	Trans-Epiphyseal	32	Hamstring	11.3	4
Lanzetti et al., 2020 [52]	*Int Orthop*	Retrospective	62	96.1	All-Epiphyseal	42	Hamstring	12.5	12
Lawrence et al., 2010 [53]	*Clin Orthop Relat Res*	Retrospective	48	12.0	All-Epiphyseal	3	Tibialis posterior, hamstring	11.3	0
Lemaitre et al., 2014 [54]	*Orthop Traumatol Surg Res*	Retrospective	50	15.0	Trans-Epiphyseal	14	Hamstring	13.6	
Liddle et al., 2008 [55]	*J Bone Joint Surg Br*	Retrospective	52	44.0	Trans-Epiphyseal	17	Hamstring	12.1	3
Mauch et al., 2011 [56]	*Sports Med Arthrosc Rehabil Ther Technol*	Retrospective	50	60.0	Trans-Epiphyseal	49	Quadriceps	13.0	21
McCarroll et al., 1988 [57]	*Am J Sports Med*	Retrospective	72	26.4	Trans-Epiphyseal	24	Patellar	13.3	12
McCarroll et al., 1994 [58]	*Am J Sports Med*	Retrospective	66	50.4	Trans-Epiphyseal	60	Patellar	14.2	31

TABLE 1 (Continued)

Author et al., year	Journal	Design	CMS	Follow-up (months)	Procedure	Knees (s)	Type of graft	Mean age	Female (*n*)
Mcintosh et al., 2006 [59]	*Arthroscopy*	Retrospective	59	41.1	Trans-Epiphyseal	16	Hamstring	13.6	5
Micheli et al., 1999 [60]	*Clin Orthop Relat Res*	Retrospective	63	66.5	All-Epiphyseal	8	Iliotibial band	11.0	1
Nakhostine et al., 1995 [61]	*J Pediatr Orthop*	Retrospective	50	52.8	All-Epiphyseal	5	Iliotibial band	14.0	0
Nikolaou et al., 2011 [62]	*Knee Surg Sports Traumatol Arthrosc*	Retrospective	67	38.0	Trans-Epiphyseal	94	Hamstring	13.7	38
Perelli et al., 2022 [63]	*Am J Sports Med*	Retrospective	70	26.6	All-Epiphyseal	34	Hamstring	13.5	11
				25.1	All-Epiphyseal	32	Hamstring	13.8	12
Pennock et al., 2018 [64]	*Orthop J Sports Med*	Retrospective	68	38.4	All-Epiphyseal	26	Hamstring	11.8	?
Redler et al., 2012 [65]	*Arthroscopy*	Retrospective	62	43.4	Trans-Epiphyseal	18	Hamstring	14.2	6
Robert et al., 1999 [66]	*Arthroscopy*	Retrospective	58	42.0	All-Epiphyseal	8	Patellar	11.4	1
Saad et al., 2021 [67]	*Medicine (Baltimore)*	Retrospective	66	19.2	All-Epiphyseal	19	Gracilis and semitendinosus	13.3	4
Sasaki et al., 2021 [4]	*Orthop J Sports Med*	Retrospective	74	41.6	All-Epiphyseal	18	Semitendinosus	12.4	10
				38.1	Trans-Epiphyseal	84	Hamstring, patellar	14.1	75
Seon et al., 2005 [68]	*J Korean Med Sci*	Retrospective	58	77.7	Trans-Epiphyseal	11	Hamstring	14.7	0
Shamrock et al., 2022 [69]	*Iowa Orthop J*	Retrospective	60	27.6	Trans-Epiphyseal	12	Hamstring	12.8	1
Shelbourne et al., 2004 [70]	*Am J Sports Med*	Retrospective	61	40.8	Trans-Epiphyseal	16	Patellar	14.8	5
Schmale et al., 2014 [71]	*Clin Orthop Relat Res*	Retrospective	64	48.0	Trans-Epiphyseal	29	Hamstring, tibialis anterior	14.0	23
Streich et al., 2010 [72]	*Knee Surg Sports Traumatol Arthrosc*	Retrospective	60	70.0	Trans-Epiphyseal	16	Semitendinosus	11.0	6
Wall et al., 2017 [73]	*Orthop J Sports Med*	Retrospective	67	43.2	All-Epiphyseal	27	Hamstring	11.0	4
Willimon et al., 2015 [74]	*Am J Sports Med*	Retrospective	66	36.0	All-Epiphyseal	21	Iliotibial band	11.8	0

(Continues)

TABLE 1 (Continued)

Author et al., year	Journal	Design	CMS	Follow-up (months)	Procedure	Knees (s)	Type of graft	Mean age	Female (n)
Wren et al., 2021 [75]	*Int J Environ Res Public Health*	Retrospective	68	7.8	All-Epiphyseal	20	Iliotibial	11.3	5
				7.0	All-Epiphyseal/Trans-Epiphyseal	29	Hamstring	14.5	13
				6.8	All-Epiphyseal/Trans-Epiphyseal	39	Quadriceps	15.0	23
				7.9	Trans-Epiphyseal	57	Patellar	16.4	35
Zhang et al., 2023 [76]	*Int Orthop*	Retrospective	66	31.6	All-Epiphyseal	6	Hamstring	12.2	2
				31.6	All-Epiphyseal	10	Hamstring	12.1	4

Abbreviation: CMS, Coleman Methodology Score.

mean Lysholm scores ranged from 80 to 99, which indicated a very good functional outcome [78].

ACL reconstruction in skeletally immature patients aims to restore knee stability, preventing further soft tissue injuries and preserving physiological growth of the lower limb, restoring the pre-injury activity level [79, 80]. On the other hand, given their proximity, the risk of growth disturbance from physeal damage with subsequent limb length discrepancy and/or angular deformity should be considered [81, 82]. Both physeal-sparing and transphyseal techniques have been described [81, 83]. The physeal-sparing techniques were associated with lesser postoperative leg length differences or axis deviations than other surgical approaches [84, 85]. In another systematic review of 13 studies (192 children), transepiphyseal or physeal-sparing techniques were compared [86]. No difference was found in Lysholm, OAK and IKDC scores, and in the rate of return to sport [86].

Between studies, heterogeneities in surgical technique were evident. Several surgical techniques of ACL reconstruction in patients with open physes have been described: epiphyseal-sparing, all-epiphyseal, partial transepiphyseal and transepiphyseal reconstruction [87, 88]. The physeal sparring technique consists of an extra-articular reconstruction using an iliotibial band autograft [89]. The graft is harvested proximally, leaving the graft intact at Gerdy's tubercle, passed deep to the fibular collateral ligament, and sutured back to itself [89]. The all-epiphyseal technique restores the anatomic ACL footprint with unique tunnel drilling and fixation techniques [90]. Several all-epiphyseal ACL reconstruction techniques have been described, including the Anderson, Ganley-Lawrence and Cordasco-Green [53, 91, 92]. The partial transphyseal technique involves transphyseal over-the-top physeal-sparing femoral graft fixation and a transphyseal tibial tunnel [53]. This avoids any damage to the femoral physis while drilling a tibial tunnel which is vertical and small limits its impacts on the tibial physis [93]. The transphyseal technique is also the standard in adults consisting of a femoral and a tibia tunnel, where the graft is allocated and fixed [94–96]. Unfortunately, given the lack of quantitative data available for inclusion, it was not possible to conduct subgroup analyses according to the surgical approach.

The indications for surgery were heterogeneous. Most authors referred to the Tanner stage for surgical planning. This staging system predicts the skeletal growth of children [97]. Based on the Tanner stage, prepubescent patients are treated with physeal-sparing techniques, adolescent patients with transepiphyseal procedures using soft tissue grafts, and older adolescents with a conventional ACL reconstruction using either soft tissue or bone-patellar tendon-bone autografts [97].

Graft choice is crucial in ACL reconstruction in children [98, 99], but between studies, heterogeneities

TABLE 2 Results of the outcome: joint laxity and PROMs.

Endpoint	At baseline	At last FU	MD	SE	95% CI	*p*
Positive Pivot shift test (%)	100 ± 0.0	14.9 ± 22.7	85.1	0.552	86.18–84.01	<0.0001
Positive Lachman test (%)	100 ± 0.0	28.7 ± 34.2	71.3	0.832	72.93–69.66	<0.0001
IKDC	49.9 ± 7.9	89.3 ± 9.7	39.4	0.304	38.80–39.99	<0.0001
Lysholm	60.8 ± 9.5	91.5 ± 16.3	30.7	0.459	29.80–31.59	<0.0001
Tegner	6.1 ± 1.8	7.2 ± 1.0	1.1	0.050	1.00–1.19	<0.0001

Abbreviations: CI, confidence interval; FU, follow-up; IKDC, International Knee Documentation Committee; MD, mean difference; PROM, patient-reported outcome measure; SE, standard error.

TABLE 3 Results of the outcome: return to sport.

Endpoint	Result
Time to Return to sport (*months*)	8.3 ± 1.9
Returned to sport	89% (690 out of 771)
Reduced the level of sport activity or league	15% (109 out of 721)
Returned to previous level of sport	84% (651 out of 771)

in graft choice were evident. A bone-patellar tendon-bone autograft has the advantage of high initial strength compared with other tissues [100, 101]. Its tendon-bone interface also allows bone-to-bone healing [102]. The drawback of bone-patellar tendon-bone autografts is the potential for donor site complications that can result in anterior knee pain and quadriceps muscle weakness [103, 104]. A hamstring tendon autograft offers the advantage of a smaller incision and fewer donor-site complications compared with a bone-patellar tendon-bone autograft [29, 103]. The disadvantage of a hamstring tendon graft is the potential for increased anterior laxity over time [103, 105]. A central-third quadriceps tendon-bone autograft is a reliable option because it has less donor-site complications, but a prolonged weakness of the quadriceps muscle has been reported [103, 106]. The results between allograft and autograft have been shown to be similar [107, 108]. Allografts have no donor-site complications and allow decreased operative time because the surgeon does not harvest the autologous graft [109]. The main disadvantage of allografts is their risk of disease transmission, the immune reaction graft vs host, and the longer incorporation time [110, 111]. Therefore, allografts must be treated and sterilized by irradiation or be fresh-frozen. Unfortunately, the effects of radiation on allografts are still unclear [112, 113]. Autografts, specifically hamstring autografts, should be recommended at first, followed by quadriceps autografts [114]. Patellar tendon autografts should be avoided given their high rate of tibial apophysis damage [114].

The current study has several limitations. Given the lack of quantitative data, subgroup analyses according to age, sex, and skeletal maturity were not possible. The two reviewers responsible for the literature search might have not identified all possible articles. Moreover, between reviewers, intraobserver agreement was not evaluated, which also might negatively influence the reliability of the literature search. The skeletal maturity was evaluated using different modalities. Moreover, patients with different ages and skeletal maturity were included. Many studies involved small groups of patients, and results should be generalised cautiously to the paediatric population. Techniques may have different modifications or nuances that may influence the rate of revision. For instance, many of the transphyseal techniques used are performed in adolescents, while physeal-sparing reconstructions tend to be favoured in prepubescent patients. Moreover, the evaluated PROMs are designed for adults, and their validity in the pediatric population is debated. Between studies, variability in the length of the follow-up was evident and long-term follow-up studies were lacking. For each outcome of interest, the number of patients included for analysis in each outcome of interest was variable, since not all studies evaluated the same endpoints. This variability could increase the risk of reporting bias and impact negatively the reliability of the present results.

CONCLUSION

ACL reconstruction in skeletally immature patients is effective in reducing laxity and PROMs at approximately 4 years of follow-up. 89% (690 out of 771 patients) of children returned to the sport at a mean of 8 months, mostly at their previous level or league. The rate of re-tear and reoperation was 9% (112 out of 1213) and 11% (75 out of 660), respectively, which is a concern. However, few articles reported data on complications, which might underestimate their real rate.

AUTHOR CONTRIBUTIONS

Filippo Migliorini: Conception and design; writing. **Nicola Maffulli:** Supervision; revision. **Michael Kurt Memminger:** Writing. **Luise Schäfer:** Literature search; data extraction; risk of bias assessment. **Riccardo Giorgino:** Literature search; data extraction; risk of bias assessment. **Federico Cocconi:** Drafting. All authors have agreed to the final version to be published and agree to be accountable for all aspects of the work.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The data sets generated during and/or analysed during the current study are available throughout the manuscript.

ETHICS STATEMENT

This study complies with ethical standards.

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REFERENCES

1. Shaw, L. & Finch, C.F. (2017) Trends in pediatric and adolescent anterior cruciate ligament injuries in Victoria, Australia 2005-2015. *International Journal of Environmental Research and Public Health*, 14, 599.
2. Turati, M., Rigamonti, L., Giulivi, A., Gaddi, D., Accadbled, F., Zanchi, N. et al. (2023) Management of anterior cruciate ligament tears in Tanner stage 1 and 2 children: a narrative review and treatment algorithm guided by ACL tear location. *The Journal of Sports Medicine and Physical Fitness*, 63, 1218–1226.
3. Kooy, C.E.W., Jakobsen, R.B., Fenstad, A.M., Persson, A., Visnes, H., Engebretsen, L. et al. (2023) Major increase in incidence of pediatric ACL reconstructions from 2005 to 2021: a study from the Norwegian Knee Ligament Register. *The American Journal of Sports Medicine*, 51, 2891–2899.
4. Sasaki, S., Sasaki, E., Kimura, Y., Yamamoto, Y., Tsuda, E. & Ishibashi, Y. (2021) Clinical outcomes and postoperative complications after all-epiphyseal double-bundle ACL reconstruction for skeletally immature patients. *Orthopaedic Journal of Sports Medicine*, 9, 232596712110513.
5. Dingel, A., Aoyama, J., Ganley, T. & Shea, K. (2019) Pediatric ACL tears: natural history. *Journal of Pediatric Orthopaedics*, 39, S47–S49.
6. Kocher, M.S., Saxon, H.S., Hovis, W.D. & Hawkins, R.J. (2002) Management and complications of anterior cruciate ligament injuries in skeletally immature patients: survey of the Herodicus Society and The ACL Study Group. *Journal of Pediatric Orthopaedics*, 22, 452–457.
7. James, E.W., Dawkins, B.J., Schachne, J.M., Ganley, T.J., Kocher, M.S., Anderson, C.N. et al. (2021) Early operative versus delayed operative versus nonoperative treatment of pediatric and adolescent anterior cruciate ligament injuries: a systematic review and meta-analysis. *The American Journal of Sports Medicine*, 49, 4008–4017.
8. Migliorini, F., Vecchio, G., Eschweiler, J., Schneider, S.M., Hildebrand, F. & Maffulli, N. (2023) Reduced knee laxity and failure rate following anterior cruciate ligament reconstruction compared with repair for acute tears: a meta-analysis. *Journal of Orthopaedics and Traumatology*, 24, 8.
9. Longo, U.G., Ciuffreda, M., Casciaro, C., Mannering, N., Candela, V., Salvatore, G. et al. (2017) Anterior cruciate ligament reconstruction in skeletally immature patients: a systematic review. *The Bone & Joint Journal*, 99-B, 1053–1060.
10. Price, M.J., Lazaro, L., Cordasco, F.A. & Green, D.W. (2017) Surgical options for anterior cruciate ligament reconstruction in the young child. *Minerva Pediatrics*, 69, 337–347.
11. Anderson, A.F. & Anderson, C.N. (2015) Correlation of meniscal and articular cartilage injuries in children and adolescents with timing of anterior cruciate ligament reconstruction. *The American Journal of Sports Medicine*, 43, 275–281.
12. Ramski, D.E., Kanj, W.W., Franklin, C.C., Baldwin, K.D. & Ganley, T.J. (2014) Anterior cruciate ligament tears in children and adolescents: a meta-analysis of nonoperative versus operative treatment. *The American Journal of Sports Medicine*, 42, 2769–2776.
13. Ardern, C.L., Taylor, N.F., Feller, J.A. & Webster, K.E. (2014) Fifty-five per cent return to competitive sport following anterior cruciate ligament reconstruction surgery: an updated systematic review and meta-analysis including aspects of physical functioning and contextual factors. *British Journal of Sports Medicine*, 48, 1543–1552.
14. Lai, C.C.H., Ardern, C.L., Feller, J.A. & Webster, K.E. (2018) Eighty-three per cent of elite athletes return to preinjury sport after anterior cruciate ligament reconstruction: a systematic review with meta-analysis of return to sport rates, graft rupture rates and performance outcomes. *British Journal of Sports Medicine*, 52, 128–138.
15. Howick, J.C.I., Glasziou, P., Greenhalgh, T., Carl, H., Liberati, A. & Moschetti, I. et al. (2011) *The 2011 Oxford CEBM Levels of Evidence*. Oxford Centre for Evidence-Based Medicine. Available from: https://www.cebm.net/index.aspx?o=5653
16. Page, M.J., McKenzie, J.E., Bossuyt, P.M., Boutron, I., Hoffmann, T.C. & Mulrow, C.D. et al. (2021) The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. *BMJ*, 372, n71.
17. Briggs, K.K., Lysholm, J., Tegner, Y., Rodkey, W.G., Kocher, M.S. & Steadman, J.R. (2009) The reliability, validity, and responsiveness of the Lysholm score and Tegner activity scale for anterior cruciate ligament injuries of the knee: 25 years later. *The American Journal of Sports Medicine*, 37, 890–897.
18. Tegner, Y. & Lysholm, J. (1985) Rating systems in the evaluation of knee ligament injuries. *Clinical Orthopaedics and Related Research*, 198, 43–49.
19. Higgins, L.D., Taylor, M.K., Park, D., Ghodadra, N., Marchant, M., Pietrobon, R. et al. (2007) Reliability and validity of the International Knee Documentation Committee (IKDC) Subjective Knee Form. *Joint, Bone, Spine*, 74, 594–599.
20. Agarwalla, A., Liu, J.N., Garcia, G.H., Gowd, A.K., Puzzitiello, R.N., Yanke, A.B. et al. (2021) Return to sport following isolated lateral opening wedge distal femoral osteotomy. *Cartilage*, 13, 846S–852S.
21. Jones, K.J., Kelley, B.V., Arshi, A., McAllister, D.R. & Fabricant, P.D. (2019) Comparative effectiveness of cartilage repair with respect to the minimal clinically important difference. *The American Journal of Sports Medicine*, 47, 3284–3293.
22. Mostafaee, N., Negahban, H., Shaterzadeh Yazdi, M.J., Goharpey, S., Mehravar, M. & Pirayeh, N. (2020) Responsiveness of a Persian version of Knee Injury and Osteoarthritis Outcome Score and Tegner activity scale in athletes with anterior

cruciate ligament reconstruction following physiotherapy treatment. *Physiotherapy Theory and Practice*, 36, 1019–1026.
23. Coleman, B.D., Khan, K.M., Maffulli, N., Cook, J.L. & Wark, J.D. (2000) Studies of surgical outcome after patellar tendinopathy: clinical significance of methodological deficiencies and guidelines for future studies. *Scandinavian Journal of Medicine & Science in Sports*, 10, 2–11.
24. Higgins, J.P.T., Thomas, J., Chandler, J., Cumpston, M., Li, T., Page, M.J. et al. (2021) *Cochrane handbook for systematic reviews of interventions version 6.2. Cochrane 2021*. Available from: www.training.cochrane.org/handbook. [Accessed February 2022].
25. Aichroth, P.M., Patel, D.V. & Zorrilla, P. (2002) The natural history and treatment of rupture of the anterior cruciate ligament in children and adolescents. A prospective review. *The Journal of Bone and Joint Surgery. British Volume*, 84, 38–41.
26. Akinleye, S.D., Sewick, A. & Wells, L. (2013) All-epiphyseal ACL reconstruction: a three-year follow-up. *International Journal of Sports Physical Therapy*, 8, 300–310.
27. Andrews, M., Noyes, F.R. & Barber-Westin, S.D. (1994) Anterior cruciate ligament allograft reconstruction in the skeletally immature athlete. *The American Journal of Sports Medicine*, 22, 48–54.
28. Arbes, S., Resinger, C., Vécsei, V. & Nau, T. (2007) The functional outcome of total tears of the anterior cruciate ligament (ACL) in the skeletally immature patient. *International Orthopaedics*, 31, 471–475.
29. Aronowitz, E.R., Ganley, T.J., Goode, J.R., Gregg, J.R. & Meyer, J.S. (2000) Anterior cruciate ligament reconstruction in adolescents with open physes. *The American Journal of Sports Medicine*, 28, 168–175.
30. Asai, K., Nakase, J., Shimozaki, K., Yoshimizu, R., Kimura, M. & Tsuchiya, H. (2021) Skeletally immature patient showed lower graft maturity than skeletally mature patient after ACL reconstruction with a rounded rectangular femoral tunnel. *Scientific Reports*, 11, 19968. Available from: https://doi.org/10.1038/s41598-021-99532-1
31. Bigoni, M., Gaddi, D., Gorla, M., Munegato, D., Pungitore, M., Piatti, M. et al. (2017) Arthroscopic anterior cruciate ligament repair for proximal anterior cruciate ligament tears in skeletally immature patients: surgical technique and preliminary results. *The Knee*, 24, 40–48.
32. Bonnard, C., Fournier, J., Babusiaux, D., Planchenault, M., Bergerault, F. & de Courtivron, B. (2011) Physeal-sparing reconstruction of anterior cruciate ligament tears in children: results of 57 cases using patellar tendon. *The Journal of Bone and Joint Surgery. British Volume*, 93, 542–547.
33. Calvo, R., Figueroa, D., Gili, F., Vaisman, A., Mocoçain, P., Espinosa, M. et al. (2015) Transphyseal anterior cruciate ligament reconstruction in patients with open physes: 10-year follow-up study. *The American Journal of Sports Medicine*, 43, 289–294.
34. Cassard, X., Cavaignac, E., Maubisson, L. & Bowen, M. (2014) Anterior cruciate ligament reconstruction in children with a quadrupled semitendinosus graft: preliminary results with minimum 2 years of follow-up. *Journal of Pediatric Orthopaedics*, 34, 70–77.
35. Cohen, M., Ferretti, M., Quarteiro, M., Marcondes, F.B., de Hollanda, J.P.B., Amaro, J.T. et al. (2009) Transphyseal anterior cruciate ligament reconstruction in patients with open physes. *Arthroscopy: The Journal of Arthroscopic & Related Surgery*, 25, 831–838.
36. Courvoisier, A., Grimaldi, M. & Plaweski, S. (2011) Good surgical outcome of transphyseal ACL reconstruction in skeletally immature patients using four-strand hamstring graft. *Knee Surgery, Sports Traumatology, Arthroscopy*, 19, 588–591.
37. Cordasco, F.A., Mayer, S.W. & Green, D.W. (2017) All-inside, all-epiphyseal anterior cruciate ligament reconstruction in skeletally immature athletes: return to sport, incidence of second surgery, and 2-year clinical outcomes. *The American Journal of Sports Medicine*, 45, 856–863. Available from: https://doi.org/10.1177/0363546516677723
38. Cruz, Jr., A.I., Fabricant, P.D., McGraw, M., Rozell, J.C., Ganley, T.J. & Wells, L. (2017) All-epiphyseal ACL reconstruction in children: review of safety and early complications. *Journal of Pediatric Orthopaedics*, 37, 204–209.
39. Demange, M.K. & Camanho, G.L. (2014) Nonanatomic anterior cruciate ligament reconstruction with double-stranded semitendinosus grafts in children with open physes: minimum 15-year follow-up. *The American Journal of Sports Medicine*, 42, 2926–2932.
40. Foissey, C., Thaunat, M., Caron, E., Haidar, I., Vieira, T.D., Gomes, L. et al. (2022) Combining anterior cruciate ligament reconstruction with lateral extra-articular procedures in skeletally immature patients is safe and associated with a low failure rate. *Arthroscopy, Sports Medicine, and Rehabilitation*, 4, e1941–e1951.
41. Fuchs, R., Wheatley, W., Uribe, J.W., Hechtman, K.S., Zvijac, J.E. & Schurhoff, M.R. (2002) Intra-articular anterior cruciate ligament reconstruction using patellar tendon allograft in the skeletally immature patient. *Arthroscopy: The Journal of Arthroscopic & Related Surgery*, 18, 824–828.
42. Gebhard, F., Ellermann, A., Hoffmann, F., Jaeger, J.H. & Friederich, N.F. (2006) Multicenter-study of operative treatment of intraligamentous tears of the anterior cruciate ligament in children and adolescents: comparison of four different techniques. *Knee Surgery, Sports Traumatology, Arthroscopy*, 14, 797–803.
43. Goddard, M., Bowman, N., Salmon, L.J., Waller, A., Roe, J.P. & Pinczewski, L.A. (2013) Endoscopic anterior cruciate ligament reconstruction in children using living donor hamstring tendon allografts. *The American Journal of Sports Medicine*, 41, 567–574.
44. Greenberg, E.M., Greenberg, E.T., Ganley, T.J. & Lawrence, J.T.R. (2014) Strength and functional performance recovery after anterior cruciate ligament reconstruction in preadolescent athletes. *Sports Health: A Multidisciplinary Approach*, 6, 309–312.
45. Guzzanti, V., Falciglia, F. & Stanitski, C.L. (2003) Physeal-sparing intraarticular anterior cruciate ligament reconstruction in preadolescents. *The American Journal of Sports Medicine*, 31, 949–953.
46. Hoshikawa, A., Hiraoka, H., Monobe, Y., Shiraki, K., Sasaki, Y. & Nakamura, H. et al. (2020) Midterm clinical results after all-epiphyseal double-bundle reconstruction of the anterior cruciate ligament in children with open physes. *Orthopaedic Journal of Sports Medicine*, 8, 232596712091008.
47. Hui, C., Roe, J., Ferguson, D., Waller, A., Salmon, L. & Pinczewski, L. (2012) Outcome of anatomic transphyseal anterior cruciate ligament reconstruction in Tanner stage 1 and 2 patients with open physes. *The American Journal of Sports Medicine*, 40, 1093–1098.
48. Koch, P.P., Fucentese, S.F. & Blatter, S.C. (2016) Complications after epiphyseal reconstruction of the anterior cruciate ligament in prepubescent children. *Knee Surgery, Sports Traumatology, Arthroscopy*, 24, 2736–2740.
49. Kocher, M.S., Garg, S. & Micheli, L.J. (2006) Physeal sparing reconstruction of the anterior cruciate ligament in skeletally immature prepubescent children and adolescents. *The Journal of Bone and Joint Surgery-American Volume*, 88(Suppl 1 Pt 2), 283–293.
50. Kohl, S., Stutz, C., Decker, S., Ziebarth, K., Slongo, T., Ahmad, S.S. et al. (2014) Mid-term results of transphyseal anterior cruciate ligament reconstruction in children and adolescents. *The Knee*, 21, 80–85.
51. Kumar, S., Ahearne, D. & Hunt, D.M. (2013) Transphyseal anterior cruciate ligament reconstruction in the skeletally

immature: follow-up to a minimum of sixteen years of age. *Journal of Bone and Joint Surgery*, 95, e1.

52. Lanzetti, R.M., Pace, V., Ciompi, A., Perugia, D., Spoliti, M., Falez, F. et al. (2020) Over the top anterior cruciate ligament reconstruction in patients with open physes: a long-term follow-up study. *International Orthopaedics*, 44, 771–778.
53. Lawrence, T.J.R., Bowers, A.L., Belding, J., Cody, S.R. & Ganley, T.J. (2010) All-epiphyseal anterior cruciate ligament reconstruction in skeletally immature patients. *Clinical Orthopaedics & Related Research*, 468, 1971–1977.
54. Lemaitre, G., Salle de Chou, E., Pineau, V., Rochcongar, G., Delforge, S., Bronfen, C. et al. (2014) ACL reconstruction in children: a transphyseal technique. *Orthopaedics & Traumatology: Surgery & Research*, 100, S261–S265.
55. Liddle, A.D., Imbuldeniya, A.M. & Hunt, D.M. (2008) Transphyseal reconstruction of the anterior cruciate ligament in prepubescent children. *The Journal of Bone and Joint Surgery. British Volume*, 90, 1317–1322.
56. Mauch, C., Arnold, M.P., Wirries, A., Mayer, R.R., Friederich, N.F. & Hirschmann, M.T. (2011) Anterior cruciate ligament reconstruction using quadriceps tendon autograft for adolescents with open physes—a technical note. *Sports Medicine, Arthroscopy, Rehabilitation, Therapy & Technology*, 3, 7.
57. McCarroll, J.R., Rettig, A.C. & Shelbourne, K.D. (1988) Anterior cruciate ligament injuries in the young athlete with open physes. *The American Journal of Sports Medicine*, 16, 44–47.
58. McCarroll, J.R., Shelbourne, K.D., Porter, D.A., Rettig, A.C. & Murray, S. (1994) Patellar tendon graft reconstruction for midsubstance anterior cruciate ligament rupture in junior high school athletes. An algorithm for management. *The American Journal of Sports Medicine*, 22, 478–484.
59. McIntosh, A.L., Dahm, D.L. & Stuart, M.J. (2006) Anterior cruciate ligament reconstruction in the skeletally immature patient. *Arthroscopy: The Journal of Arthroscopic & Related Surgery*, 22, 1325–1330.
60. Micheli, L.J., Rask, B. & Gerberg, L. (1999) Anterior cruciate ligament reconstruction in patients who are prepubescent. *Clinical Orthopaedics and Related Research*, 364, 40–47.
61. Nakhostine, M., Bollen, S.R. & Cross, M.J. (1995) Reconstruction of mid-substance anterior cruciate rupture in adolescents with open physes. *Journal of Pediatric Orthopaedics*, 15, 286–287.
62. Nikolaou, P., Kalliakmanis, A., Bousgas, D. & Zourntos, S. (2011) Intraarticular stabilization following anterior cruciate ligament injury in children and adolescents. *Knee Surgery, Sports Traumatology, Arthroscopy*, 19, 801–805.
63. Perelli, S., Costa, G.G., Terron, V.M., Formagnana, M., Bait, C., Espregueira-Mendes, J. et al. (2022) Combined anterior cruciate ligament reconstruction and modified lemaire lateral extra-articular tenodesis better restores knee stability and reduces failure rates than isolated anterior cruciate ligament reconstruction in skeletally immature patients. *The American Journal of Sports Medicine*, 50, 3778–3785.
64. Pennock, A.T., Chambers, H.G., Turk, R.D., Parvanta, K.M., Dennis, M.M. & Edmonds, E.W. (2018) Use of a modified all-epiphyseal technique for anterior cruciate ligament reconstruction in the skeletally immature patient. *Orthopaedic Journal of Sports Medicine*, 6, 232596711878176.
65. Redler, L.H., Brafman, R.T., Trentacosta, N. & Ahmad, C.S. (2012) Anterior cruciate ligament reconstruction in skeletally immature patients with transphyseal tunnels. *Arthroscopy: The Journal of Arthroscopic & Related Surgery*, 28, 1710–1717.
66. Robert, H. & Bonnard, C. (1999) The possibilities of using the patellar tendon in the treatment of anterior cruciate ligament tears in children. *Arthroscopy: The Journal of Arthroscopic & Related Surgery*, 15, 73–76.
67. Saad, L., Grimard, G. & Nault, M.L. (2021) Complication rates following all-epiphyseal ACL reconstructions in skeletally immature patients: a retrospective case series study. *Medicine*, 100, e27959.
68. Seon, J.K., Song, E.K., Yoon, T.R. & Park, S.J. (2005) Transphyseal reconstruction of the anterior cruciate ligament using hamstring autograft in skeletally immature adolescents. *Journal of Korean Medical Science*, 20, 1034–1038.
69. Shamrock, A.G., Duchman, K.R., Cates, W.T., Cates, R.A., Khazi, Z.M., Westermann, R.W. et al. (2022) Outcomes following primary anterior cruciate ligament reconstruction using a partial transphyseal (over-the-top) technique in skeletally immature patients. *The Iowa Orthopaedic Journal*, 42, 179–186.
70. Shelbourne, K.D., Gray, T. & Wiley, B.V. (2004) Results of transphyseal anterior cruciate ligament reconstruction using patellar tendon autograft in tanner stage 3 or 4 adolescents with clearly open growth plates. *The American Journal of Sports Medicine*, 32, 1218–1222.
71. Schmale, G.A., Kweon, C., Larson, R.V. & Bompadre, V. (2014) High satisfaction yet decreased activity 4 years after transphyseal ACL reconstruction. *Clinical Orthopaedics & Related Research*, 472, 2168–2174.
72. Streich, N.A., Barié, A., Gotterbarm, T., Keil, M. & Schmitt, H. (2010) Transphyseal reconstruction of the anterior cruciate ligament in prepubescent athletes. *Knee Surgery, Sports Traumatology, Arthroscopy*, 18, 1481–1486.
73. Wall, E.J., Ghattas, P.J., Eismann, E.A., Myer, G.D. & Carr, P. (2017) Outcomes and complications after all-epiphyseal anterior cruciate ligament reconstruction in skeletally immature patients. *Orthopaedic Journal of Sports Medicine*, 5, 232596711769360.
74. Willimon, S.C., Jones, C.R., Herzog, M.M., May, K.H., Leake, M.J. & Busch, M.T. (2015) Micheli anterior cruciate ligament reconstruction in skeletally immature youths: a retrospective case series with a mean 3-year follow-up. *The American Journal of Sports Medicine*, 43, 2974–2981.
75. Wren, T.L., Beltran, V., Katzel, M.J., Conrad-Forrest, A.S. & VandenBerg, C.D. (2021) Iliotibial band autograft provides the fastest recovery of knee extensor mechanism function in pediatric anterior cruciate ligament reconstruction. *International Journal of Environmental Research and Public Health*, 18, 7492.
76. Zhang, L., Liang, Q., Zhao, Z., Zhang, L., Kang, X., Tian, B. et al. (2023) Robot-assisted all-epiphyseal anterior cruciate ligament reconstruction in skeletally immature patients: a retrospective study. *International Orthopaedics*, 47, 429–435.
77. Kay, J., Memon, M., Marx, R.G., Peterson, D., Simunovic, N. & Ayeni, O.R. (2018) Over 90% of children and adolescents return to sport after anterior cruciate ligament reconstruction: a systematic review and meta-analysis. *Knee Surgery, Sports Traumatology, Arthroscopy*, 26, 1019–1036.
78. Frosch, K.H., Stengel, D., Brodhun, T., Stietencron, I., Holsten, D., Jung, C. et al. (2010) Outcomes and risks of operative treatment of rupture of the anterior cruciate ligament in children and adolescents. *Arthroscopy: The Journal of Arthroscopic & Related Surgery*, 26, 1539–1550.
79. Rohde, M.S., Cinque, M.E., LaPrade, C.M., Ganley, T.J. & Shea, K.G. (2022) The spectrum of anterior cruciate ligament reconstruction options for the pediatric and adolescent patient: a narrative review. *Journal of Athletic Training*, 57, 961–971.
80. Willson, R.G., Kostyun, R.O., Milewski, M.D. & Nissen, C.W. (2018) Anterior cruciate ligament reconstruction in skeletally immature patients: early results using a hybrid physeal-sparing technique. *Orthopaedic Journal of Sports Medicine*, 6, 232596711875533.
81. Cancino, B., Muñoz, C., Tuca, M.J., Birrer, E.A.M. & Sepúlveda, M.F. (2022) Anterior cruciate ligament rupture in skeletally immature patients. *JAAOS Global Research &*

Reviews, 6, e21.00166. Available from: https://doi.org/10.5435/JAAOSGlobal-D-21-00166
82. Pascual-Leone, N., Gross, P.W., Meza, B.C. & Fabricant, P.D. (2022) Techniques in pediatric anterior cruciate ligament reconstruction. *Arthroscopy: The Journal of Arthroscopic & Related Surgery*, 38, 2784–2786.
83. Afana, H.B. & Nau, T. (2021) Physeal-sparing anterior cruciate ligament reconstruction for skeletally immature patients: all-epiphyseal technique using quadricep tendon autograft. *Case Reports in Orthopedics*, 2021, 1–7.
84. Feroe, A.G., Hassan, M.M. & Kocher, M.S. (2022) Physeal-sparing anterior cruciate ligament reconstruction with iliotibial band autograft in the skeletally immature knee. *Arthroscopy Techniques*, 11, e1597–e1603.
85. Patil, V., Rajan, P., Hayter, E., Bartlett, J. & Symons, S. (2023) Growth disturbances following paediatric anterior cruciate ligament reconstruction: a systematic review. *Cureus*, 15, e40455.
86. Kaeding, C.C., Flanigan, D. & Donaldson, C. (2010) Surgical techniques and outcomes after anterior cruciate ligament reconstruction in preadolescent patients. *Arthroscopy: The Journal of Arthroscopic & Related Surgery*, 26, 1530–1538.
87. Brey, J.M.B. & Collis, P.N. (2015) Anterior cruciate ligament injuries in children and adolescents. *Current Orthopaedic Practice*, 26, 452–457.
88. Pierce, T.P., Issa, K., Festa, A., Scillia, A.J. & McInerney, V.K. (2017) Pediatric anterior cruciate ligament reconstruction: a systematic review of transphyseal versus physeal-sparing techniques. *The American Journal of Sports Medicine*, 45, 488–494.
89. Perkins, C.A. & Willimon, S.C. (2020) Pediatric anterior cruciate ligament reconstruction. *Orthopedic Clinics of North America*, 51, 55–63.
90. Smeltzer, K., Meyers, A. & Nelson, R. (2023) All-epiphyseal anterior cruciate ligament repair using suture ring device in the skeletally immature patient. *Arthroscopy Techniques*, 12, e745–e750.
91. Anderson, A.F. (2004) Transepiphyseal replacement of the anterior cruciate ligament using quadruple hamstring grafts in skeletally immature patients. *The Journal of Bone & Joint Surgery*, 86, 201–209.
92. McCarthy, M.M., Graziano, J., Green, D.W. & Cordasco, F.A. (2012) All-epiphyseal, all-inside anterior cruciate ligament reconstruction technique for skeletally immature patients. *Arthroscopy Techniques*, 1, e231–e239.
93. Wong, S.E., Feeley, B.T. & Pandya, N.K. (2019) Comparing outcomes between the over-the-top and all-epiphyseal techniques for physeal-sparing ACL reconstruction: a narrative review. *Orthopaedic Journal of Sports Medicine*, 7, 232596711983368.
94. Migliorini, F., Eschweiler, J., Mansy, Y.E., Quack, V., Tingart, M. & Driessen, A. (2020) Quadriceps tendon autograft for primary ACL reconstruction: a Bayesian network meta-analysis. *European Journal of Orthopaedic Surgery & Traumatology*, 30, 1129–1138.
95. Migliorini, F., Oliva, F., Eschweiler, J., Torsiello, E., Hildebrand, F. & Maffulli, N. (2023) Knee osteoarthritis, joint laxity and PROMs following conservative management versus surgical reconstruction for ACL rupture: a meta-analysis. *British Medical Bulletin*, 145, 72–87.
96. Piedade, S.R., Górios, C., Migliorini, F. & Maffulli, N. (2022) Combined anterior cruciate and lateral collateral ligaments reconstruction with ipsilateral hamstring autograft: surgical technique. *Journal of Orthopaedic Surgery and Research*, 17, 466.
97. Frank, J.S. & Gambacorta, P.L. (2013) Anterior cruciate ligament injuries in the skeletally immature athlete: diagnosis and management. *Journal of the American Academy of Orthopaedic Surgeons*, 21, 78–87.
98. De Petrillo, G., Pauyo, T., Franklin, C.C., Chafetz, R.S., Nault, M.L. & Veilleux, L.N. (2022) Limited evidence for graft selection in pediatric ACL reconstruction: a narrative review. *Journal of Experimental Orthopaedics*, 9, 9.
99. Marx, R.G., Hsu, J., Fink, C., Eriksson, K., Vincent, A. & van der Merwe, W.M. (2023) Graft choices for paediatric anterior cruciate ligament reconstruction: state of the art. *Journal of ISAKOS*, 8, 145–152. Available from: https://doi.org/10.1016/j.jisako.2023.01.001
100. Migliorini, F., Eschweiler, J., Mansy, Y.E., Quack, V., Tingart, M. & Driessen, A. (2021) Correction to: Quadriceps tendon autograft for primary ACL reconstruction: a Bayesian network meta-analysis. *European Journal of Orthopaedic Surgery & Traumatology*, 31, 1261.
101. Migliorini, F., Torsiello, E., Trivellas, A., Eschweiler, J., Hildebrand, F. & Maffulli, N. (2023) Bone-patellar tendon-bone versus two- and four-strand hamstring tendon autografts for ACL reconstruction in young adults: a Bayesian network meta-analysis. *Scientific Reports*, 13, 6883. Available from: https://doi.org/10.1038/s41598-023-33899-1
102. Noyes, F.R., Butler, D.L., Grood, E.S., Zernicke, R.F. & Hefzy, M.S. (1984) Biomechanical analysis of human ligament grafts used in knee-ligament repairs and reconstructions. *The Journal of Bone & Joint Surgery*, 66, 344–352.
103. Kunze, K.N., Moran, J., Polce, E.M., Pareek, A., Strickland, S.M., & Williams 3rd, R.J. (2023) Lower donor site morbidity with hamstring and quadriceps tendon autograft compared with bone-patellar tendon-bone autograft after anterior cruciate ligament reconstruction: a systematic review and network meta-analysis of randomized controlled trials. *Knee Surgery, Sports Traumatology, Arthroscopy*, 31, 3339–3352.
104. Schuette, H.B., Kraeutler, M.J., Houck, D.A. & McCarty, E.C. (2017) Bone-patellar tendon-bone versus hamstring tendon autografts for primary anterior cruciate ligament reconstruction: a systematic review of overlapping meta-analyses. *Orthopaedic Journal of Sports Medicine*, 5, 232596711773648.
105. Migliorini, F., Pintore, A., Oliva, F., Eschweiler, J., Bell, A. & Maffulli, N. (2023) Allografts as alternative to autografts in primary posterior cruciate ligament reconstruction: a systematic review and meta-analysis. *Knee Surgery, Sports Traumatology, Arthroscopy*, 31, 2852–2860.
106. Kataoka, K., Hoshino, Y. & Nukuto, K. (2023) Anterior cruciate ligament reconstruction: recent evolution and technical improvement. *Journal of Joint Surgery and Research*, 1, 97–102.
107. Dhillon, J., Kraeutler, M.J., Belk, J.W., McCarty, E.C., McCulloch, P.C. & Scillia, A.J. (2022) Autograft and non-irradiated allograft for anterior cruciate ligament reconstruction demonstrate similar clinical outcomes and graft failure rates: an updated systematic review. *Arthroscopy, Sports Medicine, and Rehabilitation*, 4, e1513–e1521.
108. Zhao, B.A., Yao, Y.Y., Ji, Q.X., Li, Z.Y., Cheng, B. & Pan, J.F. (2022) No difference in postoperative efficacy and safety between autograft and allograft in anterior cruciate ligament reconstruction: a retrospective cohort study in 112 patients. *Annals of Translational Medicine*, 10, 359.
109. Migliorini, F., Trivellas, A., Eschweiler, J., Knobe, M., Tingart, M. & Maffulli, N. (2022) Comparable outcome for autografts and allografts in primary medial patellofemoral ligament reconstruction for patellofemoral instability: systematic review and meta-analysis. *Knee Surgery, Sports Traumatology, Arthroscopy*, 30, 1282–1291.
110. Hulet, C., Sonnery-Cottet, B., Stevenson, C., Samuelsson, K., Laver, L., Zdanowicz, U. et al. (2019) The use of allograft tendons in primary ACL reconstruction. *Knee Surgery, Sports Traumatology, Arthroscopy*, 27, 1754–1770.
111. Steijvers, E., Ghei, A. & Xia, Z. (2022) Manufacturing artificial bone allografts: a perspective. *Biomaterials translational*, 3, 65–80.
112. Kattz, J. (2010) The effects of various cleaning and sterilization processes on allograft bone incorporation. *Journal of Long-Term Effects of Medical Implants*, 20, 271–276.
113. Nguyen, H., Morgan, D.A.F. & Forwood, M.R. (2007) Sterilization of allograft bone: effects of gamma irradiation on allograft biology and biomechanics. *Cell and Tissue Banking*, 8, 93–105.

114. Ardern, C.L., Ekås, G., Grindem, H., Moksnes, H., Anderson, A., Chotel, F. et al. (2018) 2018 International Olympic Committee consensus statement on prevention, diagnosis and management of paediatric anterior cruciate ligament (ACL) injuries. *Knee Surgery, Sports Traumatology, Arthroscopy*, 26, 989–1010.

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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