


Deciding Between ACL Reconstruction, Repair, and Conservative Treatment in Young Athletes: A Systematic Narrative Review

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Objective: The best pediatric and adolescent athlete anterior cruciate ligament (ACL) injury management method remains unknown. This systematic narrative review examined ACL reconstruction (ACLR), ACL repair, and conservative brace, or rehabilitation-based therapeutic exercise interventions with a delayed ACLR option for pediatric and adolescent ACL injury management. The primary purpose was to compare failure rates, return to sport (RTS) rates, and perceived knee function.

Methods: The PubMed, ResearchGate, Google Scholar, Sage Journals, and OVID (Medline) databases were searched. The Modified Coleman Methodology Score (MCMS) assessed study methodological quality and bias risk.

Results: Fifty-six studies were included. Group 1 (ACLR) studies were published before Group 2 (ACL repair) or Group 3 (conservative brace, or rehabilitation-based therapeutic exercise intervention with a delayed ACLR option) studies (Group 1 = 2010.8 ± 9; Group 2 = 2015.9 ± 10; Group 3 = 2018.0 ± 4, $p = 0.05$). Group 2 displayed “good” quality (MCMS = 70.2 ± 7.9), while Group 1 (MCMS = 63.3 ± 6.8) and Group 3 (MCMS = 59.8 ± 6.4) displayed “fair” quality ($p \leq 0.03$). Group 2 had more level 1 or 2 studies, and Group 1 had more level 4 studies ($p = 0.007$). Lysholm scores were similar (Group 1 = 94.4 ± 2.7, Group 2 = 92.1 ± 6.8, Group 3 = 95, $p = 0.51$). Group RTS rates were similar (Group 1 = 88.8 ± 14%, Group 2 = 94.1 ± 10%, Group 3 = 78.6 ± 21%; $p = 0.22$). Group 1 failure rates (7.4 ± 6.6%) were < Group 2 (17.0 ± 19%) ($p = 0.02$) and Group 3 (32.4 ± 18%) ($p < 0.001$).

Conclusion: Although ACLR had lower failure rates, neurocognitive, reactive strength, and psychological readiness assessments were underreported. The stronger methodological rigor for ACL repair studies was encouraging but long-term outcomes are lacking.

Keywords: adolescence, anterior cruciate ligament, athletic injuries, knee, pediatrics

Background

Sports-related ACL injuries are increasing among 13–17-year-old athletes,¹ and the number of ACLR being performed is increasing in parallel.² Most athletes return to sports (RTS) post-ACLR,³ however, reinjury rates are high.⁴ For the adolescent or pediatric athlete, an ACL tear is often more than a season-ending injury as it can lead to an identity crisis with lifelong implications. Because contemporary ACLR techniques do not fully restore native ACL function,⁵ and may risk growth-plate injury, alternative innervations have emerged. These include primary ACL repair⁶ and focused conservative brace, or rehabilitation-based therapeutic exercise interventions with a delayed ACLR option.⁷ Each option requires careful consideration of further growth potential, reinjury risk, long-term neuromuscular and biomechanical adaptations, and early knee osteoarthritis development. Unfortunately, the best pediatric and adolescent athlete ACL injury management method remains unknown.^{1–7} For these reasons, a systematic narrative review was performed to examine evidence gaps surrounding ACLR, ACL repair, and conservative brace, or rehabilitation-based therapeutic exercise interventions with a delayed ACLR option in pediatric and adolescent athletes. The primary study purpose was to determine which management method had the lowest failure rates, the highest RTS rates, and superior patient-reported

outcome measure (PROM) perceived knee function. Secondary outcomes of interest included knee laxity, muscle strength, and functional performance test results.

Methods

This systematic narrative review was performed in alignment with the Cochrane Handbook for Systematic Reviews of Interventions, following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 checklist. To minimize selection bias, two independent reviewers searched the PubMed, ResearchGate, Google Scholar, Sage Journals, and OVID (Medline) databases. The initial search was restricted to studies published between January 1, 2015–August 31, 2025. To broaden search results, this range was later expanded without date restrictions. Search terms were developed in consultation with the senior author and medical literature, incorporating standardized Medical Subject Headings (MeSH). Boolean operators “OR” and “AND” were used to combine terms across categories. Population-related terms included pediatric, adolescent, youth, young athlete, skeletally immature, and open physes. Condition terms were anterior cruciate ligament and ACL. Intervention terms included repair, primary repair, suture repair, bridge-enhanced ACL repair (BEAR) technique, reconstruction, physéal-sparing, transphyseal, conservative treatment, and non-operative. Outcome terms included arthrometer, KT-1000, Lachman, pivot-shift, goniometer, range of motion, strength, dynamometer, hop test, return to play, International Knee Documentation Committee (IKDC) score, Knee Injury and Osteoarthritis Outcome Score (KOOS), Lysholm score, and patient-reported outcome measurements (PROM).

Inclusion and Exclusion Criteria

Study eligibility was assessed using the patient/population/problem, intervention, comparison/control, and outcome (PICOS) framework. The target population was skeletally immature athletes aged 13–17 years with radiographic evidence of open physes. Interventions included ACL repair (such as the BEAR, suture, or suture anchor-based techniques), ACLR, non-surgical natural ACL healing strategies (Cross Bracing) or conservative rehabilitation therapeutic exercise-based management with a delayed ACLR option. Primary study outcomes included group RTS rates, failure rates, and PROM use and results. Secondary outcomes of interest included knee laxity (arthrometer, anterior Lachman test, pivot shift test), muscle strength/power (isokinetic or handheld dynamometry), and functional performance (single leg hop testing) test results. Eligible study designs included randomized controlled trials, cohort, and observational studies or case reports with at least five patients. Studies were excluded if non-English, unavailable in full text, if they involved multiple ligament injury surgeries, if they did not include skeletally immature patients, were solely surgical technique papers, were reviews, or consisted of solely of biomechanical or animal data.

Data Extraction

Using a standardized digital spreadsheet, two reviewers (JL, EG) independently extracted data. Variables collected included study design, participant number, age, sex distribution, skeletal maturity confirmation, growth or limb length disturbance, intervention type, comparison group, outcome measures, and follow-up duration. Discrepancies were resolved by consensus with a third reviewer (JN).

Risk of Bias and Quality Assessment

Methodological study quality and bias risk assessments were performed using the Modified Coleman Methodology Score (MCMS),⁸ a 100-point scale evaluating study size, follow-up, design, diagnostic clarity, intervention description, rehabilitation reporting, outcome validity, objectivity of assessments, statistical analysis, and study design suitability.

Statistical Analysis

Descriptive data analysis and group comparisons were performed using specialized software (IBM-SPSS ver. 29, Chicago, IL, USA). Where applicable, unweighted group study means with standard deviations, or frequencies were determined and statistically compared. Categorical data were compared using Chi-square or Fisher’s Exact tests. Continuous data were compared using either an independent samples *t*-test or a one-way ANOVA (group) and Tukey post-hoc tests. Meta-analysis elements such as group effect size determination and forest plot creation were not performed. An alpha value of $p \leq 0.05$

was selected to indicate statistically significant differences. When feasible, the biological, biomechanical, physiological, or clinical rationale for observed group differences were qualitatively discussed.

Results

Methodological Quality and Bias Risk Assessment

The initial search identified 58 studies with MCMS of 60.4 ± 9.7 (fair).^{9–67} To better focus study analysis on the methodologically strongest studies, a MCMS cut-off threshold was established of the overall mean score minus one standard deviation. This resulted in 50 studies (Group 1: ACLR, $n = 33$; Group 2: ACL repair, $n = 13$; and Group 3: conservative brace, or rehabilitation-based therapeutic exercise interventions with a delayed ACLR option ($n = 4$)). To better target long-term studies, a second search was performed resulting in an additional 13 studies identified that also underwent MCMS determination.^{68–80} This resulted in six studies being added to the review.^{69,70,76–79} With these additions, the study number increased to 56 with a mean MCMS of 64.6 ± 7.7 (Table 1) (Figure 1).

Group 1 (ACLR) studies were published earlier than Group 2 (ACL repair) or Group 3 (conservative brace, or rehabilitation-based therapeutic exercise interventions with a delayed ACLR option) studies (Group 1 = 2010.8 ± 9 ; Group 2 = 2015.9 ± 10 ; Group 3 = 2018.0 ± 4 , $p = 0.05$). Group 2 (ACL repair) studies had higher MCMS (70.2 ± 7.9) than Group 1 (ACLR) (63.3 ± 6.8) ($P = 0.009$) and Group 3 (conservative brace, or rehabilitation-based therapeutic exercise interventions with a delayed ACLR option) studies (59.8 ± 6.4) ($p = 0.03$). Overall, Group 2 studies displayed good methodological research study quality, whereas Groups 1 and 3 were fair. Group 2 had more evidence level 1 or 2 studies (prospective) than Group 1 which had more evidence level 4 studies (retrospective) ($p = 0.007$). Mean patient age, sex distribution, participant numbers, and follow-up durations were comparable between groups (Table 2).

Group 1: ACL Reconstruction

The ACLR group surgical methods are described in Table 3. Twenty one studies used a transphyseal surgical approach,^{19,21,23,27,29,32,35,40,41,44,48,49,55,56,59–61,63,66,67,77} ten studies used an “over the top” surgical approach at the femur and a transphyseal approach at the tibia,^{18,25,29,36,38,43,45,46,50,54} two studies used either an all epiphyseal or transphyseal approach,^{69,78} one study used either an all epiphyseal, partial transphyseal, or complete transphyseal approach,⁷⁰ two studies used an intraepiphyseal approach,^{22,37} and one study used the Clocheville method.⁵⁷

Group 2: ACL Repair

ACL surgical repair methods are shown in Table 4. Four studies used the BEAR technique,^{31,52,53,58} six studies used sutures or suture-anchor combinations,^{20,28,33,42,64,65} one study used the healing response technique,⁶² one study used four different methods,³⁴ and one study used small diameter transphyseal tunnels with resorbable suture tape and cortical suspension button fixation.²⁴

Group 3: Conservative Brace, or Rehabilitation-Based Therapeutic Exercise Interventions with a Delayed ACLR Option

Non-surgical ACL healing strategies using Cross bracing³⁰ and conservative brace, or rehabilitation-based therapeutic exercise interventions with a delayed ACLR option^{26,30,47,51} are shown in Table 5.

Follow-Up

Mean final follow-up timing was comparable between groups (Group 1 = 5.6 ± 3.9 years, Group 2 = 3.6 ± 1.8 years, Group 3 = 3.4 ± 3.1 years, $p = 0.12$).

Patient Reported Outcome Measures

The most used PROM for Group 1 were: the Lysholm score ($n = 15$),^{19,21,23,27,32,36,43,45,49,50,54–56,59,63} International Knee Documentation Committee (IKDC) Subjective score ($n = 10$),^{21,23,29,38,43,49,56,60,63,78} IKDC Objective score ($n = 4$),^{32,38,46,57} Cincinnati/Noyes Scoring System ($n = 3$),^{18,54,60} Knee Injury and Osteoarthritis Outcome Score (KOOS) ($n = 4$),^{36,76,78,79}

Table I Modified Coleman Methodology Scores (MCMS)

Grp	Study	#	FU	Approach	Type	Diag.	Surg. Descrip.	Rehab Descrip.	Clear Measures	Clear Timing	Reliable	Gen. Health	Recruit Subjects	Indep. Review	Written Format	Subjects Complete	Bias Control	>90%	<90%	Score
1	Andrews et al ¹⁸	0	7	10	0	5	10	5	2	2	3	0	5	0	3	3	5	0	0	60
1	Aronowitz et al ¹⁹	0	4	10	0	5	10	5	2	2	3	0	5	0	3	3	5	0	0	57
2	Bigoni et al ²⁰	0	7	10	0	5	10	5	2	2	3	0	5	4	3	3	5	5	0	69
1	Calvo et al ²¹	0	10	10	0	5	10	5	2	2	3	0	5	0	3	3	5	5	0	68
1	Cassard et al ²²	0	4	10	0	5	10	5	2	2	3	0	5	4	3	3	5	5	0	66
1	Cohen et al ²³	0	7	10	0	5	10	5	2	2	3	0	5	0	3	3	5	0	0	60
2	Dabis et al ²⁴	0	4	10	0	5	10	5	2	2	3	0	5	0	3	3	5	5	0	62
1	Demange et al ²⁵	0	10	10	10	5	10	5	2	2	3	0	5	0	3	3	5	5	0	78
3	Ekas et al ²⁶	4	10	10	0	0	5	0	2	2	3	3	5	0	3	3	5	0	0	55
1	Ellis et al ²⁷	7	7	7	0	5	10	5	2	2	3	0	5	0	3	3	5	0	0	64
1	Engelbrechtsen et al ²⁸	0	7	10	0	5	10	5	2	2	3	0	5	0	0	0	5	5	0	59
1	Falciglia et al ²⁹	4	10	10	0	5	10	5	2	2	3	0	5	0	3	3	5	0	0	67
3	Filbay et al ³⁰	7	4	0	10	5	0	5	2	2	3	0	5	0	3	3	5	5	0	59
2	Fleming et al ³¹	0	10	7	10	5	5	5	2	2	3	0	5	4	3	3	5	0	0	69
1	Fuchs et al ³²	0	7	10	0	5	10	0	2	2	3	0	5	0	3	3	5	0	0	55
2	Gagliardi et al ³³	10	7	7	0	5	10	5	2	2	3	0	5	0	3	3	5	5	0	72
2	Gaulrapp et al ³⁴	7	10	10	0	5	10	5	2	2	3	0	5	0	3	3	5	0	0	70
1	Goddard et al ³⁵	4	4	10	0	5	10	5	2	2	3	0	5	0	3	3	5	5	0	66
1	Grassi et al ³⁶	7	10	10	0	5	10	5	2	2	3	0	5	0	3	3	5	0	0	70
1	Guzzanti et al ³⁷	0	10	10	0	5	10	5	2	2	3	0	5	0	3	0	5	0	0	60
1	Henry et al ³⁸	7	4	7	0	5	10	5	2	2	3	0	5	0	3	3	5	0	0	61
1	Hui et al ³⁹	0	4	10	0	5	10	5	2	2	3	0	5	4	3	3	5	0	0	61

1	Kew et al ⁴⁰	10	7	0	0	5	5	5	2	2	3	0	5	0	3	3	5	0	0	55
1	Kilkenny et al ⁴¹	10	4	7	0	5	10	5	2	2	3	0	5	0	3	3	5	5	0	69
2	Al Kindi et al ⁴²	7	7	10	10	5	10	5	2	2	3	0	5	0	3	3	5	0	0	77
1	Kocher et al ⁴³	10	10	10	0	5	10	5	2	2	3	0	5	0	3	3	5	0	0	73
1	Kocher et al ⁴⁴	7	7	10	0	5	10	5	2	2	3	0	5	0	3	3	5	0	0	67
1	Lanzetti et al ⁴⁵	4	10	10	0	5	10	5	2	2	3	0	5	0	3	3	5	5	0	72
1	Lo et al ⁴⁶	0	10	7	0	5	10	5	2	2	0	0	5	0	3	3	5	0	0	57
3	Madelaine et al ⁴⁷	7	4	10	0	5	5	5	2	2	0	0	5	0	3	3	5	0	0	56
1	McCarroll et al ⁴⁸	7	7	7	0	5	5	5	2	2	3	0	5	0	3	3	5	0	0	59
1	McIntosh et al ⁴⁹	0	7	10	0	5	5	5	2	2	3	0	0	0	3	3	5	5	0	55
1	Micheli et al ⁵⁰	0	10	10	0	5	10	5	2	2	3	0	5	0	3	3	5	0	0	63
3	Moksnes et al ⁵¹	4	7	10	10	5	0	5	2	2	3	0	5	0	3	3	5	5	0	69
2	Murray et al ⁵²	0	4	7	10	5	10	5	2	2	3	0	5	4	3	3	5	0	0	68
2	Murray et al ⁵³	7	4	7	15	5	10	5	2	2	3	0	5	4	3	3	5	5	0	85
1	Parker et al ⁵⁴	0	4	10	0	5	10	5	2	2	3	0	5	0	3	3	5	0	0	57
1	Pennock et al ⁵⁵	7	4	7	0	5	10	5	2	2	3	0	5	0	3	3	5	0	0	61
1	Redler et al ⁵⁶	0	7	10	0	5	10	5	2	2	3	0	5	0	3	3	5	0	0	60
1	Robert et al ⁵⁷	0	7	10	0	5	10	5	2	2	3	0	0	0	0	0	5	5	0	54

(Continued)

Table I (Continued).

Grp	Study	#	FU	Approach	Type	Diag.	Surg. Descrip.	Rehab Descrip.	Clear Measures	Clear Timing	Reliable	Gen. Health	Recruit Subjects	Indep. Review	Written Format	Subjects Complete	Bias Control	>90%	<90%	Score
2	Sanborn et al ⁵⁸	7	4	7	15	5	5	5	2	2	3	0	5	4	3	3	5	5	0	80
1	Seon et al ⁵⁹	0	10	10	0	5	10	0	2	2	0	0	5	0	3	3	5	0	0	55
1	Shelbourne et al ⁶⁰	0	7	10	0	5	10	5	2	2	3	0	5	0	3	3	5	0	0	60
2	Shelbourne et al ⁶¹	10	10	10	10	5	5	0	2	2	0	0	5	0	3	3	5	0	0	70
2	Steadman et al ⁶²	0	10	10	10	5	10	5	2	2	3	0	5	0	3	3	5	0	0	73
1	Streich et al ⁶²	0	10	7	0	5	10	5	2	2	3	0	5	0	3	3	5	5	0	65
2	Turati et al ⁶⁴	0	4	10	0	5	10	5	2	2	3	0	5	0	3	3	5	0	0	57
2	Vermeijden et al ⁶⁵	10	4	10	0	5	10	5	2	2	3	0	5	0	3	3	5	5	0	72
1	Webster et al ⁶⁶	10	7	10	0	5	0	0	2	2	0	0	5	0	3	3	5	0	0	52
1	Webster et al ⁶⁷	10	7	10	10	5	10	5	2	2	0	0	5	0	3	3	5	0	0	77
1	Cordasco et al ⁷⁰	7	7	7	0	5	10	5	2	2	3	0	0	0	3	3	5	5	0	64
1	Cordasco et al ⁶⁹	10	7	7	10	5	10	5	2	2	3	0	5	0	0	0	5	5	0	76
1	Mansson et al ⁷⁶	4	10	0	0	5	10	5	2	2	3	3	0	0	3	3	5	5	0	60
1	Morgan et al ⁷⁷	10	10	7	0	5	10	5	2	2	3	0	5	4	3	3	5	0	0	74
1	Moussa et al ⁷⁸	10	7	7	0	5	5	5	2	2	3	0	5	0	3	3	5	0	0	62
1	Thorolfsson et al ⁷⁹	10	10	0	10	5	0	0	2	2	3	0	5	0	3	3	5	0	0	58

Notes: Group 1 = ACL reconstruction, Group 2 = surgical ACL repair, Group 3 = non-surgical ACL repair or conservative rehabilitation-based approach with or without delayed ACL reconstruction.

Abbreviations: Descrip, description; Indep, independent; Diag, diagnosis; Gen., general; Surg, surgery; Rehab., rehabilitation.

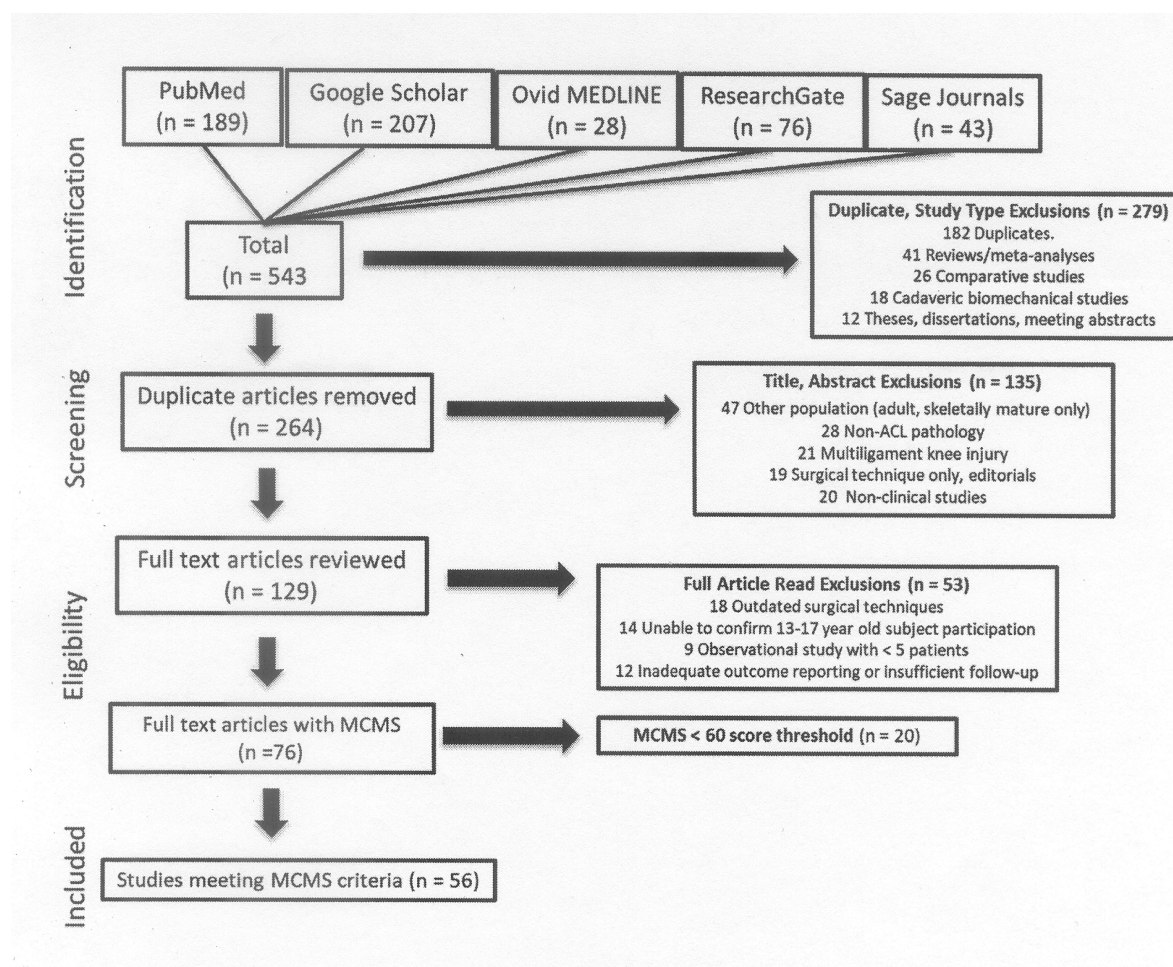


Figure 1 PRISMA study selection diagram.

Tegner Activity Scale (n = 11),^{21,27,36,45,49,55-57,63,76,78} Pediatric IKDC questionnaire (Pedi-IKDC) (n = 1),⁴⁵ Visual Analog Scale (VAS) pain score (n = 2),^{36,60} the Hospital for Special Surgery Functional Activity Brief Scale (HSS Pedi-FABS) (n = 1),⁵⁴ Short Form 36 (n = 1),⁷⁶ EQ-5D-5L (n = 1),⁷⁶ the Single Assessment Numeric Evaluation (SANE) (n = 1),⁵⁵ and the ACL-Return to Sport Index (n = 1).⁷⁸ For Group 2, the most frequently used PROM included the Lysholm score (n = 6),^{20,24,28,34,64,65} IKDC Subjective score (n = 4),^{20,31,58,65} Tegner Activity Scale (n = 5),^{20,24,28,34,64} Pedi-IKDC (n = 1),⁶⁴ ACL-RSI (n = 1),⁵⁸ KOOS (n = 2),^{24,31} SANE (n = 1),⁶⁵ Cincinnati/Noyes Knee Rating (n = 1),⁶⁵ and Objective IKDC score (n =

Table 2 Group Patient Gender and Age Demographics (Mean ± Standard Deviation)

	Subject #	# Females	# Males	Subject Age
Group 1 (ACL reconstruction)	128.9 ± 247	68.1 ± 171	66.6 ± 98	13.9 ± 3.1
Group 2 (Surgical ACL repair)	48.5 ± 51	23.3 ± 29	23.2 ± 27	16.9 ± 6.9
Group 3 (Conservative non-surgical, natural ACL healing strategies or rehabilitation therapeutic exercise-based intervention with delayed ACLR option)	55.8 ± 17	20.0 ± 7	35.8 ± 9	16.3 ± 6.6
p-value	0.42	0.59	0.28	0.13

Table 3 ACLR Study Primary Graft, Surgical Approach, Fixation, Summary Comments, Mean Follow-Up (FU), and Failure Rate

Group	Study	Publication Year	Mean Subject Age	Primary Graft	Surgical Approach	Fixation	Summary Comments	Mean FU (years)	Failure Rate
I	Andrews et al ¹⁸	1994	13.5	Achilles tendon or Fascia lata allograft	F-Over the top, T-transphyseal	Initially staples, then soft tissue washers attached to interwoven graft sutures	Did not recommend ACLR in skeletally immature athletes as the growth plate is only 6–12 months from skeletal maturity	4.8	12.5% (1/8)
I	Aronowitz et al ¹⁹	2000	13.4	Achilles tendon allo	Transphyseal	F-staples, T-pressfit	At FU 5/15 had grade I anterior Lachman signs, none had a + pivot shift test	2.1	0% (0/19)
I	Calvo et al ²¹	2014	13.0	STG auto	Transphyseal	F-button, T-IS, staple	Transphyseal drilling modified for soft tissue graft fixation away from the physis was safe without altering growth	10.6	14.8% (4/27)
I	Cassard et al ²²	2014	13.0	Short STG auto strands with synthetic tapes	Intraepiphyseal	IS synthetic tape fixation	No meniscus injuries, degenerative changes, or growth disturbances	2.8	7% (2/28)
I	Cohen et al ²³	2009	13.3	STG auto	Transphyseal	F-crosspin, T-IS, staple	Good clinical outcomes, no growth disturbances	3.8	11.5% (3/26)
I	Cordasco et al ⁶⁹	2019	15.0	QT auto; 58% with LET	All epiphyseal (n = 26) /Transphyseal (n = 57)	F and T button fixation	Excellent outcomes	2.0	3.6% (3/83)
I	Cordasco et al ⁷⁰	2024	14.1	STG auto for Groups 1 and 2. BPTB auto for Group 3.	All epiphyseal (n = 49; partial trans-physeal (n = 66); complete trans-physeal (n = 209)	F and T button fixation	Revision ACLR rates were higher and RTS rates were lower in group 2.	3.7	Group 1 = 6% (3/49); Group 2 = 20% (13/66); Group 3 = 6% (12/209)
I	Demange et al ²⁵	2014	10.7	ST auto	Nonanatomic, F-over the top, T-transphyseal	F-IS proximal to growth plate, T-post with screw/ washer	Good results, but high adulthood failure rat.	15	25% (3/12)
I	Ellis et al ²⁷	2012	16.0	BPTB auto vs allo	Transphyseal	F, T- metal IS	Function, activity and satisfaction was the same, but allo had a 15x greater failure rate	4.2	11% (9/79) -Autograft 3% (2/59) -Allograft: 35% (7/20)
I	Falciglia et al ²⁹	2016	12.4	STG auto	Partial transphyseal (avoided tibial physis) with intact distal ST, G	Staples at femur	Good results at mid- and long-term without growth disturbances	13.5	9.5% medium- term (2/21); 0% (0/12) long-term

I	Fuchs et al ³²	2002	13.2	BPTB allo	Transphyseal	Metal IS	Perceived normal or near-normal function. No instability or growth disturbances. Continued instability and high meniscal tear rates in active patients without ACLR	3.3	0% (0/10)
I	Goddard et al ³⁵	2013	13.0	Living HT allo (multi-strand)	Transphyseal	Metal IS or staples	Normal or nearly normal IKDC ligament grade, patients were active in strenuous activities, no growth disturbances	2.0	6% (2/32)
I	Grassi et al ³⁶	2021	16.3	STG auto, lateral tenodesis	Distally intact HT, over the top at femur	Staples	Similar long-term graft failure rate and contralateral ACL injury rate with other ACLR techniques	10.1	15.4% (8/52)
I	Guzzanti et al ³⁷	2003	11.4	STG auto	Eccentrically-drilled physeal-sparing tunnels	F-staple, T-suture to periosteum	Good graft isometry and knee stability with no growth disturbances	5.8	0% (0/8)
I	Henry et al ³⁸	2009	12.4	Quadriceps auto with bone	F-Intraphyseal, T-transphyseal	F=pressfit, T-IS	Compared early with delayed ACLR. Early ACLR had better subjective IKDC, otherwise comparable between groups	2.3	Delayed: 3.7% (1/27) Early: 0%
I	Hui et al ³⁹	2012	12.0	Primarily living HT allo (multi-strand)	Transphyseal	IS and staple	Excellent outcomes with high activity levels, no growth disturbances	2.1	0% (0/16)
I	Kew et al ⁴⁰	2022	16.1	HT or BPTB auto	Transphyseal	Surgeon's common practice	12% graft reinjury, 16% contralateral knee injury. Injured subjects had more HT auto and had greater, more symmetrical quadriceps strength at RTS	4.0	12% (12/100)
I	Kilkenny et al ⁴¹	2022	14.9* estimate	STG for open physes; either STG or BPTB for closed.	Transphyseal	BPTB-metal IS; STG – F-button, T-bioresorbable IS	High RTS rates with moderate re-rupture rates at 2-years. STG auto had more ipsilateral reruptures.	2.0	4.5% (16/358)
I	Kocher et al ⁴³	2018	11.2	ITB auto	Physeal-sparing. Over the top LFC	Suture fixation to F, T periosteum	Excellent outcomes, minimal growth disturbances, low mod-to-long term graft rupture rate	2.8	6.6% (9/137)

(Continued)

Table 3 (Continued).

Group	Study	Publication Year	Mean Subject Age	Primary Graft	Surgical Approach	Fixation	Summary Comments	Mean FU (years)	Failure Rate
I	Kocher et al ⁴⁴	2007	14.7	STG auto	Transphyseal	F-button, T-Metal or resorbable IS	Excellent outcomes, low revision rate, minimal growth disturbance risk	3.5	3% (2/61)
I	Lanzetti et al ⁴⁵	2020	12.5	STG auto, lateral tenodesis	F-Over the top, T-physis sparing tunnel	F-staples, T-intact distal STG	Excellent function, low complication rates	8	4.8% (2/42)
I	Lo et al ⁴⁶	1997	12.9	STG, or quadriceps patellar tendon with Kennedy Ligament Augmentation device distal insertions maintained	F-Over the top, T-transphyseal	Staples	ACLR with small drill holes through an open tibial physes did not adversely affect outcomes or growth	7.4	0% (0/5)
I	Mansson et al ⁷⁶	2014	15.2	BPTB or STG auto	Surgeon's decision	Surgeon's decision	Adolescents with ACLR had more radiographically visible OA changes. Clinical outcomes and HRQL similar to healthy subjects.	14.5	13.7% (4/29)
I	McCarroll et al ⁴⁸	1994	14.2	BPTB auto	Transphyseal	IS	Intra-articular was better for stability, fewer meniscal tears, less failure, no growth disturbances	4.2	0% (0/60) during study; 3/60 tore ACL graft >2 yrs post-ACLR
I	McIntosh et al ⁴⁹	2006	13.8	STG auto	Transphyseal	F-button, T-washer/screw	Satisfactory results. No new meniscal tears. Most RTS, but high (43.8%) revision rate	3.4	12.5% (2/16)
I	Michelli et al ⁵⁰	1999	11.0	ITB auto distally intact	Physeal-sparing, Over the top at the LFC	Sutures	Stable with excellent Lysholm scores. No growth disturbance	5.5	0% (0/17)
I	Morgan et al ⁷⁷	2016	16.0	STG auto or BPTB auto	Transphyseal	Metal IS	Over 15 years 33% had further ACL injury	16.5	5%, 8%, 12%, 15%, and 17% at 1,2,5,10,15 years
I	Moussa et al ⁷⁸	2024	16.1	Closed physes got quad STG, BPTB, or ITB (modified Macintosh); LEAPs included LET, ALL repair with DB gracilis, and combined intra-articular ACLR with modified Macintosh	Physeal-sparing or partial transphyseal	Surgeon's preference	ACLR + LEAP reduced rerupture risk, facilitated higher activity levels	4.9	2.5% (3/121) for ACLR + LEAP; 13.6% (18/132) for ACLR
I	Parker et al ⁵⁴	1994	13.3	STG auto distally attached	Physeal-sparing, Over the top at the LFC	Staples	No growth disturbances, clinical stability, but increased graft MRI signal	2.8	0% (0/6)

I	Pennock et al ⁵⁵	2019	14.8	QT or STG auto	Transphyseal	F-button, T-IS or screw-post	Good short-term outcomes, high RTS rates, low physeal abnormality rates. QT auto had a lower retear rate	2.6	QT: 4% (1/27) STG auto: 21% (12/56)
I	Redler et al ⁵⁶	2012	14.2	STG auto	Transphyseal	F-button, T-washer-post	Excellent outcomes without growth disturbances	3.6	0% (0/18)
I	Robert et al ⁵⁷	1999	11.4	BPTB auto	Clocheville Method	F-IS, T-staples	Excellent or good objective IKDC scores; alternative for patients with open physes	3.5	0% (0/8)
I	Seon et al ⁵⁹	2005	14.7	HS auto	Transphyseal	F-mostly ligament anchor screw, T-absorbable screw	Excellent Lysholm scores, no LLD > 1 cm	6.5	0% (0/11)
I	Shelbourne et al ⁶⁰	2004	14.8	BPTB auto	Transphyseal	Sutures and buttons	No growth disturbances without graft over-tensioning	3.4	6% (1/16)
I	Shelbourne et al ⁶¹	2009	15.5	BPTB auto	Transphyseal	NR	Athletes who RTS earlier did not have a higher reinjury rate	9.8	10.2% (41/402)
I	Streich et al ⁶³	2010	11.0	ST auto	Transphyseal	F-button, T-suture disk	Superior to nonoperative treatment in immature pre-pubescent patients	5.8	Operative: 0% Non-op: 58% -Defined as delayed ACLR due to instability
I	Thorolfsson et al ⁷⁹	2025	16.4	STG auto (92%); BPTB auto (4.5%); Other auto (1.8%)	NR	NR	Long-term function improvement; high RTS rates after pediatric and adolescent ACLR	10	16/81 (20%) pediatrics; 262/1311 (20%) adolescent
I	Webster et al ⁶⁶	2014	28.5	STG auto	Transphyseal	F-button, T-IS	Patients < 20 years were at greater graft rupture and contralateral ACL injury risk	4.8	4.5% (26/561)
I	Webster et al ⁶⁷	2016	17.2	STG auto	Transphyseal	F-button, T-IS	Higher failure rates in patients < 18 years particularly males. Youngest males were at greatest risk	5.0	18% (57/316)

Abbreviations: F, femur; T, tibia; auto, autograft; allo, allograft; ALL, anterolateral ligament; DB, double bundle; HRQL, health-related quality of life; IS, interference screw; ITB, iliotibial band; LEAPs, Lateral Extra-Articular Procedures; LET, lateral extra-articular tenodesis; LFC, lateral femoral condyle; LLD, limb length difference; NR, not reported; RTS, return to sports; BPTB, bone patellar tendon-bone; QT, quadriceps tendon; STG, semitendinosus-gracilis.

Table 4 Surgical ACL Repair Studies, Publication Year, Mean Subject Age, Surgical Approach, Key Findings, Follow-Up (FU), and Failure Rate

Group	Study	Publication Year	Mean Subject Age	Surgical Approach	Key Findings	FU Years	Failure Rate
2	Bigoni et al ²⁰	2016	9.2	ACL femoral re-insertion with resorbable anchor	Good short-term stability and RTS	3.6	0% (0/5)
2	Dabis et al ²⁴	2020	12.9	Sherman Types I–II, transphyseal with small diameter tunnels; femoral side repair with non-resorbable suture tape- cortical button	Excellent short-term outcomes	2.7	0% (0/20)
2	Engebretsen et al ²⁸	1988	15.0	Four ACL stump “U” sutures advanced to the femur through 2 drill holes not crossing the physeal plate	3 had good outcomes; 5/8 failed. This technique should be avoided	5.0	63% (5/8)
2	Fleming et al ³¹	2024	24.3	Bridge Enhanced ACL Restoration Method (BEAR)	At 6-year FU BEAR was similar HT ACLR	6.0	BEAR: 11% (1/9); ACLR: 14% (1/7)
2	Gagliardi et al ³³	2019	15.1* estimate	SLA compared to QT patellar bone autograft reconstruction	Higher failure risk in the SLA group	2.7	SLA: 48.8% (9/22) QT: 4.7% (6/151)
2	Gaulrapp et al ³⁴	2006	13.8	IE avulsions re-attached with cerclage wires or screws; proximal femoral avulsion tears reinserted or sutured through 2mm trans-epiphyseal femoral tunnels; augmentation with distally attached ST for patients with open physes, patellar problems, or PF risk factors	Good stabilization with no growth disturbances (similar to partial ACLR)	6.5	2.3% (1/44)
2	Al Kindl et al ⁴²	2024	30.0	Femoral ACL reattachment (82% Sherman type I) using two PEEK swivel-lock anchors	High functional scores with early outcomes; similar to ACLR	4.1	17.8% (8/45)
2	Murray et al ⁵²	2019	24.3	Bridge Enhanced ACL Restoration Method (BEAR)	Similar outcomes as ACLR with HT auto at 2 years.	2.0	0% (0/20)
2	Murray et al ⁵³	2020	17	Bridge Enhanced ACL Restoration Method (BEAR)	Noninferior PROM and AP laxity; superior knee flexor strength to HS auto ACLR at 2-year FU	2.0	BEAR: 14% (9/64) ACLR: 6% (2/35)
2	Sanborn et al ⁵⁸	2022	17	Bridge Enhanced ACL Restoration Method (BEAR)	BEAR had higher ACL-RSI scores at 6 months than ACLR with HT or BPTB auto	2.0	NR
2	Steadman et al ⁶²	2006	13	Healing response procedure with 6–10 drill holes near ACL femoral attachment to aid blood clot formation. No fixation was used.	With proper skeletally immature athlete selection stability. Function, and high RTS levels restored	5.8	23% (3/13)
2	Turati et al ⁶⁴	2021	9.2	Femoral ACL reattachment with a resorbable or all suture anchor	Restored stability and RTS activities while avoiding growth plate disturbances. 4/ 19 re-ruptured at median 3.9 years (range 1–7)	2.0	21% (4/19)
2	Vermeijden et al ⁶⁵	2021	16.0	Dual suture anchor ACL repair with suture tape augmentation	Higher failure rate in patients ≤ 21 years. May be better for ≥ 21 years with low failure (3.5%) and complications (1.2%)	2.1	11.5% (13/113)

Abbreviations: AP, anterior-posterior; SLA, suture ligament augmentation; QT, quadriceps tendon; IE, intercondylar eminence; ST, semitendinosus; Peek, polyether ether ketone; PF, patellofemoral.

Table 5 Conservative Brace, or Rehabilitation-Based Therapeutic Exercise Intervention with Delayed ACLR Option Group Studies, Publication Year, Mean Subject Age, Surgical Approach, Key Findings, Follow-Up (FU), and Failure Rate

Group	Study	Publication Year	Mean Subject Age	Surgical Approach	Key Findings	FU (Years)	Failure Rate
3	Ekas et al ²⁶	2018	15.3	Evaluated children <13 years post-ACL injury treated with active rehabilitation with delayed ACLR option	50% coped without ACLR even into adulthood; However, the others may develop instability; 33% may require meniscus surgery	8.0	Non-operative: 24/44 (54.5%) failed non-operative care needing ACLR. Operative group: 2/24 had graft failure (8.3%)
3	Filbay et al ³⁰	2023	26	Cross Bracing Protocol	90% had healing evidence on 3 month MRI. Longer FU and more trials are needed	1.0	14% (11/80) re-injured their ACL within 18m, and 9 had ACLR
3	Madalaine et al ⁴⁷	2018	12.2	4 phase rehabilitation to increase knee stability, achieve full extension and quadriceps activation to RTS (pivoting)	92% success at 4-years. Clinical instability (36%). 17% with meniscal tears, was the only predictive factor of poor conservative treatment tolerance	2.6	39.6% (21/53) had ACLR after failed non-operative management
3	Moknes et al ⁵¹	2013	11.8	Non-operative treatment algorithm	36 (78%) chose to not have ACLR at FU. Leg symmetry indices > 90% for isokinetic strength and SLH; 91% maintained pivot sports, but 38% switched from level 1 to level 2 activities	2.0	21.7% (10/46) had ACLR after failed non-operative management

Abbreviation: SLH, single leg hop.

1).³⁴ For Group 3, the most frequently used PROM were the IKDC Subjective score ($n = 2$),^{26,51} and the Lysholm score,³⁰ KOOS⁵¹ and Knee-related Quality of Life Survey³⁰ (each $n = 1$). Overall, the Lysholm score was the most used PROM with similar group scores at final follow-up: Group 1 = 94.4 ± 2.7 , Group 2 = 92.1 ± 6.8 , and Group 3 = 95 ($p = 0.51$).

Ligamentous Knee Laxity

In Group 1 (ACLR), 20 studies (51.3%, 20/39) reported anterior Lachman test results.^{18,19,21–23,25,29,32,37,38,44–46,50,54,56,59,60,63,76} In Group 2 (ACL repair), 6 studies (46.2%, 6/13) reported anterior Lachman test results.^{33,34,52,53,58,64} In Group 3 (conservative brace, or rehabilitation-based therapeutic exercise interventions with a delayed ACLR option) 3 of 4 studies (75%) reported anterior Lachman test laxity^{26,30,47} (Table 6). Eighteen of 39 (46.2%) of ACLR group studies reported pivot shift test results.^{18,19,21–23,25,32,35,39,43–46,49,54,56,63,76} Graft type ($p = 0.81$) and bone tunnel preparation/graft placement method ($p = 0.20$) did not display differing pivot shift test results. Five of 13 (38.5%) ACL repair group studies reported pivot shift test results.^{20,31,52,53,64} In

Table 6 Group Anterior Laxity and Pivot Shift Test Results

Group	Study	Side-to-Side Laxity Difference or Grade (at Last Follow-Up Unless Otherwise Stated)	Pivot Shift (at Last Follow-Up Unless Otherwise Stated)
1	Andrews et al ¹⁸	<3 mm N = 5; 3–5 mm N = 3	One case had 15 mm anterior pivot shift 9 days post ACLR (underwent revision). NR for other cases
1	Aronowitz et al ¹⁹	1.7 mm (range = 0–3 mm)	None had a positive pivot shift
2	Bigoni et al ²⁰	3 (range = 2–4 mm)	Two grade 1 pivot shift tests in 5 patients
1	Calvo et al ²¹	2.6 (range = 2.7–7 mm)	NR
1	Cassard et al ²²	0.3 mm at 134 N	NR
1	Cohen et al ²³	2.5 ± 1 mm	Grade 1 pivot shift in 2 cases and negative in remaining cases
1	Cordasco et al ⁶⁹	NR	NR
1	Cordasco et al ⁷⁰	NR	NR
1	Demange et al ²⁵	No ACL instability progression at long term FU (anterior Lachman test)	No ACL instability progression at long term FU (pivot shift)
3	Ekas et al ²⁶	Of 20 patients who did not undergo ACLR, all had a + anterior Lachman test without an endpoint. 1/24 patients with ACLR had a side-to-side Lachman test difference	Of 20 patients who did not undergo ACLR all had + Slocum tests. 4 of 24 patients with ACLR had a positive Slocum test and 11 had both positive Slocum and Lachman tests
1	Falciglia et al ²⁹	2.4 mm (range = 1–4 mm) vs 1.9 mm (range = 1–5 mm)	NR
2	Fleming et al ³¹	BEAR = 1.5 ± 1.58 mm; ACLR = 1.6 ± 3.03 mm	Similar BEAR and ACLR group pivot shift results at 6 years
1	Fuchs et al ³²	<3 mm N = 8; 3–5 mm N = 2	Post-ACLR all had a negative pivot-shift test at last FU.
2	Gagliardi et al ³³	Manual anterior Lachman SLA = median 2 mm; QT = 2 mm; KT-1000 SLA = 2 mm; QT = 1 mm	NR
2	Gaulrapp et al ³⁴	IE 1.6 mm; BPTB 1.7 mm; ST 2.7 mm; PR = 3.5 mm	NR

(Continued)

Table 6 (Continued).

Group	Study	Side-to-Side Laxity Difference or Grade (at Last Follow-Up Unless Otherwise Stated)	Pivot Shift (at Last Follow-Up Unless Otherwise Stated)
I	Goddard et al ³⁵	NR	25 (86%) had negative pivot shift. 4 (14%) had a pivot glide
I	Guzzanti et al ³⁷	1.8 mm (range = 1.5-2 mm)	NR
I	Henry et al ³⁸	Group 1 = 1.93 ± 1.2 mm; Group 2 = 1.76 ± 2 mm	NR
I	Hui et al ³⁹	NR	14 (88%) had negative pivot shift; 2 (12%) had pivot glide
I	Kew et al ⁴⁰	NR	NR
I	Kilkenny et al ⁴¹	NR	NR
I	Kocher et al ⁴⁴	Anterior Lachman test not abnormal in any knee	Pivot shift normal in 56 knees, nearly normal in 3 knees
I	Kocher et al ⁴³	NR	98.8% had a normal pivot-shift
I	Lanzetti et al ⁴⁵	1.2 mm (range = 0.9-1.5 mm)	No pivot shift difference with contralateral knee
I	Lo et al ⁴⁶	1.0 ± 1.63 mm	No patients had clinically unstable knees
3	Madelaine et al ⁴⁷	Softer anterior Lachman test endpoint in conservatively treated subjects than ACLR subjects	Conservative treated subjects more frequently had + pivot shift at last FU
I	Mansson et al ⁷⁶	Anterior Lachman test < 2 mm N = 13; 2–5 mm N = 12; KT-1000 median = 3.3 mm with MMT; 2.8 mm at 134 N	Post-ACLR: 0= 13 patients (52%), +1= 12 patients (48%)
I	McIntosh et al ⁴⁹	NR	Post-ACLR: 15 had negative pivot shift test, one had +1
I	Micheli et al ⁵⁰	1.1 ± 1.9 mm	Post-ACLR all had negative pivot shift tests
3	Moksnes et al ⁵¹	NR	Rotational knee laxity remained in conservative group; ACLR group had fewer subjects with a + pivot shift test
I	Moussa et al ⁷⁸	NR	NR
2	Murray et al ⁵²	Grade A 8/9 BEAR group; 6/7 ACLR group; Grade B 1/9 BEAR group; 1/7 ACLR group; Overall BEAR group = 1.94 ± 2.08 mm; ACLR group = 3.14 ± 2.66 mm	Similar BEAR, ACLR group pivot shift test results at 2 years.
2	Murray et al ⁵³	1.61 ± 2.16 mm BEAR; 1.77 ± 2.79 mm for HT or BPTB auto	BEAR had similar pivot shift test laxity as HT or BPTB auto groups
I	Parker et al ⁵⁴	3.6 ± 1.9 mm	None had a positive pivot shift test
I	Redler et al ⁵⁶	0.29 ± 1.07 mm	Postoperatively, pivot shift test was negative in all subjects
2	Sanborn et al ⁵⁸	2.7 ± 0.4 mm BEAR vs 2.2 ± 0.5 mm ACLR	NR
I	Seon et al ⁵⁹	2.2 mm (range = 1–4 mm)	NR
I	Shelbourne et al ⁶⁰	2.1 ± 1.2 mm (range = 0–4 mm)	NR

(Continued)

Table 6 (Continued).

Group	Study	Side-to-Side Laxity Difference or Grade (at Last Follow-Up Unless Otherwise Stated)	Pivot Shift (at Last Follow-Up Unless Otherwise Stated)
1	Streich et al ⁶³	Surgical 1.8 ± 1.4 mm vs Conservative 4.3 ± 2.9 mm	13 in the ACLR group and 3 in the conservative group had normal pivot shift tests; 3 in ACLR group and 6 in the non-ACLR group had grade 1 rotational instability. 3 others initially treated non-ACLR had a grade 2 pivot shift test
2	Turati et al ⁶⁴	2.2 mm (range = 1–3 mm)	3/14 had grade 1 “glide” pivot shift test results 2 years post-ACLR
3	Filbay et al ³⁰	3 months post-protocol initiation, 80% of subjects had no anterior Lachman test difference	At 6 months, 58% had a normal pivot shift test

Abbreviations: N, subject number; NR, not reported; HT, hamstring tendon; IE, intercondylar eminence; BPTB, bone-patellar tendon-bone; ST, semitendinosus; PR, primary repair; SLA, suture ligament augmentation; MMT, manual maximal test.

Group 3 (conservative brace, or rehabilitation-based therapeutic exercise interventions with a delayed ACLR option) 3 of 4 studies (75%) reported pivot shift test results.^{30,47,51} Each of these studies reported greater pivot shift laxity with conservative intervention management. Using the Cross Bracing protocol, Filbay et al³⁰ reported that 42.5% (17/40) of patients displayed a positive pivot shift test 6 months post-intervention. The ACLR group had more studies with $\geq 85\%$ negative pivot shift test results compared to the other groups ($p = 0.001$).

Isokinetic or Handheld Dynamometry, Single Leg Hop Testing, and Return to Sport Criteria

Group isokinetic or handheld dynamometry testing, functional hop testing, RTS decision-making criteria, and outcomes are shown in [Supplemental Table 1](#). In the ACLR group 6 studies (15.4%, 6/39)^{40,41,54,60,69,76} used isokinetic or instrumented handheld dynamometry to measure strength. In the ACL repair group 6 studies (46.2%, 6/13)^{28,31,52,53,58,65} also used isokinetic or handheld dynamometry to measure strength. In the conservative brace, or rehabilitation-based therapeutic exercise interventions with a delayed ACLR option group, 2 studies (50%, 2/4)^{26,51} used isokinetic or handheld dynamometry to measure strength. The ACL repair and conservative brace, or rehabilitation-based therapeutic exercise interventions with a delayed ACLR option groups had significantly greater isokinetic or handheld dynamometry test use frequency ($p = 0.04$).

In the ACLR group 7 studies (17.9%, 7/39)^{27,35,39,40,54,69,76} reported single leg hop testing. In the ACL repair group 6 studies (46.2%, 6/13)^{20,31,52,53,58,64} reported single leg hop testing. In the conservative brace, or rehabilitation-based therapeutic exercise intervention with delayed surgery option group, 2 studies (50%, 2/4)^{26,51} reported single leg hop testing. The ACL repair and conservative brace, or rehabilitation-based therapeutic exercise intervention with delayed surgery option groups had significantly greater single leg hop test frequency ($p = 0.05$). Group 1 (ACLR) had 16 studies that described at least basic RTS criteria (16/39, 41.0%).^{18,19,21,29,41,44,45,48,55–57,60,61,63,69,70} Group 2 (ACL repair) had 4 studies that described at least basic RTS criteria (4/13, 30.8%).^{24,58,62,65} Group 3 (conservative brace, or rehabilitation-based therapeutic exercise intervention with delayed surgery option) had one study that described at least basic RTS criteria (1/4, 25%).³⁰ Groups displayed similar RTS criteria use frequency ($p = 0.69$).

Failure and Return to Sport Rates

Group 1 displayed lower mean reported failure rates ($7.4 \pm 6.6\%$) compared to Group 2 ($17.0 \pm 19\%$) ($p = 0.02$) and Group 3 ($32.4 \pm 18\%$) ($p < 0.001$) ([Figure 2](#)). The predominant bone tunnel preparation/graft placement method was transphyseal drilling ($n = 21$), followed by physeal sparing tibial tunnel drilling with over the top femoral side graft placement ($n = 3$) or transphyseal tibial tunnel drilling with over the top femoral side graft placement ($n = 3$). Failure rate differences were not observed between different bone tunnel types or over the top graft placement ($p = 0.39$) or for different graft types ($p = 0.93$). Groups did not display statistically significant RTS rate differences ([Figure 3](#)) ([Table 7](#)).

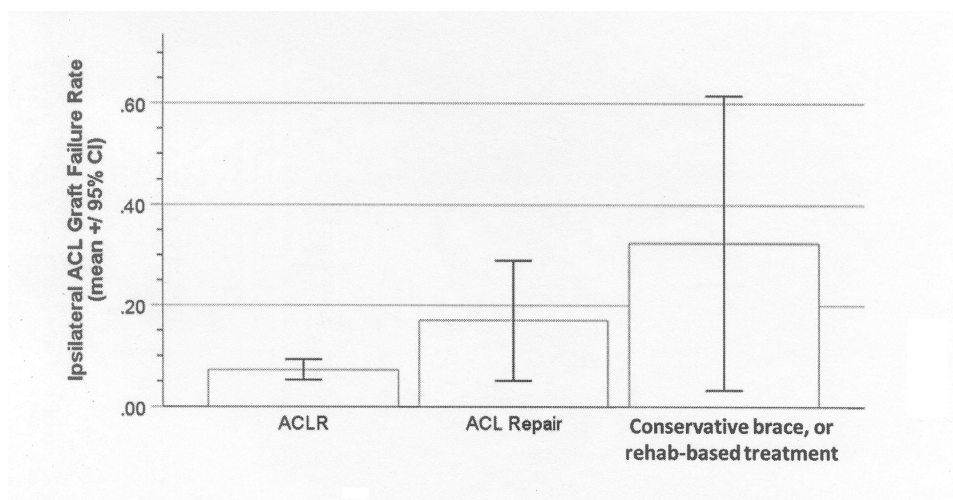


Figure 2 The ACLR group displayed lower mean reported failure rates compared to the ACL repair ($p = 0.02$) and to the conservative brace, or rehabilitation-based therapeutic exercise interventions with a delayed ACLR option groups ($p < 0.001$).

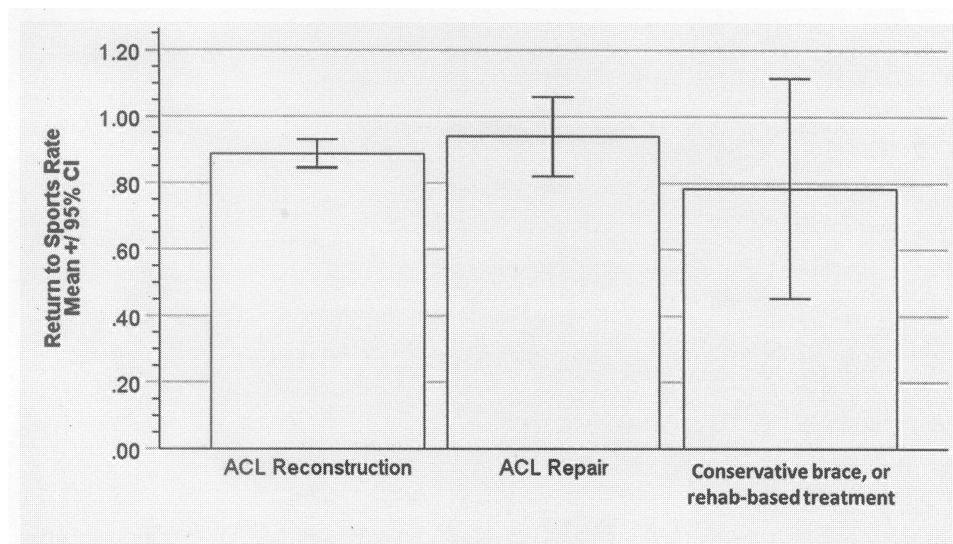


Figure 3 Groups displayed similar RTS rates ($p = 0.22$).

Among ACLR studies, graft type ($p = 0.53$) and bone tunnel preparation/graft placement method ($p = 0.22$) did not contribute to RTS rate differences.

Discussion

Comparison groups had similar mean patient age, sex distribution, participants/study, and follow-up durations. Primary and secondary results and qualitative syntheses of the biological, biomechanical, physiological, or clinical rationale for observed group differences are discussed.

Research Evidence Levels

The ACL repair group displayed good methodological research study quality with higher MCMS than the ACLR or the conservative brace, or rehabilitation-based therapeutic exercise intervention with delayed ACLR option groups. The ACL repair group also had more evidence level 1 or 2 studies than the other groups, while the ACLR group had more evidence

Table 7 Mean Group Failure and RTS Rates (Including Inclusive Comparative Study Results)

	Mean Final Follow Up Years, (Range)	ACLR Graft Failure % (95% CI) # Failures / # Treated	RTS % (95% CI) # RTS / # Treated
ACLR	5.6 (2–16.5)	7.4% (5,9)*	88.8% (0.85, 0.93)
ACL Repair	3.6 (2–6.5)	17% (4,29)	94.1% (0.82, 1.06)
Conservative management	3.4 (1–8)	32% (3,62)	78.6% (0.4, 1.10)
	Groups did not differ (p = 0.11)	*Group 1 displayed lower mean reported failure rates (7.4 ± 6.6%) compared to Group 2 (17.0 ± 19%) (p = 0.02) and Group 3 (32.4 ± 18%) (p < 0.001)	Groups did not differ (p = 0.22)

level 4 studies. This finding suggests that ACL repair studies, although lacking long-term follow-up, had methodologically stronger short-term efficacy evidence. The more recent mean publication year for this group was likely associated with stronger methodologies.

Failure Rates

The most important study finding was that the ACLR group had lower failure rates than the ACL repair, or conservative brace, or rehabilitation-based therapeutic exercise intervention with delayed ACLR option groups. The current study did not identify one particular technique that best prevented growth or alignment disturbance, minimized recurrent knee injuries, or optimized RTS outcomes. Although delaying ACLR until physeal closure increases graft options, maintaining pivot sport restrictions in young athletes can be difficult, and RTS without a functioning ACL increases secondary meniscal or articular cartilage injury risk.⁷⁶ Regardless of the surgical technique or graft used, ACLR had lower failure rates than the other groups. The graft collagen scaffold may have provided superior failure resistance to ACL repair, native ACL healing, or neuromuscularly mediated knee stability responses.

Return to Sport Rates

Return to sport rates were similar between groups. This finding, however, may be obscured by the diverse ways that RTS readiness was determined. Although group differences were not statistically significant, longer final mean follow-up timing for the ACLR group may have reduced its RTS rate compared to the other groups. For up to 2 years post-ACLR or ACL repair, the contralateral, native ACL has increased metabolic activity suggesting a systemic inflammatory process.^{81–83} With increasing contralateral ACL injuries in high-risk young athletes after non-contact ACL injury and ACLR, more time and greater scrutiny of contralateral native ACL health might be needed in addition to more stratified RTS and return to performance decision-making criteria.⁸⁴ Serial advanced imaging assessments of unilateral ACL graft and contralateral native ACL health post-ipsilateral ACL injury and ACLR may better enable re-injury (ipsilateral) or injury (contralateral) risk determination.⁸⁴

Patient Reported Outcome Measures

The Lysholm Knee Scoring Scale was the most frequently used PROM with similar scores at final follow-up for ACLR = 94.4 ± 2.7; ACL repair = 92.1 ± 6.8; and for conservative brace, or rehabilitation-based therapeutic exercise intervention with delayed ACLR option = 95 (p = 0.51). These findings suggest comparable perceived sports knee function. However, survey administration timing differed between studies and the Lysholm Knee Scoring Scale was developed primarily for adults making it potentially less valid than the ACL-RSI, the Pedi-IKDC, or the HSS Pedi-FABS for adolescent or pediatric patients.

Ligamentous Knee Laxity

Conservative interventions are encouraging, but unless high pivot-dependent activities are avoided, with decreased knee stability many patients eventually develop meniscal tears and/or articular cartilage injuries.^{51,68} Better ACLR group pivot shift test outcomes support the lower failure rates that we report.

Isokinetic or Handheld Dynamometry Strength Testing

The ACL repair and conservative brace, or rehabilitation-based therapeutic exercise intervention with delayed ACLR option groups had more frequent isokinetic or handheld dynamometry test use than the ACLR group ($p = 0.04$). More frequent isolated knee strength recovery assessments in these groups suggest that RTS decision-making for these groups may have been less post-surgery time-based than for the ACLR group.

Single Leg Hop Testing

The ACL repair and conservative brace, or rehabilitation-based therapeutic exercise intervention with delayed ACLR option groups more frequently reported single leg hop test use. This finding also suggests that RTS decisions for these groups may have been less post-surgery time based than in the ACLR group.

Return to Sport Criteria

Groups had similar RTS criteria use frequencies. The best recovery path, however, may depend less on what is currently being measured and more on rehabbing athlete characteristics that to date have remained largely unappreciated (neurocognitive, reactive strength, and psychological factors).⁵⁸ For obvious reasons, physical performance tests predominate RTS criteria. The lack of neurocognitive function, reactive strength, and psychological profile assessments, however, is worrisome. Incorporating these factors into future research and rehabilitation protocols would improve return to sport decision-making. Psychological factors are key recovery determinants post-ACL injury.^{58,66,67,85} The American Academy of Orthopaedic Surgeon guidelines⁸⁶ recommend ACLR ≤ 3 months post-ACL injury. Early ACLR, however, may not provide young athletes with sufficient cognitive appraisal time to better understand recovery, or to reflect about the future role of sports in their lives.

Existing Gaps

To better determine neuromuscular system recovery post-ACL injury intervention, ACLR studies need to make greater use of both serial instrumented muscle strength dynamometry and single leg hop tests. All future studies need to better assess neurocognitive, reactive strength, and psychological factors. Advanced imaging identification of neurocognitive activation pattern locations, amplitudes, and onset timing may help clarify which intervention produces the superior short- and long-term functional outcomes that decreases both ipsilateral ACL graft re-injury or contralateral knee injury rates.⁸⁷⁻⁸⁹

With lower failure rates, ACLR is currently the gold standard for pediatric and adolescent patients who intend to return to pivoting and cutting sports. Although ACLR had lower failure rates, PROM and RTS rates were comparable between ACLR and ACL repair. Therefore, the selected intervention should be individualized based on the evidence provided by methodologically stronger study designs. For high risk, high demand young athletes who play pivoting sports and have a non-contact ACL injury family history, increased generalized joint laxity, or genu recurvatum $\geq 10^\circ$, some recent studies recommend supplemental anterolateral ligament (ALL) repair or lateral extra-articular tenodesis (LET).⁹⁰ In addition to including more comprehensive health domain assessments, greater patient sample stratification by physiological age, sex, skeletal maturity level, sport type, and adolescent developmental phase will improve our understanding of which approach best facilitates more complete recovery,⁸¹ not just ACL graft healing or physical performance function restoration. Group difference interpretations should account for confounding factors such as skeletal maturity, sport-specific demands, baseline activity level, sex, and rehabilitation protocol variations, which were inconsistently reported across studies. Given that both ACL repair and conservative interventions preserve native ACL mechanoreceptors, fertile research areas include knee joint proprioceptive/kinesthetic position/alignment sense accuracy, lower

extremity neuromuscular activation onset timing,⁸⁸ and reactive force restoration assessments.⁸⁹ Preserving native ACL mechanoreceptors may offer potential neuromuscular control and dynamic joint stability benefits; however, direct evidence for improved long-term outcomes in skeletally immature patients is limited.^{5,91} Serial advanced imaging may help determine which intervention most effectively reduces the systematic inflammatory responses that increase contralateral native ACL metabolic activity.⁸⁴ Improved understanding of the interconnections between biological healing, mechanical stability, psychological readiness, neurocognitive, and reactive neuromuscular function should strengthen rehabilitation recovery. Well-timed, more comprehensive health domain measurements represent the next pediatric and adolescent ACL injury management frontier. Even the term RTS should evolve from simple “yes”, or “no” responses to more stratified, serial holistic health and sustainable athletic performance validations. No single intervention works best for every young athlete. Outcome success depends on effective alignment of multiple developmental, environmental, and personal factors. Reviewed studies rarely reported confounding variable differences that might have influenced recovery and reinjury risk such as rehabilitation strategies, surgical timing relative to skeletal maturity, hormonal influences (sex hormone levels), sport specialization, and socioeconomic status. To enable more meaningful intervention comparisons these factors should be reported with greater detail.

Future Directions

Rehabilitation targeting neuromuscular control and dynamic knee stability are essential not only for conservative interventions, but also post-ACLR or ACL repair. Well-designed, more comprehensive strategies can also help guide future RTS criteria development. Within motor learning of sound athletic movements lies an important opportunity to better restore and perhaps improve both physical and mental health.

Although the evidence is limited, for young active patients with Sherman grade I–II ACL tears, surgical repair may present some advantages.^{6,52} With ACL repair, autogenous tendon harvest for graft creation is not needed, reducing arthrogenic inhibition likelihood.⁹¹ Although early results are encouraging, fewer patients have undergone BEAR technique treatment and long-term follow-up is lacking. The conservative Cross Bracing protocol³⁰ presents encouraging non-surgical natural ACL healing, however, evidence for its efficacy is limited, particularly for 13–17 year patients and the 3 month braced knee flexion requirement may deter compliance. Although this intervention shows promise, the case series only had one year follow-up and the failure rate at 5–18 months post-protocol was 14%.³⁰ For some patients prolonged bracing and structured rehabilitation may also facilitate concomitant meniscal or articular cartilage injury healing, however, this data is limited, derived primarily from a small number of patient cases.

At 6 months post-ACL repair, Sanborn et al⁵⁸ reported that patients who underwent ACL repair with the BEAR technique had a mean 12.9 points higher ACL-RSI scale score (psychological readiness), which was more strongly associated with higher subjective IKDC scores (perceived sports knee function) than in patients who had ACLR with a quadrupled hamstring or bone-patellar tendon-bone autograft. Studies suggest that ACL-RSI cutoff scores of 60 and 62 are predictive of an RTS at pre-injury sports level.^{85,92} In the Sanborn et al⁵⁸ study, the BEAR group mean ACL-RSI score was 15% > those thresholds suggesting that BEAR ACL repair may translate into better early post-ACLR psychological outcomes. Webster and Feller⁸⁵ reported an ACL-RSI score of 65 as a benchmark for successful RTS 12 months post-ACLR, further supporting early psychological improvement. At 6 months post-ACLR, the mean ACL-RSI score for the BEAR group was 71.1 ± 2.9 compared to 58.2 ± 3.9 for the ACLR group. Isokinetic knee muscle strength outcomes paralleled these findings. At 6 months post-ACL repair, the BEAR group had a 10% increase in knee flexor torque (% of contralateral side) which was associated with a 2.5 point ACL-RSI score increase, while a 10% increase in knee extensor torque resulted in a 3.7 point ACL-RSI score increase. Anteroposterior knee laxity differences corresponded to decreased ACL-RSI scores in both groups (a 2 point decrease for each mm of increased laxity). These findings reinforce the interconnectedness of ligamentous joint stability, neuromuscular strength, and psychological readiness restoration, suggesting that surgical ACL repair may better support early RTS milestones. Whether or not these gains translate into sustainable mid-to-long term advantages remains to be confirmed.⁵⁸

Study Limitations

This review has several limitations. With few high-level randomized controlled studies, the overall methodological quality was only fair. Many studies were retrospective increasing bias risk, limiting evidence strength and generalizability. Retrospective designs are particularly prone to recall bias and incomplete data collection, undermining reported outcome reliability. Small sample sizes also limit statistical power, potentially concealing important intervention differences. Publication bias also cannot be excluded, as studies with positive findings are more likely reported than those with neutral or negative results. The heterogeneity in patient age ranges, skeletal immaturity confirmation, surgical techniques, rehabilitation approaches, PROM use, and operational failure and RTS criteria definitions made direct comparisons difficult. Although this review targeted young patients with open physes, several contributing studies included older individuals limiting population-specific generalizability. Additionally, outcomes reporting was inconsistent with many studies relying heavily on PROM use, while others focused more on ACL graft failure rates or athlete RTS rates. Follow-up timing also varied with most studies reporting short or mid-term results. This prevented comprehensive long-term outcome assessment of ACL graft failure rates, lower extremity growth/alignment disturbances, and post-traumatic knee osteoarthritis development. Lastly, the smaller number of conservative brace, or rehabilitation-based therapeutic exercise interventions with a delayed ACLR option studies restricts the strength of conclusions. This, however, reflects the current state of the medical literature, not a definitive lack of value for any of these emerging interventions.

Conclusion

Although ACLR had lower failure rates, neurocognitive, reactive strength, and psychological readiness assessments were underreported.⁹³ The stronger methodological rigor for ACL repair studies was encouraging but long-term outcomes are lacking.

Disclosure

The authors report no conflicts of interest in this work.

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