OXFORD JOURNAL
OF STUDENT
SCHOLARSHIP

# Comparison of Anterior Cruciate Ligament Reconstruction Techniques In Adolescents: A Systematic Review of Literature

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## ABSTRACT

**Background:** Anterior cruciate ligament (ACL) injuries in adolescents have increased significantly, with reconstructions in patients under 15 years rising 425% from 1994 to 2006. The skeletal immaturity of this population introduces unique surgical considerations regarding repair technique selection and physeal approach, yet comparative evidence on functional outcomes remains limited.

**Methods:** We conducted a systematical review of literature on PubMed from 2021 to 2025 comparing functional outcomes of different ACL reconstruction techniques in adolescent patients, with specific focus on single-bundle versus double-bundle repair methods, transphyseal versus physeal-sparing approaches, and the influence of skeletal maturity status on recovery.

**Results:** Seven studies encompassing 1,054 patients were included. Single-bundle reconstruction was the predominant technique (40.9%), while double-bundle reconstruction was documented in only one case (0.1%). Patients with open physes demonstrated superior functional outcomes compared to those with closed physes across short-and long-term follow-up periods. Single-bundle transphyseal reconstruction in skeletally immature patients yielded the highest functional scores, with weighted mean IKDC scores of 93.1 ± 6.8 short-term and 98.6 ± 2.9 long-term.

**Conclusion:** Single-bundle transphyseal reconstruction represents an effective surgical approach for adolescent ACL tears, particularly in skeletally immature patients. Skeletal maturity status at the time of surgery serves as an important prognostic factor for functional recovery. However, substantial proportions of unspecified repair techniques and physeal approaches, heterogeneity in functional scoring systems, and broad temporal categorization limit definitive conclusions. Future research should prioritize standardized outcome reporting and patient-level data analysis to better inform clinical decision-making in this population.

January 2026
Vol 3. No 1.

## INTRODUCTION

Anterior cruciate ligament (ACL) injuries represent one of the most common knee traumas among adolescent athletes, with an estimated incidence of 14 per 100,000 exposures in this population and ACL reconstructions in patients under 15 years of age having increased by 425% from 1994 to 2006 (Perkins and Willimon). This rise has been attributed to increased youth sports participation, year-round competitive play, and early single-sport specialization, particularly in pivoting sports such as basketball and soccer that place high demands on knee stability (Perkins and Willimon). However, the adolescent population presents unique challenges for ACL reconstruction due to the presence of open growth plates and ongoing skeletal development, necessitating careful consideration of surgical techniques that balance the restoration of knee stability with the preservation of normal physeal function (Perkins and Willimon; Verhagen et al.). Historically, skeletally immature patients were managed nonoperatively due to concerns about physeal injury and subsequent growth disturbances; however, delayed reconstruction has been associated with increased rates of secondary meniscal and chondral damage, highlighting the need for early surgical intervention in this demographic (Perkins and Willimon). As such, determining the optimal surgical approach for adolescent ACL reconstruction remains a critical clinical question with significant implications for both short-term functional recovery and long-term joint health (Perkins and Willimon; Verhagen et al.).

## LITERATURE REVIEW

One of the standard ways through which literature aims to assess the functional outcomes of ACL surgical repairs is through functional tests such as the International Knee Documentation Committee, Lysholm, and Tegner scores (Verhagen et al.; Sun et al.; Murray et al.). These tests rely on a consistent set of criteria, such as symptoms, range of motion, and the ability to return to pre-injury levels of activity, which make comparisons across data sets and studies more reliable (Verhagen et al.; Sun et al.; Murray et al.). Some papers, however, use a different approach. For example, other sources measure functional outcomes by assessing failure rates that may lead to additional revision surgery, allowing for a greater focus on long-term outcomes of procedures (Aga et al.; Cheatham and Johnson; Verhagen et al.). Since our study is designed to focus on both short- and long-term functional outcomes, we will adopt a third hybrid approach. While we will still use functional tests as the foundation of our data collection, we will also draw inspiration from studies which track functional test results over several intervals to have a fuller picture of patient recovery over time (Aga et al.; Sun et al.; Murray et al.).

### Major Factors

When analyzing a particular ACL repair technique, three main factors are typically considered. One of such considerations involves whether the surgeon used a single or double bundle reconstruction method. Single bundle reconstruction has been the traditional method for ACL surgical treatment that involves placing a single graft within the native ACLs original insertion points, aiming to restore the knee's original level of anterior & posterior stability (Schreiber et al.; Cheatham and Johnson; Steiner). However, some surgeons prefer an alternate method, known as the double-bundle technique, which aims to more closely replicate the anatomy and function of the native ACL by reconstructing both of the ACL's distinctive bundles: the anteromedial (AM) bundle and the posterolateral (PL) bundle (Schreiber et al.; Aga et al.). This technique allows a surgeon to also address rotational stability in the knee, which often doesn't get covered by single-bundle ACL repair (Schreiber et al.; Cheatham and Johnson). Another factor that is commonly focused on is the graft type used in the surgery, with procedures either leaning towards an autograft, typically sourced from the hamstring or quadriceps of the patient, or an allograft, which allows for a more selectable graft size and a decrease in operative time (Schreiber et al.; Sun et al.; Verhagen et al.). However, studies show that there is little to no statistical significance between success rates of these two graft types, so this will not be the main focus of our study (Schreiber et al.; Murray et al.; Verhagen et al.). Finally, a surgical repair technique tends to fall under one of two categories: transphyseal or physeal-sparing (Kaeding et al.; Perkins and Willimon; Verhagen et al.). During ACL reconstruction, small tunnels must be drilled through the bone to create a pathway for the graft placement and to fix the graft to the bone (Verhagen et al.). The transphyseal technique, as the name suggests, drills across the physis of the patient, which provides maximum stability for the knee (Perkins and Willimon; Kaeding et al.). Alternatively, the physeal-sparing technique aims to avoid crossing or drilling through the physis, instead finding alternative locations for the bone tunnels (Perkins and Willimon; Kaeding et al.). Altogether, the reconstruction method, the choice of graft type, and the drilling approach are the key factors that are typically considered when comparing ACL surgical repair techniques (Verhagen et al.; Kaeding et al.).

**The Benefits and Drawbacks of Double-Bundle Reconstruction**

Among the aforementioned factors, the variation in reconstruction method has received particular attention, with the double-bundle technique often highlighted for its potential advantages over the traditional single-bundle approach (Schreiber et al.; Aga et al.). One of the major reasons for this is that due to the way that double-bundle reconstruction closely replicates the anatomy and functions of both ACL bundles, it is able to address rotational stability more effectively than single-bundle reconstruction (Schreiber et al.; Cheatham and Johnson; Aga et al.; Steiner). Several studies, cadaveric and in vivo, found that although the single-bundle technique effectively restores anterior-posterior stability, its inability to recreate both native ACL bundles prevents it from adequately addressing rotational stability (Schreiber et al.; Cheatham and Johnson). This is a major concern due to the rising prevalence of ACL tears in the adolescent athlete population, particularly those that partake in pivoting sports such as basketball (Perkins and Willimon; Schreiber et al.). As a result, more surgeons are leaning towards a double-bundle reconstruction method in order to more accurately meet the demands that these levels and kinds of activity may have on the ACL (Schreiber et al.). Additionally, double-bundle ACL reconstruction has been found to have a variety of other benefits as well, such as providing more tissue and collagen to compensate for the effects of laxity caused by deficiencies in the secondary restraints, like the menisci, collateral ligaments and capsule, and showing lower rates of rerupture than single-bundle repair in some cases (Cheatham and Johnson; Aga et al.; Schreiber et al.). Because of these advantages, double-bundle reconstruction has been growing in popularity in recent years and is often favored as a more reliable option for ACL restoration (Schreiber et al.; Aga et al.).

This technique, however, doesn't come without its drawbacks. For example, double-bundle reconstruction has been found to take longer than single-bundle reconstruction, be more technically demanding, have a higher risk of tunnel convergence, and potentially require notchplasty, which can compromise osseous landmarks (Schreiber et al.; Aga et al.). However, an additional concern arises when considering the adolescent population. Due to the way double-bundle ACL reconstruction is designed, additional tunnels would need to be made in order to place and fixate the two grafts, namely one tunnel in the femur and one in the tibia for each graft, making it much more invasive than single-bundle reconstruction, which only requires two tunnels (Schreiber et al.; Cheatham and Johnson). Furthermore, because native ACL origin and graft insertion points are close to the distal femoral and proximal tibial physes, many standard surgical reconstruction techniques drill across them during the procedure, which is a characteristic feature of a transphyseal technique (Perkins and Willimon; Kaeding et al.; Verhagen et al.). As such, if a double-bundle reconstruction were to be attempted on a patient within the adolescent age range, it would likely require a transphyseal drilling technique in order to recreate native ACL anatomy to the degree intended with this type of procedure (Kaeding et al.). Unfortunately, this combination comes with an increased risk for growth deformities due to the higher likelihood of growth plate damage during surgery (Perkins and Willimon; Kaeding et al.). As such, double-bundle ACL reconstruction is often contraindicated in literature, with alternatives like single-bundle reconstruction or physeal-sparing techniques, which aim to avoid drilling through the physes, being highlighted while double-bundle reconstruction isn't explored further in the adolescent population (Schreiber et al.; Perkins and Willimon; Kaeding et al.). Overall, these findings suggest that while double-bundle ACL reconstruction may improve rotational stability – a notable advantage given the activity demands on the adolescent demographic – and better replicate native ACL anatomy, its higher risk of growth plate injury raises the question of whether these benefits outweigh the developmental consequences such procedures carry (Schreiber et al.; Perkins and Willimon; Cheatham and Johnson).

**Limitations of Current Literature**

Although existing literature offers insights into ACL reconstruction techniques, most studies focus on a limited set of factors, such as anterior-posterior stability, graft type, or drilling technique, without fully addressing how these factors interact to affect overall functionality or long-term performance in adolescents (Verhagen et al.; Kaeding et al.). The skeletal immaturity and unique activity demands of this population introduce additional complexity that has been relatively underexplored, highlighting the need to systematically examine multiple surgical techniques while considering a broader range of factors, including patient demographic nuances, knee stability, and complications, and analyzing how they correlate with short- and long-term functional outcomes in the adolescent population (Verhagen et al.; Perkins and Willimon; Kaeding et al.).

## METHODS

For this study, we conducted a systematic literature review according to PRISMA guidelines using the PubMed database to identify relevant sources. After defining our primary research question, we used the following research term strategy to identify potential articles of interest:

“(((((anterior cruciate ligament[MeSH Terms]) OR (ACL)) AND ((injury) OR (tear) OR (rupture) OR (surgical reconstruction) OR (surgical repair))) OR (anterior cruciate ligament reconstruction[MeSH Terms])) AND ((adolescent[MeSH Terms]) OR (pediatric)) AND ((recovery) OR (functionality) OR (recovery of function)) ) AND (("2021/01/01"[Date - Publication] : "3000"[Date - Publication]))”

This search strategy was implemented on August 14th, 2025, and our search strategy limited to articles published between January 1st 2021 to August 14th 2025, capturing a 4.5 year period. Due to the nature of our study, a filter was applied to restrict results to the following literature types: Adaptive Clinical Trial, Case Reports, Clinical Study, Clinical Trial, Clinical Trial Protocol, Clinical Trial, Phase I, Clinical Trial, Phase II, Clinical Trial, Phase III, Clinical Trial, Phase IV, Comparative Study, Controlled Clinical Trial, Dataset, Equivalence Trial, Evaluation Study, Multicenter Study, Observational Study, Pragmatic Clinical Trial, Randomized Controlled Trial, and Validation Study.

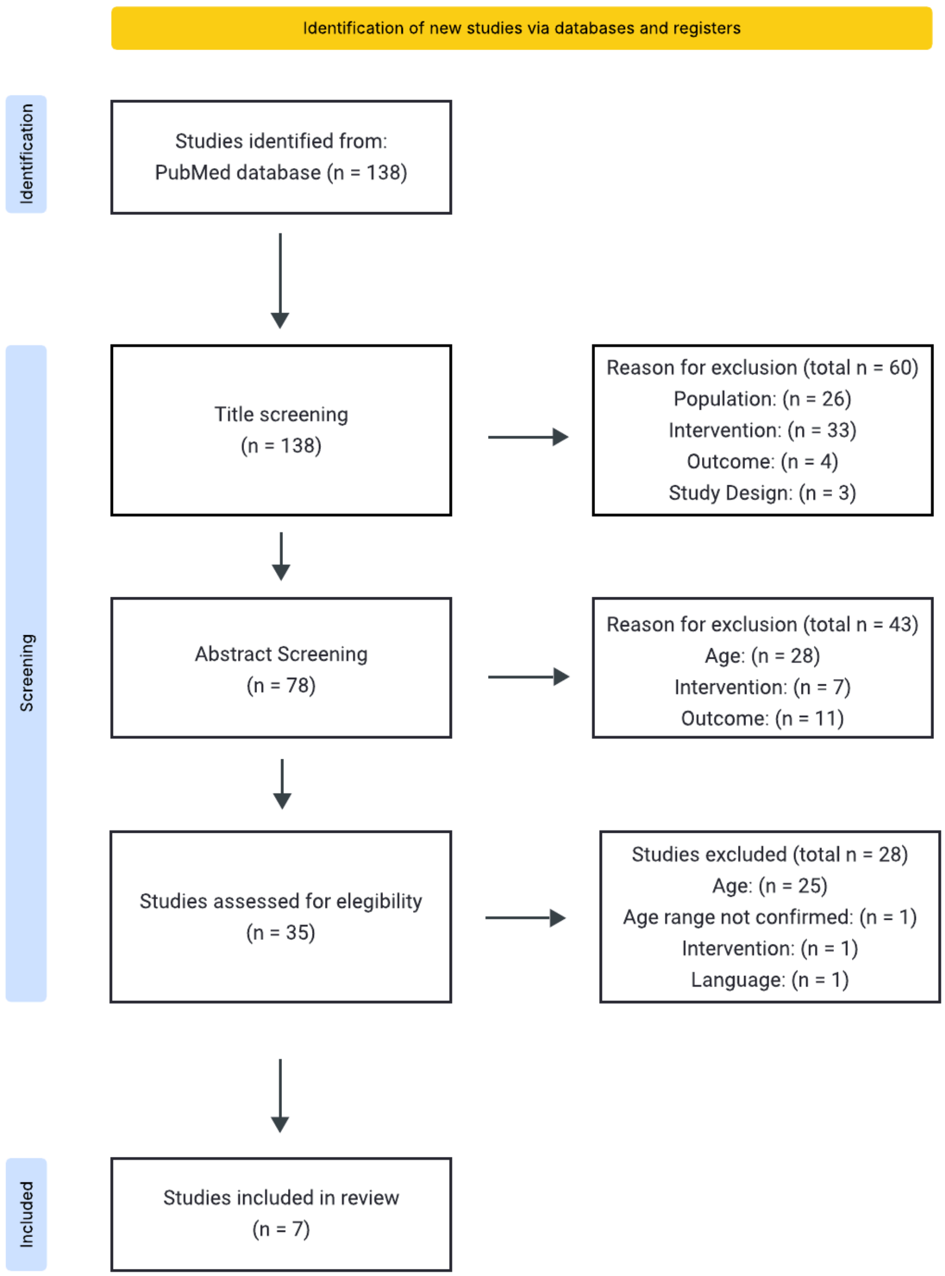
Articles were included if they met the criteria defined by our PICOTS table (Table 1). Studies were excluded if they did not provide separate data for adolescent populations (ages 10-18 years), lacked relevant outcome measures related to recovery or functionality following ACL reconstruction, were published outside our specified date ranges, were conducted on cadavers or animals, or did not provide full-text access in English. Title screening was conducted first to filter out any clearly irrelevant studies, followed by abstract screening and finally full-text reviews. Out of the initial 138 studies from the PubMed search, a total of 7 studies meeting the criteria were included in the final analysis (Figure 1). Each stage of screening was performed independently by two reviewers, with discrepancies being reconciled through discussion until consensus could be reached. All consequent data extraction was performed using a standardized form developed in Google Sheets to ensure consistency.

**Table 1.** PICOTS Framework for Study Inclusion and Exclusion Criteria

| Parameter | Inclusion Criteria | Exclusion Criteria |
|---|---|---|
| Population | Diagnosed ACL tears<br>Adolescents (10-18 yrs. old) | Adults ( ≥18 yrs.)<br>Children ( < 10 yrs.)<br>Mixed populations without separate adolescent data |
| Intervention/Comparator | Surgical ACL repair techniques | Non-operative or rehabilitation |

| | | |
|---|---|---|
| | Graft selection (allograft vs. autograft) | only management<br>Surgical technique descriptions without clinical data regarding functional outcomes |
| Outcome | Short term - time to return to regular activity, early complications, range of motion, stability test (esp. rotation), functional outcome scores<br><br>Long term - re-injury rates (tearing), knee stability over time, growth disturbance, late complications (esp. osteoarthritis), activity levels, functional outcome scores (over time) | Qualitative-only results<br>No post-surgical outcome data<br>Only intraoperative/technical measures |
| Timing | Studies published January 1st 2021 - August 14th 2025 | Studies published before January 1st 2021 |
| Setting/Study Design | Clinical and surgical settings<br>Peer-reviewed studies: randomized controlled trials, adaptive clinical trials, comparative studies, observational studies, multicenter studies, validation studies | Cadaver/animal studies<br>Non peer-reviewed studies<br>Not approved article types |
| Other | | Non-English language publications |

Figure 1. PRISMA Flow Diagram for Systematic Reviews.




**Functional Outcome Scores**

The functional outcome measures utilized across included studies encompassed several validated assessment tools, each designed to evaluate distinct aspects of knee function and recovery. The International Knee Documentation Committee (IKDC) score is a patient-reported outcome measure that assesses symptoms, function, and sports activity, providing a comprehensive evaluation of knee status with scores ranging from 0 to 100, where higher scores indicate better knee function. The Knee Injury and Osteoarthritis Score (KOOS) evaluates five dimensions of knee health – pain, symptoms, activities of daily living, sport and recreation function, and knee-related quality of life – with each subscale scored from 0 to 100 and higher scores representing better outcomes. The Tegner Activity Scale (TAS) measures activity level on a scale from 0 to 10, where higher scores reflect greater participation in demanding physical activities. The Limb Symmetry Index (LSI) quantifies the functional performance of the injured limb relative to the uninjured limb, expressed as a percentage, with values closer to 100% indicating better symmetry between limbs. The Lysholm Knee Score (LKS) assesses knee function and stability through evaluation of eight parameters including limping, locking, support, instability, pain, swelling, stair climbing, and squatting, with total scores ranging from 0 to 100 and higher scores indicating superior knee function.

## STATISTICAL ANALYSIS

### Overview

All analyses were performed using Python (version 3.11) with the pandas and numpy libraries for data manipulation and summary statistics. The purpose of this analysis was to describe and compare functional recovery outcomes following adolescent ACL reconstruction, focusing on differences by repair technique (single- vs. double-bundle), physeal approach (transphyseal vs. physeal-sparing), and physeal status (open vs. closing vs. closed).

The dataset included study-level summary data extracted from the literature, comprising mean functional scores, standard deviations (SD), and sample sizes (n=) for each outcome measure (IKDC, KOOS, Tegner, LKS). Follow-up time points were categorized as short-term (≤12 months) and long-term (>12 months) to enable temporal comparisons of recovery.

### Computation of Weighted Descriptive Statistics

Descriptive analyses were performed at five levels of aggregation:

1. Repair Technique × Outcome × Term
2. Physeal Approach × Outcome × Term
3. Physeal Status × Outcome × Term
4. Combined (Repair Technique × Physeal Approach × Physeal Status × Outcome × Term)
5. Overall Functional Recovery × Outcome × Term

For each grouping, weighted descriptive statistics were calculated to account for variability in sample sizes across studies.
The following formulas were applied:

- Weighted Mean

To ensure that studies with larger sample sizes contributed proportionally more to the estimate, weighted means were computed using:

$$\bar{x} = \left(\sum_{i=1}^{n} w_i x_i\right) / \left(\sum_{i=1}^{n} w_i\right)$$

where $\bar{x}$ is the mean functional score for study *i*, and *n* is its corresponding sample size.

- Pooled Standard Deviation

A pooled SD was derived to represent the overall dispersion of values across studies:

$$SD_{pooled} = \sqrt{\frac{\sum_{i=1}^{k}\left(\left(n_i - 1\right)SD_i^2\right)}{\sum_{i=1}^{k}\left(n_i - 1\right)}}$$

Where *SDi* is the standard deviation for study *i* and *k* is the number of studies in that subgroup.
This approach preserves the influence of within-study variance and between-study weighting, reflecting true variability in reported outcomes.

- Range (Minimum–Maximum)

The minimum and maximum of reported mean functional scores were recorded to represent the observed spread of recovery scores across included studies.

**Aggregation by Functional Outcome and Follow-Up Period**

Weighted descriptive summaries were computed separately for each functional scoring system (IKDC, KOOS, Tegner, LKS) across short-term and long-term timeframes.
This allowed direct comparison of functional recovery trajectories by outcome measure and follow-up duration, providing a descriptive overview of both early rehabilitation progress and sustained long-term knee function.

**Handling of Missing Data**

Only entries containing valid values for mean, SD, and n= were included in the weighted calculations. Studies reporting incomplete or unquantifiable functional outcomes were excluded from those specific subgroup analyses, but retained in overall descriptive summaries where appropriate. No data imputation was performed, as all statistics were computed directly from reported summary data.

**Software and Reproducibility**

All analyses were executed using reproducible Python scripts. Summary tables were exported as comma-separated values (CSV) files, providing transparency and allowing independent verification of computed weighted means, pooled SDs, and sample sizes.

## RESULTS

**Table 2.** Summary of study characteristics

| First Author | Publication Year | Country | n= | Age in years, mean | Male, n (%) | Female, n (%) |
|---|---|---|---|---|---|---|
| Screpis D | 2025 | Italy | 170 | 15.8-15.9 | 107 (62.9%) | 63 (37.1 %) |
| Casp AJ | 2021 | United States | 100 | Open physes: 15.2 ± 1.5<br>Closed Physes: 16.6 ± 1 | 41 (41%) | 59 (59%) |
| Rutnagur JD | 2024 | UK | 1 | 15 | 1 (100%) | 0 (0%) |
| Thorolfsson B | 2022 | Sweden | 522 | Mean: 17.4<br>Range: 14-19 | 208 (39.8%) | 314 (60.2%) |
| Hishimura R | 2022 | Japan | 1 | 18 | 1 (100%) | 0 (0%) |
| Asai K | 2024 | Japan | 7 | Mean: 14<br>Range: 13-16 | 2 (28.6%) | 5 (71.4%) |
| Dauty M | 2025 | France | 253 | 16.2 ± 1.6 | 134 (52.9%) | 119 (47.1%) |

**Table 3.** Summary of patient and injury characteristics

| **Category** | **Values** |
|---|---|
| **Total n=** | 1054 |
| **Age, mean (range)** | 16.7 (13-19) |

| | |
|---|---|
| **Male sex, n (%)** | 494 (46.9) |
| **Female sex, n (%)** | 560 (53.1) |
| **Unilateral Injury, n (%)** | 1053 (99.9) |
| **Concomitant injury, n (%)**<br>Meniscal Injury<br>Cartilage Injury<br>No concomitant injury or not-specified | <br>506 (48.0%)<br>125 (11.9%)<br>423 (40.1%) |
| **Duration of follow-up, mean in months** | 67.75 |
| **Skeletal maturity, n (%)**<br>Mature<br>Immature<br>Not specified | <br>764 (72.6%)<br>44 (4.2%)<br>253 (24.0%) |
| **Repair technique, n (%)**<br>Single<br>Double<br>Not specified | <br>431 (40.89%)<br>1(0.09%)<br>622 (59.01%) |
| **Graft type, n (%)**<br>Allograft<br>Autograft | <br>54 (5.12%)<br>1000 (94.88%) |
| **Physeal technique, n (%)**<br>Transphyseal or partial transphyseal<br>Physeal sparing<br>Not specified | <br>266 (25.24%)<br>13 (1.23%)<br>775 (73.53%) |

A total of seven studies were included in our systematic review, separately summarized in Table 2, encompassing a total of 1,054 patients with a mean age of 16.7 years (range, 13–19). The overall cohort is summarized in Table 3, and was comprised of 494 males (46.9%) and 560 females (53.1%). 72.6% of patients were identified to be skeletally mature, with another 4.2% being skeletally immature and the remaining 24.0% not being specified in the studies. In this cohort, single-bundle ACL reconstructions accounted for 40.9% of all surgical reconstructions, while double-bundle reconstruction was only identified to have been conducted in 0.1% of the population; the remaining 59% of cases could not be reliably classified under either approach due to a lack of specification. Additionally, autografts were used for the majority of the ACL reconstructions, with allografts only making up 5.1% of procedures. Regarding the physeal approach of the ACL reconstructions, 266 were identified to be transphyseal or partially transphyseal, and another 13 were physeal-sparing; the rest of the procedures remained unspecified due to their studies' inclusion of several physeal approaches without separate data. Follow-up duration across studies averaged 67.8 months, with reported functional outcomes being defined as falling under short-term (≤12 months) or long-term (>12 months) periods. Furthermore, functional outcomes were variably defined across studies, with different scoring systems and reference values used to assess postoperative recovery. For the purpose of our study, mean functional scores and standard deviations were summarized according to repair technique and physeal approach.

**Single-Bundle vs. Double-Bundle ACL Repair**

**Table 4.** Functional outcome stratified by single versus double bundle repair and long versus short term outcomes

| Repair_Technique | Outcome | Term | n_total | weighted_mean | pooled_sd | min_mean | max_mean |
|---|---|---|---|---|---|---|---|
| double | KOOS | Long-term (>12 mo) | 1 | 92.55 | 0 | 92.55 | 92.55 |
| double | LKS | Long-term (>12 mo) | 1 | 100 | 0 | 100 | 100 |
| single | IKDC | Long-term (>12 mo) | 347 | 89.98 | 7.2 | 87.4 | 98.6 |
| single | IKDC | Short-term (≤12 mo) | 7 | 93.1 | 6.8 | 93.1 | 93.1 |
| single | KOOS | Long-term (>12 mo) | 7 | 98.5 | 1.6 | 98.5 | 98.5 |
| single | KOOS | Short-term (≤12 mo) | 7 | 97.6 | 3.3 | 97.6 | 97.6 |
| single | LKS | Long-term (>12 mo) | 340 | 82.43 | 4.52 | 80.4 | 84.4 |
| single | LKS | Short-term (≤12 mo) | 506 | 98.5 | 3.54 | 98 | 99 |
| single | LSI H180(%) | Short-term (≤12 mo) | 506 | 87.1 | 14.46 | 85.5 | 88.7 |
| single | LSI Q180(%) | Short-term (≤12 mo) | 506 | 87.85 | 10.14 | 84.5 | 91.2 |
| single | TAS | Long-term (>12 mo) | 340 | 6.44 | 1.17 | 6.2 | 6.6 |
| unspecified | IKDC | Short-term (≤12 mo) | 100 | 83.15 | 13.35 | 78.63 | 88.29 |
| unspecified | KOOS | Long-term (>12 mo) | 1566 | 69.33 | 19.77 | 68.4 | 69.8 |
| unspecified | KOOS | Short-term (≤12 mo) | 622 | 72.31 | 18.81 | 69.5 | 97.67 |

Abbreviations: KOOS = Knee Injury and Osteoarthritis Score; LKS = Lysholm Knee Score; IKDC = International Knee Documentation Committee; LSI = Limb Symmetry Index; H = Hamstring; Q = Quadriceps; angular velocity at 180°/s; TAS = Tegner Activity Scale

In the short-term category, data was only available for the single-bundle repair technique. Based on seven reported cases recorded in Table 4, single-bundle ACL reconstruction demonstrated a weighted mean IKDC score of 93.10, with a pooled standard deviation of 6.8. Additionally, this group showed a mean score of 98.50 +/- 1.6 for KOOS. No short-term functional outcome data were reported for the double repair technique, so no comparison can be made between single- and double-bundle ACL repair in this category. However, in terms of long-term functionality, data was available for both single- and double-bundle repair techniques across multiple functional scoring systems, including IKDC, KOOS, LKS, and TAS, among others. The single-bundle repair technique demonstrated a weighted mean score of 98.50 +/- 1.6 for KOOS, while the double-bundle repair technique demonstrated a mean score of 92.55 +/- 0.0 for the same functionality score. It should be noted that the long-term double-bundle repair data was derived from a single reported case (n = 1).

**Physeal Technique**

**Table 5**. Functional outcome stratified by transphyseal vs physeal-sparing repair techniques and long versus short term outcomes

| Physeal_Approach | Outcome | Term | n_total | weighted_mean | pooled_sd | min_mean | max_mean |
|---|---|---|---|---|---|---|---|
| transphyseal | IKDC | Long-term (>12 mo) | 347 | 89.98 | 7.2 | 87.4 | 98.6 |
| transphyseal | IKDC | Short-term (≤12 mo) | 7 | 93.1 | 6.8 | 93.1 | 93.1 |
| transphyseal | KOOS | Long-term (>12 mo) | 8 | 97.76 | 1.6 | 92.55 | 98.5 |
| transphyseal | KOOS | Short-term (≤12 mo) | 7 | 97.6 | 3.3 | 97.6 | 97.6 |
| transphyseal | LKS | Long-term (>12 mo) | 341 | 82.48 | 4.52 | 80.4 | 100 |
| transphyseal | TAS | Long-term (>12 mo) | 340 | 6.44 | 1.17 | 6.2 | 6.6 |
| unspecified | IKDC | Short-term (≤12 mo) | 100 | 83.15 | 13.35 | 78.63 | 88.29 |
| unspecified | KOOS | Long-term (>12 mo) | 1566 | 69.33 | 19.77 | 68.4 | 69.8 |
| unspecified | KOOS | Short-term (≤12 mo) | 622 | 72.31 | 18.81 | 69.5 | 97.67 |
| unspecified | LKS | Short-term (≤12 mo) | 506 | 98.5 | 3.54 | 98 | 99 |
| unspecified | LSI H180(%) | Short-term (≤12 mo) | 506 | 87.1 | 14.46 | 85.5 | 88.7 |
| unspecified | LSI Q180(%) | Short-term (≤12 mo) | 506 | 87.85 | 10.14 | 84.5 | 91.2 |

Abbreviations: IKDC = International Knee Documentation Committee; KOOS = Knee Injury and Osteoarthritis Score; LKS = Lysholm Knee Score; TAS = Tegner Activity Scale; LSI = Limb Symmetry Index; H = Hamstring; Q = Quadriceps; angular velocity at 180°/s

Functional outcomes stratified by physeal approach, summarized in Table 5, revealed that transphyseal techniques were more commonly reported in the literature, accounting for 266 cases. In the short-term category, transphyseal reconstruction demonstrated a weighted mean IKDC score of 93.10 +/- 6.8 based on seven reported cases, along with a mean KOOS score of 97.60 +/- 3.3. Long-term outcomes for transphyseal approaches showed a weighted mean IKDC score of 89.98 +/- 7.2 across 347 patients, as well as a mean KOOS score of 97.76 +/- 1.6 from 8 cases. Furthermore, 341 patients displayed a LKS score of 82.48 +/- 4.52 after undergoing a procedure with a transphyseal technique. Additional long-term metrics for this physeal approach have been included in the table below. For cases with unspecified physeal approaches, short-term outcomes included a weighted mean IKDC score of 83.15 +/- 13.35 from 100 patients, and a mean KOOS score of 72.31 +/- 18.81 from 622 patients, both of which are lower than the reported scores for transphyseal methods for these respective categories. Long-term unspecified outcomes also demonstrated lower respective scores compared to transphyseal techniques, with a mean KOOS score of 69.33 +/- 19.77 across 1,566 patients. No functional outcome data was reported explicitly for physeal-sparing techniques in either the short-term or long-term categories, so comparisons cannot be made in this regard.

**Physeal Status**

**Table 6.** Functional outcome stratified by open versus closed physes and long versus short term outcomes

| Physeal_status | Outcome | Term | n_total | weighted_mean | pooled_sd | min_mean | max_mean |
|---|---|---|---|---|---|---|---|
| Closed | IKDC | Long-term (>12 mo) | 340 | 89.8 | 7.25 | 87.4 | 91.1 |
| Closed | IKDC | Short-term (≤12 mo) | 64 | 82.4 | 13.22 | 78.63 | 88.29 |
| Closed | KOOS | Long-term (>12 mo) | 1567 | 69.35 | 19.77 | 68.4 | 92.55 |
| Closed | KOOS | Short-term (≤12 mo) | 586 | 71.01 | 19.3 | 69.5 | 88.2 |
| Closed | LKS | Long-term (>12 mo) | 341 | 82.48 | 4.52 | 80.4 | 100 |
| Closed | TAS | Long-term (>12 mo) | 340 | 6.44 | 1.17 | 6.2 | 6.6 |
| Open | IKDC | Long-term (>12 mo) | 7 | 98.6 | 2.9 | 98.6 | 98.6 |
| Open | IKDC | Short-term (≤12 mo) | 43 | 85.88 | 12.79 | 83.8 | 93.1 |
| Open | KOOS | Long-term (>12 mo) | 7 | 98.5 | 1.6 | 98.5 | 98.5 |
| Open | KOOS | Short-term (≤12 mo) | 43 | 94.21 | 5.82 | 90.26 | 97.67 |
| unspecified | LKS | Short-term (≤12 mo) | 506 | 98.5 | 3.54 | 98 | 99 |
| unspecified | LSI H180(%) | Short-term (≤12 mo) | 506 | 87.1 | 14.46 | 85.5 | 88.7 |
| unspecified | LSI Q180(%) | Short-term (≤12 mo) | 506 | 87.85 | 10.14 | 84.5 | 91.2 |

Abbreviations: IKDC = International Knee Documentation Committee; KOOS = Knee Injury and Osteoarthritis Score; LKS = Lysholm Knee Score; TAS = Tegner Activity Scale; LSI = Limb Symmetry Index; H = Hamstring; Q = Quadriceps; angular velocity at 180°/s

When analyzing short-term outcomes, patients with closed physes demonstrated a weighted mean IKDC score of 82.4 +/- 13.22 from 64 patients and a mean KOOS score of 71.01 +/- 19.3 from 586 patients, as shown in Table 6. Patients with open physes, on the other hand, demonstrated higher reported scores in these respective categories, with a weighted mean IKDC score of 85.88 +/- 12.79 from 43 patients and a mean KOOS score of 94.21 +/- 5.82 from 43 patients. For long-term outcomes, patients with closed physes showed a weighted mean IKDC score of 89.8 +/- 7.25 across 340 patients and a mean KOOS score of 69.35 +/- 19.77 from 1,567 patients, while patients with open physes demonstrated a weighted mean IKDC score of 98.6 +/- 2.9 from 7 patients and a mean KOOS score of 98.5 +/- 1.6 from 7 patients. As such, long-term functional outcomes follow a similar trend of open physes corresponding to higher scores than closed physis scores. Additional long-term metrics for closed physes included a LKS score and a TAS score. For cases with unspecified physeal status, only short-term outcomes scores were identified, with the reported scores correlating to different functionality metrics. Some of these tests included LSI tests in the LSI H180 and LSI Q180 categories, although a LKS score was reported as well.

**Combined Values**

**Table 7.** Functional outcome stratified by single versus double bundle repair, transphyseal versus physeal-sparing repair technique, open versus closed physes, and long versus short term outcomes

| Repair_Technique | Physeal_Approach | Physeal_status | Outcome | Term | n_total | weighted_mean | pooled_sd | min_mean | max_mean |
|---|---|---|---|---|---|---|---|---|---|
| double | transphyseal | Closed | KOOS | Long-term (>12 mo) | 1 | 92.55 | 0 | 92.55 | 92.55 |
| double | transphyseal | Closed | LKS | Long-term (>12 mo) | 1 | 100 | 0 | 100 | 100 |
| single | transphyseal | Closed | IKDC | Long-term (>12 mo) | 340 | 89.8 | 7.25 | 87.4 | 91.1 |
| single | transphyseal | Closed | LKS | Long-term (>12 mo) | 340 | 82.43 | 4.52 | 80.4 | 84.4 |
| single | transphyseal | Closed | TAS | Long-term (>12 mo) | 340 | 6.44 | 1.17 | 6.2 | 6.6 |
| single | transphyseal | Open | IKDC | Long-term (>12 mo) | 7 | 98.6 | 2.9 | 98.6 | 98.6 |
| single | transphyseal | Open | IKDC | Short-term (≤12 mo) | 7 | 93.1 | 6.8 | 93.1 | 93.1 |
| single | transphyseal | Open | KOOS | Long-term (>12 mo) | 7 | 98.5 | 1.6 | 98.5 | 98.5 |
| single | transphyseal | Open | KOOS | Short-term (≤12 mo) | 7 | 97.6 | 3.3 | 97.6 | 97.6 |
| single | unspecified | unspecified | LKS | Short-term (≤12 mo) | 506 | 98.5 | 3.54 | 98 | 99 |
| single | unspecified | unspecified | LSI H180(%) | Short-term (≤12 mo) | 506 | 87.1 | 14.46 | 85.5 | 88.7 |
| single | unspecified | unspecified | LSI Q180(%) | Short-term (≤12 mo) | 506 | 87.85 | 10.14 | 84.5 | 91.2 |
| unspecified | unspecified | Closed | IKDC | Short-term (≤12 mo) | 64 | 82.4 | 13.22 | 78.63 | 88.29 |
| unspecified | unspecified | Closed | KOOS | Long-term (>12 mo) | 1566 | 69.33 | 19.77 | 68.4 | 69.8 |
| unspecified | unspecified | Closed | KOOS | Short-term (≤12 mo) | 586 | 71.01 | 19.3 | 69.5 | 88.2 |
| unspecified | unspecified | Open | IKDC | Short-term (≤12 mo) | 36 | 84.48 | 13.58 | 83.8 | 85.33 |
| unspecified | unspecified | Open | KOOS | Short-term (≤12 mo) | 36 | 93.55 | 6.16 | 90.26 | 97.67 |

Abbreviations: KOOS = Knee Injury and Osteoarthritis Score; LKS = Lysholm Knee Score; IKDC = International Knee Documentation Committee; TAS = Tegner Activity Scale; LSI = Limb Symmetry Index; H = Hamstring; Q = Quadriceps; angular velocity at 180°/s

When repair technique and physeal approach were analyzed together, with findings summarized in Table 7, the single-bundle transphyseal reconstruction in patients with open physes demonstrated the highest functional scores across both short-term and long-term categories. In the short-term period, this combination yielded a weighted mean IKDC score of 93.1 +/- 6.8 from 7 patients and a mean KOOS score of 97.6 +/- 3.3 from the same cohort. Long-term outcomes for this group showed a weighted mean IKDC score of 98.6 +/- 2.9 and a mean KOOS score of 98.5 +/- 1.6, both derived from 7 patients. In contrast, single-bundle transphyseal reconstruction in patients with closed physes demonstrated lower long-term scores, with a weighted mean IKDC score of 89.8 +/- 7.25 across 340 patients, along with mean LKS and TAS scores from the same patient population. The double-bundle transphyseal approach in patients with closed physes was represented by a single case (n = 1), showing a long-term KOOS score of 92.55 +/- 0.0 and a LKS score of 100.0 +/- 0.0. For cases with unspecified repair techniques and physeal approaches, functional outcomes varied considerably depending on physeal status, with patients having open physes demonstrating short-term scores of 84.48 +/- 13.58) for IKDC and 93.55 +/- 6.16 for KOOS from 36 patients, while patients with closed physes showed lower short-term IKDC scores of 82.4 +/- 13.22 from 64 patients and mean KOOS scores of 71.01 +/- 19.3 from 586 patients.

### Short-Term to Long-Term Outcome Progression

**Table 8.** Functional outcome stratified by functional scoring systems and long versus short term outcomes

| Outcome | Term | n_total | weighted_mean | pooled_sd | min_mean | max_mean |
|---|---|---|---|---|---|---|
| IKDC | Long-term (>12 mo) | 347 | 89.98 | 7.2 | 87.4 | 98.6 |
| IKDC | Short-term (≤12 mo) | 107 | 83.8 | 13.05 | 78.63 | 93.1 |
| KOOS | Long-term (>12 mo) | 1574 | 69.48 | 19.73 | 68.4 | 98.5 |
| KOOS | Short-term (≤12 mo) | 629 | 72.59 | 18.73 | 69.5 | 97.67 |
| LKS | Long-term (>12 mo) | 341 | 82.48 | 4.52 | 80.4 | 100 |
| LKS | Short-term (≤12 mo) | 506 | 98.5 | 3.54 | 98 | 99 |
| LSI H180(%) | Short-term (≤12 mo) | 506 | 87.1 | 14.46 | 85.5 | 88.7 |
| LSI Q180(%) | Short-term (≤12 mo) | 506 | 87.85 | 10.14 | 84.5 | 91.2 |
| TAS | Long-term (>12 mo) | 340 | 6.44 | 1.17 | 6.2 | 6.6 |

Abbreviations: IKDC = International Knee Documentation Committee; KOOS = Knee Injury and Osteoarthritis Score; LKS = Lysholm Knee Score; LSI = Limb Symmetry Index; H = Hamstring; Q = Quadriceps; angular velocity at 180°/s; TAS = Tegner Activity Scale

When pooling all data across surgical strategies and follow-up periods in Table 8, functional outcomes varied by metric and assessment timeframe. For IKDC scores, short-term outcomes demonstrated a weighted mean of 83.8 +/- 13.05 across 107 patients, while long-term outcomes showed a weighted mean of 89.98 +/- 7.2 across 347 patients ($p<0.001$). KOOS scores followed a similar pattern, with short-term assessments yielding a weighted mean of 72.59 +/- 18.73 from 629 patients and long-term assessments showing a weighted mean of 69.48 +/- 19.73 from 1,574 patients ($p<0.001$). Additional short-term metrics included LSI H180 scores and LSI Q180 scores, as well as a LKS score from the same cohort. Long-term outcomes for other functional assessments included a weighted mean LKS score and TAS score, each for various population sizes. The standard deviations across most metrics remained modest, with the exception of KOOS scores, which demonstrated greater variability in both short-term +/- 18.73 and long-term +/- 19.73 assessments. Across the two comparable metrics, IKDC scores showed improvement from short-term to long-term follow-up ($p<0.001$), whereas KOOS scores demonstrated minimal change between assessment periods.

## DISCUSSION

Our systematic review of adolescent ACL reconstruction revealed several key trends in surgical practice and functional outcomes. The available literature demonstrated a clear predominance of single-bundle reconstruction techniques and autograft usage in this population. When examining functional outcomes, patients with open physes consistently demonstrated superior recovery compared to those with closed physes across both short-term and long-term follow-up periods. Furthermore, when tracking functional recovery over time, IKDC scores showed a pattern of statistically significant improvement from short-term to long-term follow-up ($p<0.001$), whereas KOOS scores remained relatively stable across assessment periods. This divergence in temporal trends between scoring systems may reflect different aspects of knee function being captured by each metric, with IKDC potentially emphasizing objective knee stability while KOOS focuses more heavily on patient-reported quality of life measures. Overall, the data suggest that skeletal maturity at the time of surgery represents an important prognostic factor for functional outcomes following ACL reconstruction in adolescents, with open physes correlating with superior recovery trajectories.

**Repair Technique Considerations**

The predominance of single-bundle reconstruction techniques in our dataset reflects broader trends in contemporary adolescent ACL surgery, where this approach has remained the standard of care for skeletally immature patients. Single-bundle reconstruction offers several practical advantages that make it particularly well-suited for the adolescent population, including shorter operative times, reduced technical complexity, and fewer required bone tunnels compared to double-bundle techniques. These factors may be especially relevant when considering the anatomical constraints imposed by open growth plates, as minimizing the number of physeal crossings becomes a key consideration in preventing growth disturbances. Our findings demonstrate that single-bundle reconstruction, particularly when combined with a transphyseal approach in patients with open physes, yielded favorable functional outcomes across both short-term and long-term follow-up periods, supporting its continued use as a reliable surgical option for this demographic.

The near-absence of double-bundle reconstruction in our dataset warrants consideration within the broader context of adolescent ACL surgery. While double-bundle techniques have been advocated for their potential to more closely replicate native ACL anatomy and improve rotational stability – benefits that would theoretically be valuable for adolescent athletes engaged in pivoting sports – these advantages must be weighed against the increased technical demands and additional physeal disruption inherent to the procedure. The double-bundle approach requires four bone tunnels rather than two, effectively doubling the potential sites of growth plate violation when a transphyseal technique is employed. Given that the native ACL origin and insertion points lie in close proximity to the distal femoral and proximal tibial physes, achieving anatomically accurate graft placement with a double-bundle technique would likely necessitate multiple transphyseal tunnels in skeletally immature patients. This anatomical reality may explain the surgical community's cautious approach to double-bundle reconstruction in adolescents, as the risk-benefit calculation shifts when growth plate preservation becomes a primary concern.

The favorable outcomes observed with single-bundle transphyseal reconstruction suggest that this approach may cause less overall physeal disruption than alternative techniques when executed with appropriate surgical precision. This finding aligns with existing evidence that carefully performed transphyseal reconstruction can be safely implemented in skeletally immature patients without significant growth disturbances, particularly when surgeons employ techniques such as vertical tunnel orientation and appropriately sized grafts. The functional benefits of anatomically positioned grafts, which transphyseal techniques facilitate, may outweigh theoretical concerns about physeal violation in many cases, especially when considering the superior outcomes observed in patients with open physes who underwent this approach.

**Physeal Status and Surgical Approach**

In fact, the superior outcomes observed in patients with open physes compared to those with closed physes represents one of the most striking findings of our analysis. This pattern held consistent across both short-term and long-term follow-up periods and across multiple functional scoring systems, suggesting a robust relationship between skeletal maturity status and postoperative recovery. Patients with open physes demonstrated higher IKDC and KOOS scores than their skeletally mature counterparts in both assessment periods, indicating that skeletal immaturity at the time of surgery may confer advantages for functional recovery following ACL reconstruction. This finding has important implications for surgical timing and prognostic counseling, as it suggests that adolescents undergoing ACL reconstruction prior to physeal closure may experience more favorable functional outcome trajectories than those who undergo surgery after achieving skeletal maturity.

The favorable outcomes associated with transphyseal techniques in our dataset provide meaningful insight into surgical approach selection for adolescent ACL reconstruction. Transphyseal reconstruction demonstrated strong functional scores across both short-term and long-term follow up periods, with particularly notable results when performed in patients with open physes. The combination of single-bundle transphyseal reconstruction in skeletally immature patients yielded the highest functional outcomes in our analysis, with scores that exceed those observed in skeletally mature patients undergoing the same surgical approach, suggesting that open physes do not compromise this approach's outcomes.

The relationship between physeal status and functional outcomes further introduces important considerations for surgical planning in adolescent ACL reconstruction. Our data demonstrates that skeletal maturity status represents a meaningful prognostic factor, with open physes consistently correlating with superior recovery across multiple functional metrics. Additionally, the strong performance of transphyseal reconstruction in skeletally immature patients suggests that this approach effectively restores knee function in this population. When combined with the predominance of single-bundle techniques in contemporary practice, these findings support the continued use of single-bundle transphyseal reconstruction as a reliable surgical strategy for adolescents with ACL tears, particularly in those who have not yet achieved skeletal maturity.

**IKDC vs KOOS Scoring**

The divergent patterns observed between IKDC and KOOS scores over time provide insight into the nature of functional recovery following adolescent ACL reconstruction. For instance, IKDC scores demonstrated statistically significant improvement from the short-term to long-term follow-up ($p<0.001$), with weighted means increasing from 83.8 in the short-term period to 89.98 in the long-term period. This progressive improvement suggests that objective measures of knee function, including stability and range of motion, continue to improve beyond the initial postoperative year. The upward trajectory of IKDC scores indicates that adolescent patients experience ongoing functional gains as they progress through rehabilitation and return to activity, with the reconstructed knee achieving greater stability and performance capacity over extended follow-up periods.

In contrast, KOOS scores remained relatively stable between assessment periods, with weighted means of 72.59 in the short-term and 69.48 in the long-term, respectively. This stability across time periods suggests that patient reported outcomes related to symptoms, pain, and general quality of life reach a plateau earlier in the recovery process compared to objective functional measures. The minimal change in KOOS scores between short-term and long-term follow-up may also indicate that patients establish their perceived functional status and activity limitations relatively early after surgery, with subsequent gains in objective knee stability not necessarily translating into proportional improvements in subjective quality of life measures. These patterns highlight the importance of considering both objective and subjective outcome measures when evaluating recovery outcomes, as different metrics may capture distinct phases and aspects of the postoperative recovery process after adolescent ACL reconstruction.

**Limitations**

Several methodological limitations must be acknowledged when interpreting the findings of this systematic review. Our restriction to studies published within the past five years, while ensuring contemporary relevance, may have excluded important longer-term evolutionary trends in surgical techniques and outcome reporting. Furthermore, this constraint limits our ability to assess how ACL reconstruction approaches and their associated outcomes have developed over extended periods, potentially missing valuable historical context that could inform current practice patterns. Additionally, our reliance on published aggregate data rather than patient-level raw data prevented us from conducting more sophisticated statistical analyses and controlling for potential confounding variables at the individual patient level. This limitation restricts the depth of our analysis and our ability to account for important covariates that may influence functional outcomes, such as specific activity levels, compliance with rehabilitation protocols, or baseline functional status prior to injury.

The heterogeneity in functional outcome measurement across included studies presents an additional challenge to direct comparison and interpretation of results. Our analysis incorporated multiple functional scoring systems, including IKDC, KOOS, TAS, and LKS scores, each of which assesses different dimensions of knee function and employs distinct scoring methodologies. This variation in outcome measures complicated efforts to synthesize findings across studies and may mask important differences in recovery patterns that would be apparent with standardized assessment tools. Furthermore, within the KOOS assessment system itself, different studies reported different specific KOOS subscales and averages, such as KOOS sport or KOOS 4. For the purpose of our analysis, we generalized these distinct KOOS metrics under a single KOOS category, despite the fact that each subscale measures different aspects of knee function and patient experience. This generalization may obscure meaningful differences in specific domains of recovery and limit our ability to identify which particular aspects of knee function are most affected by different surgical approaches.

Population heterogeneity within our dataset introduces additional complexity to the interpretation of outcomes. Our analysis included a patient with Ehlers-Danlos syndrome alongside the general adolescent ACL reconstruction population, despite known biomechanical and connective tissue differences that may influence surgical outcomes and recovery trajectory for this individual. The inclusion of this population without a separate subgroup analysis may confound overall results and potentially impact the generalizability of findings to the broader adolescent population. Additionally, a large portion of cases lacked specification, especially regarding repair technique and physeal approach, with 59% of repair techniques and 73.5% of physeal approaches remaining unclassified in the original studies. This lack of specification substantially limits our ability to draw definitive conclusions about the comparative effectiveness of different surgical strategies. Skeletal maturity status was also not specified in 24% of cases, further constraining our analysis of the relationship between physeal status and functional outcomes.

The categorization for time frames employed in our analysis represents another significant limitation. By aggregating all outcomes measured within twelve months post-operatively into a single "short-term" category and all outcomes beyond twelve months post-operatively into a "long-term" category, we may have obscured important recovery milestones and patterns that occur at specific intervals within these broad timeframes. Recovery at three months post-surgery differs substantially from recovery at nine months, yet both are classified as short-term outcomes in our analysis. Similarly, outcomes at eighteen months may notably differ from those at five years, despite both falling into the long-term category. This broad aggregation masks the granular progression of functional recovery and may conceal critical periods during which different surgical approaches demonstrate distinct advantages or disadvantages. As a result, this limits our ability to identify optimal assessment intervals and may underestimate the nature of postoperative recovery in adolescent ACL reconstruction.

## CLINICAL IMPLICATION

When evaluating adolescent patients for ACL reconstruction, surgeons should consider factors such as skeletal maturity status, physeal closure, and remaining growth potential. Single-bundle transphyseal reconstruction is still recommended regardless of these factors, though patients' physeal status may affect outcomes in terms of requiring different postoperative treatment. Alternative techniques including double-bundle and physeal-sparing approaches, while technically viable, should be reserved for exceptional anatomic contraindications.

## CONCLUSION

This systematic review of 1,054 adolescent patients across seven studies demonstrates that single-bundle transphyseal reconstruction represents an effective surgical approach for ACL tears in this population, with particularly favorable outcomes observed in skeletally immature patients. Patients with open physes consistently achieved superior functional outcomes compared to their skeletally mature counterparts across both short-term and long-term follow-up periods, with IKDC scores showing statistically significant improvement over time ($p<0.001$). The combination of single-bundle reconstruction with a transphyseal approach in patients with open physes yielded the highest functional scores in our analysis, suggesting that skeletal maturity status serves as an important prognostic factor for postoperative recovery. These findings support the continued use of single-bundle transphyseal reconstruction as a reliable surgical strategy for adolescents with ACL tears, particularly in those who have not yet achieved skeletal maturity.

However, several limitations constrain definitive conclusions, including the substantial proportion of cases with unspecified repair techniques and physeal approaches, heterogeneity in functional scoring systems, and broad temporal categorization of outcomes. Future research should prioritize standardized outcome reporting with consistent follow-up intervals, patient-level data analysis, and separate evaluation of special populations. Despite these limitations, our findings provide meaningful guidance for clinical decision-making, indicating that ACL reconstruction prior to physeal closure may confer advantages for functional recovery while recognizing the importance of individualized treatment planning based on factors such as chronological age, remaining growth potential, and specific activity demands.

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