All-Epiphyseal Versus Micheli-Kocher Anterior Cruciate Ligament Reconstruction in Skeletally Immature Patients: A Systematic Review

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Background: Early physeal-sparing anterior cruciate ligament reconstruction (ACLR) is considered the optimal treatment method in the skeletally immature population to preserve the integrity of the knee joint while reducing the risk of growth disturbances and angular deformities. Contemporary treatment algorithms recommend the use of all-epiphyseal (AE) or Micheli–Kocher (MK) ACLR techniques in patients with considerable growth remaining. Nevertheless, no research exists comparing the 2 techniques. Therefore, the purpose of this review is to comprehensively compare postoperative outcomes and complication profiles following AE and MK ACLR in skeletally immature patients.

Methods: A systematic search of Embase, Medline, and PubMed was conducted from inception to April 30, 2024. All studies reporting outcomes and/or complications following AE or MK ACLR were included. Screening and data abstraction were designed in accordance with PRISMA and R-AMSTAR guidelines.

Results: Twenty-nine studies with 1177 patients were included. AE ACLR and MK ACLR yielded similar results for rates of return to preinjury level of activity (91.8% and 93.4%, respectively), negative pivot-shift (93.9% and 95.2%, respectively) and Lachman test grades (93.9% and 90.8%, respectively), IKDC subjective scores (94.0 and 93.6, respectively), ROM flexion (144.1 degrees and 136.3 degrees, respectively) and hyperextension (2.5 degrees and 3.1 degrees, respectively). AE ACLR yielded a greater risk of growth disturbances, angular deformities, and graft failures (1.5%, 1.3%, and 10.6%, respectively) but a lower risk of contralateral ACL tears (4.2%) relative to MK ACLR (0.0%, 0.0%, 6.6%, and 6.6%, respectively).

Conclusions: Both AE and MK ACLR yield promising rates of RTS, substantially limit anteroposterior laxity, surpass IKDC thresholds for substantial clinical benefit, and regain fully functional ROM to comparable levels, though they yield marginally different complication profiles. However, the majority of the included studies were moderate-quality or low-quality evidence with high statistical heterogeneity. Therefore, no statistical conclusions regarding the differences in complication profiles can be drawn. Future randomized controlled trials or large prospective cohort studies should compare the efficacy and complication profile of QT autograft AE ACLR relative to MK ACLR.

Key Words: All-epiphyseal reconstruction, anterior cruciate ligament reconstruction, knee, micheli-kocher reconstruction, skeletally immature

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A recent report of 470,126 pediatric orthopaedic surgeries conducted in the United States between 2004 and 2014 noted a 2.8-fold increase in anterior cruciate ligament reconstructions (ACLR) relative to other pediatric orthopaedic procedures.[1] This significant increase in the incidence of pediatric ACLR is likely multifactorial in nature due to heightened leisurely and competitive sports participation, improved injury recognition, and a bol-

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stered understanding of the risks associated with delaying ACLR to skeletal maturity.[2]

Delaying pediatric ACLR until skeletal maturity may be done to avoid injuries to the distal femoral and proximal tibial physes. However, the length of delay is significantly associated with chronic instability, development of irreparable meniscal injuries, and progressively severe chondral damage in this highly active patient population.[2,3] Therefore, early physeal-sparing ACLR is considered the optimal treatment method in the skeletally immature population to preserve the integrity of the knee joint while reducing the risk of growth disturbances and angular deformities.[2]

All-epiphyseal (AE) ACLR techniques have been defined as those that place the graft, tunnels, and fixation devices all within the femoral and tibial epiphyses to restore the anatomic footprint of the ACL without transgressing, or risking damage to, the epiphyseal plates.[4] Avoiding fixation on the metaphysis additionally eliminates the risk of epiphyseal plate damage caused by tethering effects, which may be observed with the physeal-sparing Anderson technique.[4] Nevertheless, an inherent risk of growth disturbances still remains following AE ACLR. It is possible for thermal damage at the time of drilling to enlarge the zone of injury beyond the tunnel diameter, consequently disrupting physeal integrity and posing a risk of iatrogenic limb shortening.[5] Conversely, hyperemia near the site of drilling may stimulate the physis, posing a risk of iatrogenic limb lengthening.[6]

The physeal-sparing Micheli-Kocher (MK) ACLR technique, also known as the modified MacIntosh technique, combines intra-articular and extra-articular reconstruction using an iliotibial band (ITB) autograft to better control the postoperative rotational laxity of the knee.[7] Briefly, a central strip of the ITB is detached proximally from the joint capsule and lateral patellar retinaculum while left attached distally to the Gerdy tubercle. The free proximal end of the ITB autograft is sutured and passed over-the-top of the lateral femoral condyle, through the tibiofemoral joint, and under the intermeniscal ligament before being sutured to the lateral intermuscular septum of the lateral femoral condyle and the proximal medial tibial periosteum.[7] Notably, MK ACLR is performed without drilling any graft tunnels, thereby preserving the integrity of the physeal plates. Although graft placement is nonanatomic in MK ACLR, it remains associated with yielding good postoperative functional outcomes and low rates of graft failure.[8]

A previously published treatment algorithm suggests considering the skeletal age of the patient to determine which operative technique to employ.[3] MK ACLR is recommended for use in patients with a skeletal age of 6 years, AE ACLR is recommended for patients with a skeletal age of 10 years, and partial transphyseal or transphyseal ACLR is recommended for patients closer to complete skeletal maturity.[3] Nevertheless, there are no reviews comprehensively comparing the efficacies of the physeal-sparing AE and MK ACLR techniques in the skeletally immature population.

Although a previous systematic review of a similar topic has been published,[9] it analyzed a small sample of studies, including those conducting transepiphyseal ACLR, and pooled MK ACLR with alternative over-the-top techniques. Therefore, an abundance of directly comparable pertinent literature eluded this initial review. The purpose of this systematic review is to provide a comprehensive comparison of the functional and clinical postoperative outcomes following AE and MK ACLR in the skeletally immature population, as well as assess their associated complication profiles and rates. The null hypothesis was assumed, specifically, that there would be no clinically significant difference in clinical or functional outcomes across AE and MK ACLR, with similar complication profiles and rates between the 2 operative techniques.

METHODS

The methodology of this systematic review was structured in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) and Revised Assessment of Multiple Systematic Reviews (R-AMSTAR) guidelines.[10,11]

Search Strategy

Independent searches of Embase, Medline, and PubMed from inception to January 8, 2024 were conducted to broadly identify all available literature reporting clinical outcomes and/or complications following AE or MK ACLR in the skeletally immature population. The same search strategy was repeated on April 30, 2024. The purpose of this systematic review was determined a priori, and pertinent inclusion/exclusion criteria were formulated accordingly to facilitate study screening and identify all primary studies available assessing postoperative outcomes following AE or MK ACLR in the skeletally immature population. References of all included studies and of pertinent review papers were manually searched to ensure that all means of study identification were exhausted. If multiple papers reported the same outcomes using identical patient cohorts, only the article with the latest follow-up period was included. If multiple papers presented overlapping but nonidentical cohorts, all articles were included, as the extent of patient overlap could not be determined. The search strategy used is presented in Appendix 1, Supplemental Digital Content 1, http://links.lww.com/BPO/A862.

Assessment of Study Eligibility

The inclusion criteria were as follows: (1) skeletally immature with ≥ 2 years of growth remaining, (2) ACL rupture reconstructed with AE or MK surgical techniques, (3) any clinical/functional outcomes or complications reported, (4) any level of evidence, and (5) studies published in English. Exclusion criteria were as follows: (1) concomitant ligament injuries or avulsion fractures, (2) congenital abnormalities, (3) use of ligament augmentation devices, (4) lateral extra-articular tenodesis (LET), (5) animal studies, (6) cadaveric studies, (7) basic science studies, (8) review articles, and (9) all data pooled with

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nonskeletally immature patients or with non-AE/MK ACLR surgical techniques.

Study Screening

Two reviewers (A.Z. and A.H.) independently screened titles, abstracts, and full texts of studies obtained from the search strategy. If a disagreement could not be resolved between the 2 reviewers, a third senior reviewer (D.dS.) was consulted.

Quality Assessment

Two reviewers (A.Z. and F.K.) independently conducted a quality assessment of all included studies using the Methodological Index for Non-Randomized Studies (MINORS) criteria.[12] This is a validated scoring tool with maximum scores of 16 and 24 for noncomparative and comparative studies, respectively. Quality assessment scores were converted to a percentage to facilitate comparison between studies.

Data Abstraction

Data were independently abstracted by 1 reviewer (A.Z.) and recorded on a Google Sheets (Google LLC, Mountain View, CA) spreadsheet. Two reviewers (A.H. and F.K.) independently reviewed the data to ensure complete accuracy. Abstracted data included study design and corresponding level of evidence, number of patients and operated knees, grafts used, follow-up duration, patient demographics (age, sex, height, weight, Tanner stage, etc.), and all reported clinical/functional outcomes and complications. The level of evidence of each paper was reported according to the authors' statement or, if unstated, was reported using the Oxford Centre for Evidence-Based Medicine (OCEBM) guidelines.[13]

Outcomes

The pivot-shift and Lachman tests are both common assessments of ACL graft laxity.[14] The more profound the pathologic motion is during the combined valgus moment, internal tibiofemoral rotation, and anterior tibial translation of the pivot-shift test, the higher the grade assigned. Similarly, progressively abnormal anterior translation of the tibiofemoral compartment yields higher grades in the Lachman test.[14]

The Pediatric International Knee Documentation Committee (Pedi-IKDC) subjective knee evaluation form is a validated modified IKDC subjective knee evaluation form developed specifically for use among pediatric patients. The Pedi-IKDC form has been found to have no clinically significant differences to the standard IKDC form.[15] These results have therefore been pooled together during abstraction.

Although graft failure, growth disturbances, and angular deformity were the primary postoperative complications of interest in this patient population, all other major and minor complications with limited or no clinical significance were still reported to comprehensively report all postoperative risks associated with AE and MK ACLR. Incidence of growth disturbance and angular deformity were reported according to the authors' statement or, if unclear, were defined as ≥ 1 cm leg length discrepancy or ≥ 3 degree side-to-side difference, respectively.[5,16] These values were adhered to whenever possible to ensure reports remained consistent across studies.

Statistical Analysis

GraphPad QuickCalcs was used to calculate the weighted kappa (κ) statistic to assess inter-rater agreement at all stages of screening. In reference to a previous study, the categorization of κ scores was determined a priori:[17] $0.00 \leq \kappa < 0.20$ indicates slight agreement, $0.20 \leq \kappa 0.40$ indicates fair agreement, $0.40 \leq \kappa < 0.60$ indicates moderate agreement, $0.80 \leq \kappa < 1.00$ indicates almost perfect agreement, and $\kappa = 1.00$ indicates perfect agreement.

Microsoft Excel (Microsoft, Redmond, WA) was used to calculate the intraclass correlation coefficient (ICC) to assess inter-rater agreement of quality assessments. In reference to a previous study, the categorization of ICC scores was determined a priori:[17] ICC < 0.50 indicates poor agreement, 0.50 ≤ ICC < 0.75 indicates moderate agreement, 0.75 ≤ ICC < 0.90 indicates good agreement, and ICC ≥ 0.90 indicates excellent agreement. In reference to a previous study, the categorization of MINORS scores was determined a priori:[18] A quality score of 0% to 24% indicates very low quality of evidence, 25% to 49% indicates low quality of evidence, 50% to 74% indicates moderate quality of evidence, and 75% to 100% indicates high quality of evidence.

A meta-analysis was conducted to determine pooled values when possible. It was decided a priori that a minimum of 3 studies, each with a sample size of at least 3 knees, would be needed to consider pooling values. All postoperative outcomes reported in 6 or more studies, with at least 3 studies in each operative group to permit pooling, are presented to ensure sufficient data is available to suitably compare results. Subgroup analyses were conducted where possible. To establish the variance of the raw proportions, a Freeman–Tukey transformation was applied.[19] The transformed proportions were then combined using the DerSimonian–Laird random effects model to incorporate the anticipated heterogeneity.[20] The proportions were back-transformed using an equation derived by Miller.[21] For continuous variables that were distributed in the approximately normal distribution, where possible, the mean values and variance reported across studies were combined using the DerSimonian–Laird random effects model to incorporate the anticipated heterogeneity.[20] The I^2 test was used to assess heterogeneity for all pooled values. In reference to a previous study, the categorization of I^2 values was determined a priori[18]: An I^2 score of 0% to 24% indicates very low statistical heterogeneity, 25% to 49% indicates low statistical heterogeneity, 50% to 74% indicates moderate statistical heterogeneity, and 75% to 100% indicates high statistical heterogeneity. For other variables, where results were presented in a nonuniform nature across studies or where there was insufficient data to pool the results, the results are presented in a narrative summary fashion. Descriptive statistics were calculated, including means, SDs, counts, proportions, ranges, and confidence intervals. Calculations were conducted using

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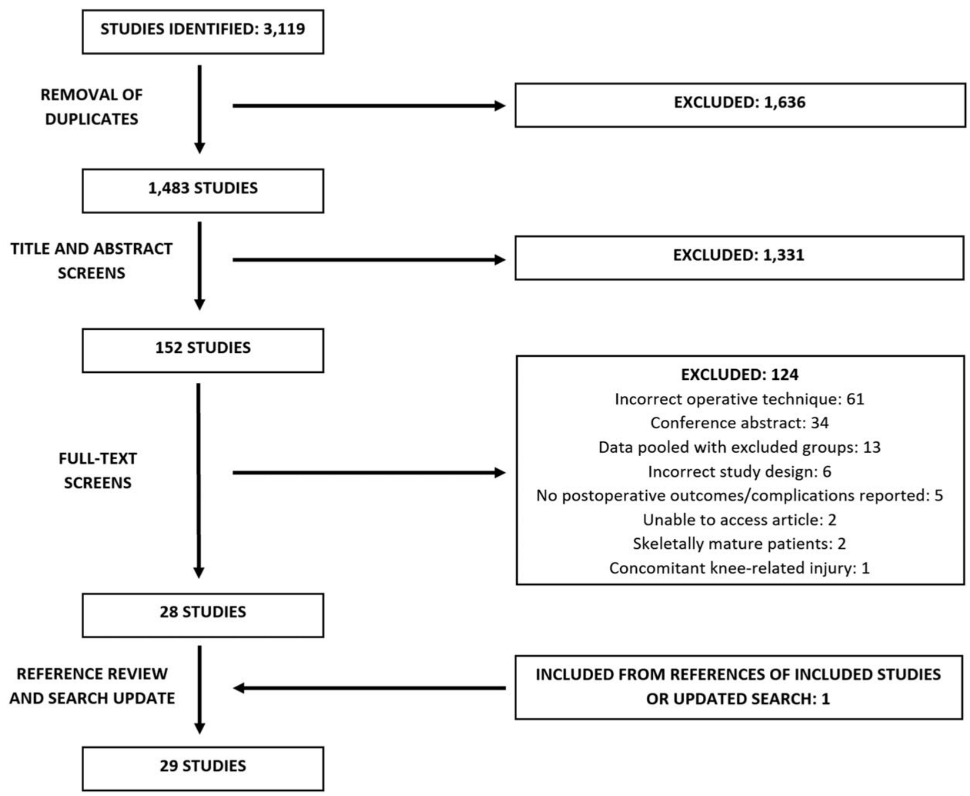

FIGURE 1. Preferred reporting items for systematic reviews and meta-analyses (PRISMA) study selection flow diagram conveying the number of studies included and excluded at each stage of the screening process.

StatsDirect statistical software (Version 3.2.7, StatsDirect software, Cheshire, UK).

RESULTS

Study Identification and Quality

The initial literature search yielded 1483 unique studies, of which 28 (1176 patients) met the inclusion and exclusion criteria for this systematic review.[5,7,8,22–46] One additional study (1 patient) was included by manually searching references of included studies and pertinent review papers.[47] No additional studies were included upon repeating the search strategy. The PRISMA flow diagram is presented in Figure 1. Almost perfect inter-rater agreement was achieved in both title/abstract ($\kappa = 0.89$) and full-text screening ($\kappa = 0.96$).

Among the 29 studies included in this systematic review, 2 (6.9%) were level II evidence, 9 (31.0%) were level III evidence, 17 (58.6%) were level IV evidence, and 1 was level V evidence (3.4%), of which 11 (555 patients) were comparative and 18 (622 patients) were noncomparative. The reviewers reached an excellent agreement in MINORS scores with an ICC of 0.960 [95% CI: 0.919–0.981]. The mean MINORS score among the included studies was $54.53 \pm 12.25\%$. One study had high quality of evidence, 23 had moderate quality of evidence, and 5 had low quality of evidence (Table 1).

Study and Patient Characteristics

All included studies were published between 1999 and 2023. A total of 1177 patients and 1182 knees were included at the final reported follow-up across the included studies. Of these, 750 knees in 749 patients underwent AE ACLR, and 432 knees in 428 patients underwent MK ACLR. Patient sex of those undergoing physeal-sparing ACLR was reported and distinguishable across 25 studies (1040 patients),[5,7,8,22,24,26–38,40–45,47] with 195 patients (18.8%) identifying as female (Table 1). Specifically, 145 of 480 reported patients (30.2%) were female in the AE ACLR group, and 50 of 365 reported patients (13.7%) were female in the MK ACLR group. The mean chronological age of patients undergoing physeal-sparing ACLR was reported in 28 studies (1151 patients),[5,7,8,22,24–47] with a pooled mean of 11.9 years (mean range, 8 to 13.3 y) (Table 1). Specifically, the age of patients undergoing AE ACLR was reported in 19 studies (723 patients) with a pooled mean of 12.1 ± 1.8 y. The age of patients undergoing MK ACLR was reported in 9 studies (428 patients) with a pooled mean of 11.6 ± 1.9 y. The mean final follow-up duration was reported in 26 studies (1159 patients)[5,7,8,22–27,29–35,37,39–47] and ranged from 6 to 43.2 months postoperatively following AE ACLR and 6-63.6 months postoperatively following MK ACLR. (Table 1).

Of the 11 (555 patients) comparative studies, 8 (487 patients) compared different operative techniques based

TABLE 1. Patient Demographics and Quality of Evidence of Included Studies

References	Experimental group (graft used if AE ACLR)	No. patients/ knees	Sex (M/F)	Age	Follow-up duration (mo)	Level of evidence	Mean MINORS score (%)
Afana[38]	AE ACLR (QT autograft – 1)	1/1	1/0	12	NR	3	56.25
Akinleye[37]	AE ACLR (Quadrupled ST/G autograft – 1 ST autograft/ posterior tibial tendon allograft – 1)	1/2	0/1	10.5	36	5	62.50
Cordasco[34]	AE ACLR (HT autograft – 23)	23/23	17/6	12.2 (9.9, 14.5)	32.1 (24, 45)	4	75.00
Cordasco[35]	AE ACLR (HT autograft – 49)	49/49	40/9	12.0 ± 1.5	41.4 ± 15.9	4	66.64
Cruz[33]	AE ACLR (HT autograft – 81 Allograft – 19 Hybrid graft – 3)	103/103	79/24	12.1 ± 1.8	21 ± 13	4	62.50
DeFrancesco[32]	AE ACLR (HT autograft – 145 Allograft – 12 Hybrid graft – 4)	161/161	126/35	12.1 ± 1.78	32.8 (0, 109)	4	70.83
Graziano[31]	AE ACLR (HT autograft – 25)	25/25	18/7	11.5 ± 1.1	24	4	68.75
Greenberg[29]	AE ACLR (HT autograft – 1)	1/1	1/0	8	24	4	56.25
Greenberg[30]	AE ACLR (HT autograft – 16)	16/16	12/4	12.3 ± 1.8	7.1 (3.0, 12.6)	4	25.00
Ithurburn[28]	AE ACLR (HT autograft – 16)	16/16	14/2	12.3 ± 1.8	NR	2	37.50
Lawrence[8]	AE ACLR (HT autograft – 2 Posterior tibialis allograft – 1)	3/3	3/0	11.33 ± 0.94	12	4	50.00
McCarthy[22]	AE ACLR (HT autograft – 2)	2/2	2/0	10.5 ± 0.5	6	4	50.00
Nathan[47]	AE ACLR (HT autograft – 1)	1/1	1/0	9	30	3	43.75
Nawabi[25]	AE ACLR (HT autograft – 15)	15/15	ND	11.9 ± 1.2	20.9 ± 8.4	4	62.50
Patel[24]	AE ACLR (ND)	162/162	125/37	12.1 ± 1.8	26.5 ± 5.2	3	58.33
Pennock[23]	AE ACLR (HT autograft – 26)	26/26	ND	ND	38.4 (2,4 60)	4	25.00
Ranade[46]	AE ACLR (HT autograft – 83)	83/83	NR	12.3 (6.3, 15.9)	15.5 (6, 66)	3	56.25
Sasaki[5]	AE ACLR (HT autograft – 18)	18/18	8/10	12.4 ± 1.2	41.6 ± 20.1	3	66.67
Wall[42]	AE ACLR (HT autograft – 27)	27/27	23/4	11.4 ± 1.9	43.23 ± 16.81	4	50.00
Zhang[40]	AE ACLR (HT autograft – 16)	16/16	10/6	12.13 ± 1.41	31.6 ± 4.5	4	58.33
Collins[36]	MK ACLR	1/1	1/0	8.8	NR	3	50.00
Kocher[7]	MK ACLR	44/44	28/16	10.3 (3.6, 14.0)	63.6 (24.0, 181.3)	4	37.50
Kocher[27]	MK ACLR	237/240	204/33	11.2 ± 1.7	25.8	4	62.50
Micheli[26]	MK ACLR	7/7	6/1	12.1 ± 1.2	47.9 ± 20.2	4	43.75
Milewski[39]	MK ACLR	13/13	ND	12.5 (10, 14)	6	2	58.35
Sugimoto[44]	MK ACLR	39/39	39/0	12.5 ± 1.3	6.9 ± 2.5	3	68.75
Sugimoto[45]	MK ACLR	33/33	33/0	12.8 ± 1.3	6.2 ± 0.7	3	54.17
Sugimoto[43]	MK ACLR	33/33	33/0	13.3 ± 1.3	6.2 ± 0.7	3	54.17
Willimon[41]	MK ACLR	21/22	21/0	11.8 (9.9, 14.0)	36.02 (12.00, 82.86)	4	50.00

Reported demographic information and study quality of included studies. The range is presented in the absence of SD if possible. ACLR indicates anterior cruciate ligament reconstruction; AE, all-epiphyseal; HT, hamstring tendon; MK, Micheli-Kocher; QT, quadriceps tendon; ST/G, semitendinosus and gracilis.

on the level of skeletal maturity only,[5,24,25,28,32,35,43,45] 2 (52 patients) compared different operative techniques based on level of skeletal maturity and patient sex,[39,44] and 1 (16 patients) compared different operative approaches to AE ACLR.[40] No studies directly compared AE and MK ACLR. Twenty studies (749 patients) reported postoperative outcomes of patients undergoing AE ACLR,[5,8,22–25,28–35,37,38,40,42,46,47] and 9 studies (428 patients) reported postoperative outcomes of patients undergoing MK ACLR.[7,26,27,36,39,41,43–45] Graft type used in AE ACLR was specified and distinguishable across 19 studies (588 knees),[5,8,22,23,25,28–35,37,38,40,42,46,47] comprising 547 (93.0%) hamstring tendon (HT) autografts, 32 allografts (5.9%), 8 (1.5%) hybrid grafts, and 1 (0.2%) quadriceps tendon (QT) autograft (Table 1). Study and patient characteristics are presented in Table 1. The reported operative techniques for patients undergoing AE ACLR are presented in Table 2.

Clinical and Functional Outcomes

Return to sports (RTS) percentage, pivot-shift test, Lachman test, International Knee Documentation Committee (IKDC) subjective scores, and range of motion (ROM) were reported in 6 or more studies following AE or MK ACLR. All raw data of the reported postoperative outcomes and complications are presented in Appendix 2, Supplemental Digital Content 2, http://links.lww.com/BPO/A863. Knee extension and flexion limb symmetry index (LSI) were reported in 8 and 6 studies, respectively, although these data were not included in the analyses as dynamometer settings were inconsistent across the studies included. These raw data, along with all other outcomes that were heterogeneously reported in at least 2 studies, are presented in Appendix 3, Supplemental Digital Content 3, http://links.lww.com/BPO/A864.

RTS rates were reported in 16 studies (11 AEs, 5 MKs; 395 patients). In 11 studies (181 patients) reporting RTS

TABLE 2. All-Epiphyseal Anterior Cruciate Ligament Reconstruction Operative Techniques

References	Operative technique
Afana[38]	QT autograft (5.0×1.0×0.5 cm) with ends augmented with fiber loop with fiber tag connected to ACL Tightrope. Tibial tunnel, 0.6×1.5 cm; femoral tunnel, 0.7×1.5-2.0 cm. Tibial and femoral fixation, soft-tissue buttons. Graft tensioned at ~20° knee flexion.
Akinleye[37]	Initial ACLR quadrupled HT (ST/G) autograft. Tibial fixation, retroscrew; femoral fixation, biointerference screw (0.7×2.3 cm).
	*I*psilateral ACLR Combined HT (ST) autograft and posterior tibial tendon allograft. Tibial fixation, retroscrew (2.0×1.0 cm); femoral fixation, biocomposite screw (1.1×2.6 cm).
Cordasco[34]	Quadrupled HT (ST) autograft (5.0-5.5×0.7-0.8 cm); gracilis harvested if ST < 0.7 cm. Graft reinforced with tightrope suture buttons on both the tibial and femoral sides. Tibial guide setting, ~50 degrees; femoral guide setting, ~95 degrees. Tibial tunnel, ~1.5-2.0 cm; femoral tunnel, ~2.0-2.5 cm. Tibial and femoral fixation, Tightrope devices tensioned until tight.
Cordasco[35]	Multistrand HT autograft. Tibial and femoral fixation, suspensory fixation.
Cruz[33]	HT autograft (5.5×0.8 cm). Graft whipstitched and looped over Ethibond suture. Reinforced with Tightrope suture buttons. Femoral guide setting, 95 degrees. Tibial tunnel, 1.5-2.0 cm; femoral tunnel, 0.9×2.0-2.5 cm. Tibial fixation, retroscrew (2.0×0.9 cm); femoral fixation, interference screw while applying 15 lbs of tension to the graft.
DeFrancesco[32]	NR
Graziano[31]	NR
Greenberg[29]	Quadrupled HT autograft (5.5×0.8 cm). Graft whipstitched and looped over Ethibond suture. Reinforced with tightrope suture buttons. Femoral guide setting, 95 degrees. Tibial tunnel, 1.5-2.0 cm; femoral tunnel, 0.9×2.0-2.5 cm. Tibial fixation, retroscrew (2.0×0.9 cm); femoral fixation, interference screw while applying 15 lbs of tension to the graft.
Greenberg[30]	NR
Ithurburn[28]	NR
Lawrence[8]	HT autograft (5.5×0.8 cm). Graft whipstitched and looped over Ethibond suture. Reinforced with tightrope suture buttons. Femoral guide setting, 95 degrees. Tibial tunnel, 1.5-2.0 cm; femoral tunnel, 0.9×2.0-2.5 cm. Tibial fixation, retroscrew (2.0×0.9 cm); femoral fixation, interference screw while applying 15 lbs of tension to the graft.
McCarthy[22]	Quadrupled HT (ST) autograft (5.0-5.5×0.7-0.8 cm); gracilis harvested if ST < 0.7 cm. Graft reinforced with tightrope suture buttons on both the tibial and femoral sides. Tibial guide setting, ~50 degrees; femoral guide setting, ~95 degrees. Tibial tunnel, ~1.5-2.0 cm; femoral tunnel, ~2.0-2.5 cm. Tibial and femoral fixation, Tightrope devices tensioned until tight.
Nathan[47]	Quadrupled HT autograft. Tibial tunnels, split 0.45 cm tunnels with 1 cm bone bridge; femoral tunnel, 0.7 cm. Tibial fixation, free ends oversewn above the tibial bone bridge; femoral fixation, XTENDOBUTTON (2.0 cm) cortically supporting endobutton (1.2 cm) attached to 2.0 cm continuous loop over the femoral tunnel.
Nawabi[25]	Quadrupled HT (ST) autograft (6.5-7.0×0.85 cm); gracilis harvested if inadequate ST diameter. Reinforced with cortical fixation devices on either side with the tightrope attachable button system on the tibial end and tightrope reverse-tensioning button on the femoral end. Tibial tunnel, ~2.0 cm; femoral tunnel, 2.0-2.5 cm. Tightrope devices tensioned until tight.
Patel[24]	HT autograft (5.5×0.8 cm). Graft whipstitched and looped over Ethibond suture. Reinforced with tightrope suture buttons. Femoral guide setting, 95 degrees. Tibial tunnel, 1.5-2.0 cm; femoral tunnel, 0.9×2.0-2.5 cm. Tibial fixation, retroscrew (2.0×0.9 cm); femoral fixation, interference screw while applying 15 lbs of tension to the graft.
Pennock[23]	Quadrupled HT (ST/G) autograft (16×0.6-0.8 cm); allograft used or alternative autograft source used if inadequate ST/G length. Tibial guide setting, 40 degrees; femoral guide setting, 95 degrees. Tibial fixation, cortical suspensory fixation device; femoral fixation, absorbable interference screw (2.3-2.5 cm). Graft secured at ~20 degrees knee flexion.
Ranade[46]	Quadrupled HT graft. Tibial guide setting, 30-35 degrees; femoral guide setting, 90-95 degrees. Tibial fixation, aperture or cortical button fixation; femoral fixation, cortical button fixation.
Sasaki[5]	Double-bundle HT (ST) autograft; harvested ST cut in half. Distal half is used for anteromedial bundle, proximal half used for posterolateral bundle. Tibial tunnels, 0.5-0.6 cm (anteromedial bundle) and 0.5-0.6 cm (posterolateral bundle); femoral tunnels, 0.5-0.6×2.0 cm (anteromedial bundle) and 0.45-0.6×2.0 cm (posterolateral bundle). Tibial fixation, tied over tibial disk; femoral fixation, cortical suspension device. Graft secured at ~20 degrees knee flexion.
Wall[42]	Quadrupled HT (ST/G) autograft (~0.45-0.55 cm diameter); harvested HT doubled and sewn side-by-side. Tibial tunnels, split 0.4–0.6 cm tunnels with 1 cm bone bridge (3/27 patients received single tibial tunnel (0.7-0.9 cm)); femoral tunnel, 0.6-0.9 cm. Tibial fixation, free ends oversewn above the tibial bone bridge; femoral fixation, endobutton, and washer or XTENDOBUTTON (2/27 patients received tibial screw fixation and femoral Endobutton fixation).
Zhang[40]	Quadrupled HT autograft. Femoral fixation, Endobutton. Graft secured at ~40 degrees knee flexion.

ACLR indicates anterior cruciate ligament reconstruction; HT, hamstring tendon; NR, not reported; QT, quadriceps tendon; ST, semitendinosus; ST/G, semitendinosus and gracilis.

following AE ACLR,[8,23,28–31,34,35,37,38,42] 140 patients were reported to RTS at the time of the final reported follow-up, for a total pooled rate of 77.3% (95% CI 47.2%-91.6%, $I^2=62.9\%$). Specifically, 6 studies (83 patients)[8,23,28,30,37,42] defined RTS as passing functional and strength assessment thresholds for RTS (≥85%–90% LSI compared with contralateral side) following AE ACLR, and reported 50 patients meeting the thresholds to RTS for a pooled rate of 60.2% (95% CI: 26.3%-79.5%, $I^2=59.5\%$). Whereas 5 studies (98 patients)[29,31,34,35,38] defined RTS as returning to competitive sports or preinjury level of activity following AE ACLR and reported 90 patients returning to sport for a pooled rate of 91.8% (95% CI: 73.2%-100.0%, $I^2=0.0\%$). In 5 studies (212 patients)[7,26,27,36,41] reporting RTS following MK ACLR, 198 patients were reported to RTS, defined as return to full play with no limitations or preinjury level of activity, for a pooled rate of 93.4% (95% CI: 80.7%-100.0%, $I^2=0.0\%$). Reported ranges for patients to return to competitive sports or preinjury level of activity following AE and MK ACLR were 9 to 22 months and 6 to 24 months, respectively.

Pivot-shift and Lachman test grades were reported in 11 studies (7 AE, 4 MK; 391 patients). In 7 studies

(98 patients) reporting outcomes following AE ACLR,[5,8,22,31,34,42,47] 92 patients achieved a negative grade in both the pivot-shift and Lachman tests, for a total pooled rate of 93.9% (95% CI: 86.6%-100.0%, $I^2 = 0.0\%$). In 4 studies (293 patients) reporting outcomes following MK ACLR,[7,26,27,41] 279 patients achieved a negative grade in the pivot-shift test and 266 patients achieved a negative grade in the Lachman test, for a total pooled rate of 95.2% (95% CI: 84.3%-100.0%, $I^2 = 0.0\%$) and 90.8% (95% CI: 59.6%-100.0%, $I^2 = 43.2\%$), respectively.

IKDC subjective scores were reported in 10 studies (6 AE, 4 MK; 364 knees). In 6 studies (162 knees) reporting outcomes following AE ACLR,[28,34,37,40,42,46] the pooled IKDC subjective score mean was 94.0 (95% CI: 92.3-96.6, $I^2 = 0.0\%$). In 4 studies (202 knees) reporting outcomes following MK ACLR,[7,27,39,41] the pooled IKDC subjective score mean was 93.6 (95% CI: 87.5-97.3, $I^2 = 89.3\%$).

ROM flexion and hyperextension were reported in 7 (4 AEs, 3 MKs; 133 knees) and 6 studies (3 AEs, 3 MKs; 112 knees), respectively. In 4 studies (42 knees) reporting outcomes following AE ACLR,[5,29,37,42] the pooled mean ROM flexion was 144.1 degrees (95% CI: 137.3-152.2 degrees, $I^2 = 61.5\%$), and in 3 studies (21 knees) reporting outcomes following AE ACLR,[5,29,37] the pooled mean ROM hyperextension was 2.5 degrees (95% CI: 0.7-4.2 degrees, $I^2 = 96.2\%$). In 3 studies (91 knees) reporting outcomes following MK ACLR,[41,43,44] the pooled mean ROM flexion and hyperextension were 136.3 degrees (95% CI: 133.1-140.1 degrees, $I^2 = 49.6\%$) and 3.1 degrees (95% CI: 2.6-3.7 degrees, $I^2 = 99.3\%$), respectively.

Postoperative Complications and Injuries

Twenty-three studies (18 AEs, 5 MKs; 900 knees)[5,7,8,22–27,29,31–38,40–42,46,47] reported the occurrence of postoperative complications, wherein 1 study (161 knees)[32] reported solely on the incidence of graft failures and contralateral ACL ruptures following AE ACLR.

Major complications following AE ACLR were reported across 18 studies (689 knees)[5,8,22–25,29,31–35,37,38,40,42,46,47] and included 73 graft failures (10.6%; 95% CI: 2.6%-18.6%, $I^2 = 78.1\%$), 8 growth disturbances (1.5%; 95% CI: 0.1%-3.0%, $I^2 = 0.0\%$), and 7 angular deformities (1.3%; 95% CI: 0.0%-3.1%, $I^2 = 0.0\%$). Other major complications following AE ACLR included 29 contralateral ACL tears/ruptures (4.2%), 22 postoperative meniscal tears/repairs/meniscectomies (3.2%), 3 superficial infections (0.6%), 2 patellar dislocations (0.4%), 2 notch impingements (0.4%), 2 incidents of arthrofibrosis (0.4%), 2 separate lysis of adhesions (0.4%), 1 lateral femoral condyle fracture (0.2%), and 1 hardware removal (0.2%). Minor complications following AE ACLR were reported across 17 studies (528 knees)[5,8,22–25,29,31,33–35,37,38,40,42,46,47] and included 3 incidents of prominent hardware (0.6%), and 1 incident of closed knee manipulation to resolve ROM deficits (0.2%).

Major complications following MK ACLR were reported across 5 studies (211 knees)[7,26,27,36,41] and included 14 graft failures (6.6%; 95% CI: 0.0%-17.5%, $I^2 = 71.4\%$). There were no growth disturbances or angular deformities reported in 5 studies (211 knees) following MK ACLR. Other major complications following MK ACLR included 14 contralateral ACL tears/ruptures (6.6%), 14 postoperative meniscal/chondral repairs (6.6%), 7 separate postoperative meniscal tears/repairs/meniscectomies (3.8%), 5 lysis of adhesions (2.4%), 1 incident of septic arthritis (0.5%), and 1 incident of wound dehiscence (0.5%). Minor complications following MK ACLR were reported across 5 studies (211 knees) and included 2 incidents of harvest-site pain (0.9%).

There was a total of 152 major complications following AE ACLR (18 studies; 689 knees), for a pooled rate of 22.1% (95% CI: 16.5%-22.0%, $I^2 = 84.9\%$), and a total of 56 major complications following MK ACLR (5 studies; 211 knees), for a pooled rate of 26.5% (95% CI: 18.8%-30.2%, $I^2 = 52.1\%$).

DISCUSSION

This is the first systematic review to report on and directly compare the postoperative outcomes and complication profiles of both AE and MK ACLR. The primary findings of this review are that there are no apparent differences in the clinical or functional outcomes between AE and MK ACLR, although there may be differences with their associated complication profiles, though this remains indefinite as comparative statistical analyses were not performed. Both AE and MK ACLR were reported to yield promising rates of RTS, substantially limit anteroposterior laxity, and retrieve acceptable knee health and fully functional ROM. However, AE ACLR may be associated with a clinically greater risk of postoperative growth disturbances, growth deformities, and graft failure and may have a lower risk of contralateral ACL tears relative to MK ACLR.

AE and MK ACLR both yielded promising and comparable rates of return to competitive sports or preinjury level of activity (91.8% and 93.4%, respectively), with overlapping reported ranges of mean time to RTS (9 to 13.5 mo and 6 to 24 mo, respectively). Notably, a previous systematic review reported 82% (95% CI: 72%-90%) of children and adolescents undergoing transphyseal ACLR returned to preinjury level of activity,[48] suggesting superior rates of RTS following physeal-sparing ACLR in the adolescent population. A considerably lower proportion of patients returned to sporting activities following AE ACLR in studies defining RTS as meeting LSI thresholds commonly used to ensure a safe and efficacious RTS (60.2%) than in studies defining RTS as a return to competitive sports or preinjury level of activity (91.8%). Although this may initially appear to demonstrate that patients are prematurely returning to sporting activities before recovering satisfactory muscular function, a common concern in this highly active population,[49] this is not supported by the complication profile of this patient cohort. Patients were at low risk of contralateral ACL tears following AE ACLR (4.2%), a complication wherein premature RTS is a predominant risk factor.[50] These findings may therefore support previously reported concerns of LSI thresholds for RTS being too stringent and that meeting discharge criteria does not show a significant

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association with reduced risk of postoperative ACL injury.[51] It is important to permit full RTS on a personalized basis once patients demonstrate both physical and psychological readiness, ideally no sooner than nine months postoperative.[52]

The proportion of negative postoperative pivot-shift (93.9% and 95.2%, respectively) and Lachman test grades (93.9% and 90.8%, respectively) were similar between AE and MK ACLR. Although a biomechanical cadaveric study previously noted that the more anatomic AE ACLR technique better restores dynamic knee stability compared with a nonanatomic over-the-top ACLR technique,[53] the findings of this review suggest that this may not translate to in-vivo clinical outcome. A recent systematic review of 16 studies (2250 patients) observed that skeletally immature patients undergoing complete transphyseal ACLR had greater postoperative anteroposterior laxity relative to the physeal-sparing techniques investigated in this review, as only 80% of patients reported negative pivot-shift and Lachman test grades at least 15 months postoperatively.[54] Although vertical transphyseal tunnels are employed to minimize physeal damage of the proximal tibia and distal femur,[55] vertical graft placement is linked to greater postoperative anteroposterior laxity and internal rotation of the knee, consequently altering cartilage loading and risking early-onset osteoarthritis in patients.[56] It is therefore important to note the promising rates of negative postoperative pivot-shift and Lachman test grades achieved in both physeal-sparing techniques examined in this review relative to previous findings following transphyseal ACLR.[54]

Postoperative IKDC subjective scores (94.0 and 93.6, respectively), knee flexion (144.1 degrees and 136.3 degrees, respectively), and knee hyperextension (2.5 degrees and 3.1 degrees, respectively) were found to be comparable to one another following AE and MK ACLR. It should be noted that 1 study (19 patients) excluded IKDC subjective and ROM results from patients that underwent revision ACLR following MK ACLR,[41] and 1 study (13 patients) excluded IKDC subjective results only from patients that underwent revision ACLR following MK ACLR,[3] which may have skewed these postoperative outcomes higher following MK ACLR. Nevertheless, both AE and MK ACLR surpassed the patient acceptable symptom state (PASS) IKDC subjective knee form the threshold of 75.9, which delineates an acceptable state of patient knee health,[57] the substantial clinical benefit (SCB) IKDC subjective knee form the threshold of 88.0, which delineates clinically significant improvement and success with regards to postoperative function,[58] and regained full functional flexion ROM (defined as ≥ 130 degrees flexion)[59] and low-grade passive hyperextension (defined as < 6.5 degrees).[60]

Although AE and MK ACLR were found to yield similar postoperative functional and clinical outcomes, there were differences within their reported complication profiles. There were 152 reported major complications among 689 operated knees (22.1%) and 3 reported minor complications among 528 operated knees (0.6%) following AE ACLR, and 56 major and 2 minor complications among 211 operated knees (26.5% and 0.9%, respectively) following MK ACLR. It should be acknowledged that there may be selection bias in the complications reported, which may overestimate the efficacies of the operative techniques. Notably, no skeletally immature patients undergoing MK ACLR experienced postoperative growth disturbances or angular deformities in this review. The absence of angular deformities, in conjunction with 90.8% of patients reporting negative postoperative pivot-shift tests between 25.8 and 63.6 months postoperation in the MK ACLR patient cohort, indicates that MK ACLR provides promising anterolateral stability in the moderate-term. However, it should be noted that 11 of the 14 patients (78.6%) with positive pivot-shift results came from the cohort with the longest reported follow-up (63.6 months). This could indicate that over-the-top reconstruction techniques may eventually trend towards overconstraining rotational movements of the knee at longer-term follow-up, as has been suggested in previous biomechanical cadaveric studies.[53] On the other hand, there were 8 growth disturbances (1.5%) and 7 angular deformities (1.3%) following AE ACLR. All of the reported growth disturbances were associated with postoperative limb shortening, which may suggest that there is a greater risk of clinically significant physeal damage than hyperemia with AE ACLR. There is an inherent risk of physeal injury in AE ACLR from drilling the all-epiphyseal tunnels. Although radiographic evidence may suggest the tunnels do not violate the physes, thermal damage at the time of drilling may enlarge the zone of injury beyond the tunnel diameter and still disrupt physeal integrity.[5] It is therefore advisable to employ intraoperative fluoroscopy to identify the open physes, if available, and utilize slower drilling speeds with a manual drill to wholly protect the integrity of the physeal plate during AE ACLR.[55] A recent systematic review of 78 studies (2,693 patients) investigating the incidence of growth disturbances following pediatric transphyseal ACLR reported that 40 of 1359 (2.9%) patients had a consequential growth disturbance of ≥ 10 mm and/or an angular deformity of ≥ 3 degrees.[61] AE ACLR appears to yield a similar risk of growth disturbances and angular deformities relative to transphyseal ACLR, with 15/688 (2.2%) total reported incidents, whereas MK ACLR seems to suitably mitigate the primary concerns of growth disturbances and angular deformities in the skeletally immature patient with 0/211 (0.0%) total reported incidents in this systematic review. These findings highlight that avoiding the use of drilled tunnels has a substantial protective effect against the considerable concerns surrounding postoperative growth disturbances and angular deformities in the skeletally immature population.

Other major complications of note in this highly active patient population are rates of contralateral ACL tears and graft failure.[62] AE ACLR demonstrated a marginally lower risk of contralateral ACL tears (4.2%) relative to MK ACLR (6.6%), although the low quality of evidence of the included studies precludes the ability to affirm whether this slight variation is due to the difference in operative technique employed. Nevertheless, these results corroborate those of a previous systematic review reporting rates of postoperative contralateral ACL tears in patients younger than 16 years of age.[63] Furthermore, AE ACLR was found to have a slightly higher risk of graft failure (10.6%) relative to MK ACLR (6.6%), although again, the low quality of evidence of included studies and absence of comparative statistical analyses challenges whether this difference is clinically significant. A recent systematic review of 1010 patients undergoing transphyseal ACLR reported a graft failure rate of 11.0%,[64] suggesting a potentially higher risk of graft failure relative to MK ACLR and a comparable risk of graft failure relative to AE ACLR in skeletally immature patients. Nevertheless, these differences should not be ascribed to the reconstruction technique alone. Of 588 knees undergoing AE ACLR in this review, 547 (93.0%) were treated with the HT autograft. Recent analyses have shown that HT autografts with < 8 mm diameter are associated with poorer postoperative functional and clinical outcomes and greater rates of graft failure,[65] though larger grafts heighten hamstring deficits, weaken medial stabilization, and may consequently increase postoperative risk of reinjury as a consequence of knee valgus instability.[66] However, the QT autograft is becoming an increasingly popular option among this patient population.[17] Although one of the primary risk factors for graft failure following pediatric ACLR was reported to be the use of soft-tissue grafts,[67] a recent systematic review of 596 patients investigating the use of QT autograft in pediatric patients suggests that the soft tissue QT autograft yields similar results to bone-QT autografts, while simultaneously reducing the risk of physis disruption.[17] With graft failure rates reported at only 2.5%, the authors believe it would be worthwhile for future research to investigate the efficacy of the QT autograft in AE ACLR to investigate whether this would reduce the risk of graft failure in the skeletally immature population.

There was an absence of baseline equivalence between the operative groups reported in this review. Specifically, 145 of 480 patients (30.2%) undergoing AE ACLR with reported sex were female, whereas only 50 of 365 (13.7%) patients undergoing MK ACLR were female. A previously published treatment algorithm suggests considering the skeletal age of the patient to determine which operative technique to employ,[3] recommending MK ACLR for patients with a skeletal age of up to 6 years and AE ACLR for patients with a skeletal age of up to 10 years.[3] A cross-sectional survey of surgeons in the Pediatric Research in Sports Medicine (PRiSM) Society, published in 2018, revealed a preference for MK ACLR in both male and female patients up to 10 years of age, with comparable preferences for either AE and MK ACLR in patients 11 to 13 years of age.[68] Interestingly, there was minimal difference in the reported age of patients between the operative groups. The pooled mean age of the AE ACLR cohort was 12.1 ± 1.8 y, whereas the MK ACLR cohort was 11.6 ± 1.9 y. Although the higher proportion of male patients undergoing MK ACLR may have skewed the mean age higher, none of the included studies in this review cited the patients' skeletal age. Therefore, it is not possible to conclude whether MK ACLR is being used on more skeletally immature patients as the aforementioned treatment algorithm suggests or if physicians may be indiscriminately employing the physeal-sparing technique of their preference. It would be ideal for future studies reporting on skeletally immature patients to additionally report the skeletal age and Tanner stage of the patients to facilitate broad comparability of their results.

LIMITATIONS

The clinical significance of the findings presented is limited by the low quality of evidence of the studies included in this review, as 26 of 29 of the included studies (89.7%) are level III or IV evidence, with no studies directly comparing the outcomes of AE and MK ACLR. Studies employing AE ACLR reported the use of various techniques that differed by graft type and fixation method, which limits the extent of comparability of their outcomes. In addition, heterogeneity in follow-up duration, RTS criteria, and definitions of graft failure, growth disturbance, and angular deformity further preclude definitive comparability of reported outcomes. Finally, moderate-to-high statistical heterogeneity was observed for many of the pooled outcomes abstracted in this study, leading to the overlap of confidence intervals between AE and MK ACLR, which preclude definitive conclusions of whether differences in outcomes and complication profiles are significant.

CONCLUSION

Both AE and MK ACLR yield promising rates of RTS, substantially limit anteroposterior laxity, surpass IKDC thresholds for acceptable knee health, and regain fully functional ROM to comparable levels, though they yield marginally different complication profiles. However, the majority of the included studies were moderate or low-quality evidence with high statistical heterogeneity. Therefore, no statistical conclusions regarding the differences in complication profiles can be drawn. Future randomized controlled trials or large prospective cohort studies should compare the efficacy and complication profile of QT autograft AE ACLR relative to MK ACLR.

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