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Contralateral Lower-Limb Training After Anterior Cruciate Ligament Reconstruction: An Updated Systematic Review and Meta-Analysis of Strength and Functional Outcomes

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ADMINISTRATIVE INFORMATION

Support - No support.

Review Stage at time of this submission - Completed but not published.

Conflicts of interest - None declared.

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Amendments - This protocol was registered with the International Platform of Registered Systematic Review and Meta-Analysis Protocols (INPLASY) on 21 September 2026 and was last updated on 21 September 2026.

INTRODUCTION

Review question / Objective Contralateral training has been proposed as an adjunct when early loading of the reconstructed limb is restricted, but its clinical effects and mechanisms after ACLR remain uncertain. We conducted an updated systematic review and meta-analysis of its effects on quadriceps strength, patient-reported knee function, and other rehabilitation outcomes.

Condition being studied Anterior cruciate ligament injuries predominantly affect physically active populations, and despite the widespread success of reconstructive surgery in restoring mechanical joint stability, the recovery of neuromuscular function remains notoriously incomplete. Even after structured rehabilitation, a substantial proportion of patients exhibit persistent quadriceps weakness and abnormal task-specific motor strategies that undermine their readiness to return to pre-injury competitive levels and elevate the risk of secondary graft rupture. Large cohort studies and consensus statements have consistently identified insufficient strength recovery as one of the most robust modifiable predictors of poor return-to-sport outcomes, reinforcing the clinical priority of early and effective neuromuscular restoration. In the initial weeks following surgery, however, rehabilitation of the involved limb faces inherent physiological constraints.

METHODS

Participant or population Participants underwent unilateral ACLR;.

Intervention The intervention included an identifiable additional exercise programme directed to the non-operated lower limb, involving repeated resistance exercise or unilateral balance practice, with postoperative strength or function of the reconstructed limb or knee assessed.

Comparator Both groups received comparable background ACLR rehabilitation, while the control group did not receive the additional contralateral programme; a time-matched control activity was permitted.

Study designs to be included Randomised controlled design. Only studies described by their authors as randomised were included; no quasi-randomised study was included. Unclear reporting of sequence generation or allocation concealment was addressed in the RoB 2 assessment.

Eligibility criteria Eligibility was determined from the intervention content, trained limb, between-group contrast, and assessed outcomes rather than study labels. Gait assessment, use of the contralateral limb as a reference, or bilateral exercise without an identifiable additional non-operated-limb component was insufficient. Eligible interventions were classified by their predominant stimulus as contralateral resistance training or balance/proprioceptive training (Table 2). Eligibility did not require a significant effect or demonstrated neural adaptation, and "cross-education" was not assigned solely because the contralateral limb was trained.

Information sources We searched PubMed/MEDLINE, Cochrane CENTRAL, Embase, Web of Science Core Collection, Scopus, PEDro, CINAHL Complete, and SPORTDiscus from database inception to 17 September 2026. The search strategy was structured around three concepts: anterior cruciate ligament reconstruction, contralateral or cross-education training, and randomized or controlled study terminology. Database-specific controlled vocabulary, field restrictions, truncation symbols, and Boolean operators were adapted to the syntax of each platform. The search strategy included terms such as "cross-training," "contralateral training," "unilateral training," "cross-transfer," "cross education," "uninjured limb," "non-operated limb," "unaffected limb," and "healthy-side training." No outcome-specific terms were used as an eligibility filter.

Main outcome(s) The primary outcomes were early postoperative quadriceps strength/strength deficit and Lysholm knee function. Lysholm was selected because comparable early data were available on the same scale; however, the outcome hierarchy was not documented as finalised before screening or extraction. Absolute or body-mass-normalised strength, bilateral strength deficit, and LSI were extracted as distinct constructs. For early quadriceps performance, reconstructed-limb strength and bilateral strength deficit were synthesised using Hedges' g; deficit values were sign-reversed so that positive effects favoured contralateral training. Because these constructs are not equivalent, the results were interpreted as a broad quadriceps-performance synthesis, and sensitivity analysis substituted Papandreou 2007 absolute isometric strength for the Papandreou 2013 deficit outcome. Strength LSI was reported separately. Outcomes were grouped at approximately 8-12 and 24-26 postoperative weeks, reflecting the assessment clusters available in the included studies rather than prespecified biological phases.

Additional outcome(s) Secondary outcomes included pain, hamstring strength, functional performance, patient-reported outcomes, balance, gait, plantar pressure, neuromuscular measures, kinesiophobia, and range of motion. Late hop pooling was restricted to single-leg hop distance LSI (reconstructed/contralateral distance × 100%); no timed hop tests were included. Minshull used the mean of three hops, Harput the best of three, and Zult the best of two. Minshull's ratios were multiplied by 100, and Zult's reported LSI was used. Mean differences were calculated as intervention minus control, with positive values indicating higher LSI. Pooling required comparable intervention contrasts, outcome constructs, measurement methods, and assessment times; otherwise, study-level or narrative synthesis was prioritised.

Data management Statistical analyses were performed in R version 4.2.3 using the meta package version 7.0-0. Mean differences (MDs) were used when outcomes were measured on the same scale, whereas standardised mean differences, expressed as Hedges' g, were used when sufficiently similar constructs were measured using different instruments or units. When multiple eligible intervention arms shared one control group, the intervention arms were combined so that the control participants were included only once.

Random-effects models with restricted maximum-likelihood estimation of τ^2 and unmodified Hartung-Knapp confidence intervals were used for the primary analyses. Common-effect estimates were reported only as sensitivity references. Statistical heterogeneity was assessed using I^2 and Cochran's Q test. Because all pooled outcomes included fewer than 10 operational study groups, funnel plots and formal tests of small-study effects were not performed.

Missing outcome data were not imputed by the review authors, and study authors were not

contacted for additional data. For each outcome and time point, the analysis population reported by the original study was used, whether based on an intention-to-treat, modified intention-to-treat, or outcome-specific analysis. Standard deviations were extracted directly when reported. When outcomes were reported only as medians and interquartile ranges, approximate means and standard deviations were calculated using the Wan method. Missing standard deviations were not reconstructed from P values, confidence intervals, or standard errors. When both endpoint and change-score data were available, endpoint data were used; no change-score standard deviations or within-participant correlation coefficients were calculated. Preoperative or other baseline measurements were extracted to describe initial group comparability but were not entered into the meta-analysis or used to calculate review-level change scores. Quantitative syntheses used postoperative endpoint values within the specified time windows. Attrition and the handling of missing outcome data in the original studies were incorporated into Domain 3 of the outcome-specific RoB 2 assessment.

Post hoc sensitivity analyses were conducted to assess the robustness of the pooled estimates. When multiple eligible reports or outcome formulations were available from the same trial family, the analysis was repeated using an alternative eligible measure. When the independence of operational study groups could not be fully established, analyses were repeated after excluding each potentially related group in turn. For outcomes contributed by at least three operational study groups, leave-one-out analyses were also performed.

Quality assessment / Risk of bias analysis Two reviewers independently assessed risk of bias and certainty of evidence, with disagreements resolved through discussion. Risk of bias was reassessed for each result contributing to a quantitative synthesis using the Cochrane RoB 2 tool, with the effect of assignment to intervention as the target estimand. Domain 1 and common aspects of Domain 2 were assessed at the trial level and carried forward only when applicable, whereas Domains 3-5 and the overall judgment were evaluated separately for each outcome and postoperative time point. Signalling questions were completed using Y/PY/PN/N/NI/NA responses, and each judgment was supported by quotations or PDF page locations from the original reports. When multiple reports belonged to the same trial family, all companion reports were considered, while each result contributed only once to a given synthesis. The certainty of evidence was assessed using the GRADE approach, with initial downgrading based on risk of bias, inconsistency, indirectness, imprecision, and publication bias. Potential publication and selective-reporting concerns were also considered qualitatively by reviewing registry identifiers and protocol information reported in the included articles, companion reports from the same trial families, and reference lists for additional reports.

Strategy of data synthesis Two reviewers independently screened titles and abstracts, assessed full texts against the PICOS criteria, and extracted data using a standardized form. Disagreements were resolved through discussion or consultation with a third reviewer. Potential overlap between reports was assessed using registration identifiers, recruitment settings and periods, sample sizes, intervention protocols, baseline characteristics, follow-up schedules, and outcome data. Reports with potential cohort overlap were assigned to operational study groups for analytical purposes; this classification did not establish confirmed cohort independence. Each operational study group contributed only one comparison to each outcome-specific and time-window-specific meta-analysis. Eligible intervention arms were combined where appropriate, with shared controls counted once.

Extracted information included study design and registration; group-specific sample sizes; demographic, anthropometric, activity, surgical, and graft characteristics; concomitant injuries and procedures; injury-to-surgery and surgery-to-intervention intervals; baseline strength, function, and limb symmetry index (LSI); rehabilitation protocols; intervention modality, contraction mode, frequency, intensity, and duration; and assessment times and instruments. Absolute strength, body-mass-normalised torque, percentage deficit, and LSI were recorded separately, as were endpoint and change scores.

Postoperative endpoint data were preferentially used when both endpoint and change scores were available. Graphically reported values were digitised and identified as approximate, graph-derived data. Medians and interquartile ranges were converted to approximate means and SDs using the Wan method where applicable. Missing-data handling and available sample sizes were recorded for each outcome and time point. Apart from the median/IQR conversions described above, no SDs were reconstructed from P values, confidence intervals, or standard errors; no change-score SDs were calculated, and no participant-level missing outcomes were imputed by the review authors. Accordingly, no within-person correlation coefficient was assumed. Study

authors were not contacted for unreported numerical data. Database records were deduplicated on 18 September 2026. Title/abstract screening and full-text assessment were completed on 18 September 2026, and the final data extraction was completed on 18 September 2026.

Subgroup analysis Sparse evidence and co-occurring study characteristics precluded reliable subgroup analysis or meta-regression and limited sensitivity analyses of registration, bias, graph-derived data, population, graft, and intervention timing.

Sensitivity analysis Post hoc sensitivity analyses were conducted to assess the robustness of the pooled estimates. When multiple eligible reports or outcome formulations were available from the same trial family, the analysis was repeated using an alternative eligible measure. When the independence of operational study groups could not be fully established, analyses were repeated after excluding each potentially related group in turn. For outcomes contributed by at least three operational study groups, leave-one-out analyses were also performed.

Country(ies) involved China.

Keywords anterior cruciate ligament reconstruction; cross education; contralateral training; quadriceps muscle; neuromuscular rehabilitation; metaanalysis.

Contributions of each author

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