

Review Article

Effectiveness of Constraint-Induced Movement Therapy on Upper-Limb Function in Children with Cerebral Palsy: A Systematic Review and Meta-Analysis of Randomized Controlled Trials

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ABSTRACT

Background: Cerebral palsy is frequently associated with persistent upper-limb impairment, particularly among children with unilateral or hemiplegic involvement. Constraint-Induced Movement Therapy is a neuroplasticity-based rehabilitation approach designed to improve functional use of the more affected upper limb through restraint of the less affected limb and intensive task-oriented practice. However, contemporary randomized evidence remains heterogeneous, and adjunctive CIMT studies require separate interpretation. **Objective:** To evaluate the effectiveness of Constraint-Induced Movement Therapy on upper-limb function in children and adolescents with cerebral palsy through a systematic review and meta-analysis of randomized controlled trials. **Methods:** A systematic search was conducted in PubMed, Scopus, Web of Science, Cochrane Library, and PEDro for English-language randomized controlled trials published from January 2015 to December 2025. Eligible studies included children or adolescents with cerebral palsy receiving CIMT, modified CIMT, expanded CIMT, or CIMT-based rehabilitation. Risk of bias was assessed using the Cochrane RoB 2 tool. Standardized mean differences using Hedges' g were pooled under a random-effects model where trials directly compared CIMT with non-CIMT control interventions. Adjunctive CIMT trials were synthesized separately. **Results:** Five randomized controlled trials involving 269 participants were included. Two trials with 110 participants were included in the primary meta-analysis. The pooled effect favored CIMT but was not statistically significant (Hedges' $g = 1.53$, 95% CI -1.35 to 4.40), with considerable heterogeneity ($I^2 = 96.6\%$). Three adjunctive trials evaluated rTMS or virtual reality combined with CIMT. rTMS showed promising additive effects, whereas virtual reality did not demonstrate clear superiority over CIMT alone. **Conclusion:** CIMT remains a promising intervention for pediatric upper-limb rehabilitation in cerebral palsy, but current evidence is limited by few directly comparable trials, imprecision, and substantial heterogeneity. Larger standardized randomized trials are needed to establish effect magnitude, optimal dosage, durability, and clinical applicability. **Keywords:** Cerebral palsy; Constraint-Induced Movement Therapy; Modified Constraint-Induced Movement Therapy; Upper-limb function; Pediatric rehabilitation; Randomized controlled trial; Systematic review; Meta-analysis.

EDITORIAL INFORMATION

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INTRODUCTION

Cerebral palsy is a lifelong neurodevelopmental condition characterized by persistent disorders of movement and posture resulting from non-progressive disturbances in the developing fetal or infant brain (1). Although the underlying brain lesion is non-progressive, the functional consequences of cerebral palsy may evolve across childhood because of growth, musculoskeletal adaptation, activity limitations, pain, and changing environmental demands (2). Upper-limb impairment is particularly important in children with

unilateral or hemiplegic cerebral palsy, where reduced selective motor control, impaired grasp and release, poor coordination, reduced spontaneous use of the affected limb, and limitations in bimanual performance can restrict self-care, play, school participation, and social engagement (3). Because these impairments directly affect functional independence and participation, upper-extremity rehabilitation remains a major priority in pediatric neurorehabilitation.

Constraint-Induced Movement Therapy is a task-oriented, neuroplasticity-based intervention developed to improve functional use of the more affected upper limb. The intervention is based on two core principles: restraint of the less affected upper limb and intensive, repetitive, goal-directed practice using the more affected limb (4). By increasing purposeful use of the affected limb, CIMT aims to reduce learned non-use, promote motor learning, and support activity-dependent cortical reorganization. Several pediatric adaptations have been developed, including modified CIMT, expanded CIMT, home-based CIMT, and group-based delivery models, to improve feasibility, acceptability, intensity, and adherence in children with cerebral palsy (5). Despite differences in restraint method, treatment setting, duration, and intensity, these approaches share the same therapeutic rationale of increasing structured, functional use of the affected upper extremity.

Previous evidence syntheses have generally suggested that CIMT may improve unimanual capacity, spontaneous use of the affected upper limb, and bimanual performance in children with unilateral cerebral palsy (4,6). However, the certainty and clinical applicability of available evidence remain limited by substantial heterogeneity in participant characteristics, intervention dosage, restraint methods, comparator interventions, outcome measures, and follow-up duration (4,7). Earlier reviews have also included older trials, mixed intervention protocols, and heterogeneous study designs, which makes it difficult to isolate the effect of contemporary CIMT protocols evaluated specifically through randomized controlled trials. More recent evidence has further expanded the field by examining CIMT in combination with adjunctive strategies such as repetitive transcranial magnetic stimulation and virtual reality, but these combined-intervention studies address a different clinical question from trials comparing CIMT directly with non-CIMT control therapy (8,9).

An updated systematic review focused on randomized controlled trials is therefore warranted to clarify the current evidence base for CIMT in pediatric cerebral palsy. Such a synthesis is clinically important because rehabilitation professionals require evidence not only on whether CIMT improves upper-limb function, but also on the precision, consistency, and applicability of treatment effects across contemporary trials. Separating direct CIMT-versus-control studies from adjunctive CIMT studies is also necessary to avoid attributing the effect of neuromodulation or technology-enhanced rehabilitation to CIMT alone. Where studies are sufficiently comparable, meta-analysis can estimate the direction and magnitude of treatment effects, while narrative synthesis can appropriately summarize clinically distinct adjunctive comparisons.

Accordingly, this systematic review and meta-analysis aimed to evaluate the effectiveness of Constraint-Induced Movement Therapy on upper-limb function in children and adolescents with cerebral palsy. Using a PICO framework, the population of interest was children and adolescents with cerebral palsy; the intervention was CIMT, modified CIMT, expanded CIMT, or related CIMT-based rehabilitation; the comparator was conventional therapy, usual care, sham intervention, or non-CIMT rehabilitation; and the primary outcome was upper-limb function assessed using validated clinical outcome measures. A secondary objective was to summarize randomized trials evaluating adjunctive interventions combined with CIMT, including rTMS and virtual reality, to determine whether these approaches provide additional benefit beyond CIMT-based training.

MATERIALS AND METHODS

This systematic review and meta-analysis was conducted to evaluate the effectiveness of Constraint-Induced Movement Therapy on upper-limb function in children and adolescents with cerebral palsy. The review was designed and reported in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses 2020 statement (10). The review question was structured using the Population, Intervention, Comparator, Outcome, and Study Design framework. The population comprised children and

adolescents aged 0–18 years diagnosed with cerebral palsy, including unilateral, hemiplegic, hemiparetic, or bilateral presentations. The intervention of interest was Constraint-Induced Movement Therapy, modified Constraint-Induced Movement Therapy, expanded Constraint-Induced Movement Therapy, or other pediatric CIMT-based rehabilitation programs. Eligible comparators included usual care, routine physical therapy, conventional rehabilitation, standard care, sham intervention, or alternative non-CIMT rehabilitation. The primary outcome was upper-limb function assessed using validated clinical outcome measures, including the Assisting Hand Assessment, Quality of Upper Extremity Skills Test, Pediatric Motor Activity Log, Wolf Motor Function Test, Melbourne Assessment, Box and Block Test, and related measures of upper-extremity performance. Only randomized controlled trials published in English between January 2015 and December 2025 were considered eligible. Non-randomized studies, quasi-experimental studies, observational studies, case reports, conference abstracts, study protocols, reviews, studies involving adult participants, studies not involving cerebral palsy, and studies not evaluating CIMT-based rehabilitation were excluded. The manuscript data specify this review type, databases, eligibility framework, RoB 2 assessment, and random-effects meta-analysis approach.

A comprehensive literature search was conducted in PubMed, Scopus, Web of Science, Cochrane Library, and the Physiotherapy Evidence Database. The search strategy combined controlled vocabulary and free-text terms related to cerebral palsy, pediatric upper-limb rehabilitation, Constraint-Induced Movement Therapy, modified Constraint-Induced Movement Therapy, expanded Constraint-Induced Movement Therapy, and randomized controlled trials. Search terms included combinations of “cerebral palsy,” “hemiplegic cerebral palsy,” “unilateral cerebral palsy,” “constraint-induced movement therapy,” “modified constraint-induced movement therapy,” “expanded constraint-induced movement therapy,” “CIMT,” “mCIMT,” “upper limb,” “upper extremity,” “hand function,” “randomized controlled trial,” and “clinical trial.” Boolean operators and database-specific syntax were applied where appropriate. Reference lists of included studies and relevant systematic reviews were also screened manually to identify additional eligible studies.

All identified records were imported into reference-management software, and duplicate records were removed before screening. Titles and abstracts were screened according to the predefined eligibility criteria, followed by full-text assessment of potentially eligible reports. Studies were included in the qualitative synthesis when they fulfilled the population, intervention, comparator, outcome, and study-design criteria. Studies were included in the primary quantitative synthesis only when they directly compared CIMT or a CIMT-based intervention with a non-CIMT control condition and reported sufficient numerical data for effect-size estimation. Trials in which all groups received CIMT and the experimental contrast was an adjunctive intervention, such as active repetitive transcranial magnetic stimulation or virtual reality, were not pooled with the primary meta-analysis because they addressed a different clinical question. These studies were synthesized separately as secondary evidence on adjunctive interventions combined with CIMT.

Data extraction was performed using a standardized extraction form designed for this review. Extracted variables included author name, publication year, country, study design, sample size, participant age, cerebral palsy subtype, intervention type, comparator condition, restraint method, treatment intensity, total therapy dose, intervention duration, follow-up period, outcome measures, and numerical outcome data. For quantitative synthesis, group means, standard deviations, change scores, post-intervention values, confidence intervals, and sample sizes were extracted where available. When multiple upper-limb outcomes were reported within the same study, a predefined outcome hierarchy was used to avoid duplication of effect sizes from a single trial. Priority was given to the Assisting Hand Assessment, followed by the Quality of Upper Extremity Skills Test, Melbourne Assessment, Pediatric Motor Activity Log, Wolf Motor Function Test, Box and Block Test, and other validated upper-limb functional measures. This hierarchy was selected to prioritize validated measures of upper-limb function and activity performance commonly used in pediatric cerebral palsy rehabilitation.

The methodological quality of included randomized controlled trials was assessed using the revised Cochrane Risk of Bias tool for randomized trials (11). Five domains were evaluated: bias arising from the randomization process, bias due to deviations from intended interventions, bias due to missing outcome data, bias in measurement of the outcome, and bias in selection of the reported result. Each domain was judged as low risk, some concerns, or high risk according to RoB 2 guidance, and an overall risk-of-bias judgment was assigned for each study. Particular attention was given to allocation sequence generation, allocation concealment, blinding of outcome assessors, completeness of outcome data, handling of missing data, and selective outcome reporting. Because participant and therapist blinding is often not feasible in rehabilitation trials involving restraint-based therapy, therapist-supervised practice, rTMS, or virtual reality, the interpretation of bias due to deviations from intended interventions emphasized whether deviations were balanced between groups and whether outcome assessment remained blinded.

Meta-analysis was performed when studies were sufficiently comparable in terms of population, intervention, comparator, and outcome construct. Because included studies used different validated upper-limb outcome scales, treatment effects were summarized using standardized mean differences with Hedges' g correction for small-sample bias. Positive effect sizes indicated superior outcomes favoring CIMT. A random-effects model was selected a priori because clinical and methodological heterogeneity was expected across trials, particularly in relation to intervention intensity, total treatment dose, type of restraint, duration of therapy, comparator condition, outcome measure, and timing of assessment (12). Statistical heterogeneity was assessed using Cochran's Q statistic, Tau^2 , and the I^2 statistic. I^2 values of approximately 25%, 50%, and 75% were interpreted as low, moderate, and substantial heterogeneity, respectively (12). Where change-score data were available, change scores were preferred; where only post-intervention data were available, post-treatment means and standard deviations were used. This approach was interpreted cautiously because change-score and post-treatment analyses may differ in precision and clinical meaning.

Studies evaluating adjunctive interventions combined with CIMT were analyzed separately from the primary CIMT-versus-control comparison. Trials comparing active rTMS plus CIMT with sham rTMS plus CIMT, active rTMS plus modified CIMT with sham rTMS plus modified CIMT, or CIMT plus virtual reality with CIMT alone were not combined with trials comparing CIMT against non-CIMT control interventions. This separation was necessary because adjunctive-intervention trials estimate the additional effect of the adjunctive modality rather than the independent therapeutic effect of CIMT. These studies were summarized narratively according to intervention type, comparator condition, outcome measure, follow-up duration, and direction of effect.

Publication bias was planned to be assessed using funnel plot inspection and Egger's regression test if at least ten studies were available for quantitative synthesis. Because fewer than ten studies were included in the primary meta-analysis, formal assessment of publication bias was not performed, as funnel plots and regression-based asymmetry tests are unreliable with a small number of studies (12). The findings were therefore interpreted in light of the small number of directly comparable trials, imprecision of pooled estimates, and degree of between-study heterogeneity.

RESULTS

Study Selection

The database search identified 412 records from five electronic databases, including PubMed ($n = 142$), Scopus ($n = 118$), Web of Science ($n = 92$), Cochrane Library ($n = 38$), and PEDro ($n = 22$). After removal of duplicate records ($n = 97$), 315 records were screened by title and abstract. Of these, 309 records were excluded because they were not related to cerebral palsy or pediatric rehabilitation ($n = 84$), were not related to Constraint-Induced Movement Therapy or upper-limb rehabilitation outcomes ($n = 132$), or were reviews, commentaries, protocols, or other non-original reports ($n = 93$). Six reports were sought for retrieval, and all were retrieved for full-text assessment. One report was excluded at the eligibility stage because it provided insufficient data for analysis. Therefore, five randomized controlled trials were included in the qualitative synthesis. Of these, two trials directly compared CIMT or CIMT-based

intervention with a non-CIMT control intervention and were included in the primary quantitative synthesis. Three trials evaluated adjunctive interventions combined with CIMT and were synthesized separately because they addressed the added effect of the adjunctive modality rather than the independent effect of CIMT.

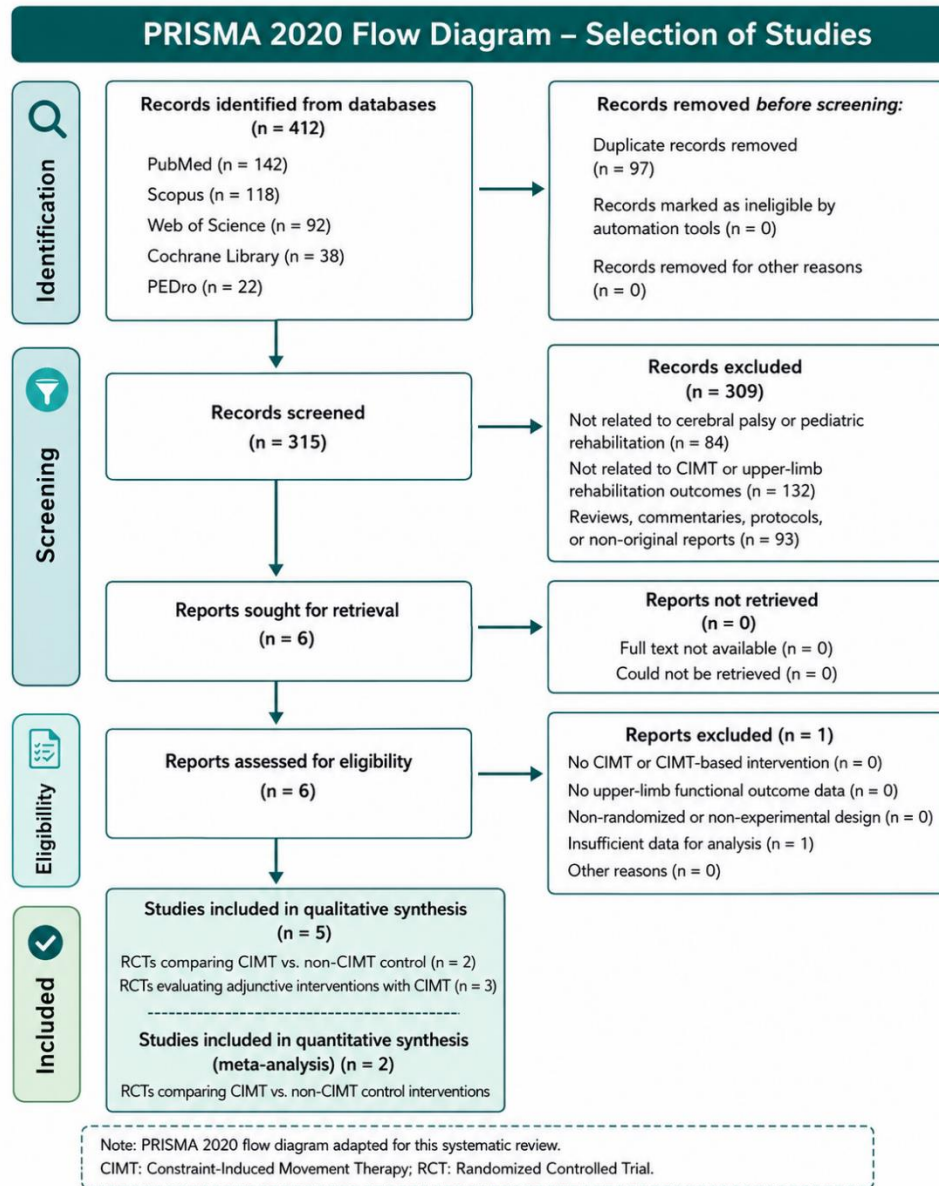


Figure 1. PRISMA 2020 Flow Diagram for Study Selection.

The PRISMA flow diagram summarizes the identification, screening, eligibility assessment, and final inclusion of randomized controlled trials evaluating Constraint-Induced Movement Therapy for upper-limb function in children with cerebral palsy. A total of 412 records were identified, 315 were screened after duplicate removal, six full-text reports were assessed for eligibility, and five randomized controlled trials were included in the qualitative synthesis. Two trials directly compared CIMT with non-CIMT control interventions and were included in the primary meta-analysis, while three trials evaluated adjunctive interventions combined with CIMT and were synthesized separately.

Characteristics of Included Studies

The five included randomized controlled trials enrolled a total of 269 children with unilateral, hemiplegic, or hemiparetic cerebral palsy. Publication years ranged from 2021 to 2025, reflecting contemporary evidence on CIMT and adjunctive upper-limb rehabilitation strategies in pediatric cerebral palsy. Sample sizes ranged from 32 to 118 participants. The included interventions comprised standard CIMT, expanded CIMT, modified CIMT, and CIMT combined with adjunctive interventions, including repetitive transcranial magnetic stimulation and virtual reality. Comparator conditions included usual customary treatment,

routine physical therapy, sham rTMS combined with CIMT, sham rTMS combined with modified CIMT, and CIMT alone. Follow-up duration varied from immediate post-treatment assessment to 12 months.

Upper-limb function was assessed using validated pediatric rehabilitation outcome measures. These included the Assisting Hand Assessment, Quality of Upper Extremity Skills Test, Pediatric Motor Activity Log, Wolf Motor Function Test, Melbourne Assessment 2, Selective Control of the Upper Extremity Scale, Peabody Developmental Motor Scales-2 Visual-Motor Integration subscale, and Canadian Occupational Performance Measure. The diversity of outcome measures reflected the multidimensional nature of upper-limb function, including unimanual capacity, bimanual performance, caregiver-reported functional use, selective motor control, and activity-level performance.

Table 1. Characteristics of Included Randomized Controlled Trials

Study	Design	Sample Size	Age / Population	CP Type	Intervention	Comparator	Dosage / Intensity	Duration	Follow-Up	Primary Outcome Measures	Synthesis Category
Ramey et al., 2021	Multisite factorial randomized controlled trial	118	Children aged 2–8 years	Hemiparetic cerebral palsy	CIMT using cast or splint restraint; 30-hour and 60-hour protocols	Usual customary treatment	30 or 60 hours of intensive CIMT	21 days	6 and 12 months	Assisting Hand Assessment, QUEST Dissociated Movement, PDMS-2 Visual-Motor Integration	Primary meta-analysis
Bakhat et al., 2022	Single-blind randomized controlled trial	38	Experimental: 7.68 ± 2.49 years; Control: 6.89 ± 2.02 years	Hemiplegic cerebral palsy	Expanded CIMT plus routine physical therapy	Routine physical therapy	4 hours/day restraint plus therapeutic activities	4 weeks	Immediate post-treatment	Pediatric Motor Activity Log, Wolf Motor Function Test Functional Ability Scale, Wolf Motor Function Test Performance Time	Primary meta-analysis
Wu et al., 2022	Assessor-blinded randomized controlled preliminary study	35	Preschool children, approximately 2–6 years	Unilateral cerebral palsy	CIMT plus active rTMS	CIMT plus sham rTMS	10 sessions of rTMS combined with CIMT	2 weeks	6 months	Melbourne Assessment 2, Selective Control of the Upper Extremity Scale	Secondary adjunctive synthesis
Gupta et al., 2023	Double-blind randomized controlled trial	46	Experimental: 7.6 ± 2.5 years; Control: 7.9 ± 2.8 years	Unilateral cerebral palsy	Modified CIMT plus real rTMS	Modified CIMT plus sham rTMS	Daily mCIMT combined with rTMS sessions	4 weeks	12 weeks	QUEST total score and subdomains	Secondary adjunctive synthesis
Roberts et al., 2025	Randomized controlled trial	32	Mean age 7.2 ± 2.6 years	Unilateral cerebral palsy	CIMT plus virtual reality	CIMT alone	Approximately 60-hour CIMT program with VR enhancement	3 weeks	Immediate post-treatment	Assisting Hand Assessment, Canadian Occupational Performance Measure	Secondary adjunctive synthesis

Abbreviations: AHA, Assisting Hand Assessment; CIMT, Constraint-Induced Movement Therapy; CP, cerebral palsy; mCIMT, modified Constraint-Induced Movement Therapy; PDMS-2, Peabody Developmental Motor Scales, Second Edition; QUEST, Quality of Upper Extremity Skills Test; rTMS, repetitive transcranial magnetic stimulation; VR, virtual reality.

Evidence Structure and Synthesis Classification

The included studies were classified into two clinically distinct evidence streams. The first evidence stream consisted of trials that directly compared CIMT or CIMT-based rehabilitation with non-CIMT control interventions. These studies addressed the primary review question and were eligible for quantitative pooling. The second evidence stream consisted of trials in which all groups received CIMT or modified CIMT, and the experimental contrast involved an adjunctive intervention, such as active rTMS or virtual reality. These studies were not pooled with the primary meta-analysis because they estimated the added effect of the adjunctive intervention rather than the independent effect of CIMT.

This separation was necessary to preserve clinical interpretability. Pooling studies in which CIMT was compared with non-CIMT control therapy together with studies in which CIMT was provided to both groups

would have combined different therapeutic questions and could have misattributed the effects of rTMS or virtual reality to CIMT alone.

Table 2. Evidence Streams and Synthesis Classification

Evidence Stream	Included Studies	Clinical Question	Intervention Contrast	Synthesis Method
Primary CIMT effectiveness evidence	Ramey et al., 2021; Bakhat et al., 2022	Does CIMT improve upper-limb function compared with non-CIMT control therapy?	CIMT or expanded CIMT versus usual customary treatment or routine physical therapy	Random-effects meta-analysis
Adjunctive neuromodulation evidence	Wu et al., 2022; Gupta et al., 2023	Does active rTMS add benefit when combined with CIMT or mCIMT?	Active rTMS + CIMT/mCIMT versus sham rTMS + CIMT/mCIMT	Narrative secondary synthesis
Technology-enhanced CIMT evidence	Roberts et al., 2025	Does virtual reality add benefit to CIMT?	CIMT + virtual reality versus CIMT alone	Narrative secondary synthesis

Risk of Bias Assessment

Risk of bias was assessed using the revised Cochrane Risk of Bias tool for randomized trials. Across the five included trials, one study was judged to have an overall low risk of bias, while four studies were judged as having some concerns. No study was judged to have an overall high risk of bias. The most frequent concern was bias due to deviations from intended interventions, which is difficult to avoid in rehabilitation trials because participants and therapists cannot usually be blinded to restraint-based therapy, treatment intensity, therapist-supervised training, rTMS procedures, or virtual reality exposure. Concerns were also noted in some studies for the randomization process, outcome measurement, or selection of the reported result. Missing outcome data was generally judged as low risk across the included trials.

The trial by Gupta et al. was judged as having low risk across all RoB 2 domains and was therefore classified as overall low risk. Ramey et al. and Wu et al. showed low risk across most domains but had some concerns related to deviations from intended interventions. Bakhat et al. had some concerns across several domains, including randomization, deviations from intended interventions, outcome measurement, and selection of the reported result. Roberts et al. had some concerns related to the randomization process, deviations from intended interventions, and selection of the reported result. Overall, the risk-of-bias profile supports cautious interpretation of the evidence but does not indicate that the findings are driven by studies with high overall risk of bias.

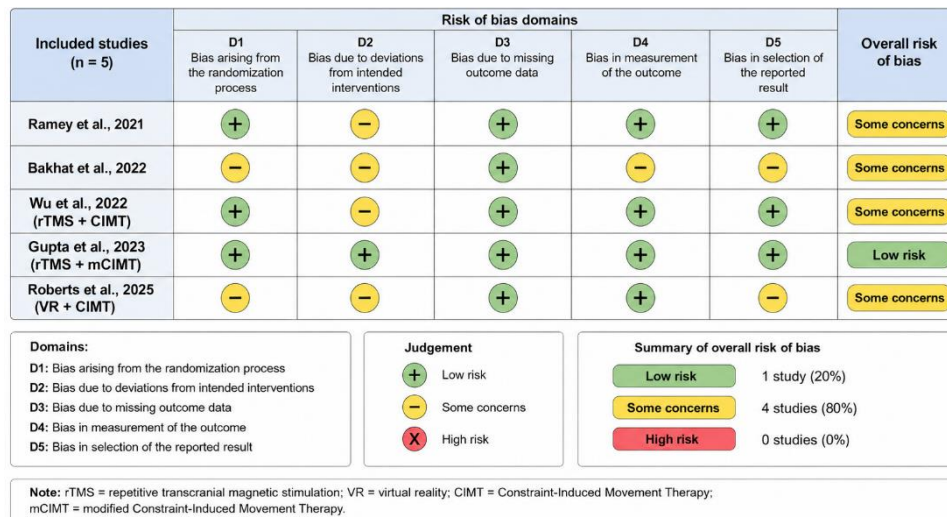


Figure 2. Risk of Bias Summary Using the Cochrane RoB 2 Tool.

The figure presents domain-level and overall risk-of-bias judgments for the five included randomized controlled trials. The evaluated domains were bias arising from the randomization process, bias due to deviations from intended interventions, bias due to missing outcome data, bias in measurement of the outcome, and bias in selection of the reported result. One study was judged as low risk overall, four studies were judged as having some concerns, and no study was judged as high risk overall.

Primary Meta-Analysis: CIMT Versus Non-CIMT Control

Two randomized controlled trials were eligible for the primary meta-analysis because they directly compared CIMT-based rehabilitation with a non-CIMT control condition. These trials contributed quantitative data from 110 participants for the pooled analysis, including 68 participants in CIMT groups and 42 participants in control groups. Because the included studies used different validated upper-limb outcome measures, treatment effects were synthesized using standardized mean differences with Hedges' *g* correction for small-sample bias. Positive values indicated effects favoring CIMT.

Ramey et al. contributed Assisting Hand Assessment change-score data and reported a small effect favoring CIMT, with Hedges' *g* = 0.09 and a 95% confidence interval from -0.41 to 0.58. This confidence interval crossed the null value, indicating that the study-level effect was not statistically significant. Bakhat et al. contributed Pediatric Motor Activity Log post-treatment data and reported a very large effect favoring expanded CIMT, with Hedges' *g* = 3.02 and a 95% confidence interval from 2.08 to 3.97. The pooled random-effects model yielded Hedges' *g* = 1.53, with a 95% confidence interval from -1.35 to 4.40. Although the point estimate favored CIMT, the pooled confidence interval crossed the null value, and the overall effect was not statistically significant.

Table 3. Primary Meta-Analysis of CIMT Versus Non-CIMT Control

Study	Outcome Used for Meta-Analysis	n: CIMT	n: Control	Effect Measure	Hedges' <i>g</i>	95% CI
Ramey et al., 2021	Assisting Hand Assessment change score	49	23	Standardized mean difference	0.09	-0.41 to 0.58
Bakhat et al., 2022	Pediatric Motor Activity Log post-treatment score	19	19	Standardized mean difference	3.02	2.08 to 3.97
Overall random effects model	Upper-limb function	68	42	Hedges' <i>g</i>	1.53	-1.35 to 4.40

The pooled result should be interpreted cautiously for three reasons. First, only two studies were available for quantitative synthesis. Second, the study-level effects were markedly different, ranging from a small effect in the larger multisite RCT to a very large effect in the smaller single-blind trial. Third, the confidence interval around the pooled effect was wide, indicating substantial imprecision. Therefore, the primary meta-analysis supports a possible beneficial direction of effect but does not provide a precise or definitive estimate of CIMT effectiveness.

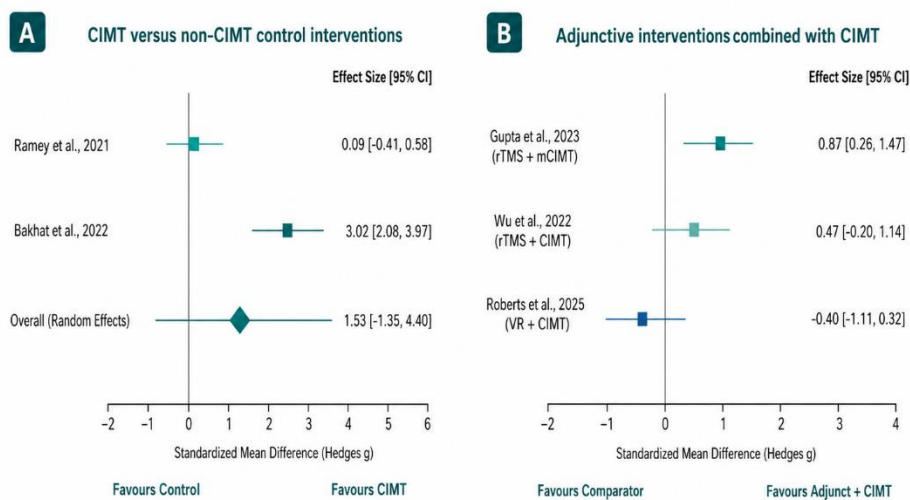


Figure 3. Forest Plot of CIMT Versus Non-CIMT Control Interventions.

The forest plot displays standardized mean differences using Hedges' *g* for trials directly comparing CIMT-based rehabilitation with non-CIMT control interventions. Positive values favor CIMT. The pooled random-effects estimate favored CIMT but was not statistically significant because the 95% confidence interval crossed the null value.

Heterogeneity of the Primary Meta-Analysis

Substantial heterogeneity was observed in the primary quantitative synthesis. Cochran's *Q* was 29.10 with 1 degree of freedom, and the *Q*-test was statistically significant. Tau² was 4.16, indicating large between-

study variance. The I^2 statistic was 96.6%, indicating considerable heterogeneity and suggesting that most of the variability in observed effects was due to between-study differences rather than chance alone.

Table 4. Heterogeneity Statistics for the Primary Meta-Analysis

Statistic	Value	Interpretation
Cochran's Q	29.10	Indicates substantial dispersion of study-level effect estimates
Degrees of freedom	1	Based on two pooled studies
Q-test p-value	<0.001	Statistically significant heterogeneity
Tau ²	4.16	Large between-study variance
I^2	96.6%	Considerable heterogeneity

The high level of heterogeneity is clinically and methodologically plausible. The two pooled studies differed in sample size, study design, intervention protocol, treatment intensity, comparator condition, outcome measure, and timing of assessment. Ramey et al. used a larger multisite factorial design with 30-hour and 60-hour CIMT protocols and longer follow-up assessments, whereas Bakhat et al. evaluated expanded CIMT combined with routine physical therapy in a smaller single-blind trial with immediate post-treatment assessment. The outcome measures also differed: the Assisting Hand Assessment captures observed bimanual performance, whereas the Pediatric Motor Activity Log reflects functional use of the affected limb in daily activities. These differences limit the interpretability of the pooled effect and explain why the overall estimate should be regarded as exploratory rather than definitive. Because only two studies were pooled, subgroup analysis, meta-regression, and meaningful sensitivity analysis were not feasible.

Secondary Synthesis: Adjunctive Interventions Combined With CIMT

Three randomized controlled trials evaluated adjunctive interventions combined with CIMT or modified CIMT. These trials were not included in the primary meta-analysis because CIMT-based rehabilitation was provided to both experimental and comparator groups. Therefore, these studies estimated the additive effect of rTMS or virtual reality rather than the independent effect of CIMT. Wu et al. evaluated active rTMS combined with CIMT compared with sham rTMS combined with CIMT in preschool children with unilateral cerebral palsy. Outcomes were assessed using Melbourne Assessment 2 and the Selective Control of the Upper Extremity Scale, with follow-up extending to six months. The findings favored active rTMS combined with CIMT over sham rTMS combined with CIMT, suggesting a possible additive effect of neuromodulation when paired with intensive upper-limb training.

Gupta et al. evaluated real rTMS combined with modified CIMT compared with sham rTMS combined with modified CIMT in children with unilateral cerebral palsy. Upper-limb function was assessed using the QUEST total score and subdomain scores over a 12-week follow-up period. The study reported superior improvement in the active rTMS group, further supporting the possibility that neuromodulation may enhance the effect of CIMT-based training. Roberts et al. evaluated CIMT combined with virtual reality compared with CIMT alone. Both groups received an intensive CIMT program of approximately 60 hours over three weeks. Outcomes included the Assisting Hand Assessment and Canadian Occupational Performance Measure. Both groups improved after intervention; however, virtual reality did not demonstrate clear superiority over CIMT alone. This finding suggests that the main therapeutic effect may be attributable to intensive CIMT-based training rather than the virtual reality adjunct.

Table 5. Secondary Synthesis of Adjunctive Interventions Added to CIMT

Study	Sample Size	Experimental Group	Comparator Group	Outcome Measures	Follow-Up	Main Finding
Wu et al., 2022	35	Active rTMS + CIMT	Sham rTMS + CIMT	Melbourne Assessment 2, Selective Control of the Upper Extremity Scale	6 months	Active rTMS combined with CIMT showed greater improvement than sham rTMS combined with CIMT
Gupta et al., 2023	46	Real rTMS + mCIMT	Sham rTMS + mCIMT	QUEST total score and subdomains	12 weeks	Real rTMS combined with mCIMT produced superior upper-limb improvements compared with sham rTMS combined with mCIMT
Roberts et al., 2025	32	CIMT + virtual reality	CIMT alone	Assisting Hand Assessment, Canadian Occupational Performance Measure	Immediate post-treatment	Both groups improved, with no clear superiority of virtual reality-enhanced CIMT over CIMT alone

Direction and Strength of Evidence Across Intervention Categories

Across the five included randomized controlled trials, the overall direction of evidence generally favored CIMT-based rehabilitation or CIMT combined with adjunctive intervention. However, the strength and interpretation of evidence differed by intervention category. The primary CIMT-versus-control evidence was limited to two trials and showed a pooled point estimate favoring CIMT, but the effect was not statistically significant and heterogeneity was considerable. The rTMS adjunctive studies showed more consistent benefit for active stimulation when added to CIMT or modified CIMT, but these findings relate to the additional effect of rTMS rather than CIMT alone. The virtual reality study did not demonstrate a clear additional effect beyond CIMT alone.

Table 6. Direction and Strength of Evidence by Intervention Category

Intervention Category	Number of Studies	Total Sample Size	Direction of Findings	Statistical Certainty
CIMT or expanded CIMT versus non-CIMT control	2	110 participants contributed to pooled analysis	Pooled point estimate favored CIMT	Low certainty due to wide confidence interval, non-significant pooled effect, and $I^2 = 96.6\%$
rTMS added to CIMT or mCIMT	2	81	Findings favored active rTMS plus CIMT/mCIMT over sham rTMS plus CIMT/mCIMT	Preliminary; not pooled with primary analysis
Virtual reality added to CIMT	1	32	No clear superiority over CIMT alone	Very limited; single-trial evidence

Publication Bias

Formal assessment of publication bias was not performed because fewer than ten studies were included in the primary meta-analysis. Funnel plot inspection and regression-based tests such as Egger's test are not reliable when applied to very small numbers of studies. Therefore, publication bias cannot be excluded. This limitation is important because rehabilitation trials with small sample sizes may be vulnerable to imprecision, selective publication, and exaggerated effect estimates.

Overall Summary of Results

This systematic review included five randomized controlled trials involving 269 children with cerebral palsy. Two trials directly compared CIMT-based intervention with non-CIMT control therapy and were included in the primary meta-analysis. The pooled random effects estimate favored CIMT, but the effect was not statistically significant and was accompanied by considerable heterogeneity. Therefore, the primary quantitative evidence suggests a possible beneficial direction of effect but does not provide definitive evidence regarding the magnitude of CIMT effectiveness. Three additional randomized trials evaluated adjunctive interventions combined with CIMT. Two rTMS trials suggested that active neuromodulation may enhance upper-limb outcomes when added to CIMT or modified CIMT, whereas one virtual reality trial did not demonstrate clear superiority of virtual reality-enhanced CIMT over CIMT alone. Overall, the evidence supports CIMT as a promising pediatric upper-limb rehabilitation intervention, but the available contemporary randomized evidence remains limited by the small number of directly comparable trials, wide confidence intervals, considerable heterogeneity, and variation in intervention protocols and outcome measures.

DISCUSSION

This systematic review and meta-analysis evaluated the effectiveness of Constraint-Induced Movement Therapy for improving upper-limb function in children and adolescents with cerebral palsy. Five randomized controlled trials involving 269 participants were included in the qualitative synthesis, while two trials directly comparing CIMT-based rehabilitation with non-CIMT control interventions were included in the primary quantitative synthesis. Three additional trials evaluated adjunctive interventions combined with CIMT and were synthesized separately because they addressed the additional effect of rTMS or virtual reality rather than the independent effect of CIMT. The pooled random-effects estimate from the two direct CIMT-versus-control trials favored CIMT, with Hedges' $g = 1.53$; however, the 95% confidence interval was wide and crossed the null value, indicating that the pooled effect was not statistically significant. Considerable heterogeneity was present, with $I^2 = 96.6\%$, which substantially limits confidence in the precision and generalizability of the pooled estimate.

The direction of effect observed in the primary analysis is broadly consistent with the theoretical basis of CIMT and previous evidence suggesting that intensive, repetitive, task-oriented practice may improve upper-limb performance in children with unilateral cerebral palsy (3,6,7). CIMT is intended to reduce learned non-use by constraining the less affected upper limb while encouraging active, purposeful use of the more affected limb. This therapeutic model is compatible with principles of motor learning and experience-dependent neuroplasticity, particularly when practice is intensive, goal-directed, and functionally meaningful (3,5). However, the present review shows that the magnitude of treatment effect varies substantially across contemporary trials. Therefore, while the findings support CIMT as a clinically promising intervention, they do not establish a definitive or stable estimate of effectiveness.

The marked difference between the two trials included in the primary meta-analysis is central to interpretation. Ramey et al. reported a small, non-significant effect favoring CIMT, whereas Bakhat et al. reported a very large effect favoring expanded CIMT (13,14). Several clinical and methodological factors may explain this discrepancy. Ramey et al. used a larger multisite factorial randomized design with 30-hour and 60-hour CIMT protocols and follow-up assessments extending to 6 and 12 months, which may provide a more conservative and externally valid estimate of treatment effect (13). In contrast, Bakhat et al. evaluated a smaller sample using expanded CIMT plus routine physical therapy over a shorter period, with immediate post-treatment assessment, which may have increased the apparent effect size (14). Smaller rehabilitation trials are also more vulnerable to sampling variation, performance-related effects, and imprecision, particularly when intervention intensity and comparator dose differ substantially.

The high heterogeneity observed in the meta-analysis is clinically plausible. The included studies differed in intervention format, restraint method, treatment intensity, total therapy dose, comparator condition, participant age, cerebral palsy subtype, outcome measure, and timing of follow-up. Differences in outcome measures are particularly important because upper-limb function in cerebral palsy is multidimensional. The Assisting Hand Assessment primarily captures bimanual performance, whereas the Pediatric Motor Activity Log reflects functional use of the affected limb in daily activities. Although standardized mean differences permit statistical pooling across different instruments, they do not fully resolve conceptual differences between outcome constructs. Consequently, the pooled estimate should be interpreted as an exploratory summary of direction and approximate magnitude rather than a definitive treatment effect (15).

The secondary synthesis provides useful but distinct evidence regarding adjunctive interventions combined with CIMT. Wu et al. and Gupta et al. evaluated active rTMS combined with CIMT or modified CIMT compared with sham rTMS combined with CIMT-based rehabilitation (8,15). Both studies suggested greater upper-limb improvement when active rTMS was added, indicating that neuromodulation may enhance the effect of intensive task-oriented training. However, these studies cannot be interpreted as direct evidence of CIMT effectiveness because CIMT was delivered to both intervention and comparator groups. Their findings instead suggest a possible additive effect of rTMS when layered onto CIMT-based rehabilitation. This distinction is methodologically important because combining these trials with direct CIMT-versus-control trials would misattribute adjunctive treatment effects to CIMT itself (11-14).

The virtual reality trial showed a different pattern. Roberts et al. compared CIMT plus virtual reality with CIMT alone and found improvement in both groups without clear superiority of the virtual reality-enhanced program (9). This suggests that the principal therapeutic driver may have been the intensive CIMT program rather than the technology adjunct. Virtual reality may still offer benefits related to engagement, motivation, feedback, and adherence, but the available evidence does not demonstrate a clear additional functional advantage beyond CIMT alone. Future studies should therefore distinguish between technologies that improve participation or acceptability and those that produce measurable additive gains in upper-limb function (15).

The risk-of-bias assessment supports cautious interpretation. One trial was judged to have low overall risk of bias, while four trials were judged as having some concerns. No included study was judged to have high overall risk of bias. The most frequent concern related to deviations from intended interventions, which is expected in rehabilitation trials because participant and therapist blinding is often not feasible.

Nevertheless, outcome assessor blinding, completeness of follow-up, and transparent outcome reporting remain essential for minimizing bias in future CIMT trials. The overall risk-of-bias profile does not invalidate the findings, but it reinforces the need to interpret effect estimates in the context of methodological limitations and small-study imprecision.

The findings have several clinical implications. CIMT may be considered a reasonable intervention option for children with unilateral or hemiplegic cerebral palsy when the goal is to improve functional use of the more affected upper limb. However, the evidence does not support a one-size-fits-all protocol. Clinical decision-making should consider child age, baseline upper-limb capacity, tolerance of restraint, cognitive and sensory profile, family support, therapy setting, and functional goals. Treatment dose and intensity should be planned carefully because intervention heterogeneity appears to be a major contributor to variability in outcomes. Clinicians should also use standardized outcome measures to monitor response, ideally capturing both capacity and real-world functional use. This review has important strengths. It focused on randomized controlled trials, separated direct CIMT-versus-control comparisons from adjunctive CIMT trials, and used standardized effect sizes to synthesize outcomes measured with different validated instruments. The separation of primary and adjunctive evidence streams improved interpretability and reduced the risk of drawing inappropriate conclusions about the independent effect of CIMT. The use of a random-effects model was also appropriate given the expected clinical and methodological heterogeneity across pediatric rehabilitation trials (7, 11).

Several limitations should be acknowledged. First, only two trials were eligible for the primary meta-analysis, limiting statistical power and preventing meaningful subgroup, sensitivity, or meta-regression analyses. Second, the pooled effect was not statistically significant and was accompanied by substantial heterogeneity, reducing certainty in the magnitude of benefit. Third, the included studies varied in CIMT protocol, comparator intensity, outcome measure, and follow-up duration. Fourth, adjunctive intervention trials could not be pooled with primary CIMT-versus-control studies because they addressed different clinical questions. Fifth, publication bias could not be assessed formally because fewer than ten studies were available for quantitative synthesis. Finally, certainty of evidence was not formally graded using GRADE, which should be addressed in future updates of this review (13).

Overall, the findings support cautious clinical optimism. CIMT remains a biologically plausible and clinically relevant intervention for pediatric upper-limb rehabilitation, and the direction of available evidence generally favors CIMT-based approaches. However, the current contemporary randomized evidence remains limited by the small number of directly comparable trials, imprecision, and substantial heterogeneity. Larger, standardized, adequately powered trials are needed before firm conclusions can be drawn regarding the magnitude, durability, and optimal delivery of CIMT effects.

Future Research Directions

Future research should prioritize adequately powered multicenter randomized controlled trials comparing standardized CIMT protocols with clearly defined control interventions. These trials should use transparent randomization procedures, allocation concealment, blinded outcome assessment, intention-to-treat analysis, and prespecified primary outcomes. Multicenter designs would improve generalizability and allow recruitment of children across different age groups, functional levels, cerebral palsy subtypes, and healthcare contexts. Standardization of CIMT delivery is essential. Future trials should clearly report restraint type, duration of restraint, daily therapy intensity, total treatment dose, therapist supervision, home-practice requirements, adherence monitoring, and progression criteria. Without consistent reporting of these intervention components, it will remain difficult to determine whether differences in outcomes reflect true treatment effects or differences in protocol delivery.

Outcome measurement should also be harmonized. Future studies should use validated and clinically meaningful measures that capture complementary domains of upper-limb function, including unimanual capacity, bimanual performance, spontaneous affected-limb use, goal attainment, participation, and caregiver-reported function. Longer follow-up periods are needed to determine whether treatment gains

are retained after intervention ends and whether improvements translate into daily activities, school participation, and quality of life.

Future studies should investigate predictors of response to CIMT. Potential moderators include age, cerebral palsy subtype, baseline motor impairment, sensory function, cognitive status, corticospinal tract organization, family adherence, and treatment dose. Identifying which children benefit most from CIMT would support individualized rehabilitation planning and more efficient use of therapy resources. Adjunctive interventions require further evaluation. rTMS combined with CIMT appears promising, but larger trials are needed to confirm whether it provides clinically meaningful additive benefit beyond CIMT alone. Future rTMS studies should standardize stimulation parameters, cortical targets, sham procedures, safety monitoring, and follow-up duration. Similarly, virtual reality, gamification, robotics, wearable sensors, and telerehabilitation should be evaluated not only for feasibility and engagement but also for measurable additional functional benefit. Future systematic reviews should be prospectively registered, include complete reproducible search strategies, incorporate trial registry and grey literature searches, and apply GRADE certainty assessment. Individual participant data meta-analysis may be particularly valuable because it would allow exploration of treatment moderators, subgroup effects, and dose-response relationships. The next stage of evidence synthesis should move beyond whether CIMT works toward determining which CIMT protocol works best, for which child, at what dose, and under what clinical conditions.

CONCLUSION

Constraint-Induced Movement Therapy remains a promising intervention for improving upper-limb function in children with cerebral palsy, particularly among those with unilateral or hemiplegic involvement. In this systematic review and meta-analysis, the pooled estimate from direct CIMT-versus-control trials favored CIMT, but the effect was not statistically significant and was accompanied by considerable heterogeneity. Evidence from adjunctive intervention studies suggests that rTMS may enhance outcomes when combined with CIMT, whereas virtual reality has not yet demonstrated clear added benefit beyond CIMT alone. Overall, the current evidence supports cautious use of CIMT within individualized pediatric neurorehabilitation programs, but larger standardized randomized trials with consistent outcome measures and longer follow-up are required to establish the true magnitude, durability, and clinical applicability of treatment effects.

REFERENCES

1. Dan B, Rosenbaum P, Carr L, Gough M, Coughlan J, Nweke N. Updated description of cerebral palsy. *Dev Med Child Neurol.* 2026;68(4):465-76.
2. Schiariti V, Shierk A, Stashinko E, Sukal-Moulton T, Feldman R, Aman C, et al. Cerebral palsy pain instruments: recommended tools for clinical research studies by the National Institute of Neurological Disorders and Stroke Cerebral Palsy Common Data Elements project. *Dev Med Child Neurol.* 2024;66:610-22.
3. Hoare BJ, Wallen MA, Thorley MN, Jackman ML, Carey LM, Imms C. Constraint-induced movement therapy in children with unilateral cerebral palsy. *Cochrane Database Syst Rev.* 2019;2019(4):CD004149.
4. Shaf Z, Kalantari M, Naddaf A. Constraint induced movement therapy in improving upper extremity function in children with spastic hemiplegia cerebral palsy: an integrated review and experts' view. 2018.
5. Durand E, Plante P, Pelletier AA, Rondeau J, Simard F, Voisin J. At-home and in-group delivery of constraint-induced movement therapy in children with hemiparesis: a systematic review. *Ann Phys Rehabil Med.* 2018;61(4):245-61.

6. Wang H, Zhou J, Shan X, Zhang L. The effectiveness of modified constraint-induced movement therapy on upper limb function in children with cerebral palsy: a systematic review and meta-analysis. *BMC Sports Sci Med Rehabil.* 2025;17(1):211.
7. Martin-Moreno G, Moreno-Ligero M, Salazar A, Lucena-Anton D, Moral-Munoz JA. Constraint-induced movement therapy versus bimanual training to improve upper limb function in cerebral palsy: a systematic review and meta-analysis of follow-ups. *Children.* 2025;12(6):804.
8. Wu Q, Peng T, Liu L, Zeng P, Xu Y, Yang X, et al. The effect of constraint-induced movement therapy combined with repetitive transcranial magnetic stimulation on hand function in preschool children with unilateral cerebral palsy: a randomized controlled preliminary study. *Front Behav Neurosci.* 2022;16:876567.
9. Roberts H, Clegg NJ, Wang W, Chapa S, Arellano B, Trahan M, et al. Constraint therapy with and without virtual reality for children with unilateral cerebral palsy: a randomized trial. *Children.* 2025;12(3):283.
10. Page MJ, McKenzie JE, Bossuyt PM, Boutron I, Hoffmann TC, Mulrow CD, et al. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. *Rev Panam Salud Publica.* 2022;46:e112.
11. Sterne JAC, Savović J, Page MJ, Elbers RG, Blencowe NS, Boutron I, et al. RoB 2: a revised tool for assessing risk of bias in randomised trials. *BMJ.* 2019;366:l4898.
12. Chandler J, Cumpston M, Li T, Page MJ, Welch V. *Cochrane handbook for systematic reviews of interventions.* Hoboken: Wiley; 2019.
13. Ramey SL, DeLuca SC, Stevenson RD, Conaway M, Darragh AR, Lo W. Constraint-induced movement therapy for cerebral palsy: a randomized trial. *Pediatrics.* 2021;148(5).
14. Bakhat W, Ahmed U, Asghar M, Hanif K, Bibi S, Ghani S. Effects of expanded constraint-induced movement therapy on hand function in children with cerebral palsy: a randomized controlled trial. *Healer J Physiother Rehabil Sci.* 2022;2(2):119-28.
15. Gupta J, Gulati S, Singh UP, Kumar A, Jauhari P, Chakrabarty B, et al. Brain stimulation and constraint induced movement therapy in children with unilateral cerebral palsy: a randomized controlled trial. *Neurorehabil Neural Repair.* 2023;37(5):266-76.