BMC Neurology

https://doi.org/10.1186/s12883-026-05314-5

Article in Press

The efficacy of robot-assisted therapy on upper limb motor function in children with cerebral palsy: a systematic review and meta-analysis

Received: 13 January 2026

Accepted: 18 August 2026

Published online: 29 August 2026

Cite this article as: Fu B., Zhou X., Fan Q. *et al.* The efficacy of robot-assisted therapy on upper limb motor function in children with cerebral palsy: a systematic review and meta-analysis. *BMC Neurol* (2026). https://doi.org/10.1186/s12883-026-05314-5

Binbin Fu, Xuan Zhou, Qing Fan, Zhengquan Chen, Yuanyuan Zhang, Xiangyue Zhou, Xiaoyan Yang, Xiaotang Cai & Qing Du

Title

The efficacy of robot-assisted therapy on upper limb motor function in children with cerebral palsy: a systematic review and meta-analysis

Binbin Fu 1,2 † (First author), B.M.

Xuan Zhou 1,2† (Co-first author), M.M.

Qing Fan 3† (Co-first author), M.M.

Zhengquan Chen 4,5 (Co-author), M.S.

Yuanyuan Zhang 6 (Co- author), M.M.

Xiangyue Zhou 1 (Co- author), B.M.

Xiaoyan Yang 1 (Co- author), M.M.

Xiaotang Cai 7* (Co-corresponding author), Ph.D.

Qing Du 1,2* (Corresponding author), Ph.D.

† These authors contributed equally to this work.

* Corresponding author.

1Department of Rehabilitation, Xinhua Hospital, Shanghai Jiao Tong University School of Medicine, Shanghai, China

2Children's Rehabilitation Innovation and Transformation Research Center of Yuanshen Rehabilitation Institute, Shanghai Jiao Tong University School of Medicine, Shanghai, China

3Department of Pediatric orthopedics, Xinhua Hospital, Shanghai Jiao Tong University School of Medicine, Shanghai, China

4Mental Health Center Affiliated to Shanghai University of Medicine & Health Sciences, Shanghai, China

5School of Health and Biomedical Sciences, RMIT University, Melbourne, Australia

6Department of Developmental and Behavioral Pediatrics, Shanghai Children's Hospital, Shanghai Jiao Tong University School of Medicine, Shanghai, China

7Department of Rehabilitation, Key Laboratory of Obstetric and Gynecologic and Pediatric Diseases and Birth Defects of Ministry of Education, West China Second University Hospital, Sichuan University,

Chengdu, China

Corresponding author

1. Name: Qing Du (Corresponding author)

Address: 1665 Kongjiang Road, Shanghai 200092, China

Tel: 86-021-25078600; Fax: 008602165030840;

Email: duqing@xinhuamed.com.cn

Abstract

Background: Cerebral palsy (CP) is the leading cause of neurodevelopmental motor disability in children, often resulting in impaired upper limb function. Although traditional interventions offer benefits, they are limited by therapist dependence and poor adherence. Robot-assisted therapy (RAT) has emerged as a promising alternative, providing repetitive and high-intensity training. However, its clinical efficacy, particularly for upper limb rehabilitation in CP, remains inconclusive.

Methods: A systematic search was performed in eight electronic databases up to June 2025. Seven randomized controlled trials (RCTs) involving 244 children with CP met the inclusion criteria. The risk of bias was assessed using the Cochrane Risk of Bias 2.0 tool. Data were synthesized using both fixed-effects and random-effects models, with effect sizes expressed as standardized mean differences (SMD) and 95% confidence intervals (CI).

Results: RAT significantly improved fine motor function (SMD = 1.02, 95% CI: 0.56–1.48, $P < 0.0001$), consistent with a clinically meaningful effect. A positive trend was observed for ADL capacity (SMD = 0.65, 95% CI: 0.07–1.22, P = 0.03), although this finding was sensitive to the removal of individual studies. Due to extreme heterogeneity ($I^2 = 96\%$), gross motor function results were not pooled across device types. Subgroup analyses suggested that exoskeleton-based RAT may offer benefits for proximal motor recovery; however, this finding is based on a single trial and should be considered hypothesis-generating. No significant improvements were found in muscle strength (SMD = 0.34, P = 0.10) or real-world participation (SMD = 0.22, P = 0.56).

Conclusions: RAT produces a clinically meaningful improvement in fine motor function, with preliminary evidence of benefit for ADL capacity. Its efficacy on gross motor function appears device-dependent but requires confirmatory evidence, and effects on muscle strength and participation remain limited.

Trial Registration: This study was prospectively registered in the PROSPERO database (Registration No. CRD42025645232).

Keywords

Cerebral palsy, robot-assisted therapy, upper limb function, neurorehabilitation.

1.Introduction

Cerebral palsy (CP) is a neurodevelopmental disorder caused by brain injury occurring during the fetal, neonatal, or early childhood period[1]. It represents the leading cause of neurological motor disability in children[2]. Such brain injuries result in permanent impairments in movement and posture[2]. Recent epidemiological data indicate that the global prevalence of CP ranges from 1.6‰ to 3.4‰ [3], underscoring its importance as a major public health concern. Clinically, children with CP typically present with delayed gross and fine motor development, impaired selective motor control, poor coordination, and abnormal postural and movement patterns[4]. Based on clinical manifestations, CP can be classified into several subtypes, among which the spastic type accounts for approximately 80% of all cases[5]. Children with spastic CP often experience various motor impairments due to muscle spasticity, and approximately 50% exhibit more severe upper limb dysfunction compared with lower limb involvement[6].

According to the conceptual framework of the International Classification of Functioning, Disability and Health for Children and Youth (ICF-CY)[7], upper limb function in children can be categorized into three domains: body functions and structures, activities (including capacity and performance), and participation. In children with CP, upper limb impairments are not only influenced by positive motor symptoms such as spasticity and abnormal muscle tone, but are also characterized by significant deficits in grasping, releasing, and manipulating objects[8]. These impairments are particularly pronounced in children with unilateral cerebral palsy (UCP), where motor dysfunctions extend beyond basic hand movements, leading to marked difficulties in activities of daily living such as eating, dressing, and personal hygiene[9]. Consequently, these children often experience lifelong challenges in fine motor execution and bimanual coordination. Limitations in upper limb function further hinder learning, play, and social participation, ultimately reducing overall quality of life and increasing caregiver burden [10].

Current motor learning theories suggest a positive correlation between motor function improvement and the intensity or repetition of practice[10]. Modified constraint-induced movement therapy (mCIMT) and bimanual intensive training (BIT) are currently the most widely applied physiotherapeutic approaches for improving upper limb function in children with CP. Although these interventions have demonstrated clinical benefits, their effectiveness is often limited by factors such as reliance on therapist expertise, variability in treatment intensity, and poor long-term patient adherence [11].

Robot-assisted therapy (RAT), as an emerging rehabilitation technology, offers a promising alternative. Currently, the robotic systems utilized in clinical neurorehabilitation predominantly fall into two distinct biomechanical categories: end-effectors, which guide distal joint trajectories to improve manual dexterity, and exoskeletons[12], which provide comprehensive proximal multi-joint support[13]. Both systems deliver high-intensity, standardized, and repetitive training through programmable devices, enabling precise control of movement parameters while incorporating biofeedback and gamified interfaces tailored to children's cognitive characteristics[14-16]. These features not only enhance engagement and motivation but also improve treatment compliance in pediatric populations. Previous studies have reported that robot-assisted interventions can alleviate muscle spasticity, improve joint range of motion, and enhance both upper and lower limb motor performance in children with CP[17, 18]. While these preliminary findings highlight the therapeutic potential of RAT, its exact efficacy across different robotic device types and distinct upper limb functional domains requires further rigorous validation.

Recently, two systematic reviews have specifically investigated the effects of RAT on upper limb function in children with CP. Evidence synthesized by Cardone et al.[19] suggests that RAT contributes to the improvement of upper limb movements and manual dexterity. While this review provided a valuable and comprehensive overview, its inclusion of diverse study designs—such as case series and observational studies—without a quantitative meta-analysis highlights an opportunity to further strengthen the evidence base by focusing strictly on randomized controlled trials. Conversely, the meta-analysis conducted by de Souza Pascoal et al.[20] demonstrated that RAT could enhance specific qualities of upper limb movement. Building upon their foundational work, which synthesized data from four initial trials, there is now a need to expand the overall evidence base across broader ICF domains, distinguish the specific clinical efficacy between end-

effector and exoskeleton devices, and explore whether clinic-based motor improvements successfully translate into real-world participation as a distal secondary outcome.

To address previous methodological limitations, this meta-analysis strictly includes randomized controlled trials (RCTs) to reliably evaluate the efficacy of RAT on upper limb function in children with CP. Guided by the ICF-CY framework, our primary research question asks: Does RAT yield superior improvements in motor capacity and participation compared to conventional or no treatment? Accordingly, we designate fine motor function and ADL capacity as primary outcomes, with gross motor function, muscle strength, and participation as secondary. We hypothesize that RAT significantly enhances fine motor skills and ADLs, but that its overall efficacy relies heavily on the specific robotic device utilized. Ultimately, this study seeks to provide evidence-based support for standardized clinical applications of RAT in pediatric neurorehabilitation.

2. Methods

This systematic review and meta-analysis was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines and the recommendations of the Cochrane Collaboration. The study protocol was prospectively registered in the PROSPERO database (Registration No. CRD42025645232).

2.1 Search Strategy

To comprehensively evaluate the effects of RAT on upper limb motor function in children with CP, a systematic search was performed in eight electronic databases: PubMed, Embase, Web of Science, CINAHL, IEEE, Scopus, ProQuest, and the Cochrane Library. The search included all studies published up to June 20, 2025. The search terms included “cerebral palsy,” “robot,” “upper limb,” and “children.” Detailed search strategies for each database are presented in the Supplementary Materials (Table S1). To ensure the completeness of the literature search, the reference lists of all included articles were also manually screened to identify any additional eligible studies.

2.2 Study Selection

All retrieved records were managed using EndNote 20. 0 (Clarivate, Philadelphia, PA, USA). After removing duplicates, two independent reviewers screened titles and abstracts for relevance, followed by full-

text assessment of potentially eligible studies. Discrepancies between reviewers were resolved through discussion, and if consensus could not be reached, a third reviewer adjudicated the disagreement.

2.3 Inclusion Criteria

Studies were selected based on the PICOS framework (Population, Intervention, Comparison, Outcomes, and Study design), and the inclusion criteria were as follows: (1) Population: Children aged 0–18 years clinically diagnosed with CP, regardless of sex, ethnicity, CP subtype, or severity level. (2) Intervention: RAT targeting upper limb function, including interventions using robotic devices alone or in combination with other technologies such as virtual reality or gamified tasks. (3) Comparison: Control interventions without robotic assistance, including no treatment, placebo, or standard therapy. (4) Outcomes: Primary outcomes included upper limb fine motor function and activities of daily living (ADL) capacity; secondary outcomes included upper limb gross motor function, muscle strength, and participation. (5) Study design: RCTs published in English.

2.4 Data Extraction

Two reviewers independently extracted the following data from all included studies: author, year of publication, country, study setting, study design, participant characteristics (e.g., CP subtype, age, sample size, sex ratio), intervention details (RAT, conventional rehabilitation, or alternative interventions), and outcome measures (fine and gross motor function of the upper limb, ADL capacity, upper limb muscle strength and participation). When key data were missing, attempts were made to contact the original authors for additional information. Any discrepancies in data extraction were resolved by discussion or, if necessary, through consultation with a third reviewer.

2.5 Risk of Bias Assessment

The methodological quality and risk of bias of the included studies were assessed using the Cochrane Risk of Bias 2.0 (ROB 2.0) tool, which evaluates five domains: randomization process, deviations from intended interventions, missing outcome data, outcome measurement, and selective reporting. Each study was rated as “low risk,” “high risk,” or “some concerns.” Two reviewers conducted the assessment independently, and disagreements were resolved through discussion. In addition, the overall quality of evidence for each

outcome was graded using the GRADE (Grading of Recommendations Assessment, Development and Evaluation) system as very low, low, moderate, or high[21].

2.6 Data Synthesis and Statistical Analysis

All statistical analyses were performed using Review Manager (RevMan) version 5.4 (Copenhagen: The Nordic Cochrane Center, The Cochrane Collaboration, 2014). The pooled effect size was expressed as the standardized mean difference (SMD) with 95% confidence intervals (CI). The magnitude of the overall effect was interpreted according to Cohen's criteria, where an SMD of 0.2 represents a small effect, 0.5 a moderate effect, and 0.8 a large effect. When studies reported outcomes as medians and interquartile ranges (IQR) or mean differences with exact p-values rather than means and standard deviations (SD), appropriate statistical conversions were performed to estimate the pooled SD according to the guidelines provided in the Cochrane Handbook for Systematic Reviews of Interventions[22].

Statistical heterogeneity across studies was assessed using the Chi-square test and quantified by the I^2 statistic. Given the inherent clinical and methodological diversity of rehabilitation interventions for cerebral palsy, a random-effects model was applied to all meta-analyses to provide a more conservative estimate of the treatment effect. The overall significance of the pooled estimates was tested using the Z-statistic. To explore potential sources of heterogeneity and evaluate specific clinical factors, a priori subgroup analyses were planned based on: (1) the type of robotic device, and (2) the intervention modality. Additionally, meta-regression analysis was planned to be conducted if 10 or more studies were included; however, if fewer than 10 studies were available, meta-regression would not be considered. Sensitivity analyses were conducted by sequentially removing individual studies to evaluate the robustness of the combined results and the influence of each study on the overall effect size.

3. Result

3.1 Search Results

A comprehensive search across eight electronic databases initially identified 1,634 records, including 195 from PubMed, 705 from Web of Science, 53 from CINAHL, 364 from EMBASE, 40 from IEEE, 99 from Scopus, 104 from ProQuest, and 74 from the Cochrane Library. In addition, 41 records were identified through other sources.

After removing 689 duplicates, 939 studies were excluded based on title and abstract screening due to irrelevance to the research topic or population. The remaining 47 articles were retrieved for full-text review. Of these, 40 were further excluded for the following reasons: non-RCT design (n = 23), no outcomes of interest (n = 10), or the participants were not limited to CP (n = 7). Ultimately, seven studies met all eligibility criteria and were included in the systematic review. The detailed study selection process is summarized in Figure 1.

INSERT FIG. 1 ABOUT HERE

3.2 Characteristics of Included Studies

A total of seven RCTs[23-29] were included in this review, involving 244 children with CP recruited from India[26, 28], Egypt[24], Turkey[23], the United Kingdom[29], Belgium[25], and Switzerland[27]. Among them, 125 participants were assigned to the intervention groups and 119 to the control groups. All studies were published between 2011 and 2025, and each adopted a single-blind design in which the outcome assessors were blinded to group allocation.

The majority of the included trials (6/7) focused on children with spastic CP, whereas one study (Hedel et al.[27]) did not specify the CP subtype. Participants' ages ranged from 5 to 18 years, and the Manual Ability Classification System (MACS) levels were predominantly within grades I–IV, except for Gilliaux et al. (2015)[25], which included children across MACS I–V. The sample sizes of individual studies varied from 15 participants (Preston et al.[29]) to 60 participants (Goswami et al.[26]).

The proportion of female participants ranged from 33.33% to 47.37%, with two studies not reporting gender distribution (Gilliaux et al.[25]; Hedel et al.[27]). All included studies reported attrition rates below 10%, suggesting good participant adherence and study feasibility. Detailed characteristics of the included studies are summarized in Table 1.

3.3 Intervention Characteristics

The types of RAT devices and intervention protocols varied considerably across the included studies. Device categories included end-effector robots, exoskeletons, and other robotic systems. Intervention parameters ranged from 30–45 minutes per session, with a total of 12–144 training sessions, conducted 2–7 times per week over an intervention period of 3–48 weeks. In three studies, RAT was combined with

conventional therapy (CT) or botulinum toxin (BT) injections (Goswami et al.[26], 2025; Preston et al.[29], 2016; Gilliaux et al.[25], 2015), whereas the remaining studies applied RAT alone. All RAT interventions incorporated gamified elements, such as virtual reality or computer-based games, to enhance children's engagement and motivation. Detailed intervention characteristics are summarized in Table 2.

3.4 Main Study Outcomes

The included studies employed a diverse range of assessment tools to evaluate upper limb function, which were systematically categorized into primary and secondary domains.

Regarding the primary outcomes, fine motor function was evaluated across four trials. Significant improvements in the RAT group were consistently reported by Peramalaiah et al. (2025), whereas Hedel et al. (2011), Gilliaux et al. (2015), and Adar et al. (2024) observed positive therapeutic trends that did not independently reach statistical significance. In terms of ADL capacity, the results were more varied; although Gilliaux et al. (2015), Adar et al. (2024), and Preston et al. (2016) all demonstrated positive therapeutic trends using tools like the ABILHAND-Kids scale, none of the individual studies reported statistically significant differences between groups independently.

With respect to secondary outcomes, the impact of RAT on gross motor function appeared to be highly dependent on the type of robotic system utilized. El-Shamy et al. (2018), utilizing an exoskeleton device, reported a massive significant improvement. Conversely, studies employing end-effector devices, such as those by Adar et al. (2024) and Goswami et al. (2025), showed more moderate or non-significant differences. Furthermore, no consistent statistical advantage for RAT over control interventions was observed for muscle strength or real-world participation across the included studies.

In addition to evaluating the influence of robotic device types, we also examined the impact of the intervention modality (RAT alone versus RAT combined with conventional therapy) across relevant outcomes. Subgroup analyses consistently demonstrated that the therapeutic effects of RAT on fine motor function, ADL capacity, and muscle strength did not significantly differ between standalone robotic interventions and combinatory protocols. This indicates that the observed clinical benefits of RAT are highly robust and not strictly dependent on the concurrent administration of conventional therapy.

Detailed outcomes and measurement tools, categorized by outcome type, are summarized in Table 3. A comprehensive narrative summary of individual study findings is provided in Supplementary Table S3.

3.5 Risk of Bias and Evidence Quality

The risk of bias assessments for the seven included randomized controlled trials are presented in Figure 2. Overall, four studies were rated as having a "low risk" of bias (El-Shamy et al., 2018; Preston et al., 2016; Gilliaux et al., 2015; and Goswami et al., 2025).

Adar et al. (2024) was judged to be at "high risk" of overall bias, primarily due to a high risk in the domain of "selection of the reported result". Additionally, two studies were classified as having "some concerns": Hedel et al. (2011) was downgraded due to concerns in selective reporting, while Peramalaiah et al. (2025) presented concerns in both the randomization process and the measurement of the outcome. Specifically, following peer review, the measurement of the outcome for both Adar et al. (2024) and Peramalaiah et al. (2025) was re-evaluated as having "some concerns" due to the use of non-population-specific assessment scales.

The overall quality of evidence for the outcome measures, assessed using the GRADE approach, ranged from "moderate" to "very low" (see Supplementary Table S2). Specifically, the certainty of evidence was "moderate" for upper limb muscle strength. The evidence for fine motor function, activities of daily living (ADL) capacity, and real-world participation was rated as "low" due to serious concerns regarding risk of bias and imprecision. Finally, the evidence quality for gross motor function was judged as "very low" owing to very serious inconsistency and imprecision.

INSERT FIG. 2 ABOUT HERE

3.6 Sensitivity Analysis

To evaluate the robustness of our overall findings, a leave-one-out sensitivity analysis was systematically performed by sequentially omitting one study at a time from the pooled meta-analyses.

For fine motor function, the sequential removal of any single study did not alter the high statistical significance of the overall pooled effect, confirming the strong robustness of these results.

Conversely, for the primary outcome of ADL capacity, the sensitivity analysis revealed that the pooled result is currently fragile. The initial overall significant improvement (P = 0.03) shifted to non-significance upon the sequential removal of any single trial: omitting Adar et al. (2024) resulted in P = 0.08; omitting Gilliaux et al. (2015) yielded P = 0.10; and omitting Preston et al. (2016) led to a borderline P = 0.05. This indicates that while RAT shows a positive trend for ADL improvement, the statistical significance is highly dependent on the cumulative power of the currently limited number of available trials. These results should therefore be interpreted with caution, highlighting the necessity for larger future RCTs.

Regarding gross motor function, the extreme heterogeneity was confirmed to be entirely driven by the single exoskeleton study (El-Shamy et al., 2018); its removal eliminated the heterogeneity but rendered the remaining end-effector subgroup non-significant. This confirms that the overall pooled estimate is unreliable and that the gross motor findings should be interpreted at the subgroup level, with the caveat that the exoskeleton subgroup contains only one trial.

4. Meta-Analysis

4.1 Primary Outcome Measures

4.1.1. Fine Motor Function

Four trials (Adar et al., 2024; Gilliaux et al., 2015; Hedel et al., 2011; Peramalaiah et al., 2025) involving a total of 86 participants (44 in the experimental groups and 42 in the control groups) evaluated the effect of RAT on fine upper limb motor function in children with CP.

The pooled analysis presented in the forest plot (Figure 3) demonstrated that the RAT group demonstrated a large improvement in fine motor function compared with the control group, with an SMD of 1.02 (95% CI: 0.56 to 1.48), and the overall effect was statistically highly significant (Z = 4.38, P < 0.0001).

Furthermore, to address the potential influence of intervention modalities (a priori design), a subgroup analysis was conducted comparing studies that utilized RAT as a standalone therapy (Adar et al., 2024; Hedel et al., 2011; Peramalaiah et al., 2025) versus RAT combined with conventional therapy

(Gilliaux et al., 2015). Both subgroups demonstrated consistent positive effects. The test for subgroup differences revealed no statistically significant discrepancy between the two modalities ($Chi^2 = 0.00$, df = 1, P = 0.99). This finding suggests that RAT confers robust therapeutic benefits for fine motor recovery, whether administered as an independent intervention or seamlessly integrated into a combined rehabilitation protocol.

Heterogeneity analysis indicated no observable between-study heterogeneity, with $Tau^2 = 0.00$, $Chi^2 = 0.14$, df = 3 (P = 0.99), and $I^2 = 0\%$, suggesting a high degree of consistency across studies. This consistency significantly strengthens the reliability of the pooled result. Several factors may explain this: firstly, all included studies employed objective and standardized measures strictly targeting fine motor skills and manual dexterity (e.g., BBT, PDMS-2 grasping), which minimizes measurement-related variability. Secondly, despite variations in specific robotic devices, RAT programs share core rehabilitation mechanisms—such as high-intensity, repetitive, and task-oriented practice—that precisely improve hand-eye coordination and finger individuation, leading to stable positive effects across different intervention protocols.

INSERT FIG. 3 ABOUT HERE

4.1.2. ADL Capacity

To strictly adhere to the ICF model and distinctively evaluate functional capacity, three randomized controlled trials (Adar et al., 2024; Gilliaux et al., 2015; Preston et al., 2016) involving a total of 50 participants (25 in the experimental groups and 25 in the control groups) were included to assess the effect of RAT on the capacity to perform upper limb activities of daily living (ADL) among children with CP.

The pooled analysis presented in the forest plot (Figure 4) demonstrated that the RAT group exhibited a moderate improvement in ADL capacity compared with the control group, with an SMD of 0.65 (95% CI: 0.07 to 1.22), and a statistically significant overall effect (Z = 2.22, P = 0.03). Although statistical heterogeneity across these studies was minimal ($Tau^2 = 0.00$, $Chi^2 = 0.15$, df = 2, P = 0.93, $I^2 = 0\%$), the sensitivity analysis (see Section 3.6) revealed that the statistical significance of the pooled estimate was

fragile: it shifted to non-significance upon the sequential removal of any single trial. Consequently, while the direction of effect is consistently positive, the current evidence for ADL improvement should be interpreted with caution and regarded as preliminary rather than confirmatory.

Furthermore, an a priori subgroup analysis was conducted to compare the efficacy of RAT as a standalone intervention (Adar et al., 2024) versus RAT combined with conventional therapy (Gilliaux et al., 2015; Preston et al., 2016). Both subgroups demonstrated positive trends in improving ADL capacity. The test for subgroup differences revealed no significant disparity between the intervention modalities ($Chi^2 = 0.00$, df = 1, P = 0.98).

The observed benefits may be attributed to the fact that RAT, by intensively improving upper limb motor control, facilitates the generalization of these motor gains into functional use during real-life tasks. Collectively, the current evidence suggests that RAT may confer benefits for the functional capacity to perform daily upper limb activities in children with CP, although larger confirmatory trials are needed to establish the reliability of this finding.

INSERT FIG. 4 ABOUT HERE

4.2 Secondary Outcomes

4.2.1 Gross Motor Function

Three trials (Adar et al., 2024; El-Shamy et al., 2018; Goswami et al., 2025) involving a total of 109 participants (54 in the experimental groups and 55 in the control groups) evaluated the effect of RAT on gross upper limb motor function. Gilliaux et al. (2015) also employed the QUEST; however, this study reported domain-specific subscores (dissociated movement, grasp, weight bearing, and protective extension) rather than a composite gross motor score, and these data were therefore not amenable to inclusion in the quantitative synthesis.

The overall between-study heterogeneity was extreme ($Tau^2 = 6.87$, $Chi^2 = 48.66$, df = 2, P < 0.00001, $I^2 = 96\%$), indicating that a single pooled estimate would be clinically uninterpretable. Accordingly, the prespecified subgroup analysis by robotic device type (End-effector vs. Exoskeleton) was prioritized over the overall synthesis.

This subgroup analysis revealed that device type accounted for nearly all the observed heterogeneity (subgroup difference: $Chi^2 = 40.06$, df = 1, $P < 0.00001$, $I^2 = 97.5\%$). The end-effector subgroup comprised two studies (Adar et al., 2024; Goswami et al., 2025; n = 79) and demonstrated a moderate, non-significant effect (SMD = 0.58, 95% CI: −0.44 to 1.60, P = 0.26; $I^2 = 71\%$).

Notably, the exoskeleton subgroup contained only a single trial (El-Shamy et al., 2018; n = 30), which independently reported an exceptionally large effect (SMD = 11.15, 95% CI: 8.04 to 14.26). Given that this finding is driven entirely by one study with a modest sample size, it should be regarded as hypothesis-generating rather than confirmatory, and the magnitude of the effect warrants cautious interpretation pending independent replication.

These findings suggest that the efficacy of RAT on gross motor function may be device-dependent. Exoskeleton devices—which provide antigravity support to proximal joints—offer a plausible biomechanical rationale for their potentially greater impact on gross motor movements compared with end-effector devices, which primarily target distal joints. However, this hypothesis remains preliminary and requires validation through future comparative trials specifically designed to test differential device effects on gross motor outcomes.

INSERT FIG. 5 ABOUT HERE

4.2.2 Muscle Strength

Three studies (Adar et al., 2024; Goswami et al., 2025; Hedel et al., 2011) involving 96 participants (49 in the experimental groups and 47 in the control groups) were included in the analysis of upper limb muscle strength. The pooled analysis (Figure 6) indicated that the RAT group did not demonstrate a statistically significant improvement in muscle strength compared with controls, with an SMD of 0.34 (95% CI: -0.06 to 0.75; Z = 1.66, P = 0.10).

No heterogeneity was observed across studies ($Tau^2 = 0.00$, $Chi^2 = 0.64$, df = 2, P = 0.73, $I^2 = 0\%$), suggesting a high degree of consistency. Furthermore, a subgroup analysis based on intervention modality (RAT alone vs. RAT combined with conventional therapy) revealed no significant subgroup differences ($Chi^2 = 0.56$, df = 1, P = 0.45). These findings indicate that current evidence does not support a significant

advantage of RAT over conventional interventions in enhancing pure upper limb muscle strength in children with CP.

This lack of effect may be attributed to the mechanistic focus of RAT on neural adaptation and motor control rather than direct muscle strengthening. Robotic interventions are designed to drive experience-dependent neuroplasticity through high-intensity, repetitive, task-oriented practice—a strategy that is effective for improving motor coordination and skill acquisition[30]. However, substantial gains in muscle strength typically require progressive resistance training with sufficient overload to induce neuromuscular adaptations[31]. The protocols employed in the included RAT trials did not incorporate the key elements of resistance training (e.g., progressive overload, high-load resistance), which may explain the absence of significant strength improvements[32].

INSERT FIG. 6 ABOUT HERE

4.2.3. Participation

To specifically address the domain of participation based on the ICF model, as distinct from functional capacity, two studies (Gilliaux et al., 2015; Preston et al., 2016) involving a total of 31 participants (16 in the experimental groups and 15 in the control groups) were included. These studies uniquely evaluated true real-world involvement in life situations utilizing the Life Habits questionnaire and the COPM.

The pooled meta-analysis (Figure 7) revealed that RAT did not yield a statistically significant improvement in real-world participation compared with the control interventions, with an SMD of 0.22 (95% CI: -0.52 to 0.97) and an overall effect that was not statistically significant ($Z = 0.59$, $P = 0.56$). Heterogeneity between the two studies was minimal ($Tau^2 = 0.02$, $Chi^2 = 1.08$, $df = 1$, $P = 0.30$, $I^2 = 8\%$), indicating highly consistent findings despite the use of different assessment tools for participation.

These findings critically highlight the distinction between capacity and performance within the ICF framework. Although our preceding analysis demonstrated that RAT significantly enhances the functional capacity to perform ADLs (Section 4.1.2), the current evidence indicates that this increased motor capacity does not automatically or directly translate into significantly greater involvement in real-world daily activities and social participation. This conceptual gap suggests that while robotic therapy is

effective for motor and functional restoration, achieving true enhancements in societal participation may necessitate additional, context-specific, or environmentally focused interventions beyond clinic-based robotic training.

INSERT FIG. 7 ABOUT HERE

The comprehensive dataset extracted for all meta-analyses, including means, standard deviations, and sample sizes across all outcome measures, is detailed in Supplementary Table S4.

5.Discussion

5.1 Principal Findings

This systematic review and meta-analysis indicate that robot-assisted therapy demonstrates varying therapeutic effects across multiple domains in improving upper limb function in children with CP. Our primary findings indicate that RAT provides a large and statistically robust improvement in fine motor function (SMD = 1.02, 95% CI: 0.56–1.48). For ADL capacity, a moderate positive effect was observed (SMD = 0.65, 95% CI: 0.07–1.22); however, leave-one-out sensitivity analyses demonstrated that the statistical significance of this finding is contingent on the inclusion of all three available trials, and the pooled estimate should therefore be regarded as preliminary rather than confirmatory.

However, no statistically significant improvements were observed in upper limb muscle strength (SMD= 0.34,95%CI: −0.06–0.75) or participation (SMD= 0.22,95%CI: −0.52–0.97) following RAT. Regarding gross motor function, extreme heterogeneity ($I^2 = 96\%$) precluded a meaningful overall synthesis. Subgroup analysis by device type indicated that the observed effects may be device-dependent; however, the exoskeleton finding is based on a single trial (El-Shamy et al., 2018) with a modest sample size and should therefore be interpreted as preliminary. While the biomechanical properties of exoskeletons—which provide proximal antigravity support—offer a plausible explanation for the differential effects, replication in larger comparative trials is needed before clinical recommendations can be made.

Overall, while RAT is a powerful tool for improving motor capacity and activity performance, its impact on body structures (strength) and social participation remains less evident at this stage, with the certainty of evidence ranging from moderate to very low according to the GRADE framework.

5.2 Clinical Significance of the Observed Effects

Beyond statistical significance, the clinical relevance of the observed improvements warrants careful consideration. For fine motor function, the pooled SMD of 1.02 represents a large effect according to Cohen's criteria. To further contextualize this finding, the Box and Block Test (BBT)—used in three of the four included fine motor trials—has an established MCID of approximately 7 blocks in children with unilateral CP, as determined by Liang et al.[33]. In the included studies, the mean BBT improvement in RAT groups ranged from 3.2 to 5.5 blocks, approaching but not consistently surpassing this threshold at the individual study level. However, the pooled large effect size (SMD = 1.02) with zero heterogeneity (I^2 = 0%) suggests that RAT produces a clinically meaningful improvement in manual dexterity when considering the cumulative evidence.

For ADL capacity, the clinical interpretation is more constrained. Although the pooled SMD of 0.65 corresponds to a moderate effect, two important limitations preclude firm conclusions regarding clinical significance. First, the ABILHAND-Kids scale—the primary ADL measure across all three included trials—lacks an established MCID for children with CP [34]. While smallest detectable change (SDC) values ranging from 1.18 logits to 5.15 points have been reported across different language versions, these thresholds reflect measurement error rather than clinical meaningfulness. Second, as discussed in Section 3.6, the pooled ADL estimate is sensitive to individual study removal, further limiting confidence in the clinical relevance of this finding.

More broadly, a critical gap exists in the pediatric CP literature: most commonly used upper limb assessment tools—including the QUEST, PDMS-2, and FMA-UE in pediatric populations—lack validated MCID thresholds. This absence represents a significant barrier to translating statistically significant findings into clinically actionable recommendations. Future research should prioritize the establishment of CP-specific MCIDs for these instruments to enable more rigorous evaluation of intervention efficacy.

5.3 Comparison with Existing Literature

The significant improvements in fine motor function and ADL capacity observed in this study align with the broader consensus that RAT is a powerful means of driving neural plasticity.[35, 36]. Theoretical

and empirical research from adult stroke populations has long demonstrated that robot-assisted therapy facilitates repetitive, task-specific training during both the acute and chronic phases[35, 36]. Such interventions have been shown to provide high-intensity exercise training with reduced therapist supervision[37], while, when used in combination with adjunctive therapies such as botulinum toxin injections, they can synergistically reduce spasticity and enhance functional outcomes[38]. In pediatric neurorehabilitation, the feasibility of these principles was first evidenced by the pilot work of Krebs et al.[39], and subsequently expanded by Qiu et al[40], who demonstrated that specialized robotic programs can effectively address functional deficits in children with CP.

Our meta-analysis further refines this evidence base by providing a high-level quantitative synthesis that builds upon the qualitative observations of Cardone et al. [19]. While Cardone's review suggested general benefits for manual dexterity, our study strictly utilizes RCT data to confirm that these gains are statistically significant in strictly controlled pediatric populations. Compared to the earlier meta-analysis by de Souza Pascoal et al. [20], which incorporated only four trials, our inclusion of seven recent RCTs offers a more robust estimation of effect sizes across the ICF "Activity" domain.

However, regarding the translation of motor capacity into actual performance, the study reached a crucially different conclusion. Unlike some previous reports that broadly claimed success in RAT, our analysis clearly identified a significant "gap" in engagement levels (P=0.55). This finding corroborates the observations of Gilliaux et al. [25], suggesting that improved motor capacity (ADL) in a clinical setting does not inherently guarantee improved social participation.

5.4 Mechanistic Insights into RAT

The clinical improvement in fine motor function (SMD = 1.02) and ADL capacity (SMD = 0.65) may be attributed to experience-dependent neuroplasticity as one potential mechanism. This process follows the fundamental principle of synaptic plasticity as described by Hebbian theory: repeated task-specific stimulation strengthens synaptic connections, promoting functional reorganization and structural remodeling of neural pathways[41]. RAT systems provide the high-dosage, task-specific repetitions required to cross the threshold for cortical remapping and synaptic strengthening via long-term potentiation

(LTP) [42, 43]. Neuroimaging studies indicate that robot-assisted rehabilitation training induces enhanced cortical activation and improved functional connectivity, accompanied by alterations in the excitability of the corticospinal tract[30]. Singhal et al.[44] used MRI-compatible hand robots combined with diffusion tensor imaging to discover that eight weeks of hand training increased the number of corticospinal tract fibers in chronic stroke patients. Newly generated fibers extended toward the motor cortex, and the thickness of the ventral central posterior gyrus significantly increased.

Meanwhile, multisensory biofeedback further optimizes this neurophysiological process. By integrating visual, auditory, and proprioceptive signals, the RAT system provides rich multimodal feedback for motor learning, facilitating the formation and refinement of internal models[45]. Research indicates that combining auditory biofeedback with visual feedback significantly enhances subjects' formation of internal models for myoelectric prosthetic hand control tasks, yielding superior results compared to visual feedback alone[45]. Multimodal feedback strategies enhance sensorimotor integration, improve closed-loop control of motor planning and execution, and promote precise recruitment of motor units[46]. Current research evidence indicates that robotic interventions, often combined with neuromodulation or virtual reality technologies, can catalyze neuroplasticity processes in ways consistent with clinically meaningful improvements. This offers translational potential for personalized, multimodal treatment strategies in the rehabilitation[30].

The preliminary observation that exoskeleton-based RAT may yield greater improvements in gross motor function is mechanistically plausible, given that exoskeletons feature joint designs aligned with human anatomy and enable independent torque control[47]. Unlike end effectors that primarily guide hand movement trajectories, exoskeletons actively counteract gravity to provide segmental stability, which may be particularly beneficial for proximal motor recovery in children with spastic CP[12, 48].

The lack of significant improvement in participation (P=0.55) highlights the persistent "capacity-performance gap" within the framework of ICF[49]. Although RAT can enhance maximum functional potential in controlled settings, the transition to real-world social habits is largely modulated by environmental and individual factors.[50].

5.5 Heterogeneity

The key finding of this study is the remarkable statistical consistency observed in fine motor function, ADL capacity, and muscle strength (I^2 =0% for all). For fine motor function, this absence of heterogeneity, combined with our sensitivity analysis, confirms that the positive therapeutic effects on manual dexterity are highly robust and generalizable across the diverse protocols utilized in the included trials. However, for ADL capacity, despite the low statistical heterogeneity, our leave-one-out sensitivity analysis revealed that the overall significance is currently fragile and heavily reliant on the cumulative power of a few small-scale trials. From a clinical perspective, this implies that while RAT is a reliable tool for enhancing fine motor dexterity in children within MACS levels I–III, its consistent translation into broader functional ADL capacity still requires validation from larger cohorts, regardless of specific session durations or concurrent therapies.

Conversely, the extreme heterogeneity in gross motor outcomes (I^2 =96%) was definitively isolated to the robotic device type. Our subgroup analysis indicates that RAT platforms are consistently effective for distal fine motor tasks, whereas gross motor gains appear to be device-dependent. However, as the exoskeleton subgroup comprised only a single trial, this observation should be considered provisional. While these findings offer preliminary insights for device selection, the observed "participation gap" (P=0.55) suggests that functional gains in a clinical setting may require additional environmental integration to manifest as social participation.

Beyond device type and intervention modality, several additional sources of clinical heterogeneity warrant consideration, including the considerable variation in treatment duration (ranging from 3 to 48 weeks) and session frequency (2–7 sessions per week) across the included trials. However, it is noteworthy that for the primary outcomes of fine motor function and ADL capacity—as well as for muscle strength—the observed statistical heterogeneity was zero (I^2 = 0%), despite this underlying protocol diversity. This indicates that the treatment effect sizes were remarkably consistent across studies, and that variations in treatment duration or frequency did not introduce meaningful bias into the pooled estimates. For gross motor function, the extreme heterogeneity (I^2 = 96%) was fully explained by device type rather than by

treatment duration, as confirmed by the prespecified subgroup analysis. Nevertheless, the relatively small number of included RCTs precluded formal meta-regression or further subgroup stratification by these protocol-level variables, and their potential moderating effects should be examined in future trials with larger and more homogeneous samples.

5.6 Limitations

While this meta-analysis provides valuable insights, several methodological constraints must be considered. The primary limitation stems from the relatively small number of included RCTs (n = 7) and the modest total sample size (N = 244). This constraint inherently restricts the statistical power to detect more subtle therapeutic effects and limits the generalizability of the findings across the diverse spectrum of CP subtypes. Consequently, the certainty of evidence for several outcomes remains "moderate" to "very low," primarily reflecting concerns regarding imprecision and the risk of bias observed in certain primary studies. This limitation is particularly evident in the ADL capacity analysis, where leave-one-out sensitivity analyses revealed that the pooled statistical significance was contingent on the inclusion of all three available trials, shifting to non-significance upon the removal of any single study.

Beyond the quantitative constraints, the absence of longitudinal follow-up data exceeding six months across most trials precludes a definitive assessment regarding the sustainability of the observed functional gains. It is also noteworthy that the lack of standardization in assessment sensitivity—specifically the use of adult-validated scales like the FMA and CUE in pediatric populations—likely introduces measurement noise that complicates the comparability of outcomes across studies. Although some studies[23, 28, 51] have applied these tools to assess pediatric populations with cerebral palsy, their clinical validity and responsiveness for this specific group have not yet been fully established. The potential ceiling effects and reduced sensitivity of these instruments in pediatric cohorts highlight the critical necessity for adopting ICF-aligned, CP-specific tools to ensure the objective measurement of RAT efficacy.

6. Conclusion

In conclusion, this systematic review and meta-analysis demonstrates that RAT produces a clinically meaningful improvement in fine motor function in children with spastic CP, with preliminary evidence of

benefit for ADL capacity. However, the therapeutic impact does not appear to extend to muscle strength or real-world participation, underscoring a persistent gap between clinic-based motor gains and social performance. Gross motor recovery appears to be device-dependent, though this observation awaits confirmation from comparative trials. Future research should prioritize large-scale, multicenter RCTs with extended follow-up to refine treatment protocols, establish CP-specific MCID thresholds, and enhance the overall certainty of evidence.

Figures

Fig. 1. Flow diagram of the selection process

Fig. 2. Quality Assessment of the Included Literature.

Fig. 3. Forest plot of the effect of RAT on upper limb fine motor function in children with CP, stratified by intervention modality.

Fig. 4. Forest plot of the effect of RAT on ADL capacity in children with CP, stratified by intervention modality.

Fig. 5. Forest plot of the effect of RAT on upper limb gross motor function in children with CP, stratified by robotic device type.

Fig. 6. Forest plot of the effect of RAT on upper limb muscle strength in children with CP.

Fig. 7. Forest plot of the effect of RAT on participation in children with CP.

Tables

Table1. Characteristics of the population included in the study.

Table 2. Details for interventions.

Table3. Outcome measures and results of the included studies.

Abbreviations

CP – Cerebral Palsy

RAT – Robot-Assisted Therapy

RCT – Randomized Controlled Trial

SMD – Standardized Mean Difference

CI – Confidence Interval

MAS – Modified Ashworth Scale

QUEST – Quality of Upper Extremity Skills Test

FMA-UE – Fugl-Meyer Assessment for Upper Extremity

BBT – Box and Block Test

MACS – Manual Ability Classification System

WeeFIM – Functional Independence Measure for Children

PedsQL – Pediatric Quality of Life Inventory

ABILHAND-Kids – Abilities of Hand Children Scale

9HPT – Nine-Hole Peg Test

VR – Virtual Reality

BT – Botulinum Toxin

Running Head

Robot-assisted therapy for cerebral palsy: A systematic review and meta-analysis

Acknowledgements

We are deeply grateful to the researchers whose studies were included in this systematic review and meta-analysis, as their contributions formed the backbone of our investigation. Additionally, we extend our thanks to everyone who provided support and guidance throughout the project.

Funding

This work was supported by the National Key R&D Program of China [grant number 2023YFC3604803].

Data availability

All data used in this analysis were extracted from publicly available studies. Additional materials are available from the corresponding author upon reasonable request.

Declarations

Ethics approval and consent to participate

As this study is a systematic review and meta-analysis of previously published data, it did not involve

new human or animal participants. Therefore, ethical approval and informed consent were not required.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

Authors' contributions

QD and XTC conceived and designed the study. BBF, XZ and QF performed the literature search and data extraction. BBF, YYZ and XYY assessed the risk of bias. BBF, ZQC and XYZ undertook the data collection. BBF, XZ and QF analyzed and interpreted the results, and discussed the findings. BBF translated the article. BBF, XZ and QF contributed equally to this work. All authors read and approved the final manuscript.

Figure1.Flow diagram of the selection process

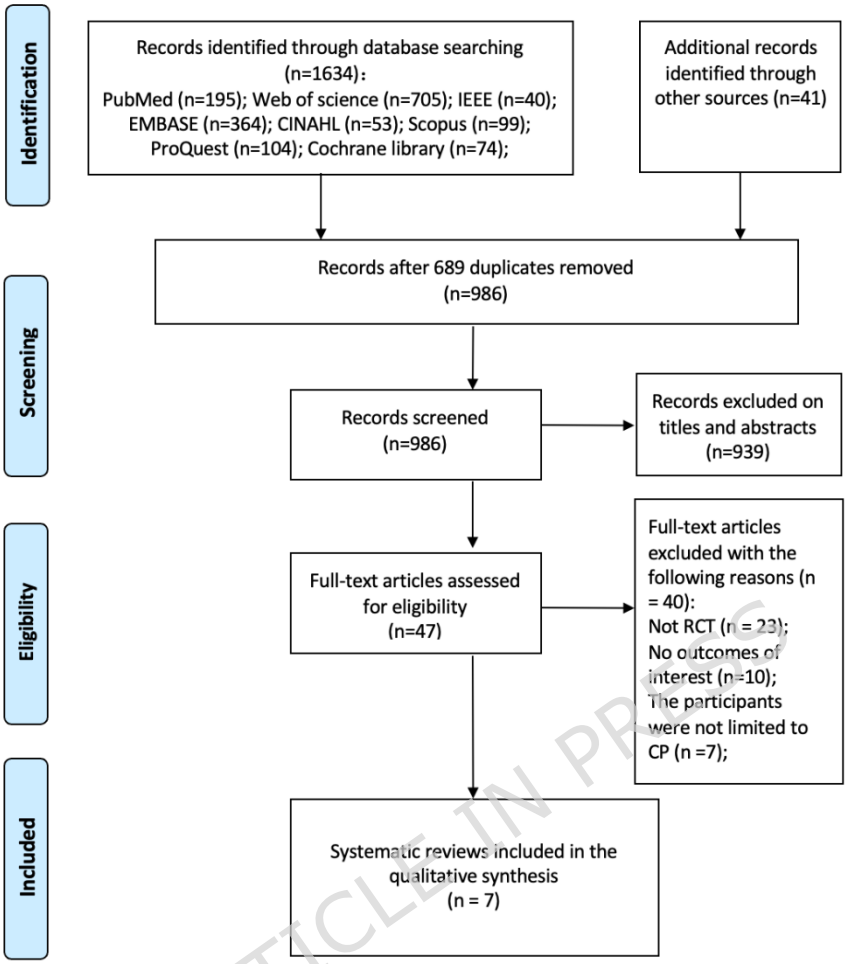


Fig. 2. Quality Assessment of the Included Literature.

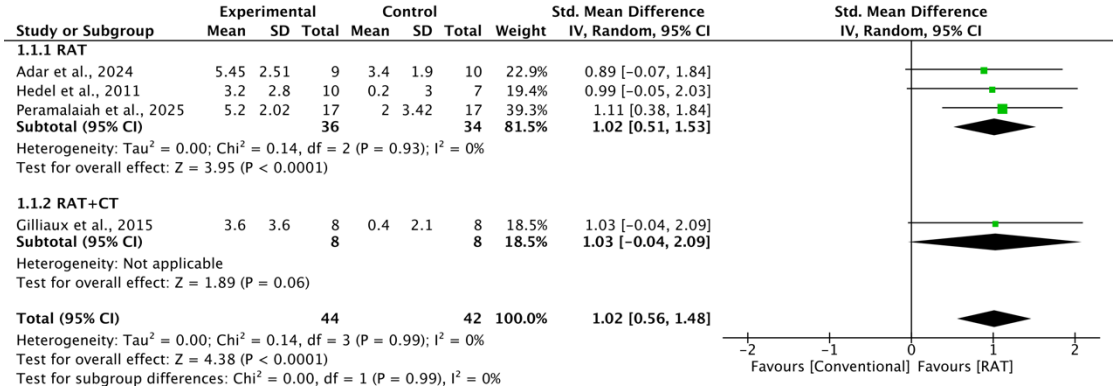


Fig. 3. Forest plot of the effect of RAT on upper limb fine motor function in children with CP, stratified by intervention modality.

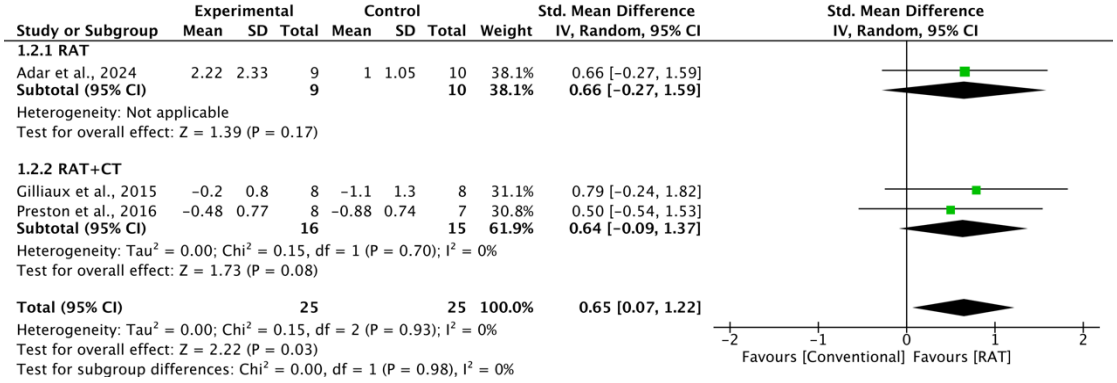


Fig. 4. Forest plot of the effect of RAT on ADL capacity in children with CP, stratified by intervention modality.

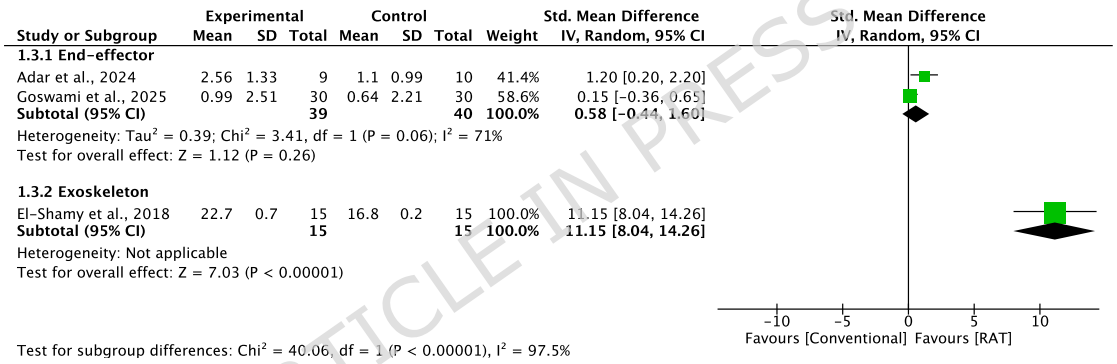


Fig. 5. Forest plot of the effect of RAT on upper limb gross motor function in children with CP, stratified by robotic device type.

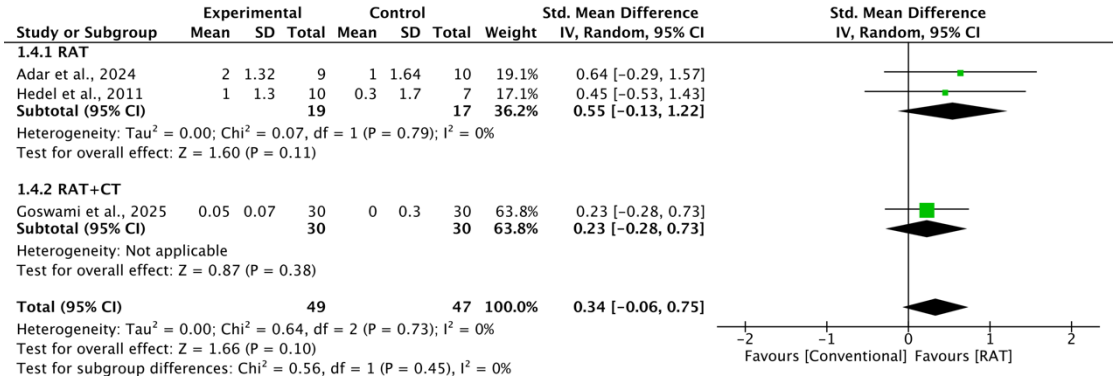


Fig. 6. Forest plot of the effect of RAT on upper limb muscle strength in children with CP.

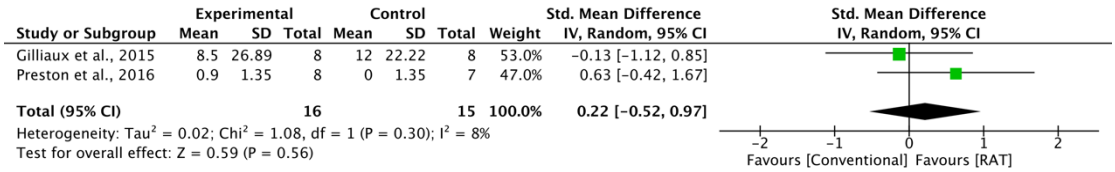


Fig. 7. Forest plot of the effect of RAT on participation in children with CP.

Table 1. Characteristics of the population included in the study

Author, year	Study design	CP (Classification)	Age (years)	Group	Sample size [female]	Female Ratio	Dropout rate	Country	Setting
Peramalaiah et al., 2025	single-blind RCT	Spastic CP, MACS I-III	4-10	G1: RAT G2: CT	G1: n=17 [8] G2: n=17 [8]	47.06 %	0%	India	Shri Dharmasthala Manjunatheshwara University
Goswami et al., 2025	Single blind multicentric pilot RCT	Hemiplegic CP, GMFCS I-III, MACS I–IV	5-18	G1: RAT G2: CT	G1: n=30 [9] G2: n=30[7]	26.67 %	8.33%	India	Senior Registrar & OC Tps, 155 Base Hospital
Adar et al., 2024	single-blind Prospective RCT	Spastic CP, MACS I-III	7-16	G1: RAT G2: CT	G1: n=9 [4] G2: n=10[5]	47.37 %	5%	Turkey	Afyonkarahisar Health Sciences University
El-Shamy et al.,	single-blind	Spastic Hemiplegia	6-8	G1: RAT	G1: n=15[6]	33.33 %	0%	Egypt	Faculty of Physical

2018	RCT	CP, MACS I-III		G2: CT	G2: n=15[4]				Therapy, Cairo University
Preston et al., 2016	pilot single-blind multicenter RCT	Spastic CP, MACS II–IV	5-12	G1: RAT+ CT+ BT G2: CT+ BT	G1: n=8[4] G2: n=7[2]	40%	0%	UK	University of Leeds
Gilliaux et al., 2015	Single-Blind RCT	Spastic CP, MACS I–V	6-16	G1: RAT + CT G2: CT	G1: n=8[NA] G2: n=8[NA]	NA	0%	Belgium	Université catholique de Louvain, Institute of Neuroscience
Hedel et al., 2011	Preliminary results of RCT	CP	6-18	G1: RAT G2: computer games	G1: n=10[NA] G2: n=7[NA]	NA	0%	Switzerland	Institute of Neuroinformatics University of Zurich

UK, United Kingdom; RCT, randomized controlled trials; CP, cerebral palsy; MACS, Manual Ability Classification System; G, group; RAT, robot-assisted therapy; CT, conventional therapy; BT, Botulinum Toxin; NA, not available;

Table 2. Details for interventions

Author, year	Interventions	Device name	Type	RAT Combined	Duration (min)	Sessions	Frequency (days/w	Weeks

							k.)	
Peramalaiah et al., 2025	RAT	game-based robotic manipulandum device (RMD) PABLO ® X 2 hand-arm therapy system (M/S tyromotion GMBH, Austria)	end-effector	computer games	45	24	3	8
Goswami et al., 2025	RAT+ CT	AMADEO hand-finger robot (Tyromotion, Graz, Austria)	end-effector	virtual reality games	30	144	3	48
Adar et al., 2024	RAT	Armeo Spring (Hocoma, AG, Switzerland)	exoskeleton	virtual reality games	40	30	5	6
El-Shamy et al., 2018	RAT	The CAAR games	other	computer	45	36	3	12
Preston et al., 2016	RAT+ CT+ BT				30	42	7	6

		system		games				
Gilliaux et al., 2015	RAT+ CT	REAPlan	end-effector	computer games	45	16	2	8
Hedel et al., 2011	RAT	YouGrabber system (YouRehab, Zurich, Switzerland)	end-effector	virtual reality games	45	12	4	3

RAT, robot-assisted therapy; CT, conventional therapy; BT, Botulinum Tox

Table 3. Outcome measures and categorization based on the ICF model of the included studies grouped by targeted outcomes.

Targeted Outcome	Author, year	Assessment Tool	ICF Domain
Fine Motor Function	Adar et al., 2024	FMA-hand; BBT*	Body Functions / Activity
	Gilliaux et al., 2015	BBT*	Activity
	Hedel et al., 2011	BBT*; 9HPT	Activity
	Peramalaiah et al., 2025	CUE; PDMS-2(grasping*, VMI)	Activity
Activities of Daily Living	Adar et al., 2024	ABILHAND-Kid**; WeeFIM	Activity
	Gilliaux et al., 2015	ABILHAND-Kids*; PEDI	Activity
	Preston et al., 2016	ABILHAND-Kids*	Activity
Gross Motor Function	Adar et al., 2024	FMA-UE*	Body Functions / Activity
	El-Shamy et al., 2018	QUEST*	Activity
	Goswami et al., 2025	QUEST*	Activity
Muscle Strength	Adar et al., 2024	Jamar Grasp*; Jamar Pinch	Body Functions
	Gilliaux et al., 2015	Muscle torque	Body Functions

Targeted Outcome	Author, year	Assessment Tool	ICF Domain
Participation	Goswami et al., 2025	Hand grip strength*	Body Functions
	Hedel et al., 2011	Grip strength*; Pinch-grip	Body Functions
	Gilliaux et al., 2015	Life Habits*	Participation
	Preston et al., 2016	COPM*	Participation
Others	Adar et al., 2024	MAS (Tone); PedsQL	Body Functions; HR-QoL
	El-Shamy et al., 2018	MAS (Tone)	Body Functions
	Gilliaux et al., 2015	Kinematics; MAS (Tone)	Body Functions

ICF, International Classification of Functioning, Disability and Health; BBT, Box and Block Test; 9HPT, Nine-Hole Peg Test; CUE, Capacities of Upper Extremity; PDMS-2, Peabody Developmental Motor Scales-2; PEDI, Pediatric Evaluation of Disability Inventory; QUEST, Quality of Upper Extremity Skills Test; FMA-UE, Fugl-Meyer Assessment of Upper Extremity; COPM, Canadian Occupational Performance Measure; MAS, Modified Ashworth Scale; PedsQL, Pediatric Quality of Life Inventory; HR-QoL, Health-Related Quality of Life.
* Indicates the primary assessment tool extracted for the quantitative meta-analysis synthesis
Body Functions / Activity indicates that the assessment tool covers aspects of both physical impairment and discrete functional task execution. Participation reflects real-world involvement in life situations as distinct from functional capacity.

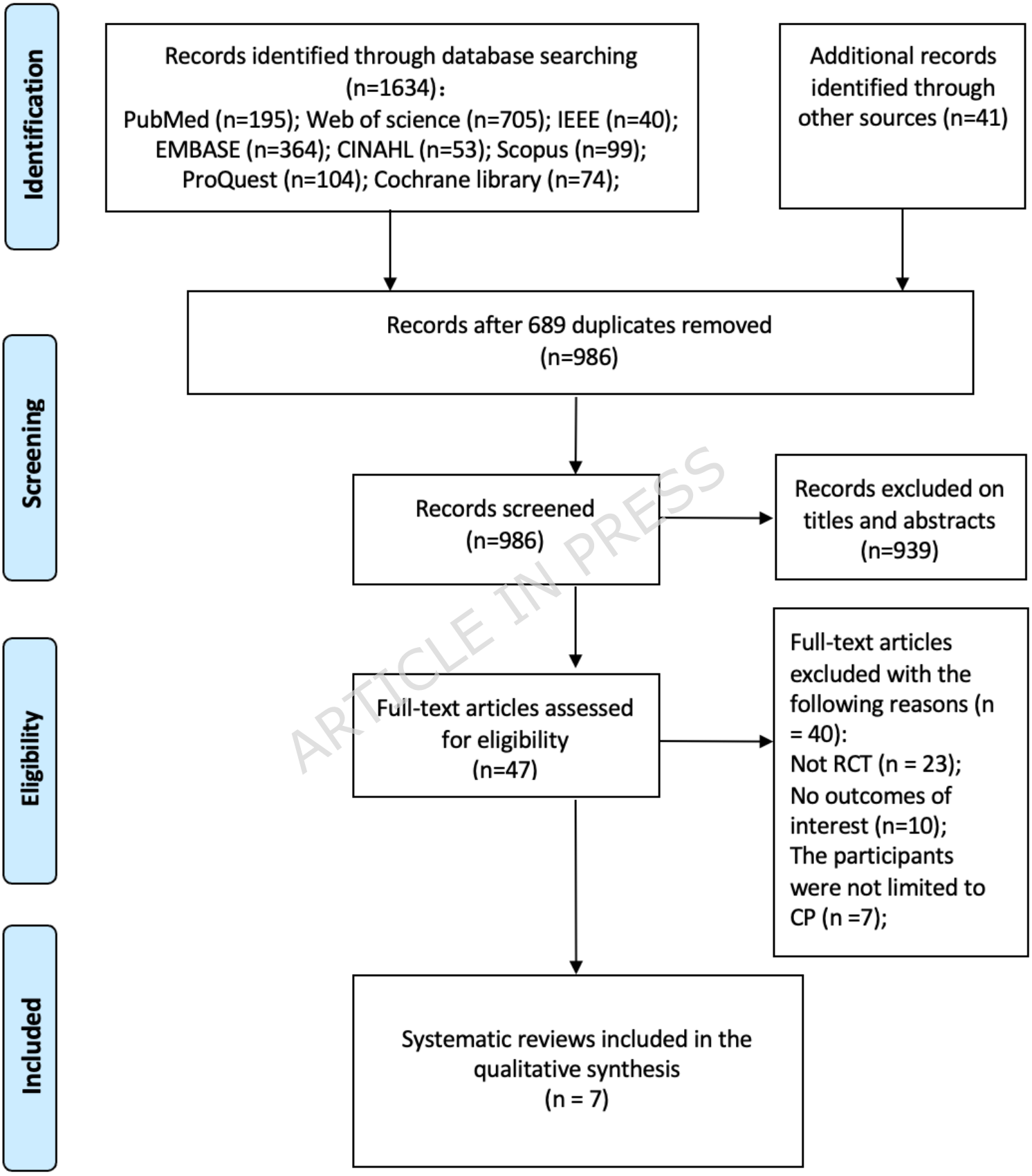
Reference

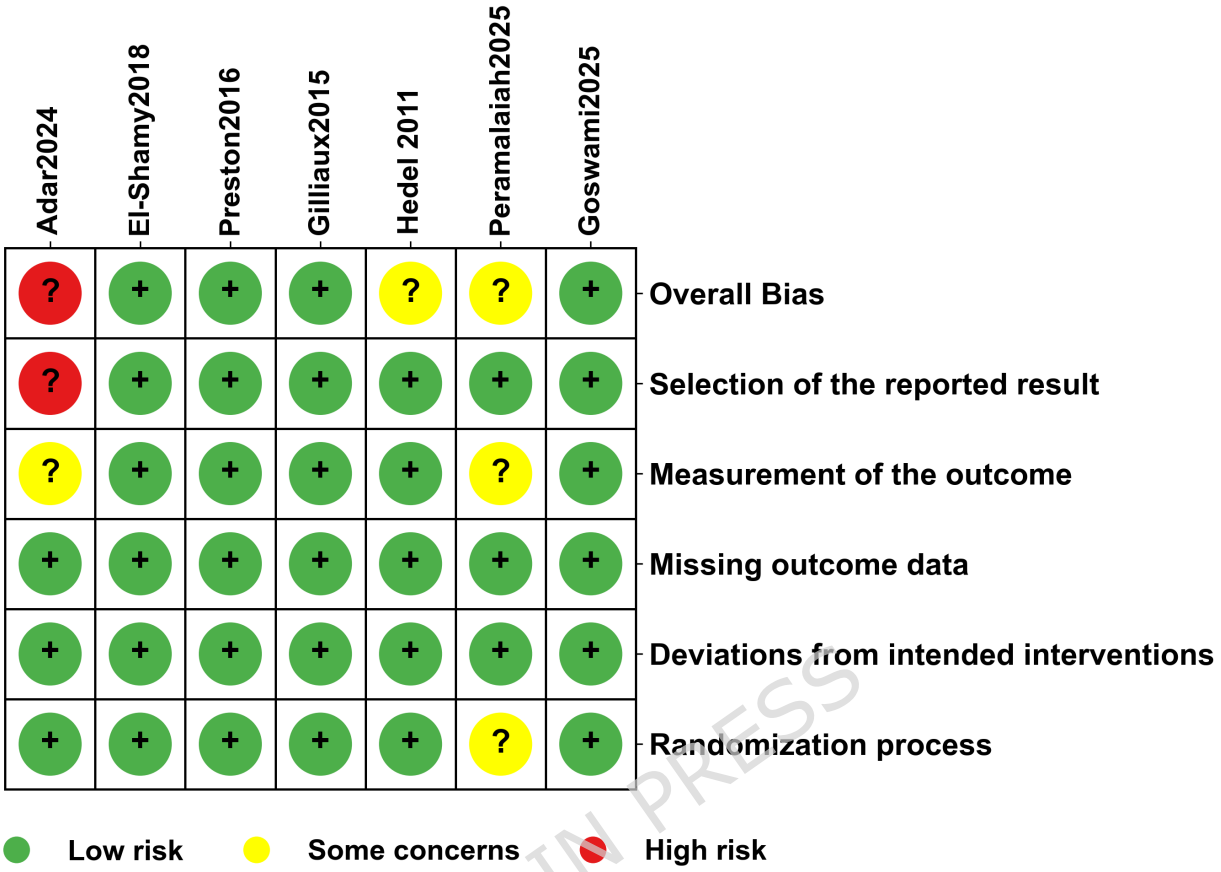
1. Dan, B., et al., *Proposed updated description of cerebral palsy*. Dev Med Child Neurol, 2025. **67**(6): p. 700-709.
2. Rosenbaum, P., et al., *A report: the definition and classification of cerebral palsy April 2006*. Dev Med Child Neurol Suppl, 2007. **109**: p. 8-14.
3. McIntyre, S., et al., *Global prevalence of cerebral palsy: A systematic analysis*. Dev Med Child Neurol, 2022. **64**(12): p. 1494-1506.
4. Patel, D.R., et al., *Cerebral palsy in children: A clinical practice review*. Curr Probl Pediatr Adolesc Health Care, 2024. **54**(11): p. 101673.
5. Krigger, K.W., *Cerebral palsy: an overview*. Am Fam Physician, 2006. **73**(1): p. 91-100.
6. Song, C.S., *Effects of Task-oriented Approach on Affected Arm Function in Children with Spastic Hemiplegia Due to Cerebral Palsy*. J Phys Ther Sci, 2014. **26**(6): p. 797-800.
7. Maritz, R., D. Aronsky, and B. Prodinger, *The International Classification of Functioning, Disability and Health (ICF) in Electronic Health Records. A Systematic Literature Review*. Appl Clin Inform, 2017. **8**(3): p. 964-980.
8. Lemmens, R.J., et al., *Arm hand skilled performance in cerebral palsy: activity preferences and their movement components*. BMC Neurol, 2014. **14**: p. 52.
9. Makki, D., J. Duodu, and M. Nixon, *Prevalence and pattern of upper limb involvement in cerebral palsy*. J Child Orthop, 2014. **8**(3): p. 215-9.
10. Nudo, R.J., *Adaptive plasticity in motor cortex: implications for rehabilitation after brain injury*. J Rehabil Med, 2003. **35**(41 Suppl): p. 7-10.
11. Novak, I., et al., *State of the Evidence Traffic Lights 2019: Systematic Review*

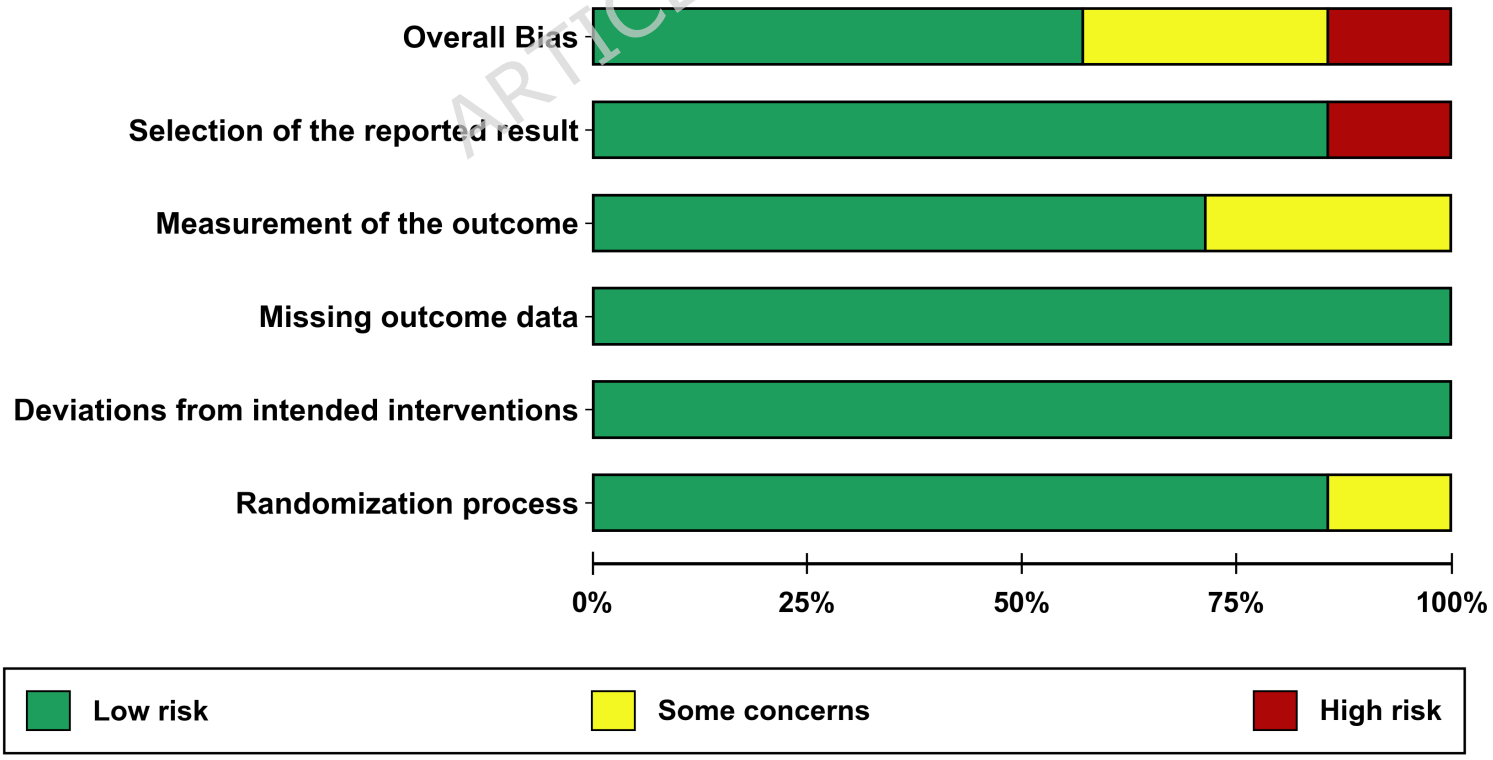
of Interventions for Preventing and Treating Children with Cerebral Palsy. Current Neurology and Neuroscience Reports, 2020. **20**(2).
12. Proietti, T., et al., *Upper-Limb Robotic Exoskeletons for Neurorehabilitation: A Review on Control Strategies*. IEEE Rev Biomed Eng, 2016. **9**: p. 4-14.
13. Maciejasz, P., et al., *A survey on robotic devices for upper limb rehabilitation*. J Neuroeng Rehabil, 2014. **11**: p. 3.
14. Lu, Z., et al., *Development of a Virtual Robot Rehabilitation Training System for Children with Cerebral Palsy: An Observational Study*. Sensors, 2024. **24**(24): p. 8138.
15. Krebs, H., et al., *Rehabilitation Robotics: Performance-Based Progressive Robot-Assisted Therapy*. Autonomous Robots, 2003. **15**(1): p. 7-20.
16. Fasoli, S.E., et al., *New horizons for robot-assisted therapy in pediatrics*. Am J Phys Med Rehabil, 2012. **91**(11 Suppl 3): p. S280-9.
17. Bishop, L., A.M. Gordon, and H. Kim, *Hand Robotic Therapy in Children with Hemiparesis: A Pilot Study*. Am J Phys Med Rehabil, 2017. **96**(1): p. 1-7.
18. Kuo, F.L., et al., *Robotic-assisted hand therapy for improvement of hand function in children with cerebral palsy: a case series study*. Eur J Phys Rehabil Med, 2020. **56**(2): p. 237-242.
19. Cardone, D., et al., *Robot-assisted upper limb therapy for personalized rehabilitation in children with cerebral palsy: a systematic review*. Front Neurol, 2024. **15**: p. 1499249.
20. de Souza Pascoal, A.F., et al., *Effects of Robot-Assisted Therapy on Upper Limb Function in Children with Cerebral Palsy: A Systematic Review with Meta-Analysis*. Phys Occup Ther Pediatr, 2026. **46**(2): p. 241-256.
21. Schünemann, H.J., et al., *GRADE guidelines: 18. How ROBINS-I and other tools to assess risk of bias in nonrandomized studies should be used to rate the certainty of a body of evidence*. J Clin Epidemiol, 2019. **111**: p. 105-114.
22. Li, T., J.P.T. Higgins, and J.J. Deeks, *Collecting data*, in *Cochrane Handbook for Systematic Reviews of Interventions*. 2019. p. 109-141.
23. Adar, S., et al., *The Effect of Robotic Rehabilitation on Hand Functions and Quality of Life in Children with Cerebral Palsy: A Prospective Randomized Controlled Study*. Am J Phys Med Rehabil, 2024. **103**(8): p. 716-723.
24. El-Shamy, S.M., *Efficacy of Armeo® Robotic Therapy Versus Conventional Therapy on Upper Limb Function in Children With Hemiplegic Cerebral Palsy*. Am J Phys Med Rehabil, 2018. **97**(3): p. 164-169.
25. Gilliaux, M., et al., *Upper Limb Robot-Assisted Therapy in Cerebral Palsy: A Single-Blind Randomized Controlled Trial*. Neurorehabil Neural Repair, 2015. **29**(2): p. 183-192.
26. Goswami, J.N., et al., *A pilot study to evaluate the efficacy of robotic biofeedback based upper limb rehabilitation in children with hemiplegic cerebral palsy*. Medical Journal Armed Forces India, 2025.
27. Hedel, H.J.A.v., et al. *Improving dexterity in children with cerebral palsy*. in *2011 International Conference on Virtual Rehabilitation*. 2011.
28. Peramalaiah, M.K., et al., *Evaluation of a Game-Based Mechatronic Device for Rehabilitation of Hand-Arm Function in Children With Cerebral Palsy: Feasibility Randomized Controlled Trial*. JMIR Rehabil Assist Technol, 2025. **12**: p. e65358.
29. Preston, N., et al., *A pilot single-blind multicentre randomized controlled trial to evaluate the potential benefits of computer-assisted arm rehabilitation gaming technology on the arm function of children with spastic cerebral palsy*. Clin Rehabil, 2016. **30**(10): p. 1004-1015.
30. Calabrò, R.S., et al., *The potential of robotics: A systematic review of neuroplastic changes following advanced lower limb rehabilitation in neurological disorders*. Neurosci Biobehav Rev, 2026. **180**: p. 106459.
31. Verschuren, O., et al., *Muscle strengthening in children and adolescents with*

spastic cerebral palsy: considerations for future resistance training protocols. Phys Ther, 2011. **91**(7): p. 1130-9.
32. Fang, Y., et al., *The effects of progressive resistance training on lower limb strength in adolescents with cerebral palsy: A systematic review and meta-analysis*. J Back Musculoskelet Rehabil, 2026. **39**(4): p. 1292-1305.
33. Liang, K.J., et al., *Measurement properties of the box and block test in children with unilateral cerebral palsy*. Sci Rep, 2021. **11**(1): p. 20955.
34. Thomé Teixeira da Silva, L.V., et al., *Selecting assessment tools to characterize upper limb function of children with cerebral palsy: A mega-review of systematic reviews*. Dev Neurorehabil, 2022. **25**(6): p. 378-391.
35. Asirvatham, T., *Letter to the Editor: "The Combined Effect of Robot-assisted Therapy and Activities of Daily Living Training on Upper Limb Recovery in Persons With Subacute Stroke: A Randomized Controlled Trial"*. Arch Phys Med Rehabil, 2024. **105**(10): p. 2008.
36. Zhang, L., et al., *Short and long-term effects of robot-assisted therapy on upper limb motor function and activity of daily living in patients post-stroke: a meta-analysis of randomized controlled trials*. J Neuroeng Rehabil, 2022. **19**(1): p. 76.
37. Miller, E.L., et al., *Comprehensive Overview of Nursing and Interdisciplinary Rehabilitation Care of the Stroke Patient A Scientific Statement From the American Heart Association*. STROKE, 2010. **41**(10): p. 2402-2448.
38. Hung, J.W., et al., *A Pilot Randomized Controlled Trial of Botulinum Toxin Treatment Combined with Robot-Assisted Therapy, Mirror Therapy, or Active Control Treatment in Patients with Spasticity Following Stroke*. Toxins (Basel), 2022. **14**(6).
39. Krebs, H.I., et al., *Robot-assisted task-specific training in cerebral palsy*. Dev Med Child Neurol, 2009. **51 Suppl 4**: p. 140-5.
40. Qiu, Q., et al., *The New Jersey Institute of Technology Robot-Assisted Virtual Rehabilitation (NJIT-RAVR) system for children with cerebral palsy: a feasibility study*. J Neuroeng Rehabil, 2009. **6**: p. 40.
41. Brown, R.E. and P.M. Milner, *The legacy of Donald O. Hebb: more than the Hebb synapse*. Nat Rev Neurosci, 2003. **4**(12): p. 1013-9.
42. Sale, M.V., et al., *Brain changes following four weeks of unimanual motor training: Evidence from behavior, neural stimulation, cortical thickness, and functional MRI*. Hum Brain Mapp, 2017. **38**(9): p. 4773-4787.
43. Madison, D.V., R.C. Malenka, and R.A. Nicoll, *Mechanisms underlying long-term potentiation of synaptic transmission*. Annu Rev Neurosci, 1991. **14**: p. 379-97.
44. Lazaridou, A., et al., *Diffusion tensor and volumetric magnetic resonance imaging using an MR-compatible hand-induced robotic device suggests training-induced neuroplasticity in patients with chronic stroke*. Int J Mol Med, 2013. **32**(5): p. 995-1000.
45. Engels, L.F., et al., *When Less Is More - Discrete Tactile Feedback Dominates Continuous Audio Biofeedback in the Integrated Percept While Controlling a Myoelectric Prosthetic Hand*. Front Neurosci, 2019. **13**: p. 578.
46. de Seta, V. and S. Romeni, *Multimodal closed-loop strategies for gait recovery after spinal cord injury and stroke via the integration of robotics and neuromodulation*. Front Neurosci, 2025. **19**: p. 1569148.
47. van Sluijs, R., et al., *Design and evaluation of the OmniSuit: A passive occupational exoskeleton for back and shoulder support*. Appl Ergon, 2024. **120**: p. 104332.
48. Bonanno, M., et al., *Rehabilitation of Gait and Balance in Cerebral Palsy: A Scoping Review on the Use of Robotics with Biomechanical Implications*. J Clin Med, 2023. **12**(9).
49. Maetzler, W., et al., *Modernizing Daily Function Assessment in Parkinson's Disease Using Capacity, Perception, and Performance Measures*. Mov Disord,

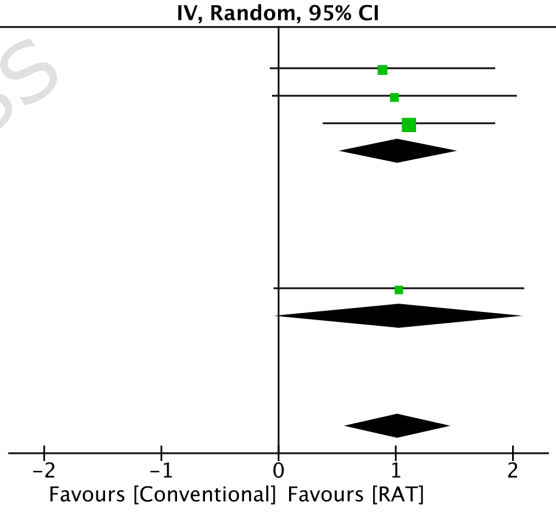
2021. **36**(1): p. 76-82.
50. Lee, J.H. and G. Kim, *Effectiveness of Robot-Assisted Gait Training in Stroke Rehabilitation: A Systematic Review and Meta-Analysis.* J Clin Med, 2025. **14**(13).
51. Woodbury, M., E.S. Grattan, and C.Y. Li, *Development of a Short Form Assessment Combining the Fugl-Meyer Assessment-Upper Extremity and the Wolf Motor Function Test for Evaluating Stroke Recovery.* Arch Phys Med Rehabil, 2023. **104**(10): p. 1661-1668.



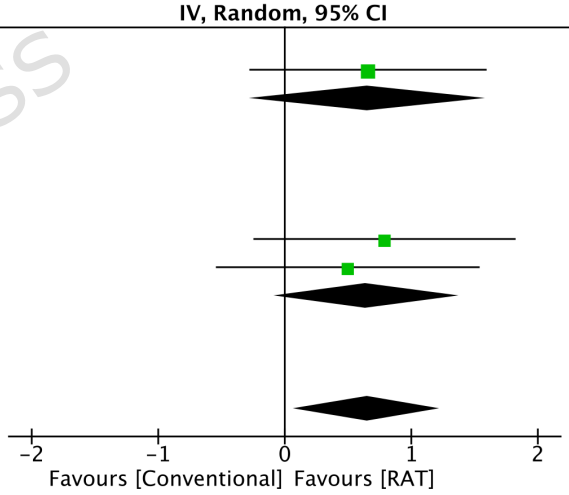




Study or Subgroup	Experimental Mean	SD	Total	Control Mean	SD	Total	Weight	Std. Mean Difference IV, Random, 95% CI
1.1.1 RAT								
Adar et al., 2024	5.45	2.51	9	3.4	1.9	10	22.9%	0.89 [-0.07, 1.84]
Hedel et al., 2011	3.2	2.8	10	0.2	3	7	19.4%	0.99 [-0.05, 2.03]
Peramalaiah et al., 2025	5.2	2.02	17	2	3.42	17	39.3%	1.11 [0.38, 1.84]
Subtotal (95% CI)			**36**			**34**	**81.5%**	**1.02 [0.51, 1.53]**
Heterogeneity: $Tau^2 = 0.00$; $Chi^2 = 0.14$, df = 2 (P = 0.93); $I^2 = 0\%$								
Test for overall effect: Z = 3.95 (P < 0.0001)								
1.1.2 RAT+CT								
Gilliaux et al., 2015	3.6	3.6	8	0.4	2.1	8	18.5%	1.03 [-0.04, 2.09]
Subtotal (95% CI)			**8**			**8**	**18.5%**	**1.03 [-0.04, 2.09]**
Heterogeneity: Not applicable								
Test for overall effect: Z = 1.89 (P = 0.06)								
Total (95% CI)			**44**			**42**	**100.0%**	**1.02 [0.56, 1.48]**
Heterogeneity: $Tau^2 = 0.00$; $Chi^2 = 0.14$, df = 3 (P = 0.99); $I^2 = 0\%$								
Test for overall effect: Z = 4.38 (P < 0.0001)								
Test for subgroup differences: $Chi^2 = 0.00$, df = 1 (P = 0.99), $I^2 = 0\%$								

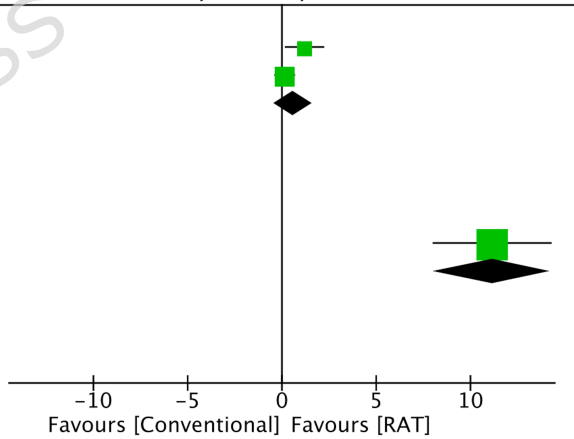


Study or Subgroup	Experimental Mean	SD	Total	Control Mean	SD	Total	Weight	Std. Mean Difference IV, Random, 95% CI
1.2.1 RAT								
Adar et al., 2024	2.22	2.33	9	1	1.05	10	38.1%	0.66 [-0.27, 1.59]
Subtotal (95% CI)			**9**			**10**	**38.1%**	**0.66 [-0.27, 1.59]**
Heterogeneity: Not applicable								
Test for overall effect: Z = 1.39 (P = 0.17)								
1.2.2 RAT+CT								
Gilliaux et al., 2015	-0.2	0.8	8	-1.1	1.3	8	31.1%	0.79 [-0.24, 1.82]
Preston et al., 2016	-0.48	0.77	8	-0.88	0.74	7	30.8%	0.50 [-0.54, 1.53]
Subtotal (95% CI)			**16**			**15**	**61.9%**	**0.64 [-0.09, 1.37]**
Heterogeneity: $Tau^2 = 0.00$; $Chi^2 = 0.15$, df = 1 (P = 0.70); $I^2 = 0\%$								
Test for overall effect: Z = 1.73 (P = 0.08)								
Total (95% CI)			**25**			**25**	**100.0%**	**0.65 [0.07, 1.22]**
Heterogeneity: $Tau^2 = 0.00$; $Chi^2 = 0.15$, df = 2 (P = 0.93); $I^2 = 0\%$								
Test for overall effect: Z = 2.22 (P = 0.03)								
Test for subgroup differences: $Chi^2 = 0.00$, df = 1 (P = 0.98), $I^2 = 0\%$								

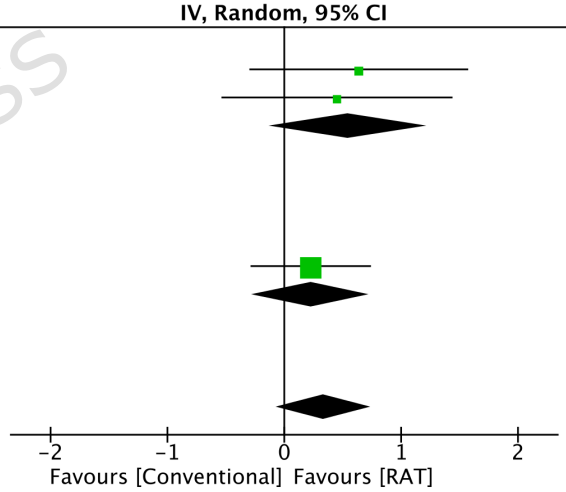


Study or Subgroup	Experimental Mean	SD	Total	Control Mean	SD	Total	Weight	Std. Mean Difference IV, Random, 95% CI
1.3.1 End-effector								
Adar et al., 2024	2.56	1.33	9	1.1	0.99	10	41.4%	1.20 [0.20, 2.20]
Goswami et al., 2025	0.99	2.51	30	0.64	2.21	30	58.6%	0.15 [-0.36, 0.65]
Subtotal (95% CI)			**39**			**40**	**100.0%**	**0.58 [-0.44, 1.60]**
Heterogeneity: $Tau^2 = 0.39$; $Chi^2 = 3.41$, df = 1 (P = 0.06); $I^2 = 71\%$								
Test for overall effect: Z = 1.12 (P = 0.26)								
1.3.2 Exoskeleton								
El-Shamy et al., 2018	22.7	0.7	15	16.8	0.2	15	100.0%	11.15 [8.04, 14.26]
Subtotal (95% CI)			**15**			**15**	**100.0%**	**11.15 [8.04, 14.26]**
Heterogeneity: Not applicable								
Test for overall effect: Z = 7.03 (P < 0.00001)								

Test for subgroup differences: $Chi^2 = 40.06$, df = 1 (P < 0.00001), $I^2 = 97.5\%$



Study or Subgroup	Experimental Mean	SD	Total	Control Mean	SD	Total	Weight	Std. Mean Difference IV, Random, 95% CI
1.4.1 RAT								
Adar et al., 2024	2	1.32	9	1	1.64	10	19.1%	0.64 [-0.29, 1.57]
Hedel et al., 2011	1	1.3	10	0.3	1.7	7	17.1%	0.45 [-0.53, 1.43]
Subtotal (95% CI)			**19**			**17**	**36.2%**	**0.55 [-0.13, 1.22]**
Heterogeneity: $Tau^2 = 0.00$; $Chi^2 = 0.07$, df = 1 (P = 0.79); $I^2 = 0\%$								
Test for overall effect: Z = 1.60 (P = 0.11)								
1.4.2 RAT+CT								
Goswami et al., 2025	0.05	0.07	30	0	0.3	30	63.8%	0.23 [-0.28, 0.73]
Subtotal (95% CI)			**30**			**30**	**63.8%**	**0.23 [-0.28, 0.73]**
Heterogeneity: Not applicable								
Test for overall effect: Z = 0.87 (P = 0.38)								
Total (95% CI)			**49**			**47**	**100.0%**	**0.34 [-0.06, 0.75]**
Heterogeneity: $Tau^2 = 0.00$; $Chi^2 = 0.64$, df = 2 (P = 0.73); $I^2 = 0\%$								
Test for overall effect: Z = 1.66 (P = 0.10)								
Test for subgroup differences: $Chi^2 = 0.56$, df = 1 (P = 0.45), $I^2 = 0\%$								



Study or Subgroup	Experimental Mean	SD	Total	Control Mean	SD	Total	Weight	Std. Mean Difference IV, Random, 95% CI
Gilliaux et al., 2015	8.5	26.89	8	12	22.22	8	53.0%	-0.13 [-1.12, 0.85]
Preston et al., 2016	0.9	1.35	8	0	1.35	7	47.0%	0.63 [-0.42, 1.67]
Total (95% CI)			**16**			**15**	**100.0%**	**0.22 [-0.52, 0.97]**

Heterogeneity: $Tau^2 = 0.02$; $Chi^2 = 1.08$, df = 1 (P = 0.30); $I^2 = 8\%$

Test for overall effect: Z = 0.59 (P = 0.56)

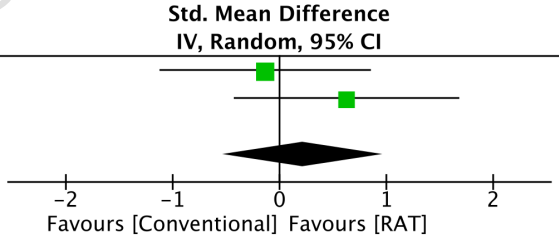


Table1. Characteristics of the population included in the study

Author, year	Study design	CP (Classification)	Age (years)	Group	Sample size [female]	Female Ratio	Dropout rate	Country	Setting
Peramalaiah et al., 2025	single-blind RCT	Spastic CP, MACS I-III	4-10	G1: RAT G2: CT	G1: n=17 [8] G2: n=17 [8]	47.06 %	0%	India	Shri Dharmasthala Manjunatheshwara University
Goswami et al., 2025	Single blind multicentric pilot RCT	Hemiplegic CP, GMFCS I-III, MACS I–IV	5-18	G1: RAT G2: CT	G1: n=30 [9] G2: n=30[7]	26.67 %	8.33%	India	Senior Registrar & OC Tps, 155 Base Hospital
Adar et al., 2024	single-blind Prospective RCT	Spastic CP, MACS I-III	7-16	G1: RAT G2: CT	G1: n=9 [4] G2: n=10[5]	47.37 %	5%	Turkey	Afyonkarahisar Health Sciences University
El-Shamy et al., 2018	single-blind RCT	Spastic Hemiplegia CP, MACS I-III	6-8	G1: RAT G2: CT	G1: n=15[6] G2: n=15[4]	33.33 %	0%	Egypt	Faculty of Physical Therapy, Cairo University
Preston et al., 2016	pilot single-blind multicenter RCT	Spastic CP, MACS II–IV	5-12	G1: RAT+ CT+ BT G2: CT+ BT	G1: n=8[4] G2: n=7[2]	40%	0%	UK	University of Leeds
Gilliaux et al., 2015	Single-Blind RCT	Spastic CP, MACS I–V	6-16	G1: RAT + CT G2: CT	G1: n=8[NA] G2: n=8[NA]	NA	0%	Belgium	Université catholique de Louvain, Institute of Neuroscience

Hedel et al., 2011	Preliminary results of RCT	CP	6-18	G1: RAT G2: computer games	G1: n=10[NA] G2: n=7[NA]	NA	0%	Switzerland	Institute of Neuroinformatics University of Zurich

UK, United Kingdom; RCT, randomized controlled trials; CP, cerebral palsy; MACS, Manual Ability Classification System; G, group; RAT, robot-assisted therapy; CT, conventional therapy; BT, Botulinum Toxin; NA, not available;

Table 2: Details for interventions

Author, year	Interventions	Device name	Type	RAT Combined	Duration (min)	Sessions	Frequency (days/wk.)	Weeks
Peramalaiah et al., 2025	RAT	game-based robotic manipulandum device (RMD)	end-effector	computer games	45	24	3	8
Goswami et al., 2025	RAT+CT	PABLO ® X 2 hand-arm therapy system (M/Stiromotion GMBH, Austria)	end-effector	computer games	30	144	3	48
Adar et al., 2024	RAT	AMADEO hand-finger robot (Tyromotion, Graz, Austria)	end-effector	virtual reality games	40	30	5	6
El-Shamy et al., 2018	RAT	Armeo Spring (Hocoma, AG,	exoskeleton	virtual reality games	45	36	3	12

		Switzerland)						
Preston et al., 2016	RAT+ CT+ BT	The CAAR games system	other	compute r games	30	42	7	6
Gilliaux et al., 2015	RAT+ CT	REAPlan	end-effect or	compute r games	45	16	2	8
Hedel et al., 2011	RAT	YouGrabber system (YouRehab, Zurich, Switzerland)	end-effect or	virtual reality games	45	12	4	3

RAT, robot-assisted therapy; CT, conventional therapy; BT, Botulinum Toxin;

Table 3. Outcome measures and categorization based on the ICF model of the included studies grouped by targeted outcomes.

Targeted Outcome	Author, year	Assessment Tool	ICF Domain
Fine Motor Function	Adar et al., 2024	FMA-hand; BBT*	Body Functions / Activity
	Gilliaux et al., 2015	BBT*	Activity
	Hedel et al., 2011	BBT*; 9HPT	Activity
	Peramalaiah et al., 2025	CUE; PDMS-2(grasping*, VMI)	Activity
Activities of Daily Living	Adar et al., 2024	ABILHAND-Kid**; WeeFIM	Activity
	Gilliaux et al., 2015	ABILHAND-Kids*; PEDI	Activity
	Preston et al., 2016	ABILHAND-Kids*	Activity
Gross Motor Function	Adar et al., 2024	FMA-UE*	Body Functions / Activity
	El-Shamy et al., 2018	QUEST*	Activity
	Goswami et al., 2025	QUEST*	Activity
Muscle Strength	Adar et al., 2024	Jamar Grasp*; Jamar Pinch	Body Functions
	Gilliaux et al., 2015	Muscle torque	Body Functions
	Goswami et al., 2025	Hand grip strength*	Body Functions
	Hedel et al., 2011	Grip strength*; Pinch-grip	Body Functions
Participation	Gilliaux et al., 2015	Life Habits*	Participation

Targeted Outcome	Author, year	Assessment Tool	ICF Domain
Others	Preston et al., 2016	COPM*	Participation
	Adar et al., 2024	MAS (Tone); PedsQL	Body Functions; HR-QoL
	El-Shamy et al., 2018	MAS (Tone)	Body Functions
	Gilliaux et al., 2015	Kinematics; MAS (Tone)	Body Functions

ICF, International Classification of Functioning, Disability and Health; BBT, Box and Block Test; 9HPT, Nine-Hole Peg Test; CUE, Capacities of Upper Extremity; PDMS-2, Peabody Developmental Motor Scales-2; PEDI, Pediatric Evaluation of Disability Inventory; QUEST, Quality of Upper Extremity Skills Test; FMA-UE, Fugl-Meyer Assessment of Upper Extremity; COPM, Canadian Occupational Performance Measure; MAS, Modified Ashworth Scale; PedsQL, Pediatric Quality of Life Inventory; HR-QoL, Health-Related Quality of Life.

* Indicates the primary assessment tool extracted for the quantitative meta-analysis synthesis

Body Functions / Activity indicates that the assessment tool covers aspects of both physical impairment and discrete functional task execution. Participation reflects real-world involvement in life situations as distinct from functional capacity.