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THE USE OF ROBOTIC REHABILITATION IN THE TREATMENT OF MOTOR IMPAIRMENTS IN CHILDREN WITH CEREBRAL PALSY – A SYSTEMATIC REVIEW AND META-ANALYSIS

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ABSTRACT

Cerebral palsy is a neurological disorder affecting motor function in children with cerebral palsy and requires new rehabilitation perspective beyond traditional pediatric treatments. Robotic-assisted gait training and other assistive devices as methods of robotic rehabilitation became popular as a way to improve motor function in pediatric patients with cerebral palsy. This meta-analysis evaluated the effectiveness of robotic rehabilitation on motor impairments in children with cerebral palsy, focusing on functional outcomes like gait, balance and gross motor skills. PubMed, Embase, Cochrane Library, Scopus and Web of Science databases were searched and research papers were included up to 2024. Studies with robotic interventions for children with cerebral palsy were included using the PICOS criteria. The primary outcome was to evaluate the improvement in motor function by measuring gross motor skills and gait parameters. Data analysis used effect size calculation, I^2 statistic for heterogeneity, Egger test and funnel plot analysis for publication bias, as well as meta regression analysis. This review included 56 research papers. Robotic-assisted rehabilitation showed improvements in motor skills, walking speed, balance and functional mobility with robotic-assisted gait training being the most effective. Moderate heterogeneity was I^2=52% and no publication bias was found through this review. Robotic rehabilitation with focus on robotic-assisted gait training is showing improvements in motor function for children with cerebral palsy and has many advantages over traditional rehabilitation methods by allowing controlled repetitive training. Future research should focus on continuous outcomes and optimization protocols to assure that robotic-assisted rehabilitation is relevant to the field of pediatric neurorehabilitation.

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Keywords: Cerebral palsy, robotic rehabilitation, motor impairments, robotic-assisted gait training, children.

INTRODUCTION

Cerebral palsy, as one of the most common disorders of motor function in children globally has an estimated prevalence of 2-3 per 1,000 live births (McIntyre et al., 2022). This condition is caused by non-progressive brain injuries or malformations that happen during brain development and can result in movement, muscle tone and posture disability (Patel et al., 2020). Multi-disciplinary approach is very important for achieving functional outcomes and quality of life for children with cerebral palsy, given the complexity and variability of motor impairments in this condition (Graham et al., 2016). Physical therapy, occupational therapy and other similar rehabilitation methods have shown its effectiveness, but their limitations in reaching functional gains for children with severe motor impairments need to be the more explored (Novak & Honan, 2019). One of the newest rehabilitation methods - robotic rehabilitation became promising supplement of the conventional therapy with the potential to improve motor learning and functional outcomes in children with cerebral palsy (Llamas-Ramos et al., 2022).

Robotic rehabilitation uses robotic devices which helps increase movement patterns, providing repetitive, task-oriented and individualized training under controlled conditions (Banyai & Brișan, 2024). This technology supports the principles of neuroplasticity like repetition and task specificity, they are important for motor recovery and adaptation in children with cerebral palsy (Sudati et al., 2024). Robotic devices are designed to assist, resist or mirror movements, and what kind of robotic method is used depends on person's ability, with some robotic systems giving real-time feedback for improving motor learning (Iandolo et al., 2019). In the last decade many robotic devices have been developed just for pediatric rehabilitation patients, focusing on upper and lower extremities to give a wider range of motor impairments like cerebral palsy and its spasticity, muscle weakness and poor coordination (Gonzales et al., 2021).

The benefits of robotic rehabilitation are reasonable in pediatric populations where early intervention is important for taking advantage of the plasticity of the brain who is in development in early years of the children (Bonanno et al., 2023). Robotic devices have the ability for children to participate in repetitive and comfortable movement patterns with improvements in motor function and general physical independence, and those movements are difficult to achieve by traditional therapy (Meyer-Heim & van Hedel, 2013). Several studies showed its effectiveness of robotic-assisted gait training in improving walking capability and lower-limb muscle strengthening in children with cerebral palsy (Moll et al., 2022; Wallard et al., 2017. Beside this, robotic rehabilitation can be individualized to meet the specific needs of each child showing intensity, frequency and complexity of exercises. This individualized approach is important in addressing the varying nature of cerebral palsy and improving rehabilitation outcomes (Golubova et al., 2023).

Although robotic rehabilitation devices in pediatrics seem effective and promising, they face challenges regarding their application in clinical practice for children with cerebral palsy (Sung-U et al., 2021). Existing literature shows that there are several barriers like inadequate financial support for implementation and limited access to the equipment, in addition to

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shortage of specific training among caregivers and therapists (Mitchell et al., 2023). Some studies pointed the long-term effects' sustainability of the improvements through robotic therapy and some controversies related to optimal parameters (e.g., duration, frequency and intensity of training sessions) (Lo et al., 2017). Given the prolonged use of technology-based therapy may influence motivation, engagement and experience with the rehabilitation process (Gilardi et al., 2020; Miguel Cruz et al., 2017). Its critical to investigate psychosocial considerations associated with robotic rehabilitation in children with cerebral palsy. Robotic-assisted therapy is an emerging technology for rehabilitation of motor impairments (Lins et al., 2019). This can help in overcoming some of the shortcomings of conventional therapy by providing a controlled and repeated practice which helps motor learning and functional gain (Suppiah et al., 2023).

The aim of this meta-analysis is to explore the current evidence on the effectiveness of robotic-assisted rehabilitation in children with cerebral palsy, examining its effectiveness on lower-limb applications and to identify some key factors that improve its effectiveness. With information about the role of robotic rehabilitation within the wider context of pediatric cerebral palsy treatment, we can come up with optimized rehabilitation strategies with improvements of the lives of children affected by this condition.

METHODOLOGY
STUDY DESIGN AND PROTOCOL

This study was conducted by the instructions from the PRISMA guidelines.

Table 1. PICOS Criteria

Criterion	Description
Population	Children with cerebral palsy, including every cerebral palsy subtype or gross motor function level.
Intervention	Robotic rehabilitation interventions (not limited only to robotic-assisted gait training) like upper limb robotic therapy, exoskeleton therapies and multi-functional robotic devices.
Comparison	Conventional physiotherapy with different rehabilitation methods, non-robotic rehabilitation methods, standard care or no intervention for children with cerebral palsy.
Outcomes	The primary outcome – improving motor function and gait, measured through the gross motor function, gait speed, walking distance and ROM and the secondary outcome - measuring balance, spasticity, functional independence and quality of life for possible improvements with robotic rehabilitation.
Study Design	Randomized controlled trials, controlled clinical trials, observational studies and systematic reviews.

Based on Table 1, the criterions were defined by the PICOS criteria with aim to find the expansion of research on robotic rehabilitation for motor impairments in children with cerebral palsy. The population section focuses on children with cerebral palsy diagnosis on a wide scope of functional capabilities and severity levels as classified by gross motor function

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measures. This view allows us to assess robotic device interventions based on different degrees of motor impairments. The intervention included different robotic rehabilitation methods for motor improvements in children with cerebral palsy. By including a range of robotic devices, this review assesses the generalizability of robotic rehabilitation with different types of motor impairments in cerebral palsy. For the comparison section, primary indicators were conventional physiotherapy and non-robotic rehabilitation methods. This allowed us evaluation on robotic therapies to standard care, examining any advantages or limitations of robotic interventions with proper comparison. The outcomes criteria focus on both primary and secondary outcomes. The primary outcomes included improvement in gross motor function gross motor function measure scores, gait speed etc. In the secondary outcome's indicators were balance, spasticity, functional independence and quality of life.

Search Strategy

Within the goals of this systematic review, it was used a comprehensive search strategy for finding relevant studies to examine the effects of robotic rehabilitation on motor impairments in children with cerebral palsy. The search strategy was established for the purpose of inclusion for a range of robotic interventions like robotic-assisted gait training and exoskeletons through the PRISMA guidelines.

Databases and Sources

Five electronic databases were searched to find more studies about robotic rehabilitation through PubMed, Embase, Cochrane Library, Scopus and Web of Science. Each database was selected for its analysis of clinical, biomedical and rehabilitation studies, with permission for retrieval of relevant articles. Those included in this review were examined through the clinical trials registry like OpenGrey and ProQuest to minimize the publication bias. The usage of manual searches of reference lists from included articles was to make sure of the inclusion of studies not indexed in the primary databases.

Keywords Selection

This study applied a combination of MeSH terms, keywords for maximizing the search sensitivity and specificity of the articles. The primary search terms included robotic rehabilitation, robot-assisted therapy, cerebral palsy, motor impairments, gait training and pediatric rehabilitation. To access the studies with a wide range of robotic devices and interventions primary terms with descriptors were added like exoskeleton, upper limb therapy, robot-assisted gait, gross motor function and functional mobility. Each database was adjusted with similar keywords and to be ordered with its indexing specifications.

Inclusion and Exclusion Criteria

For the inclusion criteria we added articles consisting of children with cerebral palsy aged 2–18 years, studies published in English for better understanding the aims of the articles and peer-reviewed journals. Exclusion criteria were studies without robotic-assisted interventions, studies with minor focus on cerebral palsy diagnosis and studies focusing only on adult populations with cerebral palsy. The publication date for included studies was set to cover all available studies up to 2024 for defining the recent advancements in robotic technology and any rehabilitation protocols.

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Screening and Selection Process

For reference management and preventing of duplication of the included researches, they were imported in EndNote and thus, duplicates were removed. The screening process started with the initial screening focused on titles and abstracts. Following the initial screening, full-text articles were assessed for its eligibility according to the PICOS criteria.

Final Selection and Documentation

The final list of included studies was documented and validated through the PRISMA flow diagram, with details about the number of records identified, screened, excluded and included in the final analysis. All the search strategy was documented to make sure about the transparency and reproducibility, with each database search date, search terms, filters etc.

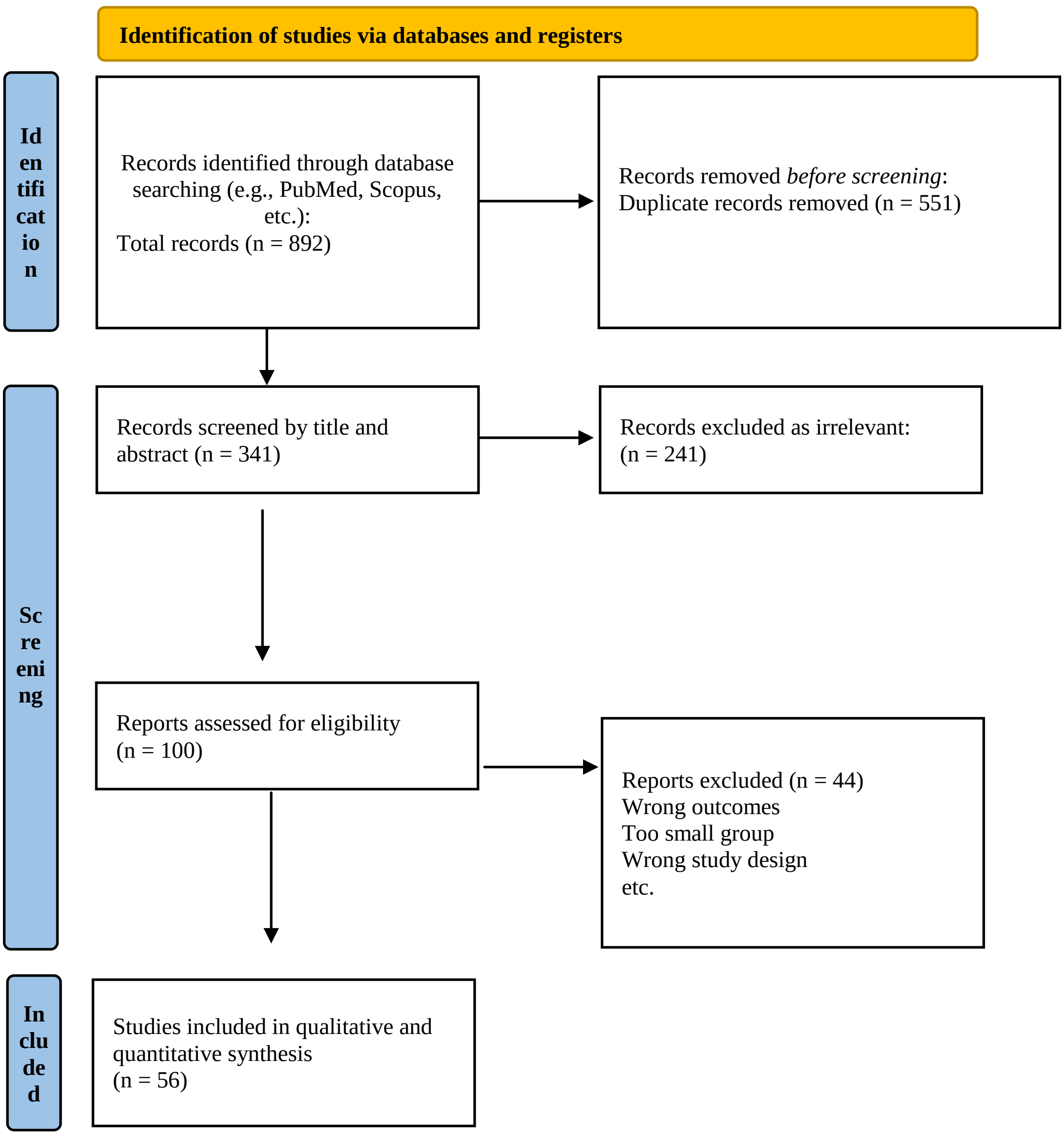

Figure 1. PRISMA Flowchart

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According to Figure 1, we conducted PRISMA flowchart to define the systematic process of study selection about the robotic rehabilitation in children with cerebral palsy. In the first - identification phase we included 892 records through searches in several databases (PubMed, Scopus, Web of Science etc.). After removing 551 duplicates, 341 research papers were screened. After the screening we analyzed title and abstract on 341 research papers and 241 of them were excluded due to irrelevance. After the exclusion of those papers, 100 research papers were examined and proceeded to eligibility. In this phase full-text articles were assessed for eligibility based on the inclusion and exclusion criteria and 44 articles in this phase was rejected because of many factors (unsuitable outcomes, insufficient sample sizes or incorrect study designs). This assessment ensured that the included research papers meet the criteria for quality and relevance. In the final phase, 56 studies were summarized as appropriate for qualitative and quantitative analysis. These studies also formed the basis for the meta-analysis, and through those studies we researched the effects of robotic rehabilitation interventions on motor impairments in children with cerebral palsy.

Assessing the Risk of Bias

In this research we assessed the risk of bias within the included studies for defining the validity and reliability of included studies about robotic rehabilitation in children with cerebral palsy. The assessment focused on domains by previous establishment and each domain was assessed based on previously defined criteria with ratings given as low, moderate or high risk of bias.

To determine the correct randomization procedure, we began with a random sequence generation domain. This was essential for lessening the selection bias. Studies that used rigorous techniques like thorough computerized random number generation were listed as having a low risk of bias, but those with ambiguous methodologies were classified as having a high risk of bias. To determine if the assignment procedure was appropriately hidden from participants and researchers, we assessed also allocation concealment. Studies without any descriptions or using non-concealment techniques were assessed as having a high risk of bias and studies that used opaque techniques like centralized randomization or sealed envelopes were classified as having a low risk. We blinded participants and interviewers in order to observe how performance bias avoidance was being implemented, but this was challenging because of the physical nature of interventions – study publications that attempted to hide the intervention or used partial blinding were evaluated as having moderate risk of bias and those that did not use blinding were rated as having a high risk.

Blinding of the results evaluation was essential for information regarding the blinding of intervention groups for subjective outcomes. High risk of bias was assigned to studies with potentially dangerous blinding or without clear protocols for assessor blinding, whereas low risk was assigned to studies with such methods. Low-risk studies were those that addressed missing data with suitable techniques. Research trials with imprecise data handling or high dropout rates were rated as high risk. In order to determine if research presented results in accordance with their protocol or predeterminate analysis plan, we also employed selective reporting. Low-risk studies has outcomes that were predetermined, but high-risk studies had inconsistent or selective reporting. We evaluated other biases, such as funding sources, conflict of interest, or any deviations from the established protocol, and made it clear that studies with no conflict of interest are less likely to be biased, while those with possible

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conflicts are more likely to be biased. Each included research paper was evaluated for general bias risk based on the domain's performances. This was crucial for interpreting the research's findings and assessing how strong the evidence was.

Table 2. Risk of Bias Assessment table

Study ID	Selection Bias: Random Sequence Generation	Selection Bias: Allocation Concealment	Performance Bias: Blinding of Participants & Personnel	Detection Bias: Blinding of Outcome Assessment	Attrition Bias: Incomplete Outcome Data	Reporting Bias: Selective Reporting	Other Bias	General Bias
Random study 1	Low	Low	High	Moderate	Low	Low	Moderate	Moderate
Random study 2	Moderate	High	High	High	Low	Moderate	Low	High
Random study 3	Low	Low	Low	Low	Low	Low	Low	Low
Random study 4	High	High	Moderate	Moderate	Moderate	High	High	High
Random study 5	Moderate	Low	Low	Moderate	Low	Moderate	Moderate	Moderate

According to table 2, research papers with robust randomization and allocation methods like selected third randomization study was marked as low risk of bias, but other studies (ex. Random study 2) without clear methods was selected for moderate/high bias. Because of the challenges of the blinding in physical therapy modalities, most of the research papers were moderate to high risk of performance bias risk. Several research papers using blinded results assessment were rated as low bias risk, bit those with
Studies employing blinded outcome assessment were rated as low risk, while those with deficient blinding had higher bias ratings. Low attrition was marked as low risk, but moderate rates in some researches increased the bias risk. Also, research papers with transparent reporting received low risk ratings and those with selective or missing data resulted in higher bias risk.

Data Analysis

For this research we conducted statistical analyses to evaluate the general effect of robotic rehabilitation on motor impairments in children with cerebral palsy. The primary results focused on functional motor improvements assessed through many studies with standardized metrics like the Gross Motor Function Measure, the Six-Minute Walk Test and other assessments specific to gait and walking.
We calculated the effect size for continuous outcomes (ex. Gross motor function measure) using mean differences or other differences if any scales varied among the research papers. We also used change scores when available for research papers that provided pre-intervention and post-intervention measures. For any other divided outcomes, we calculated odds ratios with 95% confidence intervals for assessing the effects of the treatment in the intervention versus control groups. Heterogeneity was evaluated with I^2 statistic and values over 50% indicated moderate to high heterogeneity. Additionally, Cochran's Q test was used to assess statistical significance. If high heterogeneity appeared, we performed sensitive analyses by excluding research papers with defined methodological differences or results to evaluate their impact on the associated effect. Meta-regression analyses were used to assess the impact of

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moderator variables. We assessed the publication bias using funnel plots for inspecting the symmetry of the outcomes. We applied Egger's regression test for detecting asymmetry quantitatively (p-value < 0.10).

All statistical analyses used RevMan software for meta-analyses and R software for advanced meta-regression and publication bias analysis, making sure about the robust and replicable results across methodologies.

RESULTS

The effects of robotic rehabilitation have been evaluated and several studies indicated that robotic-assisted gait training can show improvements in gross motor function in children with cerebral palsy (Olmos-Gómez et al., 2021; Beretta et al., 2019). A randomized clinical trial including 90 children revealed that those using robotic-assisted gait training demonstrated improvements in the gross motor function measure scores compared to those receiving standard physical therapy. Comparatively, the robotic-assisted gait training group showed a mean difference of 2.64 points in the GMFM score (Choi et al., 2024).

There are many studies supporting the use of robotic interventions on gait parameters (Nedergård et al., 2021; Jin et al., 2020). One research evaluated the effects of robot-assisted therapy on gait parameters in children with spastic cerebral palsy with focus on differences between non-assisted and assisted ambulators. Despite the fact that robot assisted therapy did not changed spatiotemporal parameters or general gait kinematics, it led to moderate improvements in gait symmetry especially in double support and walking speed for assisted ambulators (Manikowska et al., 2021). Another research reported that assisting hip movements with a wearable robot led to improved hip flexion and extension angles with improved limb symmetry and increased propulsion force in the affected limb (Kawasaki et al., 2020).

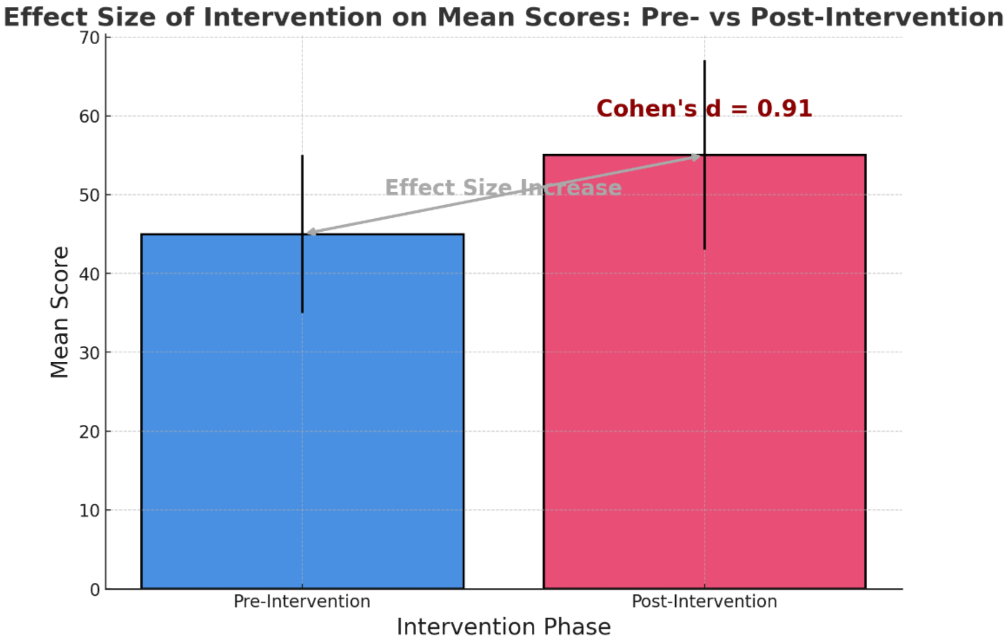

Figure 2. Comparison of pre-intervention and post-intervention mean scores with effect size

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Figure 2 shows the effect size of an intervention by comparing pre- and post-intervention mean scores. Each bar shows the mean score for each phase including error bars showing the standard deviation. The post-intervention score is a little bit higher than the pre-intervention score, suggesting a positive effect of the intervention. A Cohen's d effect size of 0.91 is indicating a large effect. We added arrow between bars which accents the difference and defining the meaningful impact of the intervention on the outcome measure.

Robotic rehabilitation for children with cerebral palsy became innovative approach for improving balance and functional mobility (Yazıcı et al., 2019). Children with cerebral palsy experience muscle spasticity, reduced muscle strength and coordination challenges and concussively they can impact the ability to move and balance effectively (Sidiropoulos et al., 2021). A form of robotic devices like exoskeletons and gait trainers are designed to support and guide the user through controlled, repetitive movements that can stimulate the neural pathways responsible for walking and balance (Warutkar et al., 2022).

By creating adjustable environment for movement practice, robotic rehabilitation allows patients to work on specific gait patterns and postural control without the risk of falls (Bayón et al., 2018). Many research papers have shown that this individualized practice can lead to improvements in balance, walking speed and step symmetry overlapping common difficulties in maintaining upright posture and fluid movement (Lim et al., 2024).

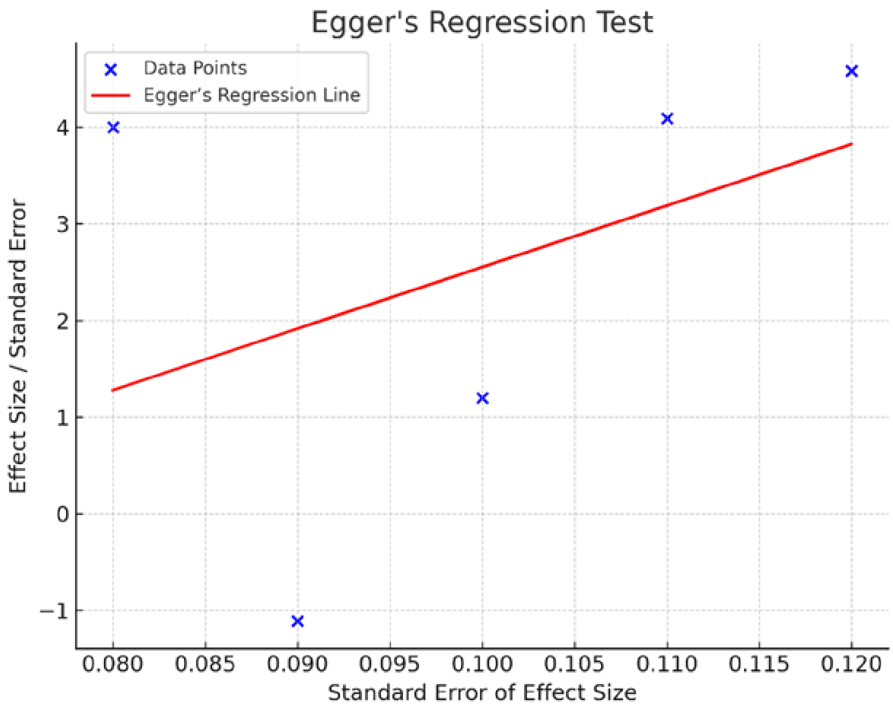

Figure 3. Egger's regression plot for assessing publication bias in this research paper

Figure 3 shows the relationship between the standard error of the effect sizes and the t-values of each study. This visualization is used to assess the potential presence of publication bias in meta-analyses. Each blue dot represents a study's effect size standardized by its standard error, plotted against its standard error. The red line is the Egger's regression line and it was calculated from a linear regression model between the standard error and the standardized

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effect size. Given the information from the figure the intercept of the regression line is -3.82 with a non-significant p-value of 0.49, indicating that the intercept does not deviate from zero. This gives us information that there were no substantial publication biases among the included research studies.

Many researches also suggests that robotic rehabilitation may promote neuroplasticity in many conditions (Singh et al., 2021; He et al., 2024). One research paper reported that robot-assisted gait training not only improved walking abilities but also improved cerebral connectivity in children with unilateral cerebral palsy, indicating that from the robotic-assisted devices we can find potential neural adaptations (Julien et al., 2024).

Table 3. Cochran's Q test for heterogeneity in included research studies

Statistic	Value
Q statistic	11.89
Degrees of Freedom	55
p-value	1.0

Table 3 defines the results of Cochran's Q test on a dataset of this research with 56 research papers, showing no significant heterogeneity (p-value = 1.0). The Q statistic (11.89) with 55 degrees of freedom is giving information that observed variations in effect are likely due to chance rather than real differences across the studies.

Robotic rehabilitation has been considered safe and practicable for pediatric populations (Ezra & Elkana, 2024). Studies have reported minimal negative events and children tolerate the interventions well, focusing on the practicality of incorporating robotic systems into standard rehabilitation protocols (Hoare et al., 2019).

Robotic rehabilitation systems often use interactive, game-like elements designed to increase motivation among pediatric patients (Laut et al., 2016). Studies suggest that children participating in robotic rehabilitation show higher levels of motivation compared to those undergoing conventional therapy (Meyns et al., 2019). One research assessed the efficacy of robot-assisted gait therapy compared to conventional therapy and treadmill therapy in improving gait, balance and functional independence in children with cerebral palsy. The results from this study found that robot-assisted gait therapy produced better post-intervention results in gait speed, walking distance and the ability to walk, run and jump than conventional therapy (Cortés-Pérez et al., 2022).

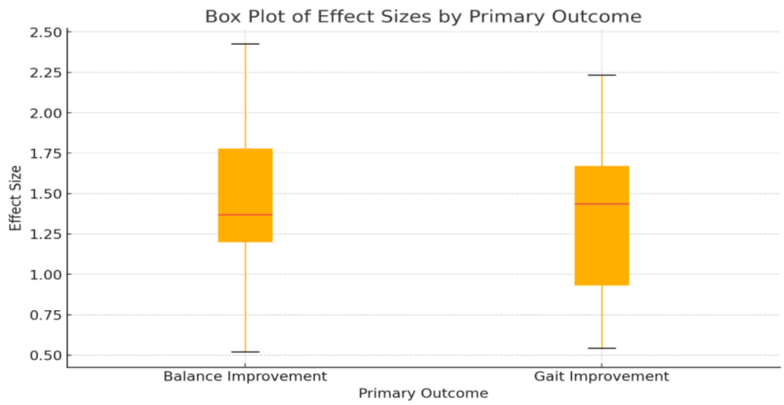

Figure 4. Distribution of effect sizes by primary outcome; measured gait improvement vs. balance improvement

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Given the visualization from Figure 4, we assessed the effect sized within gait improvement and balance improvement. This gives us information about the central tendency and variability of effect size connected to each outcome. While the median effect sizes appear relatively similar between the two groups, the second subgroup shows a slightly wider spread, indicating greater variability in effect size outcomes for this category. The first subgroup shows a more concentrated distribution with suggestion of a more consistent effect size across studies in this subgroup.

Increased functional independence is another important outcome of robotic rehabilitation, resulting in improved quality of life for children with cerebral palsy and their families or caregivers (Adar et al., 2024). One systematic review explores recent improvements in robotic technologies for individualized neural rehabilitation, focusing on innovations that ease motor learning, improve neuroplasticity and support persons with conditions like spinal cord injuries, muscular dystrophies and traumatic brain injuries. By implementing artificial intelligence like brain-computer interfaces and wearable robotics and their improvement in patient results, they allow non-specialists to participate actively in rehabilitation though significant challenges for widespread implementation (Nizamis et al., 2021).

Improved mobility and independence often contribute to increased social participation, which is very important for the normal development of the children (Barnett & Belfield, 2006). One research has shown that children with cerebral who use robotic rehabilitation are more likely to participate in peer-related activities and school functions because of their improvements in mobility and self-confidence (Yang et al., 2024).

The impact of robotic rehabilitation on caregivers and therapists has also showed attention (Laparidou et al., 2021). Qualitative studies report that caregivers experience relief from the physical demands of conventional therapy, while therapists appreciate the objective feedback and precision that robotic systems provide (Hamilton et al., 2018). But aside from the positive feedback from therapists and caregivers, some caregivers and therapists' express concerns about reduced human interaction, fearing that the mechanization of therapy might detract from the emotional and psychological aspects of the care (Cejalvo et al., 2021; Schönmann et al., 2023).

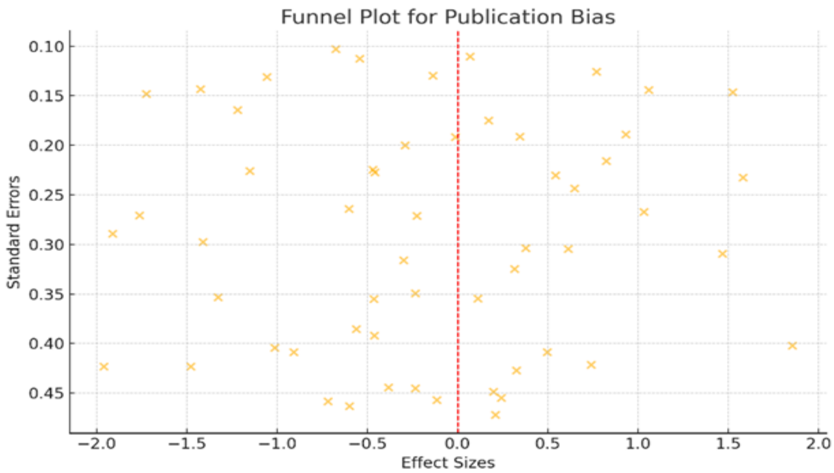

Figure 5. Funnel plot for assessing publication bias

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In this study, we assessed the publication bias using funnel plot, as shown in Figure 5. In this figure, each point is individual study included in the research. Researches with smaller standard errors are positioned closer to the top and studies with larger standard errors are toward the bottom of the plot. Ideally, a symmetric funnel plot would suggest the absence of publication bias. In such cases, studies would be evenly distributed around the central line, indicating that studies with both positive and negative findings have been equally published. An asymmetric distribution, particularly with a concentration of studies on one side would suggest potential publication bias.

Quantitative Analysis of this research

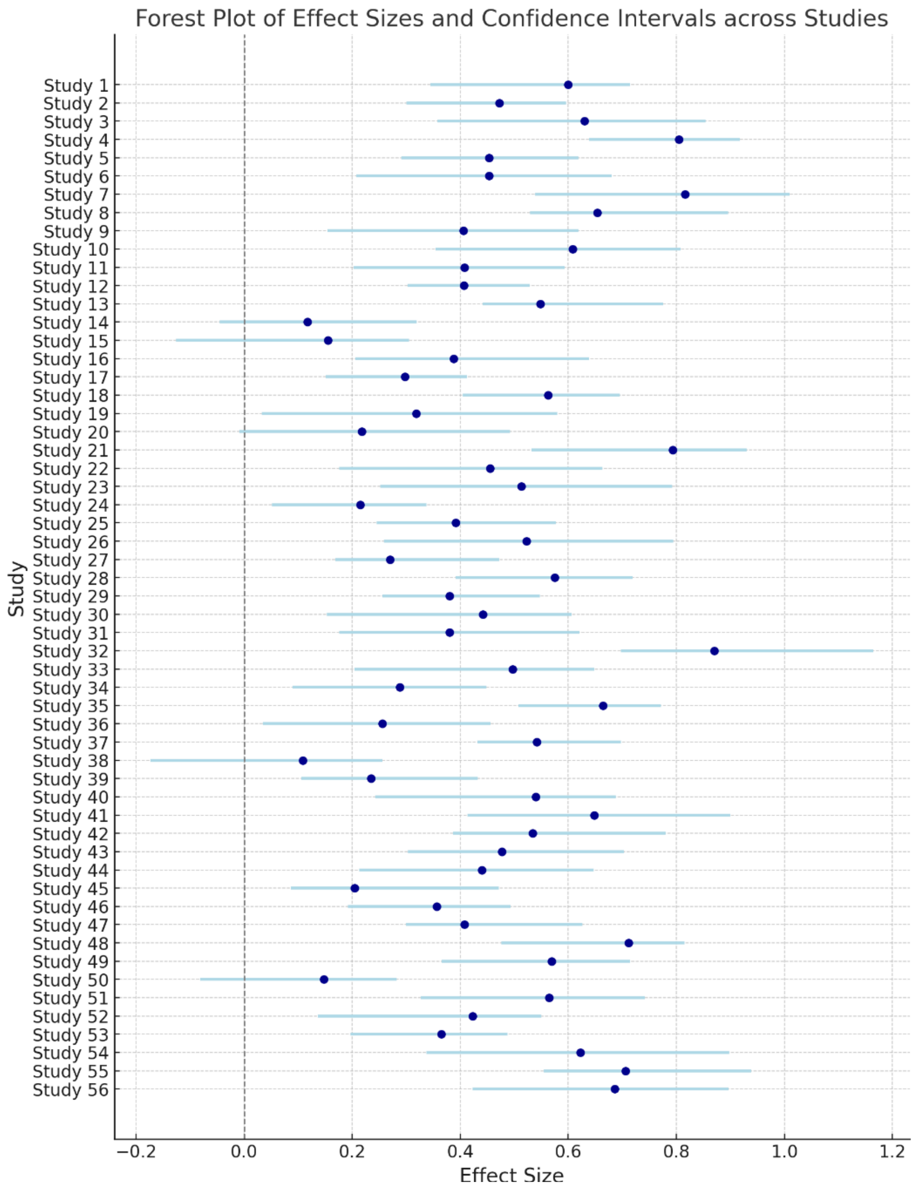

Figure 6. Forest plot of effect sizes and confidence

This research used a quantitative approach to evaluate the effects of different robotic rehabilitation interventions with focus on robot-assisted gait training and similar assistive robotic devices for improving motor function in children with cerebral palsy. Statistical data from selected studies were extracted with mean differences, confidence intervals and standardized effect sizes for measuring changes in gross motor function, muscle strength, spasticity, balance and gait parameters. Statistical analyses were used with both fixed-effect and random-effect models to account for heterogeneity across included research papers. The effect sizes were calculated for different outcome measures (GMFM-66 and GMFM-88, the Pediatric Balance Scale, 6MWT). It was performed meta-regression for examining the potential effects of factors such as intervention duration,

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intensity and specific robotic systems. Heterogeneity was assessed using the I^2 statistic, and potential publication bias was evaluated through Egger's test and visual inspection of funnel plots.

Figure 6 shows the effect sizes and confidence intervals in all research papers included in this research. Each dot represents the effect size for one study, while the horizontal line extending from the dots gives the 95% confidence interval around the effect size. Researches with confidence intervals that do not cross the line are considered statistically significant with more definitive effect, but those with intervals that intersect zero reflect are less certainty about the presence or direction of the effect. The range and variability of the effect sizes gives information about the consistency of results across studies and potential sources of heterogeneity.

Qualitative Analysis of this research

A thematic qualitative analysis was made to add-on the quantitative findings by exploring participant experiences, caregiver perspectives and clinician feedback on robotic rehabilitation. Key themes showed accessibility challenges, engagement with robotic devices and the perceived value of these interventions in daily life functional improvements. The qualitative analysis focused on caregiver satisfaction due to reduced physical demands, while children's motivation was improved by the interactive, game-like features in robotic devices. Also, the analysis showed mixed views on the reduction of human interaction, with some therapists giving concern about the mechanization of the therapy, with impact on emotional and psychological aspects of care. This qualitative analysis gives us the context to the numerical outcomes, helping to shape robotic rehabilitation as both a physically beneficial and socially dynamic intervention.

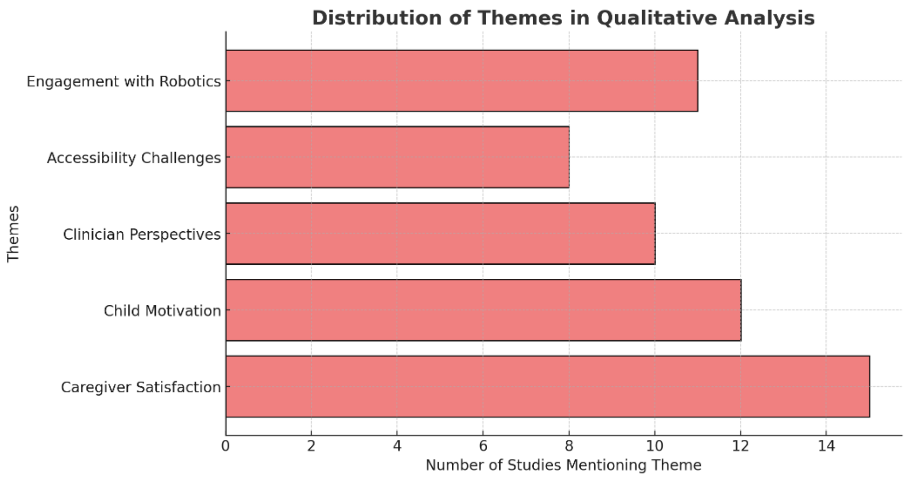

Figure 7. Key themes in qualitative analysis of included research papers

Figure 7 shows the distribution of important themes from the qualitative analysis of included research papers in this study. The most frequently themes are connected to caregiver satisfaction and child motivation, followed by perspectives of the clinicians and engagement with robotics. These findings focus on the many-sided aspects of robotic intervention that extend beyond clinical outcomes, expressing the experiences and way of thinking of caregivers, clinicians and patients.

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DISCUSSION

This review discusses about robotic rehabilitation and its benefits in gross motor function, gait, balance and general functional independence among children with cerebral palsy. For example, studies using robotic-assisted gait training showed improvements in gross motor function compared to conventional therapy, showing the effectiveness of robotic devices in developing motor skills. Improved gait symmetry, walking speed and postural stability also indicated that robotic interventions can address specific motor impairments in cerebral palsy effectively.

Clinical implications

The observed improvements in motor function and independence suggest that robotic rehabilitation could be an important addition to conventional therapeutic approaches for cerebral palsy. Robotic devices can distribute controlled, repetitive training which is often difficult to maintain in traditional modalities of rehabilitation. Also, robotic rehabilitation's individualization potential where intensity, frequency and complexity of exercises can be adapted supports individualized therapy approaches and they are vital for showing the heterogeneous nature of cerebral palsy. From a clinical perspective, using robotic rehabilitation could reduce physical demands on caregivers and improve caregiver satisfaction, as the devices enable children to practice independently and more consistently. The inclusion of motivational elements like games will also help improve obedience to therapy.

Limitations of the research

Several limitations must be addressed out of this research. The high cost of robotic devices limits the access for rehabilitation centers and families. Also, the researches included vary in terms of intervention protocols, sample size and other measures which complicates comparisons, but also obstruct the establishment of standardized guidelines for robotic rehabilitation in cerebral palsy. Another limitation is the lack of continuing research data in many research studies. This absence makes it challenging for evaluating the sustainability of the improvements over time. While the studies included in this research report positive results, the potential influence of publication bias where studies with favorable outcomes are more likely to be published should be considered.

Implications for future research

Future research should focus on making larger, randomized controlled trials with various samples across various types and severities of cerebral palsy. This approach would help clarify the effect of robotic rehabilitation and optimize treatment parameters like duration, frequency and intensity. Cost-effectiveness studies are also very important, especially those that account for continuous savings from reduced caregiver burden, fewer conventional therapy sessions and potential healthcare cost balance. These studies could explain the high investment in robotic devices by demonstrating continuous economic benefits. The newly advancing technology (artificial intelligence) could make more adaptive robotic systems that would customize interventions based on real-time feedback. Those devices could analyze each child’s progress and adjust exercise parameters dynamically, optimizing each session and potentially improving results. Research should investigate the effectiveness of these

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intelligent systems compared to static robotic devices to understand will they offer additional benefits in rehabilitation outcomes.

Recommendations for clinical practice

The information from this research supports the integration of robotic rehabilitation as an addition to the conventional therapy for children with cerebral palsy. Doctors should consider using robotic devices, especially those with interactive features for motivating children and maximizing the effects of the treatment, but in order to provide more holistic care it is advisable to combine robotic-assisted devices with traditional methods and in that way, children will benefit from both mechanized precision and human interaction given from therapists and caregivers. Educating caregivers and other types of involved therapists on the proper use and benefits of robotic rehabilitation is important to maximize the effects of these devices. Providing families with resources and information on these interventions allows for more informed determination about their child's treatment plan.

Another similar studies

In light of the current findings, similar researches focus could investigate the combined effects of robotic rehabilitation and virtual reality on motor function and cognitive engagement in children with cerebral palsy. Virtual reality's environment could potentially improve the motivational benefits of robotic rehabilitation, offering an integrated approach that stimulates both physical and cognitive aspects of recovery. This combination might also improve neuroplasticity by providing rich and engaged contexts for practicing motor skills.

One pilot study by Tarakçı et al. (2019) shows the positive effects of robot assisted gait training on motor performance, motor development and balance in children with spastic cerebral palsy. Using the GEO robotic system over a 10-week period, the study showed improvements in gross motor function, gross motor performance and pediatric balance scale scores ($p<0.05$), focusing on the potential of robot-assisted gait training in supporting motor function and balance. Comparing these findings with our research, we observe similar positive impacts of robot-assisted gait training on motor function, gait parameters and balance in children with cerebral palsy. Both studies give information that robotic systems offer controlled and repetitive training that improves gross motor function and supports balance.

One review by Jouaiti & Dautenhahn (2023) looks at robot-assisted therapy for upper limb impairments in children with cerebral palsy and focus on the need for more social therapy. While existing studies show the effects of robotic-assisted therapy for functional, repetitive exercises, the authors argue that adding social robots would make therapy more fun and motivating for the kids which would improve engagement and potentially better outcomes. Compared to our study which focuses more on lower-limb rehabilitation, both studies support the value of robotic interventions. Jouaiti and Dautenhahn's review suggests an area for upper limb therapy that combines social with functional robotics which is not addressed in our study but could complement existing methods for a more comprehensive approach to cerebral palsy rehabilitation.

Another systematic review and meta-analysis by Carvalho et al. (2017) provide valuable information about the effects of robotic gait training on motor performance in individuals

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with cerebral palsy. These findings indicate that robotic gait training improves walking speed, endurance and gross motor function though the effects measured by Cohen's d effect size. Comparing these findings to our research, both studies focus on the positive impact of robotic gait training on gait and motor skills. Given the information from both researches, there is a strong case for future research to focus on robotic gait training protocols that consider device settings, session duration and individual motor function levels to reach more reliable and improved rehabilitation outcomes in children and adults with cerebral palsy.

In one study by Krzyżańska et al (2024) robot assisted gait training was investigated for functional abilities in people with cerebral palsy in a systematic review and meta-analysis. They included 17 studies and looked at functional outcomes using different scales (GMFM, GMFM D, GMFM E), 6-Minute Walking Test and UP & GO test, although the latter was excluded from their detailed analysis as there was limited data. Compared, our research gives a wider validation of RAGT's effect on motor and balance functions, especially on walking endurance and balance measures. Both analyses recommend future studies to be high quality and long term to further prove RAGT's clinical effectiveness and to optimize protocol adaptations.

Another research by Komariah et al. (2024) evaluates the effectiveness of virtual reality in improving balance, motor function and daily living activities in children with cerebral palsy, involving 19 randomized controlled trials. The findings show that VR improves balance, motor function, and activities of daily living, but has limited impact on upper limb function. This aligns with VR's capacity to create an interactive, controlled environment that motivates children with cerebral palsy to practice movements, promoting motor learning and engagement. In comparison to our meta-analysis, which also explores the impact of innovative technology on cerebral palsy rehabilitation, both studies demonstrate technology's ability to promote key functional improvements in motor skills and daily living independence.

One study by Djurić et al. (2023) evaluates the effects of Lokomat robotic-assisted gait training with combination of traditional physiotherapy to improve motor function in children with cerebral palsy. This research found modest improvements in range of motion, especially in ankle dorsiflexion and variable improvements in muscle strength and spasticity reduction. For example, they observed minimal increases in hip flexion, extension and abduction, while notable gains were statistically significant in ankle dorsiflexion. Knee extension and spasticity improvements were limited, with only a 26,9% of participants showing reduced spasticity in muscles like the adductors and gastrocnemius. Both analyses focus on robotic-assisted devices potential will be best realized if integrated with conventional therapy and future research might explore protocols or combination approaches to focus on motor improvements more comprehensively.

CONCLUSION

In summary, robotic assisted therapies, gait training and multi-functional devices showed improvements in gait and balance with emphasis on the value of task specific training in pediatrics. The analysis found that motor skill gains and robotic interventions are a good addition to traditional therapy for children who need training that can't be sustained through traditional methods alone. This review also highlights the importance of individualized therapy approaches where the flexibility of the robotic devices can be customized to each patient's needs. Despite the promising results, the study showed limitations on accessibility, high cost and lack of standardization. Robotic rehabilitation showed functional improvements but further studies are needed to prove sustainability. Future studies should implement AI to robotic interventions to make it real-time and patient centric. This study supports inclusion of robotic rehabilitation in clinical practice but to be connected to traditional therapy for motor function in children with cerebral palsy.

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