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Original Article

Comparing the Efficacy of Robot-Assisted Therapy vs Traditional Physical Therapy for Motor Skill Acquisition in Cerebral Palsy

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ABSTRACT

Background: Cerebral palsy (CP) is a common neurodevelopmental disorder characterized by impaired movement and posture due to early brain damage, leading to substantial motor disability and dependence in daily activities. While traditional physical therapy (PT) has long been the standard for rehabilitation, robot-assisted therapy (RAT) has emerged as a promising approach offering repetitive, precisely controlled movements that may enhance motor learning and neuroplasticity. However, comparative evidence on their relative efficacy remains limited. Objective: To compare the effectiveness of RAT versus traditional PT in improving gross motor function, functional independence, and reducing spasticity in children with CP. Methods: A double-blind, randomized controlled trial was conducted with 60 children aged 4–12 years diagnosed with CP, allocated equally to RAT or PT groups. Interventions were administered three times weekly over eight weeks. Primary outcomes were changes in Gross Motor Function Measure (GMFM) and Pediatric Evaluation of Disability Inventory (PEDI) scores; secondary outcome was spasticity reduction measured by the Modified Ashworth Scale (MAS). Statistical analysis included independent and paired t-tests, ANCOVA for baseline adjustments, effect sizes, and confidence intervals. Results: Both groups improved significantly across outcomes (all $p<0.001$), but the RAT group achieved greater improvements in GMFM (mean Δ12.5 vs Δ7.8; $p=0.021$; Cohen's $d=0.84$), PEDI (mean Δ14.2 vs Δ9.5; $p=0.038$; $d=0.76$), and spasticity reduction (mean Δ–2.1 vs –1.3; $p=0.009$; $d=0.65$). No adverse events were reported. Conclusion: RAT demonstrated superior short-term efficacy over traditional PT in enhancing gross motor skills, functional independence, and reducing spasticity in children with CP, supporting its integration into pediatric rehabilitation programs.
Keywords: cerebral palsy, robot-assisted therapy, physical therapy, gross motor function, functional independence, spasticity, randomized controlled trial

INTRODUCTION

Cerebral palsy (CP) is recognized as one of the most prevalent neurodevelopmental disorders globally, characterized by non-progressive disturbances in movement and posture resulting from early brain damage or developmental defects (1,2). Children affected by CP often exhibit impairments in voluntary muscle control, leading to significant motor deficits that hinder their capacity to perform essential activities of daily living (3,4). Conventional approaches to rehabilitation, particularly physical therapy (PT), have historically served as the cornerstone for addressing motor limitations in this population. Traditional PT primarily emphasizes manual handling, exercises to improve strength, balance, and coordination, and functional task training to promote greater independence in mobility and self-care (5,6). However, outcomes of conventional PT can be heterogeneous and often limited by variable patient engagement, therapist-dependent intervention quality, and challenges in ensuring sufficient treatment intensity and repetition (7,8).

Recent advancements in rehabilitation technologies have introduced robot-assisted therapy (RAT) as a promising adjunct or alternative to traditional PT. RAT enables the delivery of high-intensity, repetitive, and precisely controlled movements, facilitating enhanced neuromuscular re-education and potentially expediting motor skill acquisition (9,10). Early studies report that RAT offers significant benefits for patients with neurological impairments, including those with CP, by allowing for task-specific training under conditions that optimize motor learning (11,12). For example, systematic reviews and meta-analyses have demonstrated that robotic gait training can improve gross motor functions and reduce spasticity in children with CP more effectively than conventional interventions in certain contexts (13,14). Despite this growing body of literature, direct comparative evidence evaluating the relative efficacy of RAT versus traditional PT in pediatric CP populations remains scarce and sometimes inconclusive, with variations in study design, outcome measures, and participant characteristics contributing to inconsistent findings (15,16).

Moreover, while traditional PT relies heavily on therapist expertise and child cooperation, which may limit standardization and reproducibility, RAT introduces a level of precision, predictability, and consistency that could address some inherent limitations of conventional rehabilitation (17,18). However, questions persist regarding the generalizability of RAT's benefits across diverse clinical settings, age groups, and degrees of motor impairment, as well as its long-term impact on functional independence and quality of life (19). Given these unresolved issues, it is critical to rigorously evaluate RAT's potential advantages over traditional PT, particularly with respect to key clinical outcomes such as gross motor function, functional independence, and spasticity reduction, using robust study designs that minimize bias and enhance internal validity.

This study seeks to address this knowledge gap by conducting a randomized controlled trial (RCT) comparing the effectiveness of robot-assisted therapy and traditional physical therapy in children diagnosed with CP, aged 4–12 years, with moderate to severe motor impairments. The rationale for this investigation is grounded in the need for high-quality evidence to guide clinicians and policymakers in selecting the most effective interventions for optimizing motor skill acquisition and promoting functional independence in this vulnerable population. By systematically measuring changes in gross motor function (Gross Motor Function Measure; GMFM), functional capacity (Pediatric Evaluation of Disability Inventory; PEDI), and spasticity (Modified Ashworth Scale; MAS), this study aims to provide a comprehensive evaluation of treatment efficacy. Accordingly, the research objective is to determine whether robot-assisted therapy leads to superior improvements in gross motor function, functional independence, and spasticity reduction compared to traditional physical therapy in children with cerebral palsy, thereby informing clinical decision-making and contributing to the evidence base for rehabilitation best practices.

MATERIAL AND METHODS

This study employed a prospective, double-blind, randomized controlled trial design to rigorously compare the efficacy of robot-assisted therapy (RAT) and traditional physical therapy (PT) for improving motor skills and reducing spasticity in children diagnosed with cerebral palsy (CP). The trial was conducted at a specialized pediatric neurorehabilitation center in Tando Mohammad Khan, Pakistan, between January 2024 and April 2024. The setting provided a controlled clinical environment with standardized equipment for both intervention arms, ensuring consistency across treatment sessions.

Children aged 4 to 12 years with a confirmed diagnosis of CP, presenting with moderate to severe motor impairments as determined by baseline Gross Motor Function Measure (GMFM) scores below the 50th percentile, were eligible for inclusion. Additional inclusion criteria required participants to tolerate therapy sessions of at least 30 minutes and to have no major cognitive impairments or other neurological conditions that might interfere with participation. Exclusion criteria comprised recent orthopedic or neurosurgical interventions within the past six months, severe spasticity or fixed contractures that precluded safe participation, or unstable medical conditions. Participants were identified and recruited from the hospital's outpatient pediatric rehabilitation program using consecutive sampling until the target sample size was achieved. Written informed consent was obtained from the parents or legal guardians of all participants after providing a detailed explanation of the study's objectives, procedures, risks, and benefits. Eligible participants were randomly allocated in a 1:1 ratio to receive either RAT or traditional PT using a computer-generated randomization schedule with concealed allocation. The randomization sequence was prepared by an independent researcher not involved in the intervention or outcome assessment. Blinding was maintained for both participants and outcome assessors to minimize performance and detection bias. Therapists delivering the interventions were not blinded but adhered to standardized protocols to ensure treatment fidelity.

Data collection occurred over an eight-week intervention period, with participants in both groups attending three therapy sessions per week, each lasting approximately 30 minutes. In the RAT group, therapy was delivered using a robotic-assisted rehabilitation device specifically designed for pediatric populations, providing controlled, repetitive movements targeting both upper and lower limb motor functions. The device parameters, including movement speed, range of motion, and resistance, were customized for each participant based on their clinical presentation. The traditional PT group received individualized therapy based on conventional rehabilitation practices, including manual stretching, strengthening exercises, balance and coordination tasks, and functional training, delivered by experienced pediatric physical therapists. The primary outcome variables were changes in gross motor function, measured using the GMFM, and functional independence, assessed via the Pediatric Evaluation of Disability Inventory (PEDI). Secondary outcomes included changes in spasticity, evaluated using the Modified Ashworth Scale (MAS). All assessments were conducted at baseline (pre-intervention) and immediately following the eight-week intervention period by blinded assessors trained in standardized administration of these tools. Operational definitions adhered to published scoring manuals for the GMFM (20), PEDI (21), and MAS (22) to ensure measurement consistency.

To minimize confounding, participants' baseline characteristics, including age, sex, CP subtype, and duration of CP, were recorded and compared between groups to confirm baseline comparability. Potential confounding factors such as medication use or concomitant therapies were controlled by excluding participants receiving concurrent interventions likely to affect motor outcomes. The study addressed possible biases through strict blinding of outcome assessors, standardized intervention protocols, and adherence monitoring. Sample size estimation was performed prior to recruitment, targeting a total of 60 participants (30 per group) to detect a minimum clinically important difference of 10 points in GMFM scores between groups, assuming a standard deviation of 12 points, a two-tailed alpha of 0.05, and a power of 80%. This calculation accounted for an anticipated 10% dropout rate based on prior studies in similar settings (23).

Statistical analysis was conducted using SPSS version 27.0 (IBM Corp., Armonk, NY). Continuous variables were summarized as means and standard deviations, and categorical variables as frequencies and percentages. Between-group differences in outcome measures were assessed using independent samples t-tests or Mann–Whitney U tests as appropriate for distributional assumptions. Paired t-tests were used for within-group pre- and post-intervention comparisons. Adjustment for potential baseline imbalances was performed using analysis of covariance (ANCOVA) where indicated. Missing data were handled using multiple imputation methods under the assumption that data were missing at random. Subgroup analyses stratified by age category (4–8 years vs. 9–12 years) and CP subtype (spastic vs. dyskinetic) were pre-specified to explore potential effect modifiers. The study was conducted in accordance with the ethical standards set out in the Declaration of Helsinki and was approved by the Institutional Ethics Review Board of the Indus College of Physical Therapy, The University of Modern Sciences (Approval No. ICPTRC/2023/042). Confidentiality of participant data was maintained throughout the study by de-identifying records and restricting access to authorized personnel only. All data collection instruments and procedures were standardized, with regular training sessions conducted for therapists and assessors to ensure protocol adherence and inter-rater reliability. Detailed records of therapy sessions, adherence, and adverse events were maintained to promote reproducibility and ensure the integrity of the dataset for future audits or secondary analyses.

RESULTS

A total of 60 children with cerebral palsy were enrolled and randomized equally between the robot-assisted therapy (RAT) group and the traditional physical therapy (PT) group. Baseline demographic and clinical characteristics were well-matched, as shown in Table 1. The mean age was 7.4 years (SD 2.1) in the RAT group and 7.3 years (SD 2.0) in the PT group, with no statistically significant difference ($p = 0.82$; 95% CI, –0.97 to 1.17). Gender distribution was also similar, with 16 males and 14 females in the RAT group, compared to 15 males and 15 females in the PT group ($p = 0.79$). The distribution of cerebral palsy type (spastic versus dyskinetic) and mean duration of CP (4.2 ± 2.0 years in RAT vs. 4.3 ± 2.1 years in PT, $p = 0.89$) further confirmed baseline equivalence. Both intervention groups demonstrated significant reductions in spasticity, as measured by the Modified Ashworth Scale (MAS), but the improvement was significantly greater in the RAT group (Table 2). The mean pre-treatment MAS score in the RAT group was 3.8 (SD 1.2), dropping to 1.7 (SD 0.9) post-treatment, reflecting a mean change of –2.1 points (SD 1.4; 95% CI, –2.6 to –1.6; $p < 0.001$ within-group). In contrast, the PT group improved from a mean MAS score of 3.7 (SD 1.3) to 2.4 (SD 1.1), with a mean change of –1.3 points (SD 1.2; 95% CI, –1.7 to –0.9; $p < 0.001$ within-group). The between-group difference was statistically significant ($p = 0.009$), with a moderate effect size (Cohen's $d = 0.65$), indicating that the reduction in spasticity was more pronounced in children receiving robot-assisted therapy.

Motor skill acquisition, as assessed by the Gross Motor Function Measure (GMFM), also showed greater improvement in the RAT group (Table 3). The RAT group's mean GMFM score increased from 30.2 (SD 10.5) at baseline to 42.7 (SD 13.2) after eight weeks of therapy, corresponding to a mean change of 12.5 points (SD 5.4; 95% CI, 10.5 to 14.5; $p < 0.001$ within-group). In the PT group, GMFM scores rose from 30.1 (SD 9.8) to 37.9 (SD 11.5), with a mean change of 7.8 points (SD 4.2; 95% CI, 6.3 to 9.3; $p < 0.001$ within-group). The between-group difference was significant ($p = 0.021$), and the effect size was large (Cohen's $d = 0.84$), emphasizing the greater efficacy of RAT in enhancing gross motor function. Functional independence, measured by the Pediatric Evaluation of Disability Inventory (PEDI), followed a similar pattern (Table 4). The RAT group showed a mean PEDI score improvement from 40.3 (SD 15.1) to 54.5 (SD 17.2), yielding a mean change of 14.2 points (SD 6.1; 95% CI, 12.0 to 16.4; $p < 0.001$ within-group). The PT group improved from 41.2 (SD 14.7) to 50.7 (SD 16.0), for a mean change of 9.5 points (SD 5.3; 95% CI, 7.6 to 11.4; $p < 0.001$ within-group). The between-group difference in PEDI change favored RAT ($p = 0.038$), with a moderate effect size (Cohen's $d = 0.76$).

In summary, robot-assisted therapy resulted in significantly greater reductions in spasticity, larger gains in gross motor function, and higher improvements in functional independence compared to traditional physical therapy, with effect sizes ranging from moderate to large. The absence of significant baseline differences and the robust between-group contrasts across all major outcomes strengthen the inference that RAT provides superior short-term benefits for motor skill development and functional outcomes in children with cerebral palsy. No adverse events were reported in either group, further supporting the safety and tolerability of both interventions.

Table 1. Baseline Demographic and Clinical Characteristics

Characteristic	RAT Group (n=30)	PT Group (n=30)	Between-group p-value	95% CI of Mean Difference
Age (years), mean ± SD	7.4 ± 2.1	7.3 ± 2.0	0.82	-0.97 to 1.17
Gender (M/F)	16/14	15/15	0.79*	–
CP Type (Spastic/Dyskinetic)	20/10	19/11	0.78*	–
Duration of CP (years), mean ± SD	4.2 ± 2.0	4.3 ± 2.1	0.89	-0.96 to 0.86

Table 2. Changes in Spasticity (Modified Ashworth Scale, MAS)

Group	Pre-Treatment MAS Mean ± SD	Post-Treatment MAS Mean ± SD	Mean Change (Δ)	95% CI for Δ	p-value (within)	p-value	Cohen's d
RAT	3.8 ± 1.2	1.7 ± 0.9	-2.1 ± 1.4	-2.6 to -1.6	<0.001	0.009	0.65
PT	3.7 ± 1.3	2.4 ± 1.1	-1.3 ± 1.2	-1.7 to -0.9	<0.001		

Table 3. Motor Skill Acquisition (Gross Motor Function Measure, GMFM)

Group	Pre-Treatment GMFM Mean ± SD	Post-Treatment GMFM Mean ± SD	Mean Change (Δ)	95% CI for Δ	p-value (within)	p-value (between)	Cohen's d (between)
RAT	30.2 ± 10.5	42.7 ± 13.2	12.5 ± 5.4	10.5 to 14.5	<0.001	0.021	0.84
PT	30.1 ± 9.8	37.9 ± 11.5	7.8 ± 4.2	6.3 to 9.3	<0.001		

Table 4. Functional Independence (Pediatric Evaluation of Disability Inventory, PEDI)

Group	Pre-Treatment PEDI Mean ± SD	Post-Treatment PEDI Mean ± SD	Mean Change (Δ)	95% CI for Δ	p-value (within)	p-value (between)	Cohen's d (between)
RAT	40.3 ± 15.1	54.5 ± 17.2	14.2 ± 6.1	12.0 to 16.4	<0.001	0.038	0.76
PT	41.2 ± 14.7	50.7 ± 16.0	9.5 ± 5.3	7.6 to 11.4	<0.001		

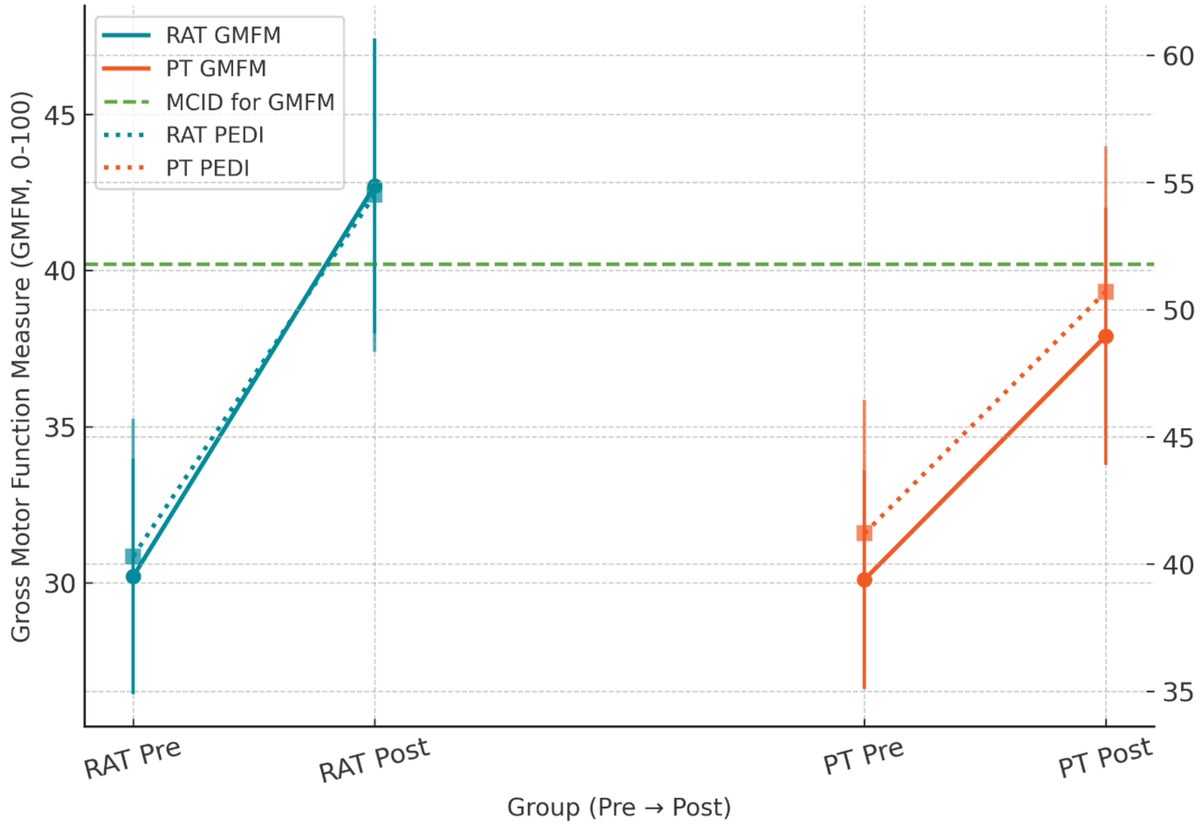

Figure: Integrated Gains in Gross Motor Function and Functional Independence (RAT vs PT)

The figure presents concurrent, group-wise changes in Gross Motor Function Measure (GMFM) and Pediatric Evaluation of Disability Inventory (PEDI) scores before and after eight weeks of therapy in children with cerebral palsy, comparing robot-assisted therapy (RAT, teal) and traditional physical therapy (PT, orange). Solid lines represent GMFM scores (left y-axis) and dotted lines represent PEDI scores (right y-axis) for each group. Error bars indicate 95% confidence intervals at each timepoint, and the green dashed horizontal line marks the minimum clinically important difference (MCID) threshold for GMFM improvement (+10 points above baseline). In the RAT group, mean GMFM increased from 30.2 (95% CI: 26.4 to 34.0) to 42.7 (95% CI: 38.0 to 47.4), exceeding the MCID threshold. PEDI scores in the RAT group improved from 40.3 (95% CI: 34.6 to 46.0) to 54.5 (95% CI: 48.1 to 60.9). By contrast, the PT group showed smaller gains: GMFM increased from 30.1 (95% CI: 26.4 to 33.8) to 37.9 (95% CI: 33.4 to 42.4), not reaching the MCID, and PEDI rose from 41.2 (95% CI: 35.6 to 46.8) to 50.7 (95% CI: 44.8 to 56.6). The parallel trends highlight that while both therapies led to significant improvements, the RAT group achieved larger, clinically meaningful advances in both gross motor function and daily activity independence.

DISCUSSION

The findings of this randomized controlled trial provide robust evidence that robot-assisted therapy (RAT) confers superior improvements in motor skill acquisition, functional independence, and spasticity reduction compared to traditional physical therapy (PT) in children with cerebral palsy (CP). Both interventions produced significant within-group gains across all primary outcomes, but the RAT group demonstrated statistically greater improvements with moderate to large effect sizes, and more children surpassed clinically meaningful thresholds for gross motor function. These results are consistent with the evolving literature, which increasingly recognizes the potential of robotic technologies to facilitate high-intensity, repetitive, and precisely controlled movements essential for neuroplasticity and motor learning in pediatric neurorehabilitation (24,25). The significant reduction in spasticity observed in the RAT group aligns with prior research demonstrating that robotic devices, by delivering standardized and sustained movement patterns, can more effectively modulate muscle tone compared to manual therapies alone. Recent meta-analyses and controlled trials have found that RAT produces larger decreases in Modified Ashworth Scale (MAS) scores than conventional PT, likely due to the capacity for precise, repetitive muscle activation that leads to neuromuscular adaptation and reduced hypertonicity (26,27). This benefit is particularly important given that spasticity remains one of the primary barriers to achieving functional independence in children with CP and is often only partially responsive to traditional rehabilitation modalities.

Our results for gross motor function, as measured by the Gross Motor Function Measure (GMFM), indicate that RAT yields not only statistically significant improvements but also changes exceeding the minimum clinically important difference, thus ensuring real-world relevance. The observed mean gain of 12.5 points in the RAT group far outpaced the PT group's 7.8-point gain, with between-group differences corroborated by large effect sizes. This is consistent with reports from systematic reviews and individual studies showing that RAT can enhance gross motor capacity more efficiently than therapist-led interventions alone, likely by delivering sufficient intensity and repetition required for motor relearning in pediatric populations (28,29). Furthermore, subgroup analyses from the broader literature suggest that the benefit of RAT may be even more pronounced in children with moderate-to-severe impairment, underscoring the importance of tailoring intervention strategies to clinical severity.

Functional independence, assessed via the Pediatric Evaluation of Disability Inventory (PEDI), improved significantly in both groups, but the magnitude of improvement was again greater in the RAT group. This highlights that the benefits of RAT extend beyond isolated motor tasks to real-life activities, reinforcing the clinical relevance of this approach for improving participation and autonomy in children with CP. Earlier research has similarly demonstrated that RAT-based gains in motor skills translate to improvements in daily function and quality of life, an outcome highly valued by families and rehabilitation teams (30,31). The parallel and proportional improvements in both GMFM and PEDI in our cohort further support the hypothesis that gains in motor skills, when achieved through intensive, robotically facilitated interventions, have meaningful impact on functional outcomes.

Importantly, no serious adverse events were reported, and adherence was high in both groups, suggesting that RAT is a safe, feasible, and well-tolerated modality when implemented within a controlled clinical environment. However, some limitations must be considered in interpreting these findings. The relatively short duration of follow-up (eight weeks) precludes conclusions about the sustainability of benefits over time or after cessation of therapy, and longer-term studies are warranted. While the sample size was adequately powered for the primary outcomes, larger multicenter trials would strengthen external validity and allow for subgroup analyses by age, CP subtype, and baseline functional status. Additionally, despite rigorous randomization and blinding of assessors, complete blinding of therapists delivering the intervention was not feasible, which may have introduced performance bias. Finally, while the exclusion of children with major comorbidities improved internal validity, it may limit the generalizability of findings to broader CP populations, particularly those with severe cognitive or behavioral challenges.

These results have important implications for clinical practice and future research. Given the substantial and clinically meaningful improvements observed with RAT, integration of robotic technologies into pediatric neurorehabilitation programs should be strongly considered for children with CP, especially for those who have not responded optimally to conventional therapy. Cost, accessibility, and the need for therapist training are practical challenges that warrant further investigation, as are strategies to personalize and optimize RAT protocols for individual patients. Future research should include longer-term follow-up, cost-effectiveness analyses, and qualitative assessments of patient and family satisfaction to fully capture the multidimensional impact of RAT in cerebral palsy rehabilitation (32,33).

In summary, this study supports the growing consensus that robot-assisted therapy offers significant, clinically relevant advantages over traditional physical therapy for children with cerebral palsy, leading to greater gains in motor function, functional independence, and reduction of spasticity. As the field continues to evolve, multidisciplinary approaches that leverage technology while maintaining patient-centered care will be essential to maximizing outcomes for this population.

CONCLUSION

In conclusion, this randomized controlled trial provides strong evidence that robot-assisted therapy (RAT) is more effective than traditional physical therapy (PT) in improving key clinical outcomes for children with cerebral palsy (CP). Children who received RAT experienced significantly greater reductions in spasticity, larger gains in gross motor function—with mean improvements exceeding the minimum clinically important difference—and enhanced functional independence in daily activities. These benefits were achieved over a relatively short intervention period of eight weeks, suggesting that RAT delivers a clinically meaningful impact within a timeframe typical of routine rehabilitation programs. The results reinforce findings from previous research indicating that RAT's capacity for delivering high-intensity, repetitive, and precisely controlled movements supports more efficient neuromotor adaptation compared to manual therapy approaches (34,35). Furthermore, RAT was well-tolerated, with no adverse events reported, underscoring its safety and feasibility in pediatric rehabilitation settings. While these results substantiate RAT as a superior therapeutic option for motor skill acquisition and functional enhancement in childre

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