Original Article

Efficacy of Virtual Reality-Based Gamified Interventions versus Conventional Therapy for Improving Motor Function in Children with Cerebral Palsy: A Randomized Controlled Trial

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ABSTRACT

Background: Cerebral palsy continues to be the leading cause of motor disability during childhood, impacting balance control, walking ability, and hand function. Virtual reality technology presents an engaging, task-focused rehabilitation approach that may enhance motor skill acquisition and treatment adherence beyond what traditional therapy achieves. To assess whether virtual reality-based gamified therapy delivered by occupational and physical therapists produces better outcomes than traditional therapy for balance, walking, and hand skills in children diagnosed with cerebral palsy.

Methods: This single-blind randomized trial enrolled 84 children (ages 6-14) with spastic cerebral palsy functioning at GMFCS levels I-III. Children were randomly divided into virtual reality treatment (n=42) or traditional therapy (n=42) groups receiving 12 weeks of intervention (three 45-minute sessions weekly). Main measurements included the Pediatric Balance Scale, 10-Meter Walk Test, and Jebsen-Taylor Hand Function Test. Additional measurements examined upper extremity quality and patient involvement.

Results: Children receiving virtual reality therapy showed markedly better progress on the Pediatric Balance Scale (mean difference: 4.8 points, 95% CI: 3.2-6.4, $p<0.001$), walking speed (0.12 m/s faster, 95% CI: 0.08-0.16, $p<0.001$), and hand function testing (8.3 seconds faster completion, 95% CI: 5.1-11.5, $p<0.001$) when compared to traditional treatment. Engagement levels were substantially higher with virtual reality ($p<0.001$). No serious safety concerns emerged.

Conclusion: Virtual reality-based gamified therapy administered by qualified therapists produces significantly better motor function improvements and higher patient involvement compared to traditional approaches in children with cerebral palsy, supporting its incorporation into routine rehabilitation services.

Keywords: *Cerebral palsy, Gamification, Motor skills, Pediatrics, Rehabilitation, Virtual reality*

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INTRODUCTION

Cerebral palsy describes a collection of permanent movement and posture challenges resulting from non-progressive injuries to the developing brain, occurring in roughly 2-3 per 1000 births worldwide[1,2]. The presentation varies widely, encompassing spasticity, uncontrolled movements, and coordination problems, often accompanied by sensory, perceptual, cognitive, and communication difficulties[3]. The most limiting aspects typically involve poor balance control, abnormal walking patterns, and impaired hand function, which together restrict independence and diminish quality of life from childhood through adulthood[4].

For decades, rehabilitation for children with cerebral palsy has centered on traditional therapy approaches provided by occupational and physical therapists. These include neurodevelopmental techniques, constraint-induced movement programs, and repetitive task practice[5,6]. While these methods have shown benefit for motor outcomes, several challenges limit their potential effectiveness. Traditional therapy frequently lacks the intensive repetition needed for learning new motor skills, struggles to keep children engaged throughout prolonged treatment courses, and may inadequately replicate functional real-world situations[7,8]. Additionally, the repetitive nature of many exercises can become monotonous, reducing motivation and compromising participation, especially for children who respond better to play-based activities[9].

Virtual reality technology represents a significant shift in rehabilitation approaches, addressing many shortcomings inherent in traditional methods[10,11]. Virtual reality creates immersive, interactive spaces where children participate in meaningful, goal-oriented tasks within digitally created environments that closely resemble actual situations[12]. The game-like features built into virtual reality systems—such as instant feedback, gradually increasing challenges, reward mechanisms, and competitive elements—create naturally motivating experiences that encourage continued participation and intensive repetition[13,14]. These characteristics align with current understanding of motor learning, which emphasizes task-specificity, frequent practice, and active involvement as essential factors for brain adaptation and functional improvement[15].

Growing research suggests virtual reality rehabilitation may yield better results than traditional approaches across various neurological conditions[16,17]. Several explanations may account for virtual reality's enhanced effectiveness. First, the immersive quality of virtual environments may promote stronger attention and mental engagement, supporting more effective motor learning through improved sensory-motor connection[18]. Second, providing enhanced feedback through multiple senses—visual, sound, and touch—assists with identifying and correcting errors, which is essential for developing new skills[19]. Third, virtual reality systems allow precise adjustment of task difficulty to match each person's abilities, maintaining an ideal challenge level that maximizes learning[20]. Finally, the entertaining game format substantially increases natural motivation, potentially enabling children to achieve the high practice volumes necessary for meaningful improvement[21].

Despite encouraging initial results, the evidence supporting virtual reality treatments for pediatric cerebral palsy remains limited and inconsistent in approach[22,23]. Earlier studies have differed greatly regarding virtual reality technology used, treatment protocols, outcome measurements, and comparison conditions, making firm conclusions about effectiveness difficult. Many previous trials have used small participant numbers, lacked proper randomization or assessment blinding, and failed to include suitable comparison groups receiving equal therapist time and treatment length[24]. Furthermore, few studies have comprehensively examined effects across multiple motor areas—balance, walking, and hand function—that together determine functional ability in children with cerebral palsy[25].

This study was designed to address these research gaps through a carefully designed randomized trial comparing virtual reality-based gamified treatment to traditional therapy in children with cerebral palsy. We predicted that virtual reality treatments, when delivered by trained occupational and physical therapists with treatment intensity matching traditional therapy, would produce better improvements in balance, walking parameters, and hand skills. We also expected virtual reality treatments would demonstrate higher patient involvement and satisfaction, factors that may contribute to continued participation and lasting functional benefits. Through comprehensive assessment tools, adequate participant numbers, and suitable comparison conditions, this trial aims to provide strong evidence to inform treatment decisions and guide virtual reality technology integration into standard pediatric rehabilitation practice.

METHODOLOGY

Study Design

This single-blind, parallel-group randomized controlled trial took place at three major pediatric rehabilitation centers from October 2024 through July 2025.

Participants

Children aged 6-14 years with confirmed spastic cerebral palsy diagnosis (affecting one side, both legs or all four limbs) functioning at Gross Motor Function Classification System (GMFCS) levels I-III were eligible for participation. Additional inclusion requirements encompassed the capability to understand and follow basic instructions, Manual Ability Classification System levels I-III, and medical stability without recent botulinum toxin injections or bone surgery within the preceding six months.

Children were excluded if they presented with poorly controlled seizure disorders, significant vision or hearing problems preventing virtual reality use, significant cognitive impairment (IQ below 50), and participation in other intervention research, history of motion sickness or virtual reality-induced discomfort, or medical contraindications to intensive physical therapy.

Sample Size

Sample size calculation used the Pediatric Balance Scale as the primary measure, expecting a 4-point average difference between groups with a standard deviation of 5.5, significance level of 0.05, and 80% power. This determined 38 participants per group were needed. Anticipating 10% dropout, we aimed to recruit 84 participants (42 per group).

Randomization and Blinding

Participants received random assignment to treatment or comparison groups using computer-generated random numbers in blocks of four, separated by GMFCS level (I-II versus III) and age group (6-9 versus 10-14 years). Assignment concealment used sequentially numbered, sealed envelopes opened by an independent coordinator following baseline evaluation. Outcome evaluators remained unaware of group assignments; however, participants and treating therapists could not be blinded due to treatment nature.

Interventions

Virtual Reality Treatment Group: Participants received virtual reality-based therapy using commercial gaming systems (Nintendo Switch with Ring Fit Adventure, Xbox Kinect with rehabilitation-specific games, and Oculus Quest 2 with age-suitable motor training programs). Certified occupational and physical therapists trained in virtual reality rehabilitation protocols delivered sessions. Each 45-minute session contained 5-minute preparation (stretching and readiness activities), 35 minutes virtual reality gaming (balance activities 15 minutes, walking training games 10 minutes, hand skill tasks 10 minutes), and 5-minute closing and reflection. Games progressively increased in difficulty based on individual achievement. Balance activities featured virtual tightrope walking, avoiding obstacles, and posture control challenges. Walking training incorporated virtual paths, stepping games, and dance-based movements. Hand skill tasks emphasized virtual object handling, sorting activities, and precision reaching exercises.

Traditional Therapy Group

Participants received standard care from occupational and physical therapists following neurodevelopmental treatment principles. Sessions matched virtual reality group length (45 minutes, three times weekly for 12 weeks) and included balance training (standing exercises, shifting weight, single-leg positions, stability ball activities), walking training (floor walking, treadmill practice, stair climbing, navigating obstacles), and hand skill training (grasping and releasing objects, manipulation exercises, using both hands together, writing practice). Both groups received equal therapist attention, encouragement, and guidance. Home exercises were not assigned to isolate treatment effects.

Outcome Measures

Primary Outcomes: The Pediatric Balance Scale served as the primary balance measure, comprising 14 items scored 0-56 where higher scores represent better balance with a meaningful clinical change of 3 points[26]. The 10-Meter Walk Test measured walking speed over the middle 6 meters of a 10-meter pathway with meaningful clinical change of 0.05 m/s[27]. The Jebsen-Taylor Hand Function Test provided timed evaluation of seven hand function activities where shorter times indicate better performance[28].

Secondary Outcomes: The Quality of Upper Extremity Skills Test examined dissociated movement, grasping, weight bearing, and protective responses through 36 items[29]. The Pediatric Evaluation of Disability Inventory -

Computer Adaptive Test assessed functional abilities in daily activities[30]. A custom Engagement Scale using 10-point ratings evaluated child's interest, enjoyment, and effort during sessions, completed by therapists after each session. The Caregiver Assistance and Resources Scale measured caregiver burden and help needed.

Evaluations occurred at baseline (T0), 6 weeks (T1), 12 weeks/end of treatment (T2), and 3-month follow-up (T3) by masked evaluators with established agreement between raters (ICC greater than 0.85).

Statistical Analysis

Data received analysis using SPSS version 28.0 following intention-to-treat principles. Baseline characteristics received comparison using independent t-tests for continuous measures and chi-square tests for categorical measures. Primary analysis used mixed-design repeated measures ANOVA to examine group × time interactions. Follow-up comparisons used Bonferroni correction. Effect sizes were calculated using Cohen's d. Missing data (under 5% overall) received handling through multiple imputation. Statistical significance was established at p less than 0.05 (two-tailed).

Ethical Considerations

The ethical approval for the study was granted by the Foundation of Medical Research and Laboratories Institutional Review Board with identification number FMRL-IRB/2024/028. Every procedural element of the study followed the fundamental ethical principles in the Declaration of Helsinki. Informed parental consent or legal guardian consent was obtained in writing, and the child provided informed verbal assent before enrollment.

All the confidentiality of the participants were held confidential through coded identifiers and secure data handling systems. Families were informed of the potential to withdraw from the study at any time without risking the standards of the child’s behavior. The therapist was present with all participants during the intervention sessions to monitor for any potential safety concerns (e.g., fatigue or discomfort).

RESULTS

Participant Flow and Baseline Characteristics

From January 2023 to March 2024, 104 children underwent eligibility screening. Of these, 84 satisfied inclusion requirements and received randomization to virtual reality treatment (n=42) or traditional therapy (n=42) groups. Four participants (virtual reality: 2, traditional: 2) withdrew during treatment due to family relocation (n=2) and declining interest (n=2). Eighty participants (95.2%) completed the 12-week treatment, and 78 (92.9%) completed the 3-month follow-up evaluation.

Baseline characteristics showed good balance between groups (Table 1). Average age was 9.8±2.4 years, with 58.3% being male. Cerebral palsy types included spastic diplegia (48.8%), hemiplegia (35.7%), and quadriplegia (15.5%). GMFCS distribution was similar between groups (p=0.76).

Table-1 Demographic Characteristics of Participants

Characteristic	VR Group (n=42)	Traditional Group (n=42)	p-value
Age (years)	9.7±2.3	9.9±2.5	0.69
Male	24 (57.1)	25 (59.5)	0.83
CP Subtype			0.88
Spastic diplegia	21 (50.0)	20 (47.6)	
Spastic hemiplegia	14 (33.3)	16 (38.1)	
Spastic quadriplegia	7 (16.7)	6 (14.3)	
GMFCS Level			0.76
Level I	16 (38.1)	18 (42.9)	
Level II	18 (42.9)	16 (38.1)	
Level III	8 (19.0)	8 (19.0)	
MACS Level,			0.82
Level I	15 (35.7)	16 (38.1)	
Level II	20 (47.6)	19 (45.2)	
Level III	7 (16.7)	7 (16.7)	
Weight (kg)	32.4±8.9	33.1±9.2	0.71
Height (cm)	134.2±14.6	135.8±15.1	0.61

Primary Outcomes

Balance (Pediatric Balance Scale)

Significant group × time interaction emerged ($F=18.42$, $p<0.001$, $\eta p^2=0.19$). The virtual reality group demonstrated greater improvement from baseline to 12 weeks (mean difference: 7.3 points, 95% CI: 6.1-8.5) compared to traditional therapy (2.5 points, 95% CI: 1.4-3.6). Between-group difference at 12 weeks reached 4.8 points (95% CI: 3.2-6.4, $p<0.001$, Cohen's $d=0.89$), surpassing the meaningful clinical change threshold. Improvements persisted at 3-month follow-up.

Walking Speed (10-Meter Walk Test)

Significant interaction effect appeared ($F=15.67$, $p<0.001$, $\eta p^2=0.17$). The virtual reality group improved walking speed by 0.18 m/s (95% CI: 0.14-0.22) versus 0.06 m/s (95% CI: 0.03-0.09) in the traditional group. Between-group difference at 12 weeks was 0.12 m/s (95% CI: 0.08-0.16, $p<0.001$, Cohen's $d=0.82$), representing a clinically important change.

PEDI-CAT Functional Skills

Both groups improved, but virtual reality group demonstrated greater gains in daily activities area (between-group difference: 3.4 points, 95% CI: 1.8-5.0, $p<0.001$) and mobility area (2.8 points, 95% CI: 1.5-4.1, $p<0.001$).

Engagement Scores

Mean engage QUEST = Quality of Upper Extremity Skills Test; PEDI-CAT = Pediatric Evaluation of Disability Inventory - Computer Adaptive Test

Hand Function (Jebsen-Taylor Hand Function Test)

The virtual reality group showed significantly greater reduction in completion time ($F=12.34$, $p<0.001$, $\eta p^2=0.14$). Mean improvement reached 12.4 seconds (95% CI: 9.8-15.0) in virtual reality group versus 4.1 seconds (95% CI: 2.3-5.9) in traditional group. Between-group difference was 8.3 seconds (95% CI: 5.1-11.5, $p<0.001$, Cohen's $d=0.75$).

Table-2 Primary Outcome Measures - Mean (SD) Scores

Outcome	Group	Baseline (T0)	6 Weeks (T1)	12 Weeks (T2)	3-Month F/U (T3)	Within-Group Change T0-T2	Between-Group Difference at T2	p-value
PBS (0-56)	VR	38.2 (6.8)	42.1 (6.2)	45.5 (5.9)	44.8 (6.1)	7.3 (6.1 to 8.5)	4.8 (3.2 to 6.4)	<0.001
	Trad	37.9 (7.1)	39.4 (6.9)	40.4 (7.0)	40.1 (7.2)	2.5 (1.4 to 3.6)		
10MWT (m/s)	VR	0.64 (0.19)	0.74 (0.18)	0.82 (0.17)	0.80 (0.18)	0.18 (0.14 to 0.22)	0.12 (0.08 to 0.16)	<0.001
	Trad	0.66 (0.20)	0.69 (0.19)	0.72 (0.19)	0.71 (0.20)	0.06 (0.03 to 0.09)		
JTHFT (seconds)	VR	48.6 (12.3)	42.8 (11.5)	36.2 (10.8)	37.1 (11.2)	-12.4 (-15.0 to -9.8)	-8.3 (-11.5 to -5.1)	<0.001
	Trad	47.8 (13.1)	45.9 (12.8)	43.7 (12.6)	44.2 (12.9)	-4.1 (-5.9 to -2.3)		

PBS = Pediatric Balance Scale; 10MWT = 10-Meter Walk Test; JTHFT = Jebsen-Taylor Hand Function Test; VR = Virtual Reality; Trad = Traditional; F/U = Follow-up

Secondary Outcomes

Quality of Upper Extremity Skills Test

The virtual reality group showed superior improvements in total scores (mean difference: 8.9 points, 95% CI: 6.2-11.6, $p<0.001$) compared to traditional therapy (3.2 points, 95% CI: 1.5-4.9). Dissociated movement and grasping areas showed the largest between-group differences ($p<0.001$) (Table 3).

Adverse Events and Adherence

No serious adverse events occurred in either group. Three participants in the virtual reality group experienced mild temporary discomfort from virtual reality (dizziness, nausea) during early sessions, resolving with shorter session lengths and gradual adaptation. Minor muscle discomfort was reported equally between groups (VR: 5 cases; Traditional: 6 cases). Participation rates were excellent in both groups (VR: 96.3%; Traditional: 94.8%, p=0.54).

Subgroup Analyses

Exploratory subgroup examination revealed virtual reality treatments were especially effective for children with GMFCS levels I-II (p<0.001 for all primary outcomes) compared to level III, where benefits existed but were reduced. Age subgroups (6-9 versus 10-14 years) showed no significant different treatment effects.

Cerebral palsy type examination indicated hemiplegia and diplegia subgroups benefited more than quadriplegia, though smaller numbers limited firm conclusions.

Table-3 Change in Scores from Baseline to 12 Weeks

Outcome	Group	Baseline	12 Weeks	Change	Between-Group Difference	p-value
QUEST Total (0-100)	VR	64.3 (14.2)	73.2 (13.1)	8.9 (6.2 to 11.6)	5.7 (2.8 to 8.6)	<0.001
	Trad	63.8 (15.1)	67.0 (14.8)	3.2 (1.5 to 4.9)		
PEDI-CAT Daily Activities	VR	42.8 (8.6)	48.5 (8.2)	5.7 (4.2 to 7.2)	3.4 (1.8 to 5.0)	<0.001
	Trad	43.2 (8.9)	45.5 (8.7)	2.3 (1.1 to 3.5)		
PEDI-CAT Mobility	VR	38.6 (9.2)	44.1 (8.8)	5.5 (4.1 to 6.9)	2.8 (1.5 to 4.1)	<0.001
	Trad	39.1 (9.5)	41.8 (9.3)	2.7 (1.6 to 3.8)		
Engagement Score (1-10)	VR	8.6 (0.8)	8.7 (0.9)	0.1 (-0.2 to 0.4)	2.4 (2.0 to 2.8)	<0.001
	Trad	6.4 (1.1)	6.3 (1.2)	-0.1 (-0.4 to 0.2)		

DISCUSSION

This randomized controlled trial offers strong evidence that virtual reality-based gamified treatments delivered by qualified occupational and physical therapists significantly exceed traditional therapy in improving balance, walking, and hand skills in children with cerebral palsy. The superior outcomes observed in the virtual reality group across all main measurements, combined with substantially higher involvement scores, support incorporating virtual reality technology into standard pediatric rehabilitation services for this population.

The 4.8-point benefit in PBS scores observed in the virtual reality group substantially surpasses the established meaningful clinical change of 3 points, demonstrating not just statistically significant but clinically relevant improvements in posture control and balance ability[26]. These results align with brain function principles suggesting immersive virtual reality environments may strengthen balance training through several pathways. The rich multi-sensory feedback provided by virtual reality systems—combining visual, sound, and body position information—may support more effective sensory-motor connection processes essential for posture control[18]. Additionally, virtual reality-based balance challenges can be precisely adjusted to maintain ideal difficulty levels that promote motor learning without causing excessive instability or fear of falling, factors that often restrict traditional balance training intensity.

The 0.12 m/s improvement in walking speed in the virtual reality group represents a functionally significant enhancement in walking capacity. Research shows that speed increases of this size in pediatric cerebral palsy populations translate to meaningful improvements in community mobility and participation in age-appropriate activities[27]. The walking training games used in our virtual reality approach incorporated elements such as rhythmic timing, goal-directed stepping activities, and simulated environmental navigation that may have enhanced walking pattern learning through increased motivation and task-specificity compared to traditional treadmill or floor walking practice. The continued improvements observed at 3-month follow-up suggest these gains reflect genuine motor learning rather than temporary performance effects, an encouraging finding with implications for lasting functional outcomes.

Hand skill improvements, as shown by 8.3-second reductions in Jebsen-Taylor test completion times, demonstrate virtual reality treatments' effectiveness extends beyond gross motor areas to include upper limb function. The virtual object handling tasks used in our approach required precise reaching, grasping, and using both hands together—skills directly applicable to daily living activities such as eating, dressing, and schoolwork. The game format of these tasks likely promoted higher practice amounts than achievable with traditional hand skill exercises, taking advantage of the repetition-dependent nature of motor skill learning[19]. Additionally, the immediate visual feedback inherent to virtual reality systems may have accelerated error identification and motor plan improvement processes critical for refining precision movements.

Perhaps the most striking finding was the substantial difference in involvement scores between groups (mean difference: 2.4 points on 10-point scale), representing a large effect size (Cohen's d=2.28). This heightened involvement likely contributed to the superior motor outcomes observed in the virtual reality group through multiple pathways. First, increased motivation enables sustained attention and mental engagement during practice, factors that enhance motor learning efficiency[21]. Second, higher involvement allows children to tolerate longer practice durations and more repetitions, increasing the total amount of task-specific training—a critical factor for brain adaptation. Third, the enjoyment associated with gamified treatments may reduce perception of effort and tiredness, allowing children to practice at higher intensities than would be sustainable with traditional exercises. The sustained high involvement throughout the 12-week virtual reality treatment contrasts sharply with the slight decline observed in traditional therapy, suggesting virtual reality systems may be particularly valuable for maintaining long-term participation in pediatric populations. This finding has important clinical implications, as poor participation represents a widespread challenge in pediatric rehabilitation that significantly undermines treatment effectiveness. The ability of virtual reality treatments to maintain natural motivation over extended periods may translate to improved long-term functional paths when implemented as part of ongoing rehabilitation programs.

Our findings support and extend previous research examining virtual reality treatments in pediatric cerebral palsy. A combined analysis by Chen and colleagues reported moderate effects of virtual reality on balance and motor function, but noted substantial variation across included studies and called for larger, high-quality trials[22]. Our study addresses these concerns through careful randomization, adequate participant numbers, blinded evaluation, and appropriate comparison conditions matching treatment intensity. Similarly, Luna-Oliva and team showed improvements in balance and gross motor function following Kinect-based treatments, though their study lacked a traditional therapy comparison group receiving equivalent therapist attention[23].By ensuring both groups received equal therapist contact time and encouragement, our design isolates the specific contributions of virtual reality technology beyond general therapist interaction effects.

Recent combined reviews have highlighted the need for studies examining virtual reality effects across multiple motor areas simultaneously and including follow-up evaluations to assess retention[24]. Our comprehensive evaluation covering balance, walking, and hand function, coupled with 3-month follow-up data, provides more complete evidence regarding virtual reality's therapeutic potential and durability of effects. The maintained improvements at follow-up suggest the motor learning achieved through virtual reality training exhibits reasonable stability, though additional research examining longer-term outcomes remains warranted.

Clinical Implications

The superior outcomes and involvement associated with virtual reality treatments support their integration into clinical practice for pediatric cerebral palsy rehabilitation. However, successful implementation requires consideration of several practical factors. First, virtual reality systems must be selected based on appropriateness for pediatric use, with age-suitable content, adjustable difficulty levels, and strong safety features. Second, therapists require training not only in virtual reality system operation but also in principles of motor learning and how to optimize virtual reality parameters to achieve therapeutic goals. Third, virtual reality treatments should be viewed as additions to, rather than wholesale replacements for, traditional therapy techniques. Certain therapeutic goals—such as hands-on facilitation techniques, passive stretching, and individualized activity adaptations—remain best addressed through traditional approaches[25].

Cost considerations warrant discussion, as virtual reality systems represent initial investments that may challenge facilities with limited resources. However, several factors suggest virtual reality treatments may prove cost-effective over time. Commercial gaming systems utilized in our study are increasingly affordable (under $500 USD for basic setups), multiple patients can utilize the same equipment, and the enhanced involvement may reduce total therapy hours required to achieve functional gains. Formal cost-effectiveness studies comparing virtual reality to traditional therapy would provide valuable evidence to guide resource decisions.

Strengths and Limitations

This study demonstrates several important strengths including rigorous randomized controlled trial design with adequate participant numbers, proper randomization procedures, and blinded outcome evaluation. The comprehensive outcome measurements assessed multiple motor areas, while an active comparison group received equivalent therapist attention controlling for non-specific therapy effects. High participation rates and low dropout ensured robust data collection, with follow-up evaluation allowing examination of treatment effect retention. Multi-center recruitment enhanced applicability to diverse clinical settings, and detailed treatment protocols enable study replication.

Several limitations warrant acknowledgment. First, therapist and participant blinding proved impossible given the treatment nature, potentially introducing performance and detection bias despite blinded evaluator protocols. Second, our participant sample included only children with spastic cerebral palsy at GMFCS levels I-III; findings may not apply to more severely affected children or other cerebral palsy types. Third, the 3-month follow-up period provides limited insight into long-term functional paths extending into adolescence and adulthood. Fourth, while involvement received assessment through therapist ratings, we did not employ objective measures of neural engagement such as brain wave monitoring. Fifth, the variety of virtual reality systems utilized prevents firm conclusions about optimal system characteristics. Finally, we did not assess potential dose-response relationships or identify optimal treatment duration.

Recommendations for Future Research

Several research directions merit priority attention including dose-response studies investigating optimal virtual reality treatment intensity, long-term outcome studies extending beyond one year, mechanism studies employing brain imaging to elucidate neural mechanisms, and technology optimization studies identifying critical virtual reality system characteristics. Expanded population studies should include children at GMFCS levels IV-V and other cerebral palsy types, while home-based program evaluations should assess telerehabilitation models. Personalization algorithm development, cost-effectiveness analyses, participation outcome studies, and implementation science research would further advance the field and support clinical adoption of virtual reality technology in pediatric rehabilitation.

CONCLUSION

This randomized controlled trial demonstrates that virtual reality-based gamified treatments administered by occupational and physical therapists significantly improve balance, walking speed, and hand skills in children with cerebral palsy compared to traditional therapy approaches. The superior motor outcomes, coupled with substantially enhanced patient involvement, support the clinical integration of virtual reality technology into standard pediatric cerebral palsy rehabilitation services. The maintained improvements at 3-month follow-up suggest these gains reflect genuine motor learning rather than temporary effects.

While virtual reality should complement rather than replace traditional therapy techniques, the evidence supports its role as a valuable tool for enhancing rehabilitation effectiveness and patient participation. The game-like nature of virtual reality interventions addresses a critical challenge in pediatric rehabilitation—maintaining motivation and engagement throughout extended treatment courses. Future research should examine long-term functional outcomes, optimal treatment parameters, and implementation strategies to facilitate widespread clinical adoption of this promising technology. As virtual reality systems become increasingly affordable and accessible, their integration into routine clinical practice offers substantial potential to improve outcomes for children with cerebral palsy.

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Author Contributions
Iqra Wahaj collected data and drafted the manuscript. **Amenah Salim** assisted in data collection and literature review. **Faraz Iqbal Tipu** analyzed the data and interpreted the findings. **Noor-us-Saba** revised the manuscript critically. **Akbar Mughal** supervised the study and approved the final draft. All authors approved the final version of the manuscript.

Ethical Approval
This study received approval from the Foundation of Medical Research and Laboratories Institutional Review Board (Reference#FMRL-IRB/2024/028).

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Conflict of Interests
None.

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