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Efficacy of transcranial direct current stimulation and mirror therapy on motor development in children with spastic cerebral palsy: a randomised clinical trial

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Abstract

Introduction. Cerebral palsy (CP) is a neurological disorder caused by a brain injury that severely affects children's motor development. This study investigates the effects of two non-invasive techniques: transcranial direct current stimulation (tDCS) and mirror therapy (MT), on motor development in children with spastic quadriplegic cerebral palsy.

Methods. A randomised, double-blind clinical trial was conducted at Ghurki Hospital's rehabilitation centre in Lahore, which involved 93 diagnosed CP patients divided into three groups. Group A received tDCS, MT, and routine physical therapy (RPT); group B received MT and RPT; and group C received tDCS and RPT. tDCS and MT were applied for 15 min per side over two weeks, while RPT lasted 20 min for ten weeks. Motor development was assessed using three tools: developmental age via the Shoaib sensorimotor development tool, gross motor function through the Gross Motor Function Measure (GMFM) and Time Up and Go test (TUG), and fine motor skills using the Nine-Hole Peg Test (NHPT) and Box and Block Test (BBT). Assessments were conducted at baseline, after two weeks, and after ten weeks.

Results. Group A showed significant improvements in gross and fine motor development ($p < 0.05$). Compared with the other groups, effect sizes were $\eta^2 = 0.451$ for developmental age, $\eta^2 = 0.575$ for motor development, $\eta^2 = 0.575$ for GMFM scores, $\eta^2 = 0.090$ for TUG scores, $\eta^2 = 0.085$ for NHPT scores, and $\eta^2 = 0.139$ for BBT scores.

Conclusions. This trial highlights the effectiveness of combining tDCS, MT, and RPT in enhancing motor skills in cerebral palsy patients.

Key words: cerebral palsy, motor development, mirror therapy, transcranial direct current stimulation

Introduction

Cerebral palsy is a neurological disorder caused by injuries to the developing brain [1]. It affects a child's overall motor development by disturbing motor skills, speech, sensory development, balance, social interaction, and reflex integration [2]. Eventually, this deficiency can lead to social deprivation and neuromuscular abnormalities that affect their physical, cognitive, and social development [3, 4]. CP can be classified based by gross motor function Level, the affected brain area, and the body regions involved. When the pyramidal system (motor cortex) is compromised, resulting in involvement of all four limbs and the trunk, the condition is referred to as spastic quadriplegic CP (SQCP). Among CP subtypes, spastic quadriplegic cerebral palsy represents one of the most severe forms, characterised by involvement of all four limbs and the trunk, leading to profound functional limitations and dependence [5].

Over the past 40 years, the prevalence of CP has significantly increased, now at 2.0 cases per 1,000 live births [6]. In Iran, the rate is 2.06 cases per 1,000 live births [7], whereas in Pakistan, it stands at 1.22 per 1,000 live births [8]. Prenatal, perinatal, and postnatal factors, including low birth weight, birth malformations, placental anomalies, meconium aspiration, Caesarean section, and postpartum seizures, influence CP development [9].

Neuroscience advances have shown that the growing brain has significant neuroplastic capacity, especially in early childhood, enabling neuronal networks to remodel in response to task-specific training and targeted stimulation [10]. Neuroplasticity-driven rehabilitation techniques seek to take advantage of this adaptability by directly altering cortical excitability and strengthening functional motor connections. Goal-directed functional training, bimanual therapy, and reflex inhibitory techniques are examples of traditional paediatric rehabilitation procedures that remain crucial, but their results may be limited when applied alone, especially in children with severe motor deficits [11]. As a result, interest in adjunct neuromodulatory therapies that potentially improve the efficacy of traditional therapy has grown.

Transcranial direct current stimulation (tDCS) is a non-invasive brain stimulation technology that uses low-intensity electrical currents to regulate neuronal excitability in the cerebral cortex [12]. Anodal tDCS applied across the primary motor cortex has been demonstrated in paediatric neurorehabilitation to enhance cortical activation, lessen stiffness, and improve upper limb function, walking, and balance in children with spastic cerebral palsy [13]. When paired with physical therapy, multiple randomised controlled studies and systematic reviews show that tDCS can safely improve motor outcomes, including gross motor function, functional mobility, and motor learning [14].

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Evidence from adult stroke rehabilitation further supports the neuromodulatory benefits of tDCS, showing improvements in upper limb function, balance, and functional recovery, especially when integrated into task-oriented motor training [15]. These findings provide a strong translational rationale for applying tDCS in paediatric populations with motor deficits.

The positive aspects of tDCS, including its non-invasiveness, affordability, portability, and relative ease of administration in clinical and research settings, largely explain its growing recognition [12]. Paediatric research suggests that tDCS is usually well tolerated, with few side effects, mostly minor tingling or scalp discomfort [16]. Nevertheless, tDCS remains largely in the research pipeline despite positive findings. Limitations include inconsistent outcome measures across studies, patient demographic heterogeneity, and variations in stimulation procedures (intensity, duration, electrode montage) [17]. Additionally, children's long-term effects and optimal dosage parameters remain unknown, reinforcing the need for thorough, carefully monitored trials using unbiased assessment instruments.

Technological advancements in medical sciences have led to new treatment strategies that directly activate the CNS, potentially rearranging neuronal connections and improving motor performance [5]. Anodal tDCS applied to the primary motor cortex in CP patients improves balance and gait parameters and decreases spasticity in the shoulder, elbow, and wrist [13]. When tDCS is delivered via anodes, it depolarises brain activity in an excitatory manner, whereas cathodal stimulation inhibits it through repolarisation [12].

Mirror therapy (MT) is a neuroplasticity-based technique that improves motor planning and execution by activating mirror neurons in the premotor and motor cortices through visual feedback. Mirror treatment has been shown to improve upper limb dexterity, grip strength, coordination, and functional use of the affected limb in children with cerebral palsy [18]. Systematic reviews have found moderate evidence that mirror treatment improves motor outcomes in paediatric CP populations [19]. Furthermore, MT has been demonstrated to facilitate bilateral motor integration and cortical transformation, making it especially appropriate for children with unilateral or bilateral motor deficits [20].

In mirror therapy, when patients view and follow various motions of their limbs in the mirror, mirror neurons in the premotor cortex are reflected and stimulated [18], potentially increasing motor cortex activity and enhancing grip power, neuromuscular coordination, range of motion (ROM), speed, and activities of daily life [21]. This also applies to rehabilitating children with CP [22]. Mirror therapy, a neuroplasticity -based bottom-up method, was developed to enhance unilateral muscle function and is being studied for two-sided motor deficits [18]. It promotes neuroplastic changes in CP patients, enhancing their motor development [23]. The most common classical strategies used for motor development are bimanual training, goal-directed functional training, reflex inhibitory patterns, and home exercise programs [11]. Routine physical therapy used goal-directed functional training and reflex inhibitory patterns.

A literature review revealed a lack of comprehensive evidence regarding the combined use of advanced neuroplasticity-based treatments, such as tDCS and MT, for improving motor development and functional outcomes in CP patients. Although MT and tDCS have both shown potential to improve motor function and balance and reduce spasticity, little evidence shows their combined synergistic effects when used simultaneously, their long-term effects, or their application across heterogeneous CP populations. Bridging this research gap may open avenues for effective, comprehensive, and novel intervention approaches for rehabilitating children with CP. The study aims to investigate the impact of tDCS and MT on motor development and functional improvements in CP patients, based on the principles of neuroplasticity and central nervous system (CNS) stimulation. This evidence-based and safe interventional protocol will improve the quality of life of CP patients, minimise the burden on healthcare resources, and move beyond the constraints of conventional rehabilitation methods.

Subjects and methods

A randomised, double-blind clinical trial was conducted to evaluate the effects of tDCS and mirror therapy interventions on gross and fine motor development in the SQCP population. The trial was registered in the Iranian Registry of Clinical Trials on 26th January 2024 (registration number IRCT 20231227060542N1), enhancing transparency and accountability by allowing public access to trial details and methodology. A pilot study was conducted to calculate the sample size. The mean motor development score for group I was 19, and for group II was 23.87. Using Open Epi software with 80% power and a 0.05 significance level, the initial sample size was calculated to be 29 participants per group [5]. To account for expected dropouts, the sample size was increased to 31 participants per group, making a total of 93 participants.

The diagnosed SQCP patients were referred to Ghurki Hospital's Rehabilitation Centre from 1 February to 31 August 2024. To maximise participation in the study, an effective social media campaign was launched. At the start of the study, 145 patients were assessed for eligibility, and 93 were found eligible to participate. The criteria included: children aged between three and seven years [5], a functional level of I–III on the Gross Motor Functional Classification System (GMFCS) [23, 24], a muscle tone score of two or less on the modified Ashworth scale [19], and the ability to understand and respond to verbal commands or use communication aids. Exclusion criteria were set to avoid confounding factors and included: ataxic and athetoid CP, any musculoskeletal or neurological surgery containing metal implants (nails or rods in upper and lower limbs, cranial implant, cochlear implant and ventriculoperitoneal shunt) [24, 25], and botox application. Every child who was included in the trial had previously received traditional physical therapy as part of their regular cerebral palsy treatment. These traditional therapies included stretching and posture exercises, basic strengthening, balance training, and functional task practice, as recommended in outpatient paediatric rehabilitation settings. Before enrolling in the trial, none of the subjects had received mirror therapy, transcranial direct current stimulation, or any other neuromodulatory therapies. Furthermore, no participant received advanced neurorehabilitation procedures concurrently with the intervention.

Before the study commenced, the treatment procedures, frequency, assessment timelines, potential benefits, and any associated risks were carefully addressed to the parents or caregivers of the participants.

Out of 93 participants, thirty-one were stratified based on GMFCS level and then equally randomised into three groups: group A [tDCS, MT & routine physical therapy (RPT)], group B (MT & RPT), and group C (tDCS & RPT). Randomisation within each stratum was performed using a computer-generated sequence, maintaining a 1:1:1 ratio. Allocations were stored in sealed, opaque envelopes, and each participant received a unique trial ID (*e.g.*, A2, B11, C3). Both participants

and data analysts were blinded to allocation, randomisation, and treatment groups to minimise bias and improve result reliability. Two trained physical therapists, with the same professional background and equivalent expertise, implemented the treatment plan. The trial was designed and conducted following the CONSORT (Consolidated Standards of Reporting Trials) guidelines to ensure methodological rigor, transparency, and comprehensive reporting of all aspects of the randomised controlled trial (Figure 1).

The patients were seated in a CP chair to optimise comfort and postural support throughout the procedure. Their hip and knee joints were kept at a 90-degree flexion position to ensure good alignment. They rested their forearms on a table placed in front of them for additional stability. A wireless, rechargeable tDCS device (Framed Company model Segal Stim SG-2023004) was used for stimulation. The device used two large-surface sponge electrodes (5–7 cm in diameter), well saturated with 0.9% physiological saline solution to improve conductivity and reduce skin irritation. The electrodes were carefully placed over the patient's head, using anatomical landmarks to ensure precise stimulation. To prevent electrode displacement during the session, adjustable straps held the electrodes firmly in place, minimising stimulation artefacts and ensuring consistent delivery of the desired current intensity [24]. To address left-sided limb deficits, the anode electrode of the tDCS apparatus was placed over the right primary motor cortex (M1), a primary neural area in charge of the contralateral limb, while the cathode electrode was placed over the opposite supraorbital area (over the left eyebrow), to complete the electric circuit. Electrode placement followed the standardised 10–20 EEG international system to ensure anatomical precision. Conversely, for right-sided limb deficits, the anode was placed over the left M1 and the cathode over the right supraorbital area. This hemisphere-specific montage aimed to enable excitatory anodal stimulation of the lesioned hemisphere to induce cortical plasticity and motor re-

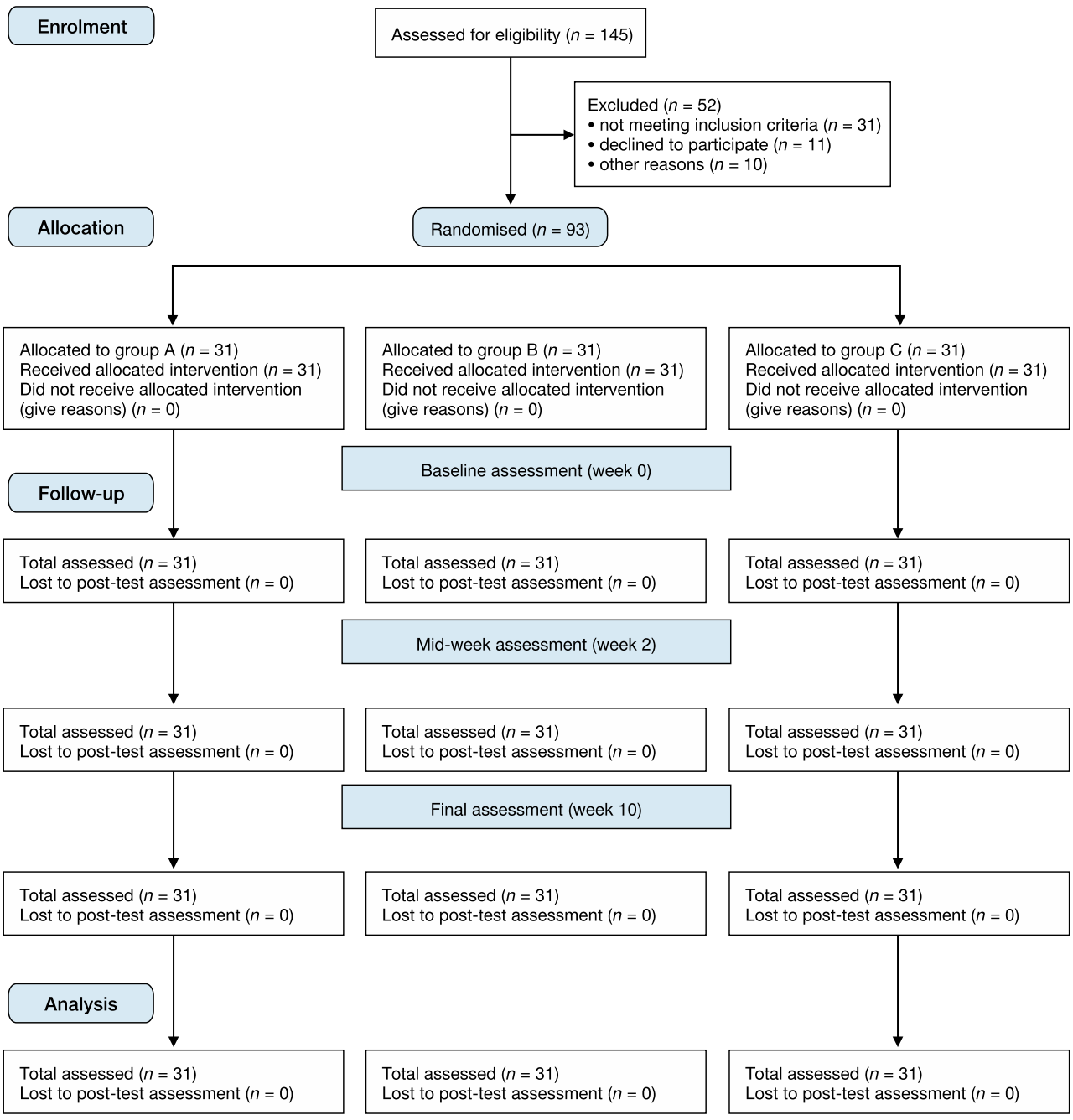


Figure 1. CONSORT flow diagram of participant recruitment and follow-up

covery, while cathodal placement over the supraorbital area served as a reference point to direct current flow without affecting underlying brain activity [26, 27]. When tDCS is applied, brain excitability persists for 20 min. To maximise its effect, stimulation was first delivered to the right hemisphere for 15 min, followed immediately by 15 min on the left, with only a brief pause to reposition the electrodes. This ensured the continuous activation of the target areas. tDCS was administered at 2 mA, with each hemisphere receiving 15 min of stimulation, totalling 30 min per session. The treatment spanned two weeks, with 5 sessions per week [5, 23,24].

Mirror therapy was administered using a standardised protocol, with a 35 × 35 cm mirror placed vertically along the patient's midline to create a visual illusion of bilateral limb movement. The patient was seated on a mat in front of the mirror in a supportive, distraction-free environment to optimise focus and engagement.

To target the left-sided extremities, the left limb was placed behind the mirror, concealed from direct view, while the right extremity was positioned in front of the mirror, fully visible to the patient; to target the right-sided extremities, the right limb was hidden behind the mirror and the left limb was placed in front, creating the illusion of movement in the affected limb through its mirrored reflection. The treatment lasted 30 min. The first 15 min of exercises focused on the right upper and lower extremities, while the next 15 min focused on the left upper and lower extremities [28]. The upper-extremity MT program included pronation, supination and elbow, wrist, and finger flexion and extension [29]. In contrast, the lower-extremity MT program included activities such as ball rolling, rocker-boarding, and cycling with a stationary unit [30]. There were a total of 10 mirror therapy (MT) sessions, each lasting 30 min, conducted five times per week over a period of two weeks, which involved three sets of twenty repetitions of each of the exercises demonstrated, and provided each of the participants with feedback on how to minimise distractions [24].

RPT was administered for 20 min per session, divided into two 10-minute segments: goal-directed functional training (GDFT) and reflex inhibitory patterns (RIPs). GDFT involved functional tasks aligned with the patient's abilities, focusing on activities such as rolling, sitting, standing, and walking. In the RIPs phase, exaggerated or diminished primitive, postural, and righting reflexes, such as rooting, sucking, protective extension, Landau, startle, primary standing and walking, tonic labyrinthine, symmetrical and asymmetrical tonic neck reflexes, and head-on-body, body-on-head, and body-on-body reflexes, were stimulated and positioned to promote integration, facilitating coordinated motor development.

The study included three groups: group A received tDCS, MT, and RPT; group B received MT and RPT; and group C received tDCS and RPT. Participants were monitored throughout the intervention period for any adverse events related to tDCS or mirror therapy.

All participants received 10 sessions of tDCS and MT, for 15 min on both sides, along with 20 min of RPT, five days a week. After these initial sessions, only the 20-minute RPT continued until the 10th week. The third outcome assessment was conducted at the end of the 10-week follow-up period. The study explicitly defined the primary outcomes as motor development and developmental age. Secondary outcomes included gross motor function (Gross Motor Function Measure, GMFM-66), functional mobility [Timed Up and Go Test (TUG)], and fine motor function [Nine-Hole Peg Test (NHPT) and Box and Block Test (BBT)].

Developmental age and motor development were assessed by the Shoaib Sensorimotor Development Tool (SSDT), whose reliability was 0.977 [31]. Gross motor development was assessed using the GMFM-66 and TUG, with reliabilities of 0.999 and 0.098, respectively [17, 32]. Fine motor development was assessed using the NHPT and BBT, with reliabilities of 0.88 and 0.91–0.97, respectively [33, 34]. The progress of every patient was recorded at baseline, after two weeks, and after ten weeks of follow-up using an extended RPT program. This was intended to meet ethical requirements for participants' recovery and provide them with the best possible chance of recovery [15].

Statistical analysis was performed using SPSS version 26.0. Before parametric testing, the Shapiro–Wilk test assessed data normality and ensured that the dataset met the assumptions for the following analyses. Descriptive statistics described the study variables: categorical and nominal data were presented as frequencies and percentages, whereas continuous variables were presented as mean ± standard deviation to provide a clear picture of central tendency and dispersion. To compare between-group effects and within-group changes at multiple time points of measurement (baseline, 2-week post-intervention, and follow-up at 10 weeks), an inferential statistical analysis using repeated measures ANOVA was applied. Post hoc pairwise comparisons were performed using the Bonferroni correction for multiple comparisons. All statistical analyses were performed using a two-tailed 95% confidence interval, and the statistical significance threshold was $p < 0.05$. Missing data were minimal and were handled using complete-case analysis, as all participants included in the final analysis completed baseline and post-intervention assessments.

Results

A total of 93 children with spastic quadriplegic cerebral palsy completed the study and were included in the analysis. Baseline demographic and clinical characteristics, including age, gender, GMFCS level, and muscle tone, were comparable across the three groups, confirming successful randomisation ($p > 0.05$).

At baseline, all outcome measures were comparable among the three intervention groups, confirming successful randomisation. Over the 10-week intervention period, group A showed the greatest improvements across primary and secondary outcomes consistently compared with groups B and C. The most pronounced effects were seen in the primary outcomes, where group A achieved significantly greater improvement in developmental age and motor development as measured by the SSDT, with large between-group effect sizes. Improvements were noted as early as two weeks for motor development and further increased by week ten. Secondary outcomes demonstrated a similar pattern, with group A showing the greatest enhancement in gross motor function, functional mobility, and fine motor performance. Overall, the findings indicate that the intervention applied in group A was more effective in accelerating developmental progression and motor function than the comparator interventions.

The overall mean age was 5.45 ± 0.84 years. The sample included 53% females and 47% males. By GMFCS level, 52% were level II, 39% level III, and 9% level I. Tone assessment showed Grade I+ as the most frequent (45%), followed by grade II (37%), grade I (11%), and grade III (7%) (Table 1).

Table 1. Demographics

Variables		Group A (n = 31)	Group B (n = 31)	Group C (n = 31)	Total (n = 93)
Age [years (mean ± *SD*)]		5.19 ± 0.246	5.87 ± 0.365	5.29 ± 0.230	5.45 ± 0.841
Gender [*n* (%)]	males	16 (17)	13 (14)	14 (15)	43 (47)
	females	15 (16)	18 (20)	17 (18)	50 (53)
Level of CP on GMFCS [*n* (%)]	level I	4 (4)	2 (2)	3 (3)	9 (9)
	level II	15 (16)	17 (19)	16 (17)	48 (52)
	level III	12 (13)	12 (13)	12 (13)	36 (39)
Tone on MAS [*n* (%)]	grade I	6 (6)	3 (3)	2 (2)	11 (11)
	grade I	12 (13)	12 (13)	17 (19)	41 (45)
	grade II	11 (12)	14 (15)	9 (10)	34 (37)
	grade III	2 (2)	2 (2)	3 (3)	7 (7)

CP – cerebral palsy, GMFCS – Gross Motor Function Classification System, MAS – Modified Ashworth Scale

Table 2. Between-group comparison of developmental age, motor development, gross motor functions, and fine motor functions

Variables	Timeline	Group A (tDCS+MT+RPT) (n = 31) (mean ± *SD*)	Group B (MT+RPT) (n = 31) (mean ± *SD*)	Group C (tDCS+RPT) (n = 31) (mean ± *SD*)	Total (n = 93) (mean ± *SD*)	*F*	*p*-value	Eta squared	95% confidence interval	
									lower	upper
Developmental Age-SSDT (weeks)	baseline	17.45 ± 2.17	17.25 ± 2.54	17.39 ± 2.20	17.36 ± 2.30	0.042	0.959	0.001	0.000	0.011
	after 2 weeks	17.62 ± 2.09	17.38 ± 2.63	17.55 ± 2.25	17.51 ± 2.32	0.077	0.926	0.002	0.000	0.024
	after 10 weeks	33.32 ± 1.42	27.13 ± 2.50	28.74 ± 4.20	29.73 ± 2.70	37.01	0.000	0.451	0.292	0.559
Motor Development-SSDT	baseline	19.74 ± 2.42	19.65 ± 2.56	20.00 ± 2.24	19.79 ± 2.41	0.179	0.836	0.004	0.000	0.042
	after 2 weeks	28.32 ± 1.85	22.01 ± 0.93	24.32 ± 1.05	24.88 ± 1.27	176.65	0.000	0.797	0.718	0.840
	after 10 weeks	42.97 ± 3.19	33.35 ± 3.35	36.87 ± 3.84	37.73 ± 3.46	60.801	0.000	0.575	0.432	0.662
Gross Motor-GMFM	baseline	58.06 ± 2.32	57.74 ± 1.98	58.65 ± 2.27	58.15 ± 2.19	1.344	0.266	0.029	0.000	0.110
	after 2 weeks	79.77 ± 5.55	77.29 ± 6.98	78.48 ± 6.15	78.51 ± 6.23	1.223	0.299	0.026	0.000	0.105
	after 10 weeks	133.23 ± 4.96	113.45 ± 8.65	125.97 ± 7.32	123.67 ± 0.98	1.134	0.001	0.575	0.433	0.662
Gross Motor-TUG (s)	baseline	24.58 ± 1.98	25.03 ± 2.15	24.94 ± 2.25	24.85 ± 2.13	0.386	0.681	0.009	0.000	0.062
	after 2 weeks	18.68 ± 2.61	21.26 ± 2.97	19.71 ± 3.81	19.88 ± 3.13	5.189	0.007	0.103	0.009	0.219
	after 10 weeks	15.68 ± 2.61	18.09 ± 3.04	16.71 ± 3.81	16.83 ± 3.15	4.470	0.014	0.090	0.004	0.203
Fine Motor-NHPT (s)	baseline	65.01 ± 2.88	65.19 ± 2.88	65.55 ± 2.72	65.25 ± 2.83	0.300	0.741	0.007	0.000	0.055
	after 2 weeks	52.09 ± 2.75	53.51 ± 3.57	52.71 ± 2.73	52.77 ± 3.02	1.694	0.190	0.036	0.000	0.123
	after 10 weeks	42.78 ± 5.31	45.19 ± 2.88	45.19 ± 2.65	44.38 ± 3.61	4.171	0.019	0.085	0.002	0.195
Fine Motor-BBT (s)	baseline	85.02 ± 2.88	85.19 ± 2.88	85.55 ± 2.72	85.25 ± 2.82	0.300	0.741	0.007	0.000	0.055
	after 2 weeks	61.45 ± 3.38	61.74 ± 3.39	62.16 ± 2.92	61.78 ± 3.23	0.376	0.688	0.008	0.000	0.061
	after 10 weeks	53.97 ± 7.56	59.49 ± 3.31	57.74 ± 5.82	57.07 ± 5.56	7.257	0.001	0.139	0.025	0.261

tDCS – transcranial direct current stimulation, MT – mirror therapy, RPT – routine physical therapy, SSDT – Shoaib Sensorimotor Development Tool, GMFM – Gross Motor Functional Measure, TUG – Timed Up and Go Test, NHPT – Nine-Hole Peg Test, BBT – Box and Block Test
$p < 0.05$ indicates statistically significant results

Between-group comparison of developmental age, motor development, gross motor functions, and fine motor functions

Data were normally distributed, as confirmed by the Shapiro–Wilk test; therefore, parametric tests were used for analysis. At baseline, the developmental age was similar across groups, with a mean of 17.36 ± 2.30 weeks. Group A showed the most significant gain at 10 weeks (33.32 ± 1.42 weeks), in contrast to group B (27.13 ± 2.50 weeks) and group C (28.74 ± 4.20 weeks), with effect size of $F = 37.01$ ($p = 0.00$, $\eta^2 = 0.451$) (Table 2) (Figure 2). Baseline motor development scores were not statistically different among groups (19.79 ± 2.41). Following 10 weeks of intervention, group A demonstrated the highest gain (42.97 ± 3.19), while group C recorded (36.87 ± 3.84) and group B (33.35 ± 3.35), with effect size of $F = 60.801$ ($p = 0.00$, $\eta^2 = 0.575$) (Table 2) (Figure 2).

Gross motor scores in GMFM-66 at baseline were equivalent (mean = 58.15 ± 2.19). After 10 weeks, group A had the greatest improvement (133.23 ± 4.96), followed by group C

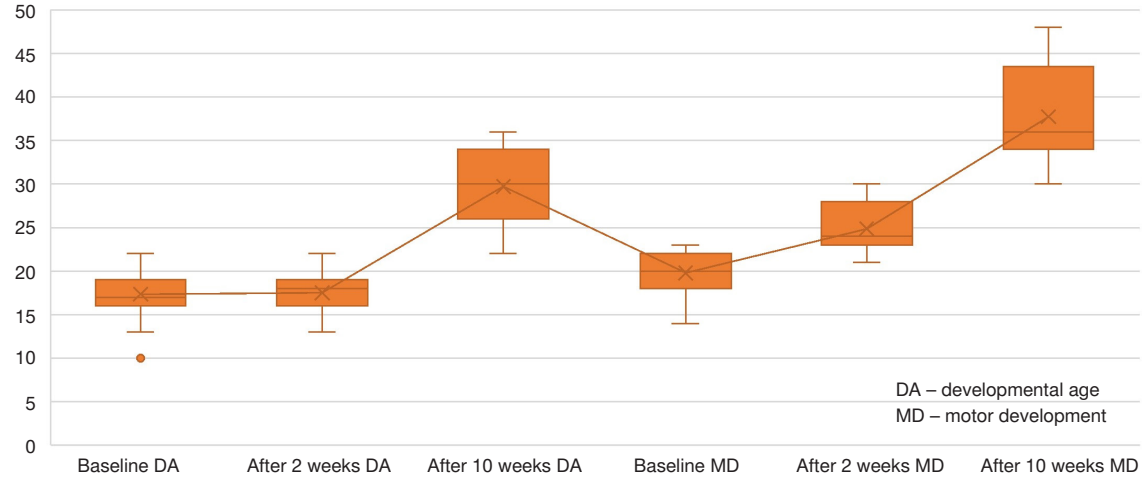


Figure 2. Graphical illustration of developmental age and motor development

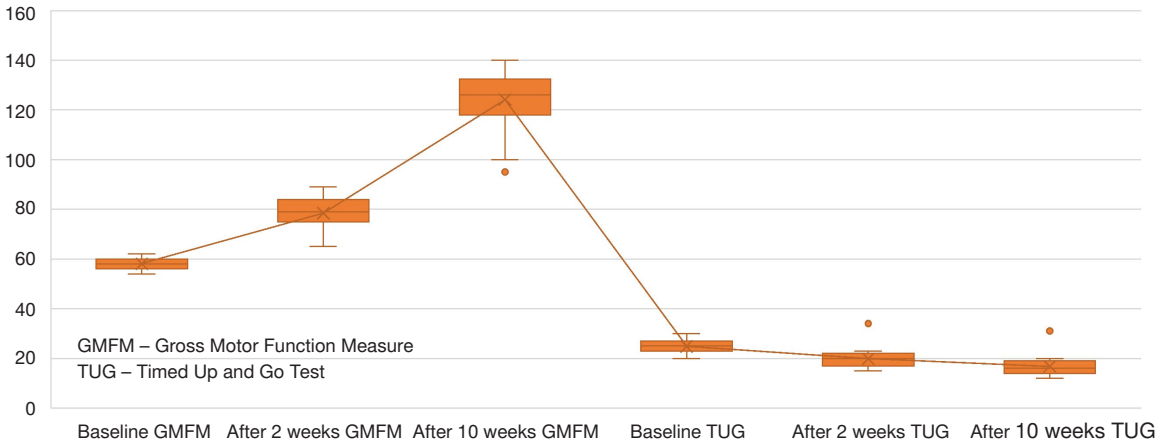


Figure 3. Graphical illustration of gross motor development

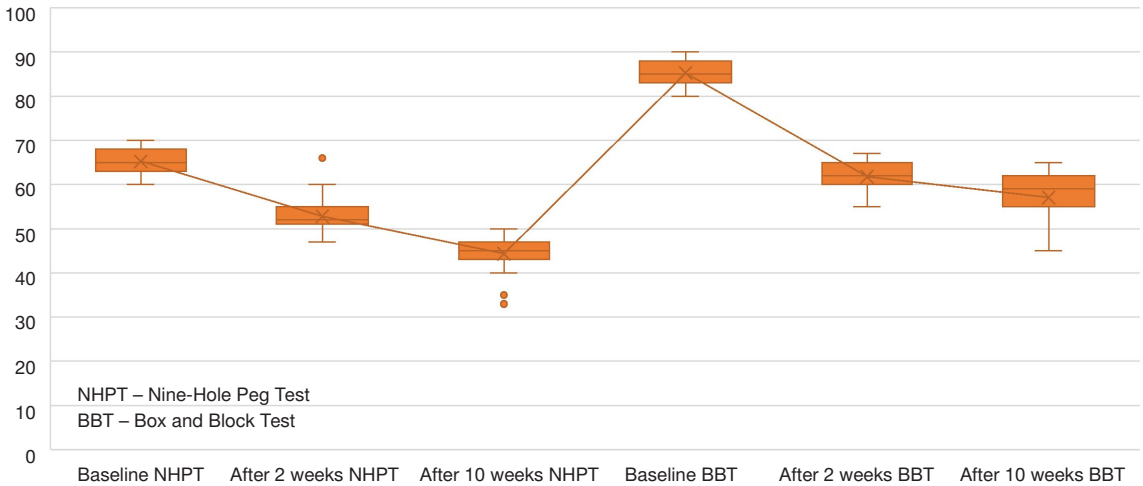


Figure 4. Graphical illustration of fine motor development

(125.97 ± 7.32) and group B (113.45 ± 8.65), with effect size of $F = 1.134$ ($p = 0.001$, $\eta^2 = 0.575$) (Table 2) (Figure 4). Baseline TUG scores were comparable between the groups (mean = 24.85 ± 2.13 s). Group A had the greatest decrease at week 10, with 15.68 ± 2.61 s, compared with group C, with 16.71 ± 3.81 s, and group B, with 18.09 ± 3.04 s, with effect size of $F = 4.47$ ($p = 0.014$, $\eta^2 = 0.090$) (Table 2) (Figure 3).

Baseline scores in the NHPT were homogeneous among the groups (mean = 65.25 ± 2.83 s). After 10 weeks, group A was progressed the fastest, with scores of 42.78 ± 5.31 s, followed by groups B and C, which scored 45.19 ± 2.65 s each, with effect size of $F = 4.171$ ($p = 0.019$, $\eta^2 = 0.085$) (Table 2) (Figure 4). In baseline scores, nearly similar mean values were recorded for the groups in BBT (85.25 ± 2.82 s). After 10 weeks, again, the maximum percentage of improvement was seen in group A, with a difference of 53.97 ± 7.56 s, followed by group C and group B, with values of 57.74±5.82 s and 59.49 ± 3.31 s, respectively; with effect size of $F = 7.257$ ($p = 0.001$, $\eta^2 = 0.139$) (Table 2).

Table 3. Groupwise comparison of developmental age, motor development, gross motor functions, and fine motor functions

Dependent variable	Timeline	(I) group	(J) group	Mean difference (I–J)	*p*-value	95% confidence interval	
						lower bound	upper bound
Developmental age	baseline	A	B	0.161	1.000	–1.271	1.594
		B	C	–0.129	1.000	–1.561	1.303
		C	A	–0.032	1.000	–1.465	1.400
	after 2 weeks	A	B	0.226	1.000	–1.221	1.672
		B	C	–0.161	1.000	–1.608	1.285
		C	A	–0.065	1.000	–1.511	1.382
	after 10 weeks	A	B	6.194	0.000	4.372	8.016
		B	C	–1.613	0.100	–3.435	0.209
		C	A	–4.581	0.000	–6.403	–2.759
Motor development	baseline	A	B	0.097	1.000	–1.397	1.591
		B	C	–0.355	1.000	–1.849	1.139
		C	A	0.258	1.000	–1.236	1.752
	after 2 weeks	A	B	6.323	0.000	5.492	7.153
		B	C	–2.323	0.000	–3.153	–1.492
		C	A	–4.000	0.000	–4.830	–3.170
	after 10 weeks	A	B	9.613	0.000	7.461	11.765
		B	C	–3.516	0.000	–5.668	–1.364
		C	A	–6.097	0.000	–8.249	–3.945
Gross Motor–GMFM	baseline	A	B	0.323	1.000	–1.040	1.685
		B	C	–0.903	0.328	–2.265	0.459
		C	A	0.581	0.903	–0.782	1.943
	after 2 weeks	A	B	2.484	0.364	–1.391	6.359
		B	C	–1.194	1.000	–5.069	2.681
		C	A	–1.290	1.000	–5.165	2.585
	after 10 weeks	A	B	19.774	0.000	15.350	24.198
		B	C	–12.516	0.000	–16.940	–8.092
		C	A	–7.258	0.000	–11.682	–2.834
Gross Motor–TUG	baseline	A	B	–0.452	1.000	–1.772	0.868
		B	C	0.097	1.000	–1.223	1.417
		C	A	0.355	1.000	–0.965	1.675
	after 2 weeks	A	B	–2.581	0.006	–4.548	–0.613
		B	C	1.548	0.174	–0.419	3.516
		C	A	1.032	0.611	–0.935	3.000
	after 10 weeks	A	B	–2.419	0.011	–4.400	–0.438
		B	C	1.387	0.273	–0.594	3.368
		C	A	1.032	0.621	–0.949	3.013
Fine Motor–NHPT	baseline	A	B	–0.194	1.000	–1.944	1.557
		B	C	–0.355	1.000	–2.106	1.396
		C	A	0.548	1.000	–1.202	2.299
	after 2 weeks	A	B	–1.419	0.210	–3.307	0.468
		B	C	0.806	0.900	–1.081	2.694
		C	A	0.613	1.000	–1.274	2.500
	after 10 weeks	A	B	–2.419	0.043	–4.779	–0.060
		B	C	0.000	1.000	–2.360	2.360
		C	A	2.419	0.043	0.060	4.779
Fine Motor–BBT	baseline	A	B	–0.194	1.000	–1.944	1.557
		B	C	–0.355	1.000	–2.106	1.396
		C	A	0.548	1.000	–1.202	2.299
	after 2 weeks	A	B	–0.290	1.000	–2.299	1.718
		B	C	–0.419	1.000	–2.428	1.589
		C	A	0.710	1.000	–1.299	2.718
	after 10 weeks	A	B	–5.516	0.001	–9.127	–1.905
		B	C	1.742	0.727	–1.869	5.353
		C	A	3.774	0.037	0.163	7.385

GMFM – Gross Motor Functional Measure, TUG – Time Up and Go Test, NHPT – Nine-Hole Peg Test, BBT – Box and Block Test
"0" indicates statistically significant results.

Groupwise comparison of developmental age, motor development, gross motor functions, and fine motor functions

The groupwise comparison analysis indicated significant treatment effects favouring group A. At 10 weeks, group A showed greater improvement in developmental age than group B (6.194, $p < 0.001$) and group C (–4.581, $p < 0.001$). Motor development results were even more striking, with group A outperforming both groups by 2 weeks ($p < 0.001$) and increasing to a 9.613-point advantage over group B at 10 weeks ($p < 0.001$). Gross motor function (GMFM) improved markedly more in group A (19.774 points) than in group B at 10 weeks ($p < 0.001$). Fine motor changes appeared somewhat later, but noteworthy BBT differences were present at 10 weeks (–5.516, $p = 0.001$). All groups were equivalent at baseline (all p =1.000), again attesting to the intervention's success, particularly with sustained application over 10 weeks (Table 3).

Pairwise comparison of developmental age, motor development, gross motor functions, and fine motor functions

The research demonstrated significant improvements in developmental and motor function indicators over ten weeks. Developmental age showed a slight increase from baseline to week 2 ($p = 0.010$), followed by substantial progress from week 2 to week 10 ($p < 0.001$). By week 10, there was a significant improvement compared with baseline ($p < 0.001$). In motor development, notable improvements were observed from baseline to week 2 ($p < 0.001$) and highly significant gains from week 2 to week 10 ($p < 0.001$), with a strong positive change by week 10 compared to baseline (*CI:* 16.73 to 19.14, $p < 0.001$).

In gross motor development or function, as measured by the GMFM, there was a significant improvement from baseline to week 2 ($p < 0.001$) and strong incremental improvement from week 2 to week 10 ($p < 0.001$). Overall, there was a considerable improvement from baseline to week 10 ($p < 0.001$). Additionally, the time taken for gross motor activity, measured by the TUG, showed notable improvement from baseline to week 2 ($p < 0.001$), further improvements were reported from week 2 to week 10 ($p < 0.001$), as well as a significant reduction in time from baseline to week 10 ($p < 0.001$).

In the fine motor development or skills category, the NHPT demonstrated a significant improvement from baseline to week 2 ($p < 0.001$), with additional gains observed from week 2 to week 10 ($p < 0.001$), resulting in a substantial reduction in time compared to baseline by week 10 ($p < 0.001$). Similarly, the BBT exhibited a strong improvement from baseline to week 2 (*CI*: 23 to 23.93, $p < 0.001$), smaller gains from week 2 to week 10 ($p < 0.001$), and significant overall improvement from baseline to week 10 ($p < 0.001$). Overall, the study indicates substantial advancements in both developmental and motor skills over the 10-week period (Table 4).

No adverse events or complications related to tDCS or mirror therapy were observed during the study period. All participants tolerated the interventions well, and no sessions were discontinued due to discomfort, safety concerns, or intervention-related side effects.

Table 4. Pairwise comparison of developmental age, motor development, gross motor functions, and fine motor functions

Variables	Blending at different time points	Mean ± *SD*	95% confidence interval of the difference		*p*-value
			lower	upper	
Developmental Age-SSDT	baseline – 2 weeks	–0.16 ± 0.60	–0.28	–0.04	0.010
	2 weeks – 10 weeks	–12.22 ± 3.87	–13.01	–11.42	0.000
	10 weeks – baseline	12.38 ± 3.89	11.58	13.18	0.000
Motor Development SSDT	baseline – 2 weeks	–5.09 ± 3.60	–5.83	–4.34	0.000
	2 weeks – 10 weeks	–12.85 ± 3.72	–13.61	–12.08	0.000
	10 weeks – baseline	17.94 ± 5.84	16.73	19.14	0.000
Gross Motor-GMFM	baseline – 2 weeks	–20.37 ± 6.72	–21.75	–18.98	0.000
	2 weeks – 10 weeks	–45.70 ± 11.86	–48.14	–43.26	0.000
	10 weeks – baseline	66.06 ± 10.52	63.90	68.23	0.000
Gross Motor-TUG	baseline – 2 weeks	4.97 ± 3.49	4.25	5.69	0.000
	2 weeks – 10 weeks	3.05 ± 0.43	2.97	3.14	0.000
	10 weeks – baseline	–8.02 ± 3.50	–8.74	–7.30	0.000
Fine motor-NHPT	baseline – 2 weeks	12.47 ± 1.84	12.09	12.85	0.000
	2 weeks – 10 weeks	8.39 ± 3.23	7.72	9.05	0.000
	10 weeks – baseline	–20.86 ± 2.76	–21.43	–20.29	0.000
Fine motor-BBT	baseline – 2 weeks	23.46 ± 2.27	23.00	23.93	0.000
	2 weeks – 10 weeks	4.72 ± 6.05	3.47	5.97	0.000
	10 weeks – baseline	–28.18 ± 5.55	–29.33	–27.04	0.000

SSDT – Shoaib Sensorimotor Development Tool, GMFM – Gross Motor Functional Measure, TUG – Time Up and Go Test, NHPT – Nine-Hole Peg Test, BBT – Box and Block Test
$p < 0.05$ – indicates statistically significant results

Discussion

The current study demonstrates that the combination of transcranial direct current stimulation and mirror therapy with routine physical therapy significantly improves motor development, gross motor function, fine motor skills, and functional mobility in children with spastic quadriplegic cerebral palsy. Group A showed the largest improvements across all outcome measures, including developmental age, motor development (SSDT), GMFM, TUG, NHPT, and BBT, compared to MT + RPT (group B) or tDCS + RPT (group C). These results support the study hypothesis that a multi-modal neurorehabilitation approach yields superior motor outcomes relative to single-component interventions.

Our results are consistent with previous studies showing the positive effects of mirror therapy and tDCS in paediatric neurorehabilitation. For instance, Waqas *et al.* [23, 24] found that children with spastic CP had much better motor results when tDCS and functional training were coupled. Similarly, mirror therapy alone has shown to improve manual dexterity and upper-limb coordination in children with CP [19]. However, our study addressed the combined effects of both therapies over 10 weeks, indicating larger functional benefits, whereas the majority of prior studies evaluated tDCS and MT individually, sometimes in short-term protocols with small sample group sizes.

Group C exhibited somewhat smaller benefits than the combined intervention, while group B showed notable but smaller improvements. These results demonstrate the added benefit of combining mirror therapy and tDCS in improving motor outcomes compared with either technique alone. This is consistent with other research in paediatric neurorehabilitation demonstrating that multimodal therapies yield greater functional gains than single-component strategies [5, 35].

The current study contributes to the evidence supporting the beneficial effects of combining tDCS and mirror treatment on motor outcomes in children with spastic cerebral palsy in several significant ways, even though earlier research has shown similar effects [25]. First, our study included a 10-week intervention period and used a comprehensive panel of developmental measures, such as developmental age, fine motor skills, and gross motor skills (GMFM-66) to assess broader functional gains beyond isolated motor parameters, in contrast to previous research that mainly examined short-term motor outcomes. Second, unlike most prior research that assessed tDCS and MT separately or as dual-component therapies, this study investigated the synergistic impact of integrating both modalities concurrently with RPT. This tri-modal approach reflects a more ecologically sound rehabilitation technique that emulates actual clinical practice. This study directly measures the additive impact of integrated tDCS and MT, which has not been systematically evaluated before, using the current randomised, double-blinded trial design with three comparison arms (combined intervention *vs.* tDCS + RPT *vs.* MT + RPT).

These design variations collectively place our study as a new contribution that offers empirical evidence for optimal, multi-modal rehabilitation procedures in children with spastic quadriplegic cerebral palsy, extending beyond merely retesting preexisting assumptions.

A pilot study titled "Efficacy of tDCS and MT for Rehabilitation of SQCP" provided further evidence for this theory. It demonstrated that children with spastic quadriplegic CP experienced significant improvements in gross motor function, range of motion, and spasticity when tDCS and MT were applied together. In addition to confirming the neuromodulatory activity of tDCS, this study highlights the crucial role of mirror treatment in translating increased cortical excitability into meaningful outcomes. Particularly when combined with tDCS, the interactive visual and sensory feedback that MT offers seems to improve cortical remodelling and motor planning [5].

By illustrating the psychological and neurochemical advantages of this combination strategy, a different study, "Effects of tDCS and MT on Mental Health and Dopamine Level among SQCP" provided additional insight. Along with motor improvements, the results also showed decreased anxiety and elevated dopamine, indicating that MT is not just a physical modality but also has psychosocial and neurochemical components to neurorehabilitation. This demonstrates that by activating both the motor and cognitive-affective systems, MT enhances tDCS [24].

Anodal tDCS enhances therapeutic outcomes by enhancing cortical excitability and lowering the threshold for cortical activation, thereby stimulating motor cortex regions. Consequently, when anodal tDCS is applied to the primary motor cortex during motor task training, it maximises motor skill acquisition and improvement [35]. Consistent with the present study's findings, Hyuk-Shin Cho conducted a randomised controlled trial examining the effects of MT combined with tDCS on functional recovery in stroke patients. Although the study populations differed, the electrode placement and tDCS intensity were consistent with those used in Cho's study. The findings showed that MT combined with tDCS improves upper-extremity functional recovery in stroke patients by activating motor regions in the brain. This underscores its significant role in promoting neuroplasticity and recovery, which is tested in our study [29].

In a comprehensive review, Hassan *et al.* [16] concluded that tDCS is a new, relatively easy, low-risk, low-cost treatment modality that can be delivered at home or in a clinic to produce meaningful changes in gait, balance, gross motor function, and rigidity. According to a randomised control trial by Gillick *et al.* [36], most children with hemiparesis appear to tolerate tDCS well, and it appears to be safe. They also found that children with hemiparetic CP could benefit from anodal tDCS in conjunction with physical therapy to enhance hand function [36]. Similarly, Aree-uea *et al.* [37] found that anodal tDCS helps overcome stiffness in children with CP. Multiple research projects have explored the impact of tDCS on different areas of motor function in CP patients, adding to the current body of knowledge. Anodal tDCS was found to significantly enhance CP patients' gait symmetry and step length [38]. This is consistent with research by Grecco *et al.* [14] that shows gains in gross motor function after tDCS use.

The results of the present study for functional mobility, as indicated by the TUG, are also well-supported by existing literature on the combined outcomes of tDCS and motor training interventions. Lazzari *et al.* [25] conducted a randomised controlled trial comparing the synergistic effects of tDCS with virtual reality training in CP with 20 participants, who were randomly assigned to an experimental and control group. After one month of intervention, Lazzari *et al.* [25] noted statistically significant differences between the two groups in TUG performance, with the active tDCS group showing better results on both static and dynamic balance tests. These observations support the neurophysiological hypothesis that anodal tDCS, when administered over the primary motor cortex, can enhance the impact of simultaneous motor rehabilitation by increasing cortical excitability and promoting neuroplastic change. The alignment of their findings with the TUG measures from the present study indicates that tDCS may be a useful neuromodulatory enhancement for all forms of mo-

tor training, whether in virtual reality or traditional therapy. This could ultimately lead to measurable improvements in functional mobility improvements on tasks that require integrated balance and coordination.

The methodology and results of the current study align with earlier tDCS studies in CP groups, especially regarding electrode placement procedures. As validated by Fregni *et al.* [39] and followed by several subsequent studies, the standard montage placing the anode on the primary motor cortex (M1) and the cathode on the contralateral supraorbital area has proven to be consistently effective in improving functional mobility outcomes. This electrode configuration, replicated in our current investigation, has been shown neurophysiologically to effectively modulate cortical excitability, with anodal stimulation facilitating M1 activation while cathodal placement minimising current dispersion. Functional improvements in the TUG reported in prior studies using this montage further validate its therapeutic potential. This consistency across studies strengthens evidence for tDCS as a neuromodulatory intervention and indicates that the Fregni protocol reliably targets improvements in motor function in neurorehabilitative environments. The alignment of our TUG outcome with existing research highlights the replicability of tDCS effects and the strength of this specific electrode-placement intervention to enhance functional mobility in populations with CP.

Premotor cortex activity is a possible target for tDCS to increase dexterity since it is linked to complicated motor skills and motor development. The influence of premotor cortex tDCS on the results of a Strength-Dexterity test in healthy people was investigated by Pavlova *et al.* [40]. The study shows that tDCS across the left premotor cortex can enhance dexterity-demanding task efficiency. The tactics used to execute the task determine the effective stimulation polarity. Furthermore, the study demonstrates the functional significance of the connections between the right and left premotor cortex.

The cerebellar tDCS impacts on the alteration of cerebellar functions in motor areas of fine motor dexterity and motor speed were investigated by Kinakool *et al.* [41] in 2020. Findings indicate that tDCS modulates motor speed, suggesting that it can be an effective therapeutic tool for managing neurological diseases that cause motor impairments [41]. Mahmoodifar *et al.* [42] examined the influence of anodal tDCS in addition to selective motor training on fine motor abilities of children with autism spectrum disorder (ASD) aged 6–14 years. Eighteen children with ASD split into two groups were assessed. In the experimental group, participants were administered 20 min of 1.5 mA anodal tDCS over the left primary motor cortex before motor training to enhance fine motor skills. The other nine participants formed a sham group, which was given the same training sessions with simulated tDCS. The results suggest that tDCS may be an effective addition to fine motor skill training for children with ASD.

In contrast, Sobierajewicz *et al.* [43] explored how tDCS may influence sequence-specific learning in conjunction with motor imagery above the main motor cortex. The study included four participant groups: a control group (no stimulation) and anodal, cathodal, and sham stimulation. The findings demonstrated that motor imagery impacts sequence learning, whereas tDCS had no additional effect.

Limitations

Despite the promising findings, this study has several limitations. A major limitation is the absence of a control group that received only RPT or no treatment at all, which makes it difficult to isolate the effects of the experimental interventions. Participant heterogeneity and variability in tDCS parameters may have impacted the outcomes, highlighting the need for standardised protocols. Moreover, the 10-week follow-up period limits our understanding of the long-term effects, and the lack of neuroimaging (fMRI/EEG) makes it difficult to draw conclusions about the underlying neural mechanisms. Placebo or learning effects are potential limitations of this study. Additionally, comparisons with other rehabilitation strategies, such as Constraint-Induced Movement Therapy (CIMT) or virtual reality, were not conducted. We included participants with GMFCS levels I to III due to their minimal impairments, which facilitated smoother participation. Future studies should consider including participants with levels IV and V.

Conclusions

This randomised clinical trial demonstrates combining tDCS and MT with routine physical therapy yields greater improvements in motor development, gross motor function, fine motor skills, and functional mobility in children with spastic quadriplegic cerebral palsy than interventions that did not integrate both modalities. While both interventions showed individual benefits, the combined group showed a more pronounced synergistic effect. The interventions were safe, feasible, and well tolerated, with no adverse events reported. The results suggested that combining tDCS and mirror therapy may be a promising adjunct to conventional paediatric rehabilitation, warranting further investigation through larger trials with extended follow-up and objective neurophysiological assessments to confirm long-term efficacy and generalisability. These findings support integrating multi-modal neurorehabilitation strategies into clinical practice for children with cerebral palsy.

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Ethical approval

The research related to human subjects complied with all the relevant national regulations and institutional policies, followed the tenets of the Declaration of Helsinki, and was approved by the University of Lahore's Research Ethics Committee (approval No.: REC-UOL-626-12-2023, December 20, 2023). Trial registration: IRCT20231227060542N1 on 26-01-2024, https://irct.behdasht.gov.ir/

Informed consent

Informed consent was obtained from all individuals included in this study. Parents, caregivers, and legal guardians provided written permission for their children before the commencement of participation.

Disclosure statement

No author has any financial interest or received any financial benefit from this research.

Conflict of interest

The authors state no conflict of interest.

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