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ORIGINAL RESEARCH

Conjunct Effects of Transcranial Direct Current Stimulation with Mirror Therapy on Motor Control and Muscle Performance in Spastic Quadriplegic Cerebral Palsy Children: A Randomized Clinical Trial

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Video abstract

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Background: Cerebral palsy (CP) is a birth-related non-progressive neuromotor brain disorder characterized by abnormalities of muscular tonicity, gross and fine motor skills, gait, and posture. It impacts motor control and muscle performance, which are emergent rehabilitation challenges in cerebral palsy children. Mirror therapy (MT) and transcranial direct current stimulation (tDCS) are novel treatment strategies to enhance muscle performance and motor control.

Methods: A randomized clinical trial was conducted at Ghurki Hospital Lahore, Pakistan. One hundred and five spastic quadriplegic CP (SQCP) children aged three to seven years were included. Randomization was carried out using Version 1.0 of Randomized Allocation Software. Allocation was done to three groups (35 in each group) with a 1:1:1 ratio with a unique identity number. Group I (tDCS+MT+Routine Physical Therapy (RPT), Group II (MT+RPT), and Group III (tDCS + RPT). Each patient received ten sessions of tDCS and MT, lasting for 15 minutes per side along with 20 minutes of RPT five days a week for ten weeks. Motor control was assessed by the Fugl-Meyer assessment tool, and muscle performance was measured using an isokinetic dynamometer and assessed at baseline, the 2nd, and the 10th week of follow-up and was analyzed using SPSS version 26.

Results: The results indicated a significant improvement after 10 weeks in the mean scores of motor control upper extremities, lower extremities, and trunk) with P-values of <0.000, <0.001, and <0.001, respectively. The mean scores of muscle performance (isokinetic strength) for right and left-sided elbow and knee flexors and extensors showed significant changes with P-values of 0.04, 0.01, 0.02, 0.02, 0.03, 0.05, 0.05, and 0.02, respectively. Similarly, muscle performance (isokinetic power) for these muscle groups also demonstrated significant changes, with P-values of 0.04, 0.01, 0.04, 0.02, 0.03, 0.05, 0.05, and 0.02, respectively.

Conclusion: tDCS and MT in combination significantly impacted motor control and muscle performance, enhancing elbow and knee musculature strength and power among SQCP patients.

Trial Registration: IRCT20231227060542N1 on 26-01-2024 https://irct.behdasht.gov.ir/.

Keywords: mirror therapy, motor control, muscle performance, transcranial direct current stimulation

Introduction

Cerebral palsy is brain damage related to birth that affects motor development in children.[1] This leads to decreased muscular function, poor control, and difficulty with movement and posture.[2] The most common forms of cerebral palsy

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in Pakistani children are spastic quadriplegia and spastic diplegia.[3] Globally, CP incidence ranges from 2 to 2.5 cases per 1000 live births [4] and in Pakistan, out of 1000 live births, the rate is 1.22 cases.[5] Major neuromuscular impairments include poor muscle tone, muscle atrophy, loss of strength, and problems with balance and coordination. These issues lead to functional limitations.[6] Neuro-developmental guidelines emphasize the importance of proximal trunk control for distal limb movement, balance, and functional mobility.[7]

Evidence-based approaches in rehabilitation have led to innovative strategies to enhance neuromuscular functioning by directly activating the central nervous system (CNS). One such strategy is tDCS, which has shown promising results in improving motor skills and overall physical function.[8] This non-invasive technique, based on top-down intervention, has shown a potential to increase cortical plasticity and improve muscle performance and motor control among stroke, CP, and attention deficit hyperactive disorder patients.[9–11] The method of anodal tDCS, which uses two electrodes, is affordable, portable, and simple to use.[12] Anodal stimulation depolarizes brain action potentials, causing excitatory effects, while cathodal stimulation repolarizes them, acting as an inhibitory mechanism. However, this phenomenon is still debated.[13]

Mirror neurons in the premotor cortex become active when patients observe their extremities in a mirror. This visual feedback can stimulate the motor cortex, leading to improvements in several areas like grip strength, motor control, range of motion, and increased movement speed.[14] Additionally, this activation can support the performance of daily tasks.[15] This concept can also be applied to rehabilitation for children with cerebral palsy.[16] MT, based on neuroplasticity and originally developed to improve unilateral muscle performance, is now being explored for bilateral motor impairments. This approach follows a bottom-to-top strategy, aiming to enhance motor function by leveraging the brain's ability to adapt and reorganize among CP patients.[17]

Conventional physical therapy strategies used to improve MC and MP in cerebral palsy include manual training, context-focused treatment, task-oriented functional training (TOFT), reflex inhibitory patterns (RIPS), and home exercise programs.[18] TOFT and RIPS, in particular, are integrated into routine physical therapy.

Neuromuscular development combines motor control and performance for coordinated movement and skill learning. Damage to the CNS can hinder this process, affecting control and function in both the trunk and limbs.[19] Muscle architecture significantly impacts muscle performance. CP patients experience muscular atrophy with shorter fascicle lengths in comparison to typically developing individuals.[20] Optimal muscle performance in the context of strength and power is vital for motor control. Weakness in these areas significantly limits activities, affecting gross and fine motor skills, gait, balance, and coordination in CP children.[21]

Neuromuscular development, in the context of motor control and muscle performance, has been addressed in the stroke population using techniques like tDCS and MT. However, these methods have not been extensively explored either individually or in combination for individuals with Spastic CP. Researchers aim to see the effects of tDCS and MT on motor control and muscle performance among spastic cerebral palsy patients. This integrated method could improve the functional and structural status of CP patients, making daily living activities easier, enhancing gross and fine motor tasks, reducing energy consumption, and ultimately improving their quality of life.

Materials and Methods

Study Design

A double-blinded randomized clinical trial was conducted using a three-arm study design to compare different interventions simultaneously. After its initiation, the study was formally and retrospectively registered in the Iranian Registry of Clinical Trials (IRCT20231227060542N1) on January 26, 2024, to ensure transparency and adherence to regulatory standards. The trial was conducted as per the guidelines of consolidated standards of reporting trials (CONSORT) (Figure 1).

Sample Size

After the pilot research, the Open-Epi tool was used to calculate the sample size. The mean values of motor control were 55.65 for group I, and 50.05 for group II with a 0.351 effect size.[22] With a power of 90% and a significance level of 0.05,

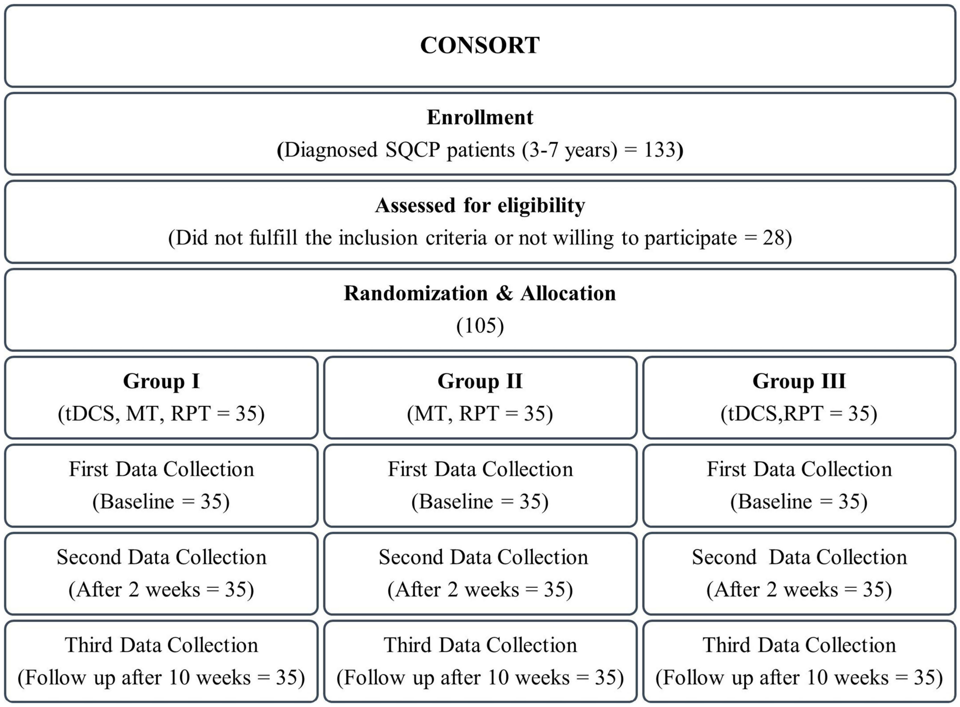

Figure 1 Consort Diagram.

the calculated minimum sample size was 4 patients per group. To account for a potential 20% dropout rate, we adjusted the sample size to 5 patients per group. Thus, while the minimum sample size was determined to be 5 patients, we opted to include 35 patients in each group, resulting in a total of 105 patients across the three groups.

Participants

One hundred and five SQCP patients were recruited from the Department of Physical Therapy at Ghurki Hospital, Lahore, Pakistan, after a holistic assessment according to international guidelines from 27th January to 31st July 2024. An effective social media campaign was launched two months before the assessment period to maximize participation response. Initially, 133 patients were screened out of which 105 SQCP children aged between 3 and 7 years,[23] GMFCS Level I–III,[24] Muscle tone ≥2 in MAS,[25] and ability to understand verbal commands, level I–III on communication classification system were included in the study.[26] Other types of CP such as (ataxia, athetoid), any metallic implant, history of cancer, orthopedic, neurosurgical surgery, and Botox treatment that underwent within 6 months [23,24] were excluded from the study.

Randomization, Allocation, and Blinding

One hundred and five patients were randomly assigned into three groups (Group I: tDCS+MT+RPT, Group II: MT+RPT, Group III: tDCS+RPT), with 35 patients in each group. Randomization was carried out using Version 1.0 of Randomized Allocation Software (developed by the Department of Anesthesia, Isfahan University of Medical Sciences, Isfahan, Iran). Allocation was done to three groups with a 1:1:1 ratio with a unique identity number. In this double-blinded study, care providers of children were blinded to their assigned groups, while outcome assessors were blinded to the treatment regimens and research hypotheses. The treatment and assessments were conducted by two separate individuals. Two physical therapists, already working in the setting, participated in providing care and delivered the treatment protocol to children, shared by the primary investigators of the study.

Ethical Consideration

By following Helsinki guidelines, the study was approved by the University of Lahore's research ethics committee on December 20, 2023 (REC-UOL-626-12-2023). Written informed consent was obtained from parents, guardians, and capable patients, ensuring their legal rights. The procedures, confidentiality, benefits, and any potential discomfort a CP child might experience during the research were thoroughly explained to the parents or guardians.

Interventions

Transcranial Direct Current Stimulation

The patients were seated comfortably on a CP chair, with their hip and knee joints positioned at 90 degrees and their forearms resting on a table in front of the chair. For the groups receiving tDCS, a wireless rechargeable tDCS device (Segal Stim SG-2023004 by Framed Company) was used. This device used two 5–7 cm-long sponge electrodes that were soaked in 0.9% physiological saline. The electrodes were carefully wrapped around the patient's head and securely fastened to ensure proper contact and positioning.[23] For patients with affected left-sided extremities, the anode electrode was placed on the right main motor cortex (M1), and the cathode electrode was positioned on the contralateral supraorbital area. Conversely, for patients with affected right-sided extremities, the setup was reversed, the anode electrode was placed on the left main motor cortex (MI), while the cathode electrode was positioned on the contralateral supraorbital area as per recommendations of 10–20 EEG international system.[27,28] The brain remains excited for up to 20 minutes following tDCS. Therefore, we applied 15 minutes of stimulation to the right side, immediately followed by stimulation on the left side, with no additional rest time beyond what was necessary to change the electrodes. This approach was designed to effectively target and maintain the heightened excitability of the brain. The tDCS was administered at a current intensity of 2 milli amperes, with stimulation applied to each brain hemisphere for 15 minutes, resulting in 30 minutes of stimulation in total. This regimen was followed five times weekly for two consecutive weeks[22] (Figure 2).

Mirror Therapy

MT was carried out by concealing the left-sided extremities with a 35 × 35 centimeter mirror and placing the right-sided extremities in front of it. During the first 15 minutes, the patient moved his right upper and lower extremities, which were visible in the mirror. Following this, the technique was repeated for the left-sided extremities during the next 15 minutes.[29] Each 30-minute session of MT comprised ten sets of 20 repetitions for each exercise, with two-minute breaks

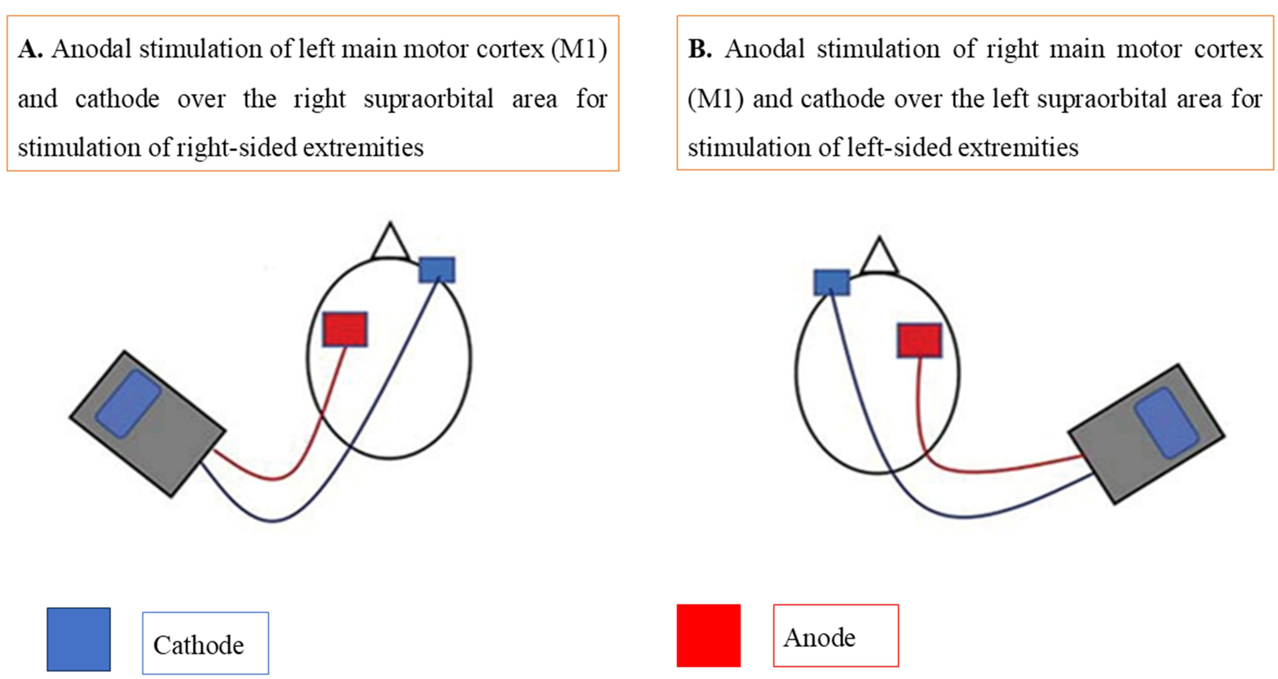

Figure 2 Schematic diagram of tDCS application. (**A**) Anodal stimulation of right-sided extremities. (**B**) Anodal stimulation of Left-sided extremities.

between sets.[30] The upper extremity MT program included exercises such as pronation, supination, and flexors–extensors of the fingers, wrist, and elbow.[31] For the lower extremities, the program featured activities like ball rolling, rocker-boarding, and pedaling.[32] During the sessions, the patient also received feedback to help them improve their focus and execution of the exercises, ensuring that the therapy was both effective and engaging.

Routine Physical Therapy

TOFT and RIPS were administered for ten minutes each, totaling twenty minutes as part of the RPT program, with a frequency of five days a week for ten weeks. TOFT focuses on tasks tailored to the patient's functional level and competencies, with exercises structured around their strengths and skills like activities regarding rolling, sitting, standing, and walking. During the RIPs regime, any absent, diminished, or exaggerated primitive, postural, or righting reflexes were addressed through repeated stimuli with good posture for its integration (Moro, startle, sucking, primary standing, primary walking, tonic labyrinthine, symmetrical and asymmetrical tonic neck reflex, head on body, body on head and body on body reflexes).

Outcome Measures

Patients received 10 sessions of tDCS and MT, each lasting 15 minutes per side (right and left), and 20 minutes of RPT as a follow-up. An independent assessor examined each patient's motor control-upper extremity (UE) motor control-lower extremity (LE), and motor control-trunk (T) using the FMA-UE, FMA-LE, and EMG biofeedback with reliability (0.86, 0.935, 0.95), respectively.[33–37] The patient was seated comfortably, and after ensuring a quiet and comfortable environment, an assessor filled out a 66-point questionnaire for the upper limb tasks and a 34-point questionnaire for lower limb tasks. For each task, a score was assigned: unable to perform = 0, assistance required = 1, and independently performed = 2. The biofeedback machine was set up with an inflation pressure of 60 mm Hg and positioned under the patient lying on their back. The patient was asked to do a "draw in" maneuver, engaging his or her core muscle with that task. Then, as the patient executed this maneuver, the pressure decrease was recorded in mm Hg. For muscle performance (isokinetic strength and power), the isokinetic dynamometer [38,39] with a reliability of 0.94 was used after assessing its calibration for better functioning. The patient was placed safely with the concerned joint aligned to the axis of rotation of the machine, and the speed was set at 60°/s. The patient was told to give his maximal effort for three contractions. Strength was measured in Newton meters (Nm) and power in Watts (W). Patients were assessed at baseline, after 10 sessions (or two weeks), and after a ten-week follow-up. The assessments adhered to the standard physical therapy treatment of extended RPT. The extended RPT program was developed to ensure patients had the highest chance of recovery and meeting ethical standards. Neuromuscular, biomechanical, biochemical, and morphological changes that support the development of control and muscle performance begin in the second week and mature between 8 and 12 weeks.[24]

Statistical Analysis

The data were analyzed using SPSS 26.0 (Chicago, USA). The normality of data was determined by using the Shapiro–Wilk test. Descriptive statistics were used to summarize categorical/nominal variables in terms of frequencies and percentages, while continuous variables were summarized with the mean and standard deviation. For inferential statistics, a two-way ANOVA was applied for between-group analysis. A repeated measures ANOVA was used for within-group comparisons across different time points (baseline, after 2 weeks, and after 10 weeks). Post hoc group comparisons were conducted using the Bonferroni test. The Box plot was drawn for estimation and data visualization. The analysis was conducted with a 95% confidence interval, and statistical significance was set at $P < 0.05$.

Results

During the study, 105 SQCP patients completed their treatment, with a mean age of 4.74 ± 1.02 years. The mean height in meters for Group-I was 0.92 ± 0.12, for Group-II was 0.94 ± 0.10, and for group-III was 0.944 ± 0.11. The mean weight in kilograms for Group I was 17.75 ± 1.61, for Group II was 17.908 ± 1.64, and for Group III was 17.88 ± 1.70. In terms of body mass index (kg/m^2), 39 patients (37%) were categorized as underweight, 60 patients (57%) as normal weight, and 6 patients (6%) as overweight (Table 1).

Table 1 Demographics

Variables	Group I (35)	Group II (35)	Group III (35)	Total (105)
	n (%)	n (%)	n (%)	n (%)
Age (Years)				
Mean ± Standard Deviation	4.66±1.03	4.71±1.01	4.86±1.02	4.74±1.02
Height (Meters)				
Mean ± Standard Deviation	0.92±0.12	0.94±0.10	0.944±0.11	0.93±0.11
Weight (Kilogram)				
Mean ± Standard Deviation	17.75±1.61	17.90±1.64	17.88±1.70	17.84±1.65
Body Mass Index (kg/m^2)				
Under-weight	12 (11)	13 (12)	14 (14)	39 (37)
Normal	21 (20)	20 (19)	19 (18)	60 (57)
Over-weight	2 (1)	2 (1)	2 (1)	6 (6)

Comparison of Baseline Characteristics of Patients as Determined by Measurement

At baseline, their motor control (upper extremities, lower extremities, and trunk) and muscular performance, in terms of strength and power of the right and left-sided elbow and knee flexors and extensors, yielded p-values greater than 0.05, indicating group uniformity (Table 2).

Table 2 Comparison of Baseline Characteristics

Variables	Domains	Group-I tDCS+MT+RPT (n=35)	Group-II MT+RPT (n=35)	Group-III tDCS+RPT (n=35)	P value
Motor Control	Upper Extremity	22.34±2.57	23.51±2.96	22.85±2.40	0.187
	Lower Extremity	6.20±1.75	6.40±1.64	6.20±1.68	0.849
	Trunk	5.20±1.74	5.40±1.63	5.14±1.55	0.791
Isokinetic Strength	Right Elbow Flexors	3.2±1.69	3.4±1.63	3.14±1.65	0.79
	Right Elbow Extensors	3.22±1.96	3.31±1.72	3.14±1.74	0.91
	Left Elbow Flexors	3.31±1.58	3.25±1.54	3.14±1.57	0.9
	Left Elbow Extensors	3.25±1.58	3.25±1.54	3.14±1.53	0.94
	Right Knee Flexors	6.17±1.54	6.25±1.54	6.25±1.52	0.97
	Right Knee Extensors	6.14±1.5	6.25±1.54	6.25±1.52	0.99
	Left Knee Flexors	6.2±1.63	6.25±1.54	6.25±1.52	0.95
	Left Knee Extensors	6.2±1.63	6.25±1.54	6.25±1.52	0.97

(*Continued*)

Table 2 (Continued).

Variables	Domains	Group-I tDCS+MT+RPT (n=35)	Group-II MT+RPT (n=35)	Group-III tDCS+RPT (n=35)	P value
Isokinetic Power	Right Elbow Flexors	3.2±1.69	3.4±1.63	3.24±1.65	0.8
	Right Elbow Extensors	3.22±1.96	3.31±1.72	3.22±1.81	0.91
	Left Elbow Flexors	3.31±1.58	3.25±1.54	3.23±1.56	0.9
	Left Elbow Extensors	3.25±1.58	3.25±1.54	3.21±1.55	0.94
	Right Knee Flexors	6.25±1.54	6.25±1.52	6.21±1.50	0.93
	Right Knee Extensors	6.24±1.54	6.25±1.52	6.21±1.52	0.93
	Left Knee Flexors	6.22±1.54	6.25±1.52	6.20±1.52	0.94
	Left Knee Extensors	6.17±1.55	6.25±1.52	6.18±1.52	0.97

Motor Control

Between-Group Comparison of Motor Control-UE, Motor Control-LE, and Motor Control-T

The study found significant differences in mean motor control scores for upper extremity, lower extremity, and trunk control between three groups after ten weeks, as determined by repeated ANOVA. At baseline, no significant differences were noted in any of the scores. After ten weeks, significant changes were observed in motor control-UE ($P < 0.001$, $n_2 = 0.385$), motor control-LE ($P < 0.001$, $n_2 = 0.369$), and motor control-T ($P < 0.001$, $n_2 = 0.270$) across all groups. Changes after two weeks were noted but not statistically significant (Table 3 and Figure 3).

Table 3 Between-Group Comparison of Motor Control-UE, Motor Control-LE, and Motor Control-T

Variables	Assessment	Motor Control							
		Group-I tDCS +MT+RPT (n=35)	Group-II MT +RPT (n=35)	Group-III tDCS+RPT (n=35)	Total (n=105)	P value	Eta-Squared (n_2)	95% Confidence Interval	
								Lower	Upper
Motor Control-UE	Baseline	22.34±2.57	23.51±2.96	22.85±2.40	22.90±2.64	0.187	0.032	0	0.111
	After 2 weeks	36.40±2.47	36.20±3.16	36.62±2.98	36.40±2.87	0.825	0.004	0	0.039
	After 10 weeks	54.14±2.77	47.80±4.53	52.65±2.80	51.53±3.36	0.001*	0.385	0.234	0.496
Motor Control-LE	Baseline	6.20±1.75	6.40±1.64	6.20±1.68	6.26±1.69	0.849	0.003	0	0.036
	After 2 weeks	12.62±0.84	12.37±0.97	12.80±1.02	12.60±0.94	0.169	0.034	0	0.114
	After 10 weeks	18.05±0.96	15.88±1.60	17.54±1.01	17.15±1.19	0.001*	0.369	0.217	0.482

(*Continued*)

Table 3 (Continued).

Variables	Assessment	Motor Control							
		Group-I tDCS +MT+RPT (n=35)	Group-II MT +RPT (n=35)	Group-III tDCS+RPT (n=35)	Total (n=105)	P value	Eta-Squared (n₂)	95% Confidence Interval	
								Lower	Upper
Motor Control-T	Baseline	5.20±1.74	5.40±1.63	5.14±1.55	5.24±1.64	0.791	0.005	0	0.044
	After 2 weeks	8.00±1.13	7.82±1.31	7.77±1.23	7.86±1.22	0.723	0.006	0	0.051
	After 10 weeks	18.14±2.15	16.29±2.28	16.22±2.15	16.88±2.19	0.001*	0.270	0.076	0.328

Notes: "*" indicates statistically significant results. "UE" indicates (upper extremity), "LE" indicates (lower extremity), "T" indicates (trunk).

Groupwise Comparison of Motor Control-UE, Motor Control-LE, and Motor Control-T

The Bonferroni test for multiple comparisons showed no significant differences between groups I & II, II & III, and III & I at baseline and after two weeks for motor control scores (UE, LE, and T). However, after ten weeks, significant differences were found between groups I & II and II & III for all three motor control measures (P = 0.000) with marginal confidence intervals (Table 4).

Muscle Performance (Isokinetic Strength)

Between-Group Comparison of Right and Left Elbow and Knee (Flexors and Extensors)

After ten weeks, the repeated measures ANOVA revealed significant differences in mean isokinetic strength scores for right- and left-sided elbow and knee flexors and extensors. Findings include significant differences in right elbow flexors (P = 0.04,

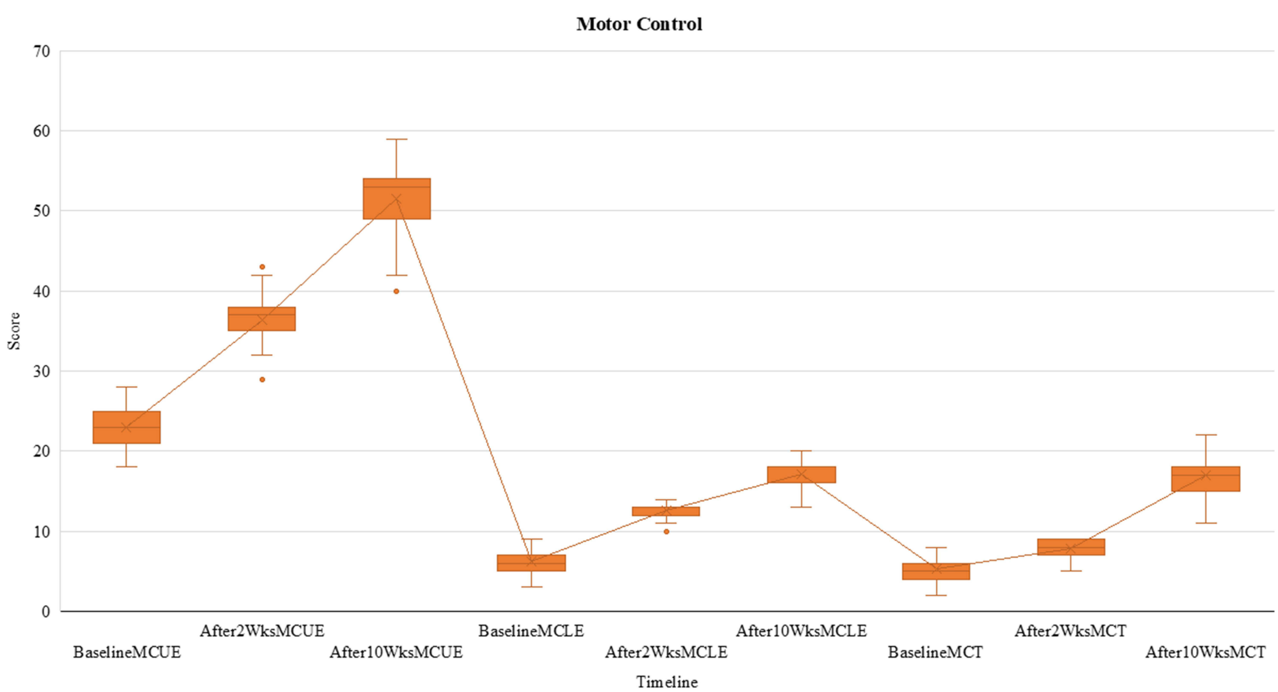

Figure 3 Graphical representation of Motor Control.

Table 4 Groupwise Comparison of Motor Control-UE, Motor Control-LE, and Motor Control-T

Variables	(I) groups	(J) groups	Mean Difference (I-J)	95% Confidence Interval	
				Lower Bound	Upper Bound
Motor Control-UE (Baseline)	I	II	−1.17	−2.72	0.38
	II	III	0.66	−0.89	2.20
	III	I	0.51	−1.03	2.06
Motor Control-UE (2 weeks)	I	II	0.20	−1.48	1.88
	II	III	−0.43	−2.11	1.25
	III	I	0.23	−1.45	1.91
Motor Control-UE (10 weeks)	I	II	6.34	4.32	8.36
	II	III	−4.85	−6.88	−2.84
	III	I	−1.49	−3.51	0.53
Motor Control-LE (Baseline)	I	II	−0.20	−1.18	0.78
	II	III	0.20	−0.78	1.18
	III	I	0.00	−0.98	0.98
Motor Control-LE (2 weeks)	I	II	0.26	−0.30	0.81
	II	III	−0.43	−0.98	0.12
	III	I	0.17	−0.38	0.72
Motor Control-LE (10 weeks)	I	II	2.17	1.46	2.89
	II	III	−1.65	−2.37	−0.94
	III	I	−0.51	−1.23	0.20
Motor Control-T (Baseline)	I	II	−0.20	−1.16	0.76
	II	III	0.26	−0.70	1.21
	III	I	−0.06	−1.01	0.90
Motor Control-T (2 weeks)	I	II	0.17	−0.55	0.89
	II	III	0.06	−0.66	0.77
	III	I	−0.23	−0.95	0.49
Motor Control-T (10 weeks)	I	II	2.20	1.01	3.39
	II	III	−0.03	−1.22	1.16
	III	I	−2.17	−3.36	−0.98

Notes: "UE" indicates (upper extremity), "LE" indicates (lower extremity), "T" indicates (trunk). "-" means this value could be less than zero.

$n_2 = 0.063$), right elbow extensors ($P = 0.01$, $n_2 = 0.071$), left elbow flexors ($P = 0.02$, $n_2 = 0.095$), left elbow extensors ($P = 0.02$, $n_2 = 0.074$), right knee flexors ($P = 0.03$, $n_2 = 0.069$), right knee extensors ($P = 0.05$, $n_2 = 0.058$), left knee flexors ($P = 0.05$, $n_2 = 0.057$), and left knee extensors ($P = 0.02$, $n_2 = 0.074$) among the groups (Table 5 and Figure 4).

 https://doi.org/10.2147/JMDH.S506784

Table 5 Between-Group Comparison of Right and Left Elbow and Knee Flexors and Extensors for Isokinetic Strength

Variables	Assessments	Isokinetic Strength							
		Group-I tDCS+MT +RPT (n=35)	Group-II MT+RPT (n=35)	Group-III tDCS+RPT (n=35)	Total (n=105)	P value	Eta Squared (n_2)	Confidence Interval (95%)	
								Lower	Lower
Right Elbow Flexors	Baseline	3.2±1.69	3.4±1.63	3.14±1.65	3.24±1.65	0.79	0.005	0	0.044
	After 2 weeks	4.2±0.75	4.17±0.78	4.11±0.75	4.16±0.76	0.89	0.002	0	0.028
	After 10 weeks	7.45±0.65	7±0.84	7.34±0.87	7.26±0.78	0.04*	0.063	0	0.16
Right Elbow Extensors	Baseline	3.22±1.96	3.31±1.72	3.14±1.74	3.22±1.81	0.91	0.002	0	0.028
	After 2 weeks	4.14±0.73	4.17±0.78	4.11±0.76	4.14±0.75	0.95	0.016	0	0.077
	After 10 weeks	7.51±0.74	6.94±0.83	7.48±0.85	7.31±0.81	0.01*	0.071	0	0.17
Left Elbow Flexors	Baseline	3.31±1.58	3.25±1.54	3.14±1.57	3.23±1.56	0.90	0.002	0	0.025
	After 2 weeks	4.25±0.78	4.02±0.74	4.11±0.76	4.12±0.76	0.45	0.001	0	0.013
	After 10 weeks	7.51±0.73	6.97±0.83	7.42±0.85	7.30±0.80	0.02*	0.095	0.009	0.202
Left Elbow Extensors	Baseline	3.25±1.58	3.25±1.54	3.14±1.53	3.21±1.55	0.94	0.001	0	0.017
	After 2 weeks	4.2±0.78	4.02±0.74	4.11±0.76	4.11±0.76	0.65	0.008	0	0.058
	After 10 weeks	7.51±0.91	6.97±0.91	7.42±0.85	7.30±0.89	0.02*	0.074	0.001	0.174
Right Knee Flexors	Baseline	6.17±1.54	6.25±1.54	6.25±1.52	6.22±1.53	0.97	0.001	0	0.006
	After 2 weeks	8.08±0.78	8.02±0.74	8.02±0.78	8.04±0.76	0.36	0.02	0	0.087
	After 10 weeks	15.42±0.81	15.14±0.91	15.42±0.84	15.32±0.85	0.03*	0.069	0	0.168
Right Knee Extensors	Baseline	6.14±1.5	6.25±1.54	6.25±1.52	6.21±1.52	0.99	0.001	0	0.013
	After 2 weeks	8.11±0.78	8.02±0.74	8.02±0.78	8.05±0.76	0.45	0.006	0	0.049
	After 10 weeks	15.42±0.81	15.14±0.91	15.42±0.84	15.31±0.86	0.05*	0.058	0	0.152
Left Knee Flexors	Baseline	6.2±1.63	6.25±1.54	6.25±1.52	6.23±1.56	0.95	0	0	0
	After 2 weeks	8.11±0.84	8.02±0.94	8.02±0.78	8.05±0.76	0.74	0.016	0	0.077
	After 10 weeks	15.44±0.81	15.15±0.91	15.42±0.80	15.33±0.84	0.05*	0.057	0	0.151
Left Knee Extensors	Baseline	6.2±1.63	6.25±1.54	6.25±1.52	6.23±1.56	0.97	0.001	0	0.006
	After 2 weeks	8.11±0.84	8.02±0.94	8.12±0.78	8.08±0.76	0.82	0.004	0	0.039
	After 10 weeks	15.62±0.81	15.14±0.91	15.32±0.84	15.36±0.85	0.02*	0.074	0.001	0.174

Note: "*" indicates statistically significant results.

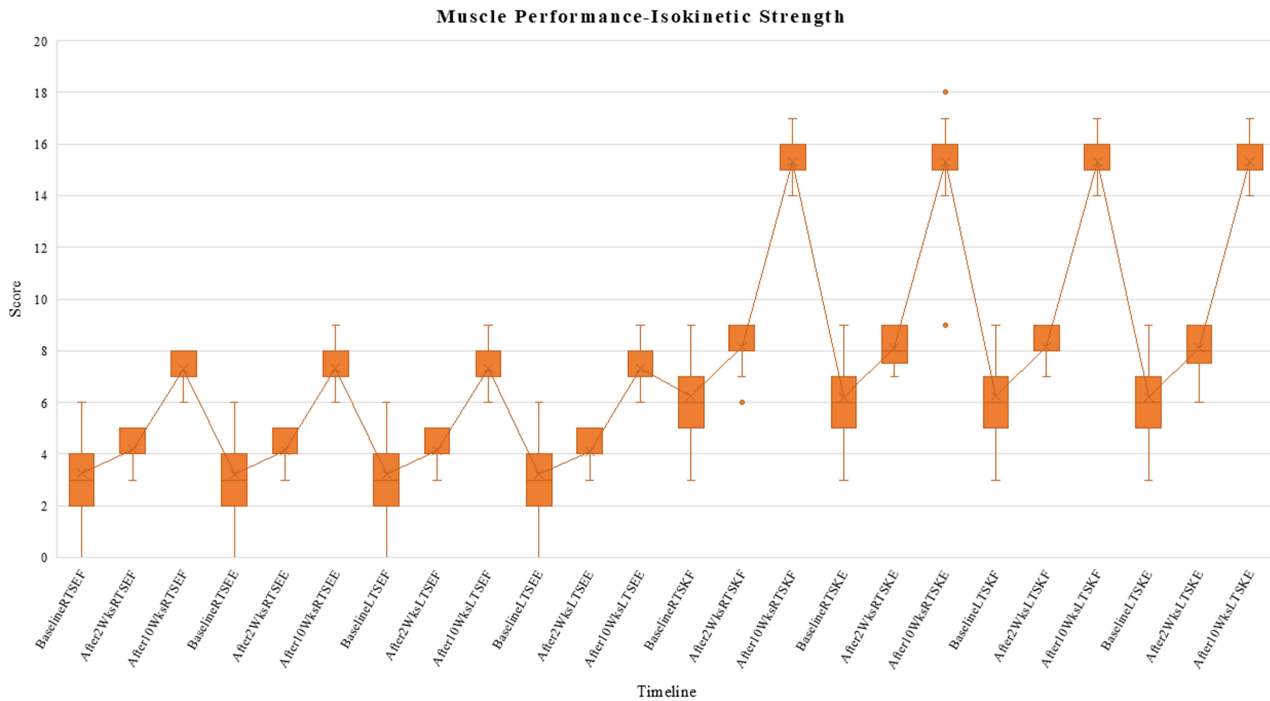

Figure 4 Graphical representation of Muscle Performance (Isokinetic Strength).

Muscle Performance (Isokinetic Power)

Between-Group Comparison of Right and Left Elbow and Knee Flexors and Extensors

After ten weeks, the repeated measures ANOVA indicated significant differences in mean power scores for right and left elbow and knee flexors and extensors. Important findings included differences in the power of right elbow flexors (P = 0.04, n_2 = 0.063), right elbow extensors (P = 0.01, n_2 = 0.095), left elbow flexors (P = 0.04, n_2 = 0.074), left elbow extensors (P = 0.02, n_2 = 0.074), right knee flexors (P = 0.03, n_2 = 0.066), right knee extensors (P = 0.05, n_2 = 0.066), left knee flexors (P = 0.05, n_2 = 0.066), and left knee extensors (P = 0.02, n_2 = 0.066) among the groups (Table 6 and Figure 5).

Table 6 Between-Group Comparison of Right and Left Elbow and Knee Flexors and Extensors for Isokinetic Power

Movement	Assessments	Isokinetic Power							
		Group-I tDCS+MT +RPT (n=35)	Group-II MT+RPT (n=35)	Group-III tDCS+RPT (n=35)	Total (n=105)	P value	Eta Squaredn_2	95% Confidence Interval	
								Lower	Upper
Right Elbow Flexors	Baseline	3.2±1.69	3.4±1.63	3.14±1.65	3.24±1.65	0.80	0.004	0	0.043
	After 2 weeks	4.2±0.75	4.17±0.78	4.11±0.75	4.16±0.76	0.89	0.002	0	0.028
	After 10 weeks	7.45±0.65	7.14±0.84	7.34±0.87	7.31±0.78	0.04*	0.063	0	0.16
Right Elbow Extensors	Baseline	3.22±1.96	3.31±1.72	3.14±1.74	3.22±1.81	0.91	0.002	0	0.025
	After 2 weeks	4.14±0.73	4.17±0.78	4.11±0.76	4.14±0.75	0.95	0.001	0	0.013
	After 10 weeks	7.51±0.74	6.94±0.83	7.48±0.85	7.31±0.81	0.01*	0.095	0.009	0.202

(*Continued*)

Table 6 (Continued).

Movement	Assessments	Isokinetic Power							
		Group-I tDCS+MT +RPT (n=35)	Group-II MT+RPT (n=35)	Group-III tDCS+RPT (n=35)	Total (n=105)	P value	Eta Squaredn₂	95% Confidence Interval	
								Lower	Upper
Left Elbow Flexors	Baseline	3.31±1.58	3.25±1.54	3.14±1.57	3.23±1.56	0.90	0.002	0	0.028
	After 2 weeks	4.25±0.78	4.02±0.74	4.11±0.76	4.12±0.76	0.45	0.016	0	0.077
	After 10 weeks	7.51±0.73	6.97±0.83	7.42±0.85	7.30±0.80	0.04*	0.074	0.001	0.174
Left Elbow Extensors	Baseline	3.25±1.58	3.25±1.54	3.14±1.53	3.21±1.55	0.94	0.001	0	0.017
	After 2 weeks	4.2±0.78	4.02±0.74	4.11±0.76	4.11±0.76	0.65	0.008	0	0.058
	After 10 weeks	7.54±0.90	6.97±0.89	7.42±0.92	7.30±0.89	0.02*	0.074	0.001	0.174
Right Knee Flexors	Baseline	6.25±1.54	6.25±1.52	6.14±1.45	6.21±1.50	0.94	0.001	0	0.017
	After 2 weeks	8.28±0.73	8.02±0.74	8.11±0.77	8.14±0.74	0.36	0.02	0	0.087
	After 10 weeks	15.54±0.87	15.20±0.86	15.42±0.83	15.38±0.85	0.03*	0.066	0	0.163
Right Knee Extensors	Baseline	6.24±1.54	6.25±1.52	6.14±1.50	6.21±1.52	0.95	0.001	0	0.013
	After 2 weeks	8.17±0.76	8.03±0.74	8.11±0.77	8.10±0.75	0.74	0.006	0	0.049
	After 10 weeks	15.54±0.87	15.11±0.86	15.42±0.83	15.35±0.85	0.05*	0.066	0	0.163
Left Knee Flexors	Baseline	6.22±1.54	6.25±1.52	6.14±1.5	6.20±1.52	0.95	0.001	0	0.013
	After 2 weeks	8.17±0.76	8.03±0.74	8.11±0.77	8.10±0.75	0.45	0.016	0	0.077
	After 10 weeks	15.54±0.87	15.02±0.86	15.42±0.83	15.32±0.85	0.05*	0.066	0	0.163
Left Knee Extensors	Baseline	6.17±1.55	6.25±1.52	6.14±1.50	6.18±1.52	0.95	0.001	0	0.013
	After 2 weeks	8.17±0.76	8.03±0.74	8.11±0.77	8.10±0.75	0.82	0.004	0	0.039
	After 10 weeks	15.44±0.88	15.14±0.86	15.32±0.86	15.30±0.86	0.02*	0.066	0	0. 163

Note: "*" indicates statistically significant results.

Groupwise Comparison of Isokinetic Strength and Power of Right and Left Elbow and Knee Flexors and Extensors

The results of the Bonferroni test for multiple comparisons for strength between groups after ten weeks revealed that there was a significant difference between groups I & II (P = 0.039) for Right elbow Flexors, between groups III & I (P = 0.033) for Right elbow Extensors, between groups I & II, II & III (P = 0.014, P = 0.021) for Left elbow Flexors, between groups II & III (P = 0.025) for Left Elbow Extensors, between group III & I (P = 0.028) for right Knee Flexors, between group III & I (P = 0.025) for Left knee extensors. (Table 6). Moreover, the results of multiple comparisons for power between groups after ten weeks showed that, there was a significant difference between groups I & II (P = 0.036) for Right Elbow Flexors, between groups I & II, II & III (P = 0.014, P = 0.021) for Right Elbow Extensors, between group II & III (P = 0.049) for Left Elbow Flexors, between group II & III (P = 0.025) for Left Elbow extensors, between group I & II (P = 0.037) for right Knee Flexors, between group I & II (P = 0.037) for Left knee extensors (Table 7).

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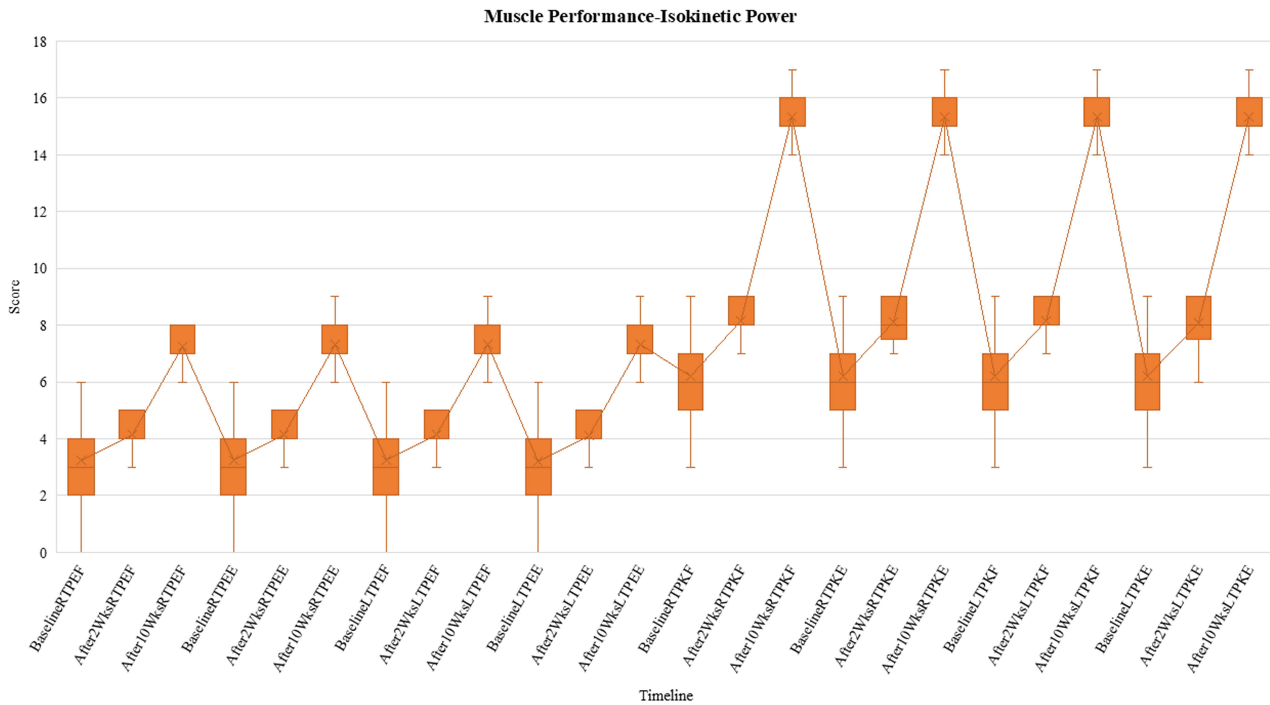

Figure 5 Graphical representation of Muscle Performance (Isokinetic Power).

Pairwise Comparison of Motor Control and Muscle Performance (Isokinetic Strength and Power)

Pairwise comparisons of motor control (UE, LE, T) and isokinetic strength and power (right and left-sided elbow and knee-flexors–extensors) indicated statistically significant changes in all pairings of these nineteen outcomes with ($P < 0.001$) with marginal upper and lower bounds in terms of confidence interval (Table 8).

Table 7 Groupwise Comparison of Isokinetic Strength and Power of Right and Left Elbow and Knee Flexors and Extensors

Variables	(I) Groups	(J) Groups	Isokinetic Strength			Isokinetic Power		
			Mean Difference (I-J)	95% Confidence Interval		Mean Difference (I-J)	95% Confidence Interval	
				Lower	Upper		Upper	Lower
Right Elbow Flexors (Baseline)	I	II	−0.200	−1.158	0.758	−0.0571	−1.120	0.777
	II	III	0.257	−0.701	1.215	−0.171	−0.691	1.205
	III	I	−0.057	−1.015	0.901	0.257	−1.034	0.863
Right Elbow Flexors (2 weeks)	I	II	0.029	−0.418	0.475	0.029	−0.418	0.475
	II	III	0.057	−0.390	0.504	0.057	−0.390	0.504
	III	I	−0.086	−0.532	0.361	−0.086	−0.532	0.361
Right Elbow Flexors (10 weeks)	I	II	0.457*	0.016	0.898	0.457*	0.016	0.898
	II	III	−0.343	−0.784	0.098	−0.343	−0.784	0.098
	III	I	−0.114	−0.555	0.327	−0.114	−0.555	0.327

(*Continued*)

Table 7 (Continued).

Variables	(I) Groups	(J) Groups	Isokinetic Strength			Isokinetic Power		
			Mean Difference (I-J)	95% Confidence Interval		Mean Difference (I-J)	95% Confidence Interval	
				Lower	Upper		Upper	Lower
Right Elbow Extensors (Baseline)	I	II	0.057	−0.851	0.965	−0.086	−1.053	0.882
	II	III	0.114	−0.794	1.023	0.171	−0.796	1.139
	III	I	−0.171	−1.080	0.737	−0.086	−1.053	0.882
Right Elbow Extensors (2 weeks)	I	II	0.229	−0.215	0.672	−0.029	−0.470	0.413
	II	III	−0.086	−0.529	0.358	0.057	−0.385	0.499
	III	I	−0.143	−0.586	0.300	−0.029	−0.470	0.413
Right Elbow extensors (10 weeks)	I	II	−0.457	−0.967	0.053	0.571*	0.092	1.051
	II	III	−0.086	−0.596	0.424	−0.542*	−1.023	−0.063
	III	I	0.542*	0.033	1.053	−0.029	−0.508	0.451
Left Elbow Flexors (Baseline)	I	II	−0.086	−1.053	0.882	0.057	−0.851	0.965
	II	III	0.171	−0.796	1.139	0.114	−0.794	1.023
	III	I	−0.086	−1.053	0.882	−0.171	−1.080	0.737
Left Elbow Flexors (2 weeks)	I	II	−0.029	−0.470	0.413	0.229	−0.215	0.672
	II	III	0.057	−0.385	0.499	−0.086	−0.529	0.358
	III	I	−0.029	−0.470	0.413	−0.143	−0.586	0.300
Left Elbow Flexors (10 weeks)	I	II	−0.029	−0.508	0.451	−0.114	−0.630	0.402
	II	III	0.571*	0.092	1.051	0.571*	0.055	1.088
	III	I	−0.542*	−1.023	−0.063	−0.457	−0.973	0.059
Left Elbow Extensors (Baseline)	I	II	0.015	−0.910	0.910	0.000	−0.910	0.910
	II	III	0.114	−0.796	1.025	0.114	−0.796	1.025
	III	I	−0.114	−1.025	0.796	−0.114	−1.025	0.796
Left Elbow Extensors (2 weeks)	I	II	0.171	−0.275	0.618	0.171	−0.275	0.618
	II	III	−0.086	−0.532	0.361	−0.086	−0.532	0.361
	III	I	−0.086	−0.532	0.361	−0.086	−0.532	0.361
Left Elbow Extensors (10 weeks)	I	II	−0.114	−0.630	0.402	−0.114	−0.630	0.402
	II	III	0.571*	0.055	1.088	0.571*	0.055	1.088
	III	I	−0.457	−0.973	0.059	−0.457	−0.973	0.059
Right Knee Flexors (Baseline)	I	II	−0.086	−0.990	0.819	0.000	−0.910	0.910
	II	III	0.000	−0.904	0.904	0.114	−0.796	1.025
	III	I	0.086	−0.819	0.990	−0.114	−1.025	0.796

(*Continued*)

Table 7 (Continued).

Variables	(I) Groups	(J) Groups	Isokinetic Strength			Isokinetic Power		
			Mean Difference (I-J)	95% Confidence Interval		Mean Difference (I-J)	95% Confidence Interval	
				Lower	Upper		Upper	Lower
Right Knee Flexors (2 weeks)	I	II	0.057	−0.400	0.514	0.257	−0.188	0.702
	II	III	−0.257	−0.714	0.200	−0.086	−0.531	0.359
	III	I	0.200	−0.257	0.657	−0.171	−0.616	0.274
Right Knee Flexors (10 weeks)	I	II	0.143	−0.383	0.668	0.542*	0.024	1.062
	II	III	0.429	−0.097	0.954	−0.429	−0.948	0.091
	III	I	−0.571*	−1.097	−0.046	−0.114	−0.634	0.405
Right Knee Extensors (Baseline)	I	II	−0.114	−1.024	0.795	−0.029	−0.938	0.881
	II	III	0.029	−0.881	0.938	0.114	−0.795	1.024
	III	I	0.086	−0.824	0.995	−0.086	−0.995	0.824
Right Knee Extensors (2 weeks)	I	II	0.086	−0.366	0.538	0.143	−0.309	0.595
	II	III	−0.143	−0.595	0.309	−0.086	−0.538	0.366
	III	I	0.057	−0.395	0.509	−0.057	−0.509	0.395
Right Knee extensors (10 weeks)	I	II	0.114	−0.538	0.766	0.542*	0.024	1.062
	II	III	0.514	−0.138	1.166	−0.429	−0.948	0.091
	III	I	−0.629	−1.280	0.023	−0.114	−0.634	0.405
Left Knee Flexors (Baseline)	I	II	−0.057	−0.958	0.844	−0.029	−0.938	0.881
	II	III	0.029	−0.872	0.929	0.114	−0.795	1.024
	III	I	0.029	−0.872	0.929	−0.086	−0.995	0.824
Left Knee Flexors (2 weeks)	I	II	0.086	−0.358	0.529	0.229	−0.215	0.672
	II	III	−0.229	−0.672	0.215	−0.086	−0.529	0.358
	III	I	0.143	−0.300	0.586	−0.143	−0.586	0.300
Left Knee Flexors (10 weeks)	I	II	0.114	−0.415	0.643	0.542*	0.024	1.062
	II	III	0.400	−0.129	0.929	−0.429	−0.948	0.091
	III	I	−0.514	−1.043	0.015	−0.114	−0.634	0.405
Left Knee Extensors (Baseline)	I	II	−0.086	−0.998	0.826	−0.086	−1.004	0.832
	II	III	0.086	−0.826	0.998	0.114	−0.804	1.032
	III	I	0.000	−0.912	0.912	−0.029	−0.947	0.890
Left Knee Extensors (2 weeks)	I	II	0.086	−0.378	0.550	0.114	−0.350	0.578
	II	III	−0.114	−0.578	0.350	−0.086	−0.550	0.378
	III	I	0.029	−0.435	0.492	−0.029	−0.492	0.435

(*Continued*)

Table 7 (Continued).

Variables	(I) Groups	(J) Groups	Isokinetic Strength			Isokinetic Power		
			Mean Difference (I-J)	95% Confidence Interval		Mean Difference (I-J)	95% Confidence Interval	
				Lower	Upper		Upper	Lower
Left Knee Extensors (10 weeks)	I	II	0.114	−0.402	0.630	0.542*	0.024	1.062
	II	III	0.457	−0.059	0.973	−0.429	−0.948	0.091
	III	I	−0.571*	−1.088	−0.055	−0.114	−0.634	0.405

Notes: "*" indicates statistically significant results. "-" means this value could be less than zero.

Table 8 Pairwise Comparison of Motor Control and Muscle Performance (Isokinetic Strength and Power)

Outcome Measures		Blending at Different Treatment Times	Mean Difference	95% Confidence Interval	
				Lower	Upper
Motor control	**Motor Control-UE**	Baseline - 2 weeks	−13.505	−14.100	−12.910
		2 weeks - 10 weeks	−15.124	−16.192	−14.056
		10 weeks - Baseline	28.629	27.526	29.731
	Motor Control-LE	Baseline - 2 weeks	−6.333	−6.698	−5.969
		2 weeks - 10 weeks	−4.562	−4.882	−4.242
		10 weeks - Baseline	−10.895	−11.343	−10.448
	Motor Control-T	Baseline - 2 weeks	−2.619	−2.951	−2.287
		2 weeks - 10 weeks	−9.076	−9.453	−8.700
		10 weeks - Baseline	−11.695	−12.187	−11.203
Isokinetic Strength	**Right Elbow Flexors**	Baseline - 2 weeks	−0.914	−1.259	−0.569
		2 weeks - 10 weeks	−3.105	−3.319	−2.890
		10 weeks - Baseline	−4.019	−4.369	−3.669
	Left Elbow Flexors	Baseline - 2 weeks	−0.914	−1.262	−0.566
		2 weeks - 10 weeks	−3.171	−3.401	−2.941
		10 weeks - Baseline	−4.086	−4.440	−3.732
	Right Elbow Extensors	Baseline - 2 weeks	−0.895	−1.215	−0.576
		2 weeks - 10 weeks	−3.171	−3.401	−2.941
		10 weeks - Baseline	−4.067	−4.402	−3.731
	Left Elbow Extensors	Baseline - 2 weeks	−0.895	−1.219	−0.571
		2 weeks - 10 weeks	0.000	−0.208	0.208
		10 weeks - Baseline	−4.095	−4.431	−3.759

(*Continued*)

Table 8 (Continued).

Outcome Measures		Blending at Different Treatment Times	Mean Difference	95% Confidence Interval	
				Lower	Upper
	Right Knee Flexors	Baseline - 2 weeks	−1.905	−2.225	−1.584
		2 weeks - 10 weeks	−7.200	−7.442	−6.958
		10 weeks - Baseline	−9.105	−9.442	−8.768
	Left Knee Flexors	Baseline - 2 weeks	−1.905	−2.222	−1.588
		2 weeks - 10 weeks	−7.200	−7.435	−6.965
		10 weeks - Baseline	−9.105	−9.440	−8.770
	Right Knee Extensors	Baseline - 2 weeks	−1.895	−2.218	−1.572
		2 weeks - 10 weeks	−7.190	−7.445	−6.936
		10 weeks - Baseline	−9.086	−9.460	−8.712
	Left Knee Extensors	Baseline - 2 weeks	−1.895	−2.224	−1.567
		2 weeks - 10 weeks	−7.219	−7.458	−6.981
		10 weeks - Baseline	−9.114	−9.450	−8.779
Isokinetic Power	**Right Elbow Flexors**	Baseline - 2 weeks	−0.905	−1.246	−0.564
		2 weeks - 10 weeks	−3.105	−3.319	−2.890
		10 weeks - Baseline	−4.010	−4.356	−3.663
	Left Elbow Flexors	Baseline - 2 weeks	−0.895	−1.215	−0.576
		2 weeks - 10 weeks	−3.181	−3.410	−2.952
		10 weeks - Baseline	−4.076	−4.410	−3.742
	Right Elbow Extensors	Baseline - 2 weeks	−0.914	−1.262	−0.566
		2 weeks - 10 weeks	−3.171	−3.401	−2.941
		10 weeks - Baseline	−4.086	−4.440	−3.732
	Left Elbow Extensors	Baseline - 2 weeks	−0.895	−1.219	−0.571
		2 weeks - 10 weeks	−3.200	−3.436	−2.964
		10 weeks - Baseline	−4.095	−4.431	−3.759
	Right Knee Flexors	Baseline - 2 weeks	−1.924	−2.247	−1.601
		2 weeks - 10 weeks	−7.181	−7.415	−6.947
		10 weeks - Baseline	−9.105	−9.441	−8.769
	Left Knee Flexors	Baseline - 2 weeks	−1.924	−2.246	−1.602
		2 weeks - 10 weeks	−7.200	−7.435	−6.965
		10 weeks - Baseline	−9.124	−9.461	−8.787
	Right Knee Extensors	Baseline - 2 weeks	−1.895	−2.218	−1.572
		2 weeks - 10 weeks	−7.190	−7.445	−6.936
		10 weeks - Baseline	−9.086	−9.460	−8.712

(*Continued*)

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Table 8 (Continued).

Outcome Measures		Blending at Different Treatment Times	Mean Difference	95% Confidence Interval	
				Lower	Upper
	Left Knee Extensors	Baseline - 2 weeks	−1.905	−2.236	−1.573
		2 weeks - 10 weeks	−7.219	−7.458	−6.981
		10 weeks - Baseline	−9.124	−9.461	−8.787

Notes: "UE" indicates (upper extremity), "LE" indicates (lower extremity), "T" indicates (trunk). "-" means this value could be less than zero.

Significant Findings

The study examined the effects of an intervention on spastic quadriplegic cerebral palsy patients who were stratified into three groups according to their treatment protocols. The initial assessment of motor control and muscle performance showed no difference between the groups. However, after the ten-week intervention period, notable improvements were evident in motor control scores with P-values <0.001 for both the upper and lower extremities and trunk control between groups (I & II), and (II & III). Isokinetic strength and power scores for elbow and knee flexors and extensors also showed notable differences, reflecting the efficacy of the interventions. These findings showed the differential impacts of treatments across the groups of studies, demonstrating that the intervention significantly enhanced the motor control and muscle performance of the participants involved. Notably, the tDCS group, whether administered alone or in combination, exhibited superior performance compared to the mirror therapy group (Supplementary File).

Discussion

MT and tDCS significantly improved motor control in spastic quadriplegic cerebral palsy children. After a ten-week treatment period, significant improvements were observed in both upper and lower extremity motor control, as well as trunk control, compared to baseline measurements. The combination of tDCS and MT (Group I) demonstrated greater efficacy than either treatment administered alone, with the tDCS group (Group III) outperforming the MT group. The current study findings suggest that noninvasive brain-stimulating interventions contribute to marked improvements in neuromuscular development. Additionally, the results of the present study showed marked improvement in isokinetic strength and power for elbow and knee flexors and extensors, which are essential for daily activities and sustained functional performance. Pairwise comparisons of motor control subdomains and muscle performance indicated statistically significant changes across all assessed outcomes.

The current study highlights the powerful synergy between tDCS and MT in improving motor control and muscle performance in children with spastic quadriplegic cerebral palsy. Significant gains in upper and lower extremity function, along with enhanced isokinetic strength and power, underscore the efficacy of these non-invasive interventions. The sequential application of tDCS before MT, as supported by research from Vlotinou et al, maximizes therapeutic benefits and promotes neuroplasticity.[40] By targeting the primary motor cortex, this approach not only fosters functional recovery but also paves the way for tailored rehabilitation strategies that can significantly enhance activities of daily living for affected children.

Vlotinou et al conducted a review on transcranial direct current stimulation in conjunction with mirror therapy for upper extremity rehabilitation in chronic stroke patients. Researchers demonstrated that the time-dependent interaction effects of sequential application of tDCS before MT are more advantageous and time-efficient than administering tDCS and MT simultaneously. This study is aligned with the current study findings for the improvement in the upper extremity function, therefore the target population of the current study is different. The findings of the current study are particularly relevant to cerebral palsy, where ischemic injury occurs. By targeting the affected areas with these combined techniques, neuroplasticity is promoted, resulting in improved muscle strength, power, and motor control.[40] Furthermore, tDCS seems to be especially beneficial for improving daily function and hand movement control when applied sequentially before MT, suggesting that this approach warrants consideration as a potentially effective therapeutic strategy.[41] The current study findings align with the study by Vlotinou due to the sequential treatment, as tDCS was administered before MT is the same in both studies.

tDCS is a non-invasive neuromodulatory method in which low-intensity electrical currents are delivered to the scalp to stimulate specific areas of the cerebral cortex, resulting in de-polarization or hyper-polarization of the neuronal membrane within a particular group of neurons. The differentiation between anodal and cathodal stimulation in tDCS remains a topic of substantial scholarly debate. In the current study, anodal stimulation was applied to the primary motor cortex (M1) and cathodal stimulation was applied to the contralateral supraorbital region. The mechanism of application of tDCS is aligned with a study conducted by de Moura MCDS in which he conducted a systematic review and meta-analysis on the effects of tDCS on balance improvement and proved that most of the studies showed that tDCS improved balance in cerebral palsy children when it is specifically applied to the primary motor cortex area (M1).[42] This approach to the application of tDCS is further supported by a review conducted by Elsner B, which indicated that anodal stimulation, particularly when applied to the left inferior frontal gyrus, is the most effective tDCS intervention for improving functional outcomes in patients with ischemic injuries.[43] The findings are aligned with the present study investigation in which anodal stimulation was administered to both the right and left primary motor cortex to facilitate motor function in the upper and lower extremities.

Another research by Santos LV et al supported our findings by applying a similar approach to promote neurological and musculoskeletal development in individuals with cerebral palsy, specifically targeting enhancements in muscle performance and motor control. However, the findings indicate that owing to the limited number of studies and the methodological variability among them, there exists only weak evidence supporting the use of tDCS in conjunction with MT for adults post-stroke and children with CP.[44] Notably, children with spastic hemiparetic CP exhibited transient motor improvements following a single session of anodal tDCS applied to the primary motor cortex.[45]

tDCS was administered according to two distinct protocols to individuals with cerebral palsy with GMFCS Level I, II, III, and IV. In an RCT conducted by Hassan, Z. et al the anodal stimulation of tDCS was applied to the primary motor cortex area, whereas the cathodal was applied to the contralateral supraorbital region. The treatment protocol was administered as four sessions per week over four weeks in total 16 sessions in spastic cerebral palsy children. This study treatment protocol was aligned with the current study concerning the intensity that was 2 mA and the placement of electrodes.[46]

Similarly, the double-blinded RCT was conducted by Duarte et al whose protocol of tDCS comprised five sessions per week over a condensed two-week period, resulting in a total of 10 sessions. This protocol primarily focused on assessing changes in balance and functional performance in combination with treadmill training on CP, rather than directly measuring muscle performance or motor control.[47] In contrast to the first protocol, the present study employed a similar approach to the second protocol but expanded the outcome measures to include a total of 10 sessions, with five sessions per week over two weeks, aimed at evaluating potential changes in both muscle performance (including strength and power) and motor control that resulted in significant improvements in both outcome measures upon analysis.

Similarly, in alignment with the present study on the importance of mirror therapy, a systematic review by Khan, Z. et al indicates that MT is effective in improving upper limb motor function in individuals with hemiplegic cerebral palsy, underscoring its potential as a therapeutic intervention for facilitating neuroplasticity and promoting motor recovery. The evidence supports the integration of MT into comprehensive rehabilitation programs aimed at optimizing functional outcomes for this population.[48] Furthermore, a review by Park et al in alignment with our results proved that mirror-mediated therapeutic interventions within occupational therapy practices showed a marked improvement and potential benefits in cerebral palsy children.[15]

In addition, a pilot study was conducted by Waqas, S., et al to evaluate the effects of tDCS and MT on motor control and muscle performance in patients with spastic quadriplegic cerebral palsy. The results revealed significant improvements, thereby providing empirical support for the underlying hypotheses of this investigation. Notably, this study demonstrated that both tDCS in conjunction with MT and MT administered independently produced remarkable enhancements in motor function and muscle performance. These findings suggest a synergistic effect of combining neuromodulatory techniques with rehabilitative therapies, highlighting the potential for integrated approaches to optimize therapeutic outcomes for individuals with spastic quadriplegic CP.[22]

In alignment with our study, Gygax et al proved that mirror therapy is feasible in children with hemiplegia and it tends to improve the muscle strength and dynamic function of the paretic arm. The possible durable improvement in function after cessation of therapy points towards neuronal mechanisms that go beyond an isolated increase in primary motor cortex excitability. One mechanism may be by activation of the mirror neuron system.[49]

Another study by Smorenburg et al concluded that mirror visual feedback of the impaired arm has the opposite effect of "uncompromised" apparent symmetrical motion in children with spastic hemiparetic cerebral palsy. This study provided deep insights into the beneficial effects of the use of mirror therapy in patients with cerebral palsy that somehow align with our study in the importance of the combined effects of mirror therapy and tDCS.[50]

Interventions have shown significant improvements in motor control and muscle performance in patients with spastic cerebral palsy. However, this study focused on GMFCS levels I to III, specifically on spastic quadriplegic CP, which presents unique challenges and leaves other forms of CP unexplored. Future research should compare motor control and performance across all GMFCS levels (I to V) in individuals with spastic CP. Additionally, inconsistencies in muscle strength and power among the groups indicate a need for well-planned follow-up studies to address these variations. While the treatment groups were designed to maximize benefits, a significant limitation was the absence of a rehabilitation therapy (RPT) only group, which complicates the ability to isolate the added effects of tDCS and other treatments over standard RPT. Furthermore, the study did not consider the adverse effects of tDCS dosage or the long-term sustainability of these results within the given timeframe, aspects that should be addressed in future investigations to ensure a holistic understanding of the treatment's efficacy. It would be beneficial to investigate the effect of optimal rest periods between bilateral brain stimulation sessions within the cerebral palsy population.

Conclusion

TDCS and MT in combination may have a significant impact on motor control and muscle performance, enhancing both the strength and power of elbow and knee musculature among SQCP patients.

Data Sharing Statement

All relevant data are included within the manus cript text, tables, and supplementary file.

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Disclosure

The authors report no conflicts of interest related to this work.

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