

RESEARCH

Open Access



Effect of anodal transcranial direct current stimulation on balance in children with autism spectrum disorder

Omnia A. Abubakr¹, Manal M. Mahdi Omar², Sara Ali³ and Dina Y. Elalfy^{4*}

Abstract

Background Autism spectrum disorder (ASD) is a neurodevelopmental delay condition. Although behavioural abnormalities are the primary indicators of the disorder, still a significant number of children with ASD present with motor abnormalities. Research has also identified deficiencies in their postural stability, and their gait patterns, which impaired their motor coordination. Transcranial direct current stimulation (tDCS) is a safe, accessible brain stimulation method, the impact of tDCS on the primary motor cortex during motor training, which demonstrated improvements in balance and motor skills in ASD children had been investigated. The present study seeks to examine the effect of anodal tDCS over the primary motor cortex on balance in patients with ASD.

Results Both groups showed significant difference in MABC-2 balance subscale and QNST when baseline was compared to post-intervention and to the follow-up parameters. Both the post-intervention and follow-up balance subscale of MABC-2 and QNST were significantly higher in group I (who received tDCS sessions and neuro-rehabilitation programme) compared to group II (who received rehabilitation programme only). Similarly, the percentage of change from baseline to post-intervention and to 2-month follow-up of both MABC-2 balance subscale and QNST was significantly higher in group I in comparison to group II.

In group I, there was a positive correlation between the Quick Neurological Screening Test (QNST) and both childhood autism rating scale (CARS) scores and Vineland scores. In group II, there was a negative correlation between the Movement Assessment Battery for Children-2 (MABC2) and CARS scores and a positive correlation between the MABC2 and Vineland. In both groups, there was a negative correlation between MABC2 SD and BMI.

Conclusions tDCS is a non-invasive new adjuvant therapeutic approach in ASD. The current study revealed that severe autistic symptoms are associated with greater motor deficits. Immediately after applying tDCS sessions alongside neurorehabilitation programme, balance subscales and neurological deficits improved significantly more than applying neurorehabilitation programme alone and this effect continued in the follow-up.

Keywords Autism spectrum disorder, Transcranial direct current stimulation, Balance and motor skills, Movement Assessment Battery for Children-2, Quick Neurological Screening Test

*Correspondence:

Dina Y. Elalfy
denaelalfy@yahoo.com

Full list of author information is available at the end of the article

Background

Autism spectrum disorder (ASD) is a neurodevelopmental delay condition characterized by behavioural and adaptive functional abnormalities [1].

Although behavioural abnormalities are the primary indicators of the disorder, still a significant number of children with ASD present with motor abnormalities, and went through rehabilitation and balance-based exercises due to the adverse effects of motor control issues on their daily lives. Approximately 83% of children with ASD experience varying degrees of difficulty with gross and fine motor functions [2]. Research has also identified deficiencies in their postural stability, and their gait patterns, which impaired their motor coordination, led to presence of dyspraxia, and delay in the acquisition of their motor milestones and basic motor skills [3].

A persistent concern for individuals with ASD is standing balance, as many have not achieved the same level of balance as typically developing individuals. When comparing autistic children to their typically developing peers, the former demonstrate poor postural or balance control, evidenced by postural sway in both double-leg and single-leg stances. Maintaining proper balance is crucial for performing daily activities such as dressing, bathing, and engaging in recreational pursuits like sports and bicycling. Children with autism spectrum disorder (ASD) may face challenges in participating in these social and recreational activities [4], which can negatively affect their social cognition, communication, and overall engagement. Furthermore, these difficulties hinder their ability to explore their environment, thereby impacting both social and motor development. In this population, such challenges may also contribute to social communication disorders, including social isolation and anxiety [5].

At the neuroanatomical level of individuals with ASD, abnormalities exhibit in the sub-cortical white matter connectivity and the cerebellum, also atypical connections in the frontal-striatal areas, due to impaired connectivity between the primary sensory areas and motor areas, and abnormalities in the frontal-parietal network, as evidenced increase of the volume and surface area of their grey matter. Neuro-functional impairments in this population include inadequate multisensory integration, impaired sensory input processing, and difficulties with self-other mapping. These deficits are posited to underlie the variations in motor performance observed among children with ASD, supporting the hypothesis that transcranial direct current stimulation (tDCS) applied to motor cortical areas may enhance motor abilities in this clinical group [6].

Transcranial direct current stimulation (tDCS) is a safe, accessible brain stimulation method, considered to be

non-invasive that employs surface electrodes to administer a low-intensity monophasic electrical current to the scalp. This technique induces long-lasting changes in cortical excitability [7].

The polarity of the current plays a crucial role in cortical regulation: cathodal stimulation exerts an inhibitory effect by hyperpolarizing the neuronal cell membrane, whereas anodal stimulation enhances the cortical excitability by promoting depolarization of the neuronal cell membrane [8].

Certain aspects of movement, such as strength, movement direction, speed, and acceleration, are linked to the primary motor cortex. Numerous studies involving individuals across various life stages have employed anodal tDCS over this brain region to demonstrate that cortical modulation of neural networks can be facilitated. This modulation can enhance and support the learning and consolidation of motor patterns, particularly when stimulation is combined with motor training [9].

The impact of anodal tDCS over the left dorsolateral prefrontal cortex [10–13] or the temporoparietal junction have predominantly been investigated in clinical trials involving autistic children. These studies aim to modulate dysfunctional areas directly associated with the disorder's core diagnostic characteristics, namely impaired executive functions and social communication. Previous trials have demonstrated a reduction in the severity of the disorder's symptoms, particularly concerning social and nonverbal communication, a decrease in stereotyped behaviours, and an enhancement in their working memory [14, 15].

Currently, there exists only one clinical trial that investigates the impact of tDCS on the primary motor cortex during motor training, which demonstrated improvements in balance and motor skills in ASD children [6].

The present study seeks to examine the effect of anodal tDCS over the primary motor cortex on balance in patients with ASD.

Methodology

Participants

This study was conducted from July 2024 to July 2025, involving 60 children diagnosed with ASD who were recruited from the outpatient clinic of the Special Needs Care Centre, Faculty of Postgraduate Childhood Studies, Ain Shams University. The participants adhered to the following criteria:

Inclusion criteria

Participants were aged between 6 and 17 years and were diagnosed with Autism Spectrum Disorder (ASD) in accordance with the Diagnostic and Statistical Manual of Mental Disorders, Fifth Edition (DSM-5) [16].

Participants exhibited balance disorders, scoring at or below the 15th percentile on balance subscale of the Movement Assessment Battery for Children-2 (MABC-2) [17]. They demonstrated the ability to comprehend and communicate with motor training instructors and were capable of executing the prescribed motor learning instructions. There was no alteration in medication within the 6 months preceding the study or during its duration, and participants did not engage in other regular exercise programmes.

Exclusion criteria

These include individuals with a history of epilepsy or seizures, neurological or neuromuscular disorders or syndromes other than autism spectrum disorder (ASD), those who have undergone orthopaedic or neurological surgery within 12 months prior to the intervention, or have had any neurosurgical procedures, as well as those with orthopaedic deformities requiring surgical intervention, metallic implants all over the body, or hearing devices, and those who might show difficulty in cooperation, and understanding the proposed activities needed in the present study.

Randomization and blinding

Following the selection of participants based on the established eligibility criteria and the completion of the pre-intervention assessment, randomization was executed by an independent statistician utilizing a simple computer-generated randomization method. Participants were randomly allocated in a 1:1 ratio into two groups, each comprising 30 patients: the experimental ASD group and the control (sham) group. This study was conducted in a double-blind manner, ensuring that the investigators, participants, and their families were unaware of the participants' group assignments. The interventions were administered by an independent, trained physiotherapist who was not involved in this study.

Sample size

Utilizing the PASS 15 programme for sample size calculation, an examination of results from a prior study (Mahmoodifar and Sotoodeh, 2020) [6] indicated that transcranial direct current stimulation (tDCS) significantly enhances motor skill training in children and adolescents with autism spectrum disorder. Assuming an effect size difference of 0.7 between the two groups concerning the improvement in balance scores, and accounting for a 5% adjustment for dropout rate, a sample size of at least 30 patients per group is required to achieve 80% power to reject the null hypothesis of zero effect size. This calculation is based on a population effect size of

0.70 and a significance level (alpha) of 0.05, employing a one-sided two-sample equal-variance *t*-test.

Assessment

All participants underwent comprehensive history taking and clinical examination, which included the diagnosis of ASD by semi-structured interview based on DSM-5 criteria, and the assessment of ASD severity by applying the Childhood Autism Rating Scale (CARS). This scale comprises 14 domains evaluating autism behaviours, and a 15th domain assessing general impressions of autism. The total score ranges from 15 to 60, where a score of 30–36.5 indicates mild to moderate degree of autism, and a score of 37–60 signifies severe degree of autism [18].

Additionally, the adaptive behaviour of individuals with ASD was evaluated using the Vineland Adaptive Behaviour Scales, Second Edition (Vineland-II). This standardized assessment tool measures adaptive behaviour in individuals from birth to 90 years of age, assessing daily living skills, including social and practical abilities. It is widely utilized in clinical and educational settings to identify strengths and weaknesses, support diagnoses, and develop intervention plans.

The total score ranges from 20 to 160, categorized as follows:

Weak adaptive behaviour: 20–70, weak-average: 71–85, average: 86–114, average-high: 115–129, and high: 130–160 [19].

The primary outcome was evaluated using the balance subscale of the Movement Assessment Battery for Children-2 (MABC-2), a validated and reliable instrument for assessing and identifying impairments in individuals with ASD. This tool includes various tests tailored for distinct age groups: from 3 to 6 years, from 7 to 11 years, and from 12 to 17 years. The balance subscale comprises three items for each age category, consisting of two dynamic and one static test; a child's raw score can be converted into an age-based standard score and percentile equivalent for each subscale. Percentiles serve as "Traffic Lights" to facilitate interpretation when communicating test results to caregivers and educators, with the following zones: (a) the Red zone: represents percentile scores at or below the 5th percentile, (b) the Amber zone: represents percentile scores between the 6th and 15th percentile, and (c) the Green zone: represents percentile scores above the 15th percentile. The balance subscale of the MABC-2 was administered at baseline, immediately following the intervention, and 2 months post-intervention [17].

The Quick Neurological Screening Test (QNST) was applied to assess the secondary outcome at three distinct time duration: baseline, immediately following the

intervention, and 2 months post-intervention. The QNST is a concise, standardized instrument designed to evaluate neurological function, requiring approximately 10–15 min for administration. It examines various dimensions of neurological function, including cranial nerves, motor function, sensory perception, and coordination. The scoring system categorizes results as follows: a normal score ranges from 0 to 25, a suspicious score from 26 to 50, and a pathological score is indicated by scores greater than 50 [20].

Evaluation of adverse effects of tDCS

Subsequent to each session and during the follow-up period, participants and their families were queried regarding any side effects experienced as a result of the stimulation process.

Intervention

The transcranial direct current stimulation (tDCS) sessions were administered by a trained physiotherapist utilizing a Brain PremierE1 device (Shenzhen Yingchi Technology Co, China). Round sponge electrodes with a diameter of 5 cm, soaked in saline, were employed to deliver the direct current. Group I received stimulation of the left primary motor cortex (M1) (C3) via the anodal electrode of the tDCS, in accordance with the International System of Electrode Placement EEG 10–20 (Fig. 1); the cathodal electrode was positioned over the right supraorbital region (Fp2).

The current parameters were as follows: duration of 20 min and an intensity of 1 mill ampere, with a 30-s ramp-up and ramp-down. Conversely, group II received sham tDCS over the same area for the same duration (20 min);

however, the stimulator was deactivated after 30 s to ensure participant blinding. Participants in each group attended 10 sessions of the respective intervention (5 sessions per week for 2 weeks). Participants who failed to attend at least 8 sessions in total were excluded from the study [6].

Neurorehabilitation programme

Immediately following transcranial direct current stimulation (tDCS), all participated children of both groups were engaged in individualized exercises tailored to their performance on the balance subscale of the Movement Assessment Battery for Children-2 (MABC-2). Each participant underwent 10 sessions, over 2 weeks with five sessions per week, each lasting 30 min. The exercises were designed to enhance both static and dynamic balance and included activities such as balance board exercises, Swiss ball exercises, balancing on one foot, walking on tiptoes, walking on a balance beam heel-to-toe both forward and backward, and jumping and hopping on one leg in both straight and zigzag patterns [6, 21]. All the previous steps are illustrated in the flow diagram (Fig. 2).

Results

Demographic data and clinical characteristics

This study comprised 60 participants, including 51 males and 9 females, with ages ranging from 6 to 16 years. The mean body mass index (BMI) of the participants was 20.95 ± 1.5 . The mean Childhood Autism Rating Scale (CARS) score was 35.73 ± 6.26 , while the mean Vineland Adaptive Behaviour Scales score was 111.9 ± 20.94 . No statistically significant differences were observed in the aforementioned parameters between the two groups under study (Table 1).

Correlation between each of BMI, CARS, and Vineland scores with the other studied parameters in group I and group II before intervention

In group I, there was a negative correlation between MABC2 SD and BMI indicating that with increased body weight there is more motor deficit. There was a positive correlation between the QNST and CARS scores indicating that the more the severe the autistic symptoms the more the deficit in QNST.

There was a positive correlation between the QNST and Vineland scores indicating that lower adaptive function is associated with more neurological deficit in QNST.

In group II, there was a negative correlation between MABC2 SD and BMI indicating that with increased body weight there is more motor deficit.



Fig. 1 tDCS electrodes placement; anodal electrode over left primary motor area (C3), the cathode over the right supraorbital area (Fp2)

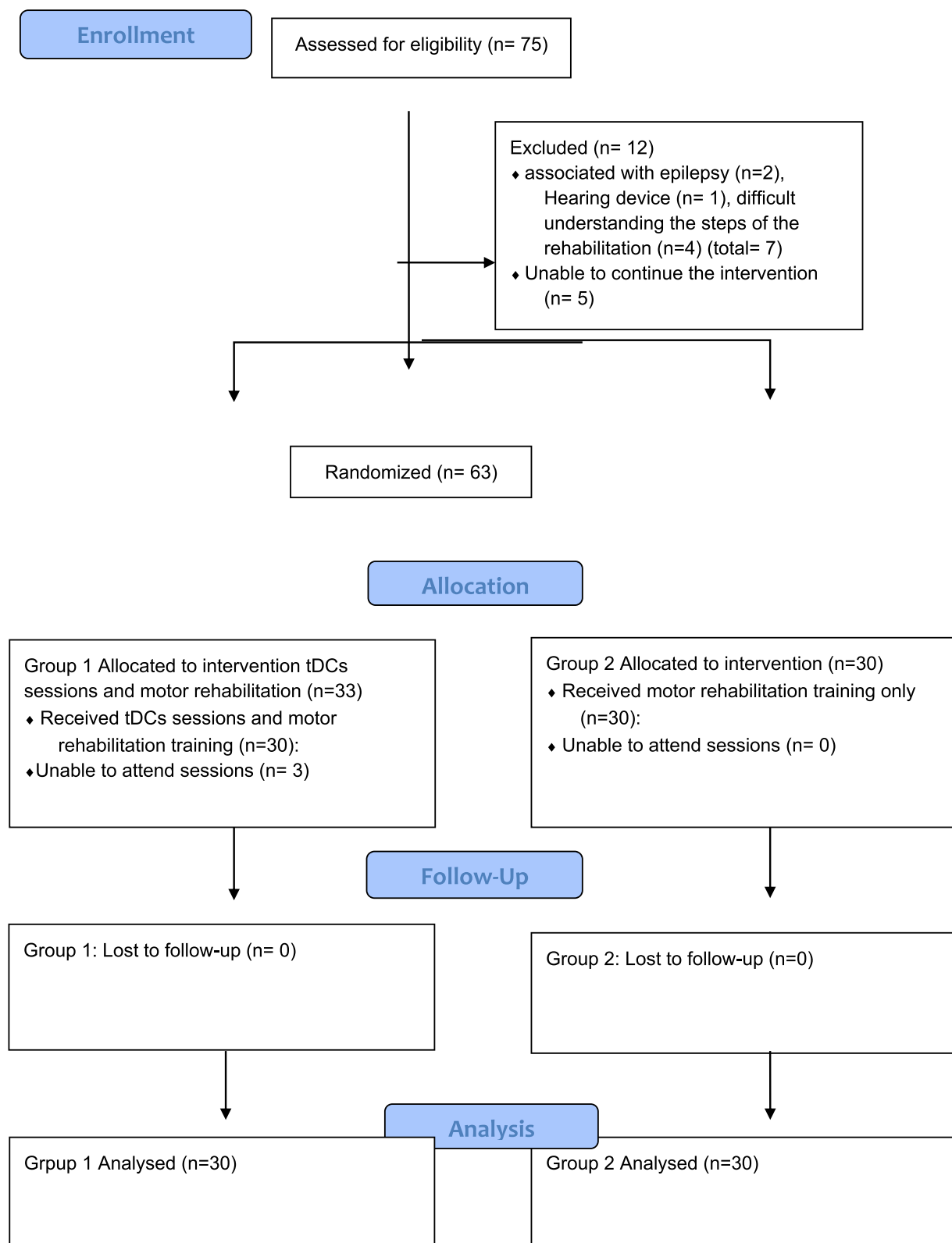
**Fig. 2** Flow diagram

Table 1 Demographic and clinical characteristic of the participants

		All participants No- 60	Group I No. = 30	Group II No. = 30	Test value	P-value	Sig.
Sex	Females	9 (15.0%)	4 (13.3%)	5 (16.7%)	0.131*	0.718	NS
	Males	51 (85.0%)	26 (86.7%)	25 (83.3%)			
Age	Mean $\pm$ SD	12.7 $\pm$ 2.48	12.57 $\pm$ 3.00	12.83 $\pm$ 1.86	−0.414•	0.681	NS
	Range	6 - 16	6–16	10–16			
Height (cm)	Mean $\pm$ SD	146.98 $\pm$ 12.37	145.57 $\pm$ 15.36	148.40 $\pm$ 8.46	−0.885•	0.380	NS
	Range	110 - 162	110–162	135–160			
Weight (kg)	Mean $\pm$ SD	45.87 $\pm$ 9.79	44.40 $\pm$ 11.50	47.33 $\pm$ 7.62	−1.164•	0.249	NS
	Range	21 - 60	21–60	38–59			
BMI	Mean $\pm$ SD	20.95 $\pm$ 1.5	20.58 $\pm$ 1.75	21.32 $\pm$ 1.12	−1.942•	0.057	NS
	Range	17.44 - 24.03	17.44–24.03	19.9–23.05			
CARS	Mean $\pm$ SD	35.73 $\pm$ 6.26	34.83 $\pm$ 6.02	36.63 $\pm$ 6.46	−1.116•	0.269	NS
	Range	30 - 51	30–51	30–50			
Vineland	Mean $\pm$ SD	111.9 $\pm$ 20.94	108.27 $\pm$ 17.19	115.53 $\pm$ 23.86	−1.353•	0.181	NS
	Range	79 - 148	79–148	80–148			

P-value > 0.05: Non-significant

P-value < 0.05: Significant

P-value < 0.01: Highly significant

*: Chi-square test

•: Independent t-test

Table 2 Correlation between each of BMI, CARS and Vineland scores with the other studied parameters in group I and group II before intervention

	BMI		CARS		Vineland	
	r	P-value	r	P-value	r	P-value
Group I						
MABC-2 balance subscale (pre)						
Total score	−0.311	0.095	−0.170	0.369	0.320	0.084
SD	−0.463**	0.010	−0.090	0.637	0.158	0.403
Percentile	−0.325	0.080	−0.019	0.919	0.081	0.669
QNST total score pre	0.182	0.335	0.493**	0.006	−0.413*	0.023
Group II						
MABC-2 balance subscale (pre)						
Total score	−0.715**	0.000	−0.401*	0.028	0.515**	0.004
SD	−0.337	0.069	−0.295	0.113	0.379*	0.039
Percentile	−0.586**	0.001	−0.293	0.116	0.491**	0.006
QNST total score pre	0.118	0.535	−0.329	0.076	−0.284	0.128

P-value > 0.05: Non-significant

*P-value < 0.05: Significant

**P-value < 0.01: Highly significant Spearman correlation coefficient

There was a negative correlation between the MABC2 and CARS scores indicating that more severe autistic symptoms is associated with more motor deficit.

There was a positive correlation between the MABC2 and Vineland scores indicating that higher adaptive function is associated with better motor function (Table 2).

Outcome parameters

- At baseline and according to the comparable percentiles of the balance subscale of MABC-2, participants in both groups were in the red zone (percentile ≤ 5). There was no significant difference between

Table 3 Comparison between group I and group II regarding MABC-2 balance subscale and QNST

Parameter				Group I No. = 30	Group II No. = 30	Test value	P-value	Sig.
MABC-2 balance subscale	Pre	Total score	Mean $\pm$ SD	15.07 $\pm$ 1.86	14.83 $\pm$ 1.78	-0.795 $\neq$	0.427	NS
			Range	10–17	13–17			
		SD	Mean $\pm$ SD	4.53 $\pm$ 0.82	4.33 $\pm$ 0.71	-1.506 $\neq$	0.132	NS
			Range	2–5	3–5			
		Percentile	Mean $\pm$ SD	3.90 $\pm$ 1.62	3.40 $\pm$ 1.52	-1.260 $\neq$	0.208	NS
			Range	0.5–5	2–5			
	Post	Total score	Mean $\pm$ SD	125.42 $\pm$ 38.04	28.12 $\pm$ 23.80	-6.492 $\neq$	0.000	HS
			Range	64.29–171.43	11.76–84.62			
		SD	Mean $\pm$ SD	182.17 $\pm$ 79.90	37.56 $\pm$ 21.47	-6.602 $\neq$	0.000	HS
			Range	75–300	20–75			
		Percentile	Mean $\pm$ SD	1796.53 $\pm$ 1159.56	609.33 $\pm$ 1233.85	-5.096 $\neq$	0.000	HS
			Range	640–4800	80–3700			
	follow-up	Total score	Mean $\pm$ SD	133.25 $\pm$ 47.10	25.12 $\pm$ 19.79	-6.664 $\neq$	0.000	HS
			Range	75–228.57	5.88–58.82			
		SD	Mean $\pm$ SD	187.67 $\pm$ 97.88	30.22 $\pm$ 26.11	-6.701 $\neq$	0.000	HS
			Range	80–375	0–66.67			
		Percentile	Mean $\pm$ SD	1982.50 $\pm$ 1418.45	160.00 $\pm$ 147.62	-6.719 $\neq$	0.000	HS
			Range	640–4900	0–400			
QNST	Pre	Total score	Mean $\pm$ SD	29.30 $\pm$ 13.53	24.71 $\pm$ 9.24	-0.520 $\neq$	0.603	NS
			Range	8–59	9–45			
	Post	Total score	Mean $\pm$ SD	7.46 $\pm$ 3.59	26.93 $\pm$ 10.00	-4.893 $\neq$	0.000	HS
			Range	1–35	8–37			
	Follow up	Total score	Mean $\pm$ SD	12.20 $\pm$ 9.90	26.93 $\pm$ 10.00	-4.893	0.000	HS
			Range	2–42	9–40			

P-value > 0.05: Non-significant*P*-value < 0.05: Significant*P*-value < 0.01: Highly significant $\neq$: Mann-Whitney test

both groups regarding MABC-2 balance subscale total score, SD, and percentile ($p=0.427$, 0.132 , 0.208 respectively) and QNST ($p=0.603$) at baseline (Tables 3, 4, 5).

- Both the post-intervention and 2-month follow-up balance subscale of MABC-2 and QNST were significantly higher in group I in comparison to group II (Table 3).
- Both patient groups showed a statistically significant difference in MABC-2 balance subscale and QNST when the baseline was compared to post-intervention and when the baseline was compared to the follow-up parameters (Table 4). Similarly, when the two

groups were compared regarding the percentage of change from baseline to post-intervention and from baseline to 2-month follow-up for the MABC-2 balance subscale and QNST, the percentage of change was significantly higher in group I in comparison to group II (Table 5).

tDCS's adverse effects

tDCS was well tolerated; in group I, 4 patients (13.33%) reported tingling sensation under the active electrodes which disappeared after few seconds of stimulation; irritability was reported by the mother of 3 children while

Table 4 Comparison of outcome parameter (pre, post and at follows up) among each patient group

Parameter				Pre	Post	Follow-up	Test value	P-value	Sig.
MABC-2- balance	Group I	Total score	Mean $\pm$ SD	15.07 $\pm$ 1.86	34.07 $\pm$ 7.36	34.80 $\pm$ 6.71	46.974 $\neq$	0.000	HS
			Range	10–17	19–46	26–46			
		SD	Mean $\pm$ SD	4.53 $\pm$ 0.82	12.77 $\pm$ 4.31	12.73 $\pm$ 4.27	49.164 $\neq$	0.000	HS
			Range	2–5	6–19	8–19			
		Percentile	Mean $\pm$ SD	3.90 $\pm$ 1.62	67.33 $\pm$ 34.08	64.89 $\pm$ 31.04	49.164 $\neq$	0.000	HS
			Range	0.5–5	9–99.9	25–99.9			
	Group II	Total score	Mean $\pm$ SD	14.83 $\pm$ 1.78	18.90 $\pm$ 3.39	18.53 $\pm$ 3.71	48.857 $\neq$	0.000	HS
			Range	13–17	15–24	15–27			
		SD	Mean $\pm$ SD	4.33 $\pm$ 0.71	5.87 $\pm$ 0.82	5.53 $\pm$ 1.04	42.857 $\neq$	0.000	HS
			Range	3–5	5–7	5–8			
		Percentile	Mean $\pm$ SD	3.40 $\pm$ 1.52	17.27 $\pm$ 23.70	8.20 $\pm$ 6.84	42.857 $\neq$	0.000	HS
			Range	2–5	5–76	5–25			
QNST	Group I	Total	Mean $\pm$ SD	29.30 $\pm$ 13.53	7.46 $\pm$ 3.59	12.20 $\pm$ 9.90	–4.789 $\neq$	0.000	HS
			Range	8–59	1–35	2–42			
	Group II	Total	Mean $\pm$ SD	29.50 $\pm$ 11.83	26.93 $\pm$ 10.00	26.93 $\pm$ 10.00	–4.169 $\neq$	0.000	HS
			Range	9–45	8–37	9–40			

P-value > 0.05: Non-significant

P-value < 0.05: Significant

P-value < 0.01: Highly significant

 $\neq$: Friedman test**Table 5** Comparison between group I and II regarding the percentage of change of the outcome parameters

Percentage of change				Group I	Group II	Test value	P-value	Sig.
MABC-2 balance subscale	post	Total score	Mean $\pm$ SD	125.42 $\pm$ 38.04	28.12 $\pm$ 23.80	–6.492 $\neq$	0.000	HS
			Range	64.29–171.43	11.76–84.62			
		SD	Mean $\pm$ SD	182.17 $\pm$ 79.90	37.56 $\pm$ 21.47	–6.602 $\neq$	0.000	HS
			Range	75–300	20–75			
		Percentile	Mean $\pm$ SD	1796.53 $\pm$ 1159.56	609.33 $\pm$ 1233.85	–5.096 $\neq$	0.000	HS
			Range	640–4800	80–3700			
	Follow up	Total score	Mean $\pm$ SD	133.25 $\pm$ 47.10	25.12 $\pm$ 19.79	–6.664 $\neq$	0.000	HS
			Range	75–228.57	5.88–58.82			
		SD	Mean $\pm$ SD	187.67 $\pm$ 97.88	30.22 $\pm$ 26.11	–6.701 $\neq$	0.000	HS
			Range	80–375	0–66.67			
		Percentile	Mean $\pm$ SD	1982.50 $\pm$ 1418.45	160.00 $\pm$ 147.62	–6.719 $\neq$	0.000	HS
			Range	640–4900	0–400			
QNST	post	Total score	Mean $\pm$ SD	–78.59 $\pm$ 13.85	–12.56 $\pm$ 3.91	6.664	0.000	HS
			Range	–40.68 – –96.67	–6.25 – 17.78			
	Follow up	Total score	Mean $\pm$ SD	–61.11 $\pm$ 14.00	–6.99 $\pm$ 4.62	–6.681 $\neq$	0.000	HS
			Range	–80.56 – –28.81	–11.11 – 0			

P-value > 0.05: Non-significant

P-value < 0.05: Significant

P-value < 0.01: Highly significant

 $\neq$: Mann-Whitney test

sleepiness was reported by the mother of one patient (10%, 3.33%) respectively, both disappeared by the fourth day of tDCS sessions.

Discussion

Autism is classified as a developmental disorder, as defined by the DSM-5, which identifies two primary symptom domains: abnormal communication and social interaction, and restricted, repetitive stereotyped behaviours, interests, or other activities [16]. Specific motor signs associated with autism were first described in 1943 by Kanner, who noted motor clumsiness in children with the disorder [22]. For several decades, clinicians and researchers have advocated for increased attention to issues affecting motor skills [23].

Altered motor coordination is prevalent among individuals with autism, impacting various movements such as abnormal manual dexterity, poor balance, and irregular gait. However, motor coordination is not thoroughly assessed, resulting in under diagnosed and untreated motor coordination deficits [24, 25].

The tDCS is a non-invasive brain stimulation technique that has gained prominence in the recent few last years as an adjuvant treatment for many neurological and psychiatric conditions [14, 26–28].

In this study, 60 autistic individuals were divided into two groups, with no significant differences between the groups in terms of sex, age, height, weight, or body mass index (BMI). Additionally, their Childhood Autism Rating Scale (CARS) and Vineland scores showed no significant differences, indicating that their symptoms and adaptive behaviours are within the same range. Furthermore, both groups exhibited no significant differences in the results of the Quick Neurological Screening Test (QNST) and the Movement Assessment Battery for Children-2 (MABC-2) regarding coordination and balance abilities. Group I was exposed to both tDCS and a neuro-rehabilitation programme to improve balance, while group II participated in the neuro-rehabilitation programme only.

According to the MABC-2, the total balance subscale scores of 60 autistic individuals indicated that 100% of the sample fell within the “red zone,” with scores at or below the 5th percentile. The total score for group I, which received tDCS in conjunction with a neuro-rehabilitation programme, ranged from 10 to 17 on the balance subscale, with a mean of 15.07 ± 1.86 . In contrast, group II, which received only the neuro-rehabilitation programme, exhibited scores ranging from 13 to 17, with a mean of 14.83 ± 1.78 . Both groups were positioned within the red zone percentile scale, with group I scoring between 0.5 and 5, and group II scoring between 2 and 5, indicating pathological neurological balance and

coordination dysfunction. Neurological soft signs have emerged as an obvious and promising method for assessing autism-associated motor impairment [29, 30].

Motor problems in autism spectrum disorder (ASD) are common yet often overlooked features of autism. Recognition and management of these issues could be enhanced by incorporating a domain-specific “specifier” into the ASD diagnostic criteria. The inclusion of motor impairment as a diagnostic specifier could facilitate new opportunities for occupational therapy and other motor skill interventions and accommodations [23, 25, 31].

In this study, the correlation between motor function, the severity of ASD symptoms, and adaptive behaviour demonstrated an equivocal relationship of significance, consistent with the findings of other studies.

These studies indicate that although the severity of autistic symptoms is related to motor dysfunction, the relationship is not statistically significant [22–24].

In the current study, group I exhibited a significant correlation between neurological dysfunction, as measured by the QNST, and the severity of autistic symptoms on the CARS ($p=0.006$). Furthermore, greater neurological dysfunction on the QNST was significantly correlated with poorer adaptive behaviour in autistic children and adolescents, as assessed by the Vineland Adaptive Behaviour Scale ($p=0.023$).

In group I, there was no significant correlation between the severity of symptoms on CARS and the poor adaptive score on Vineland scale, with MABC-2 balance subscale, while in group II, there was a significant negative correlation. The severity of symptoms in autistic children and adolescents, as measured by the CARS, and the lower scores on the Vineland Adaptive Behaviour Scales, demonstrated a significant correlation with poorer outcomes on the balance subscale of the MABC-2, with p -values of 0.028 and 0.004, respectively. Conversely, no significant correlation was observed between the severity of symptoms on the CARS or the Vineland and neurological function as assessed by QNST in group II of autistic children and adolescents. The findings suggest that assessing motor function in individuals with autism may require multiple scales to capture the full extent of motor deficits. Utilizing a comprehensive motor function assessment battery could more effectively identify subtle signs of neurological dysfunction. In this study, among the 60 participants, motor coordination difficulties were identified using the Quick Neurological Screening Test (QNST). Specifically, 5.88% of the participants scored above 50, indicating a higher likelihood of pathological motor incoordination. Meanwhile, 52.94% of the sample scored between 26 and 50, which is considered a suspicious range, and 41.18% scored below 25, indicating normal motor coordination. These findings are consistent

with other studies that report clinically significant motor problems in individuals with autism, ranging from 50 to 95% [23, 32].

In this study, the range of QNST scores for group I was 8 to 59, with a mean of 29.3 ± 13.53 , while group II exhibited a score range of 9 to 45, with a mean of 29.5 ± 11.83 . Both groups fall within the suspicious score range, indicating the presence of neurological soft signs (NSS). This result is consistent with other studies that have identified obvious deficits in motor coordination dysfunction and sensory disintegration as markers in the diagnosis of autism [22].

Despite substantial evidence indicating the presence of motor impairments in individuals with ASD and the clinical significance of these impairments, motor problems are not yet included in the diagnostic criteria [29, 32].

In this study, the neurological dysfunction of the sample was classified within the suspicious range (26–50) on the QNST and within the red zone (≤ 5 th percentile) on the MABC-2 scale, categorizing them under neurological soft signs. Autistic individuals evidently require comprehensive support to develop the motor skills necessary for successful engagement in daily activities, as well as in their physical, cognitive, and social domains [25, 33].

Establishing a motor specifier could facilitate referrals for comprehensive motor assessments by neuropsychiatrists, physical therapists, and occupational therapists. This would also enable autistic children to access motor-related services [23, 24, 29].

Persistent motor difficulties in individuals with autism constitute a substantial impediment to the execution of autistic children's daily activities, social and cognitive development. These challenges are often accompanied by impaired imitation, which subsequently leads to a series of deficits in emotional expression, social sharing, joint attention, and pretend play [10, 23].

Although individuals with autism may exhibit significant motor difficulties, a relatively small number receive a diagnosis of Developmental Coordination Disorder (DCD) [23].

Research has demonstrated a considerable overlap in the behavioural motor characteristics seen in autism, which are regarded as NSS, and those associated with DCD [22–24, 29].

There is also an overlap between social and communication disabilities, which manifest in the representation of self and others [10, 30, 31, 34].

Regarding the results of the MABC-2 balance subscale, group I, prior to intervention, was positioned in the red zone percentile (0–5th percentile), with scores ranging from 0.5 to 5 and a mean of 3.90 ± 1.62 . Similarly, group II's pre-intervention results also placed them in the red zone percentile, with scores ranging from 2 to 5 and a

mean of 3.40 ± 1.52 . There was no significant difference between the two groups ($p=0.20$).

Following the intervention, group I exhibited a substantial improvement in their balance subscale percentile scores, ranging from 9 to 99.9, with a mean of 67.33 ± 34.08 . In contrast, group II demonstrated a range of 5 to 76, with a mean of 17.27 ± 23.70 . The difference between the groups was statistically significant ($p=0.0001$), indicating a highly significant effect in group I, which comprised individuals with ASD who were exposed to both transcranial direct current stimulation (tDCS) and rehabilitation. The follow-up results revealed that group I maintained a percentile scale range of 25 to 99.9, with a mean of 64.89 ± 31.04 , suggesting that the group exposed to tDCS and rehabilitation remained in the favourable range after 2 months. Conversely, group II's range decreased to 5 to 25, with a mean of 8.20 ± 6.84 , indicating deterioration in balance subscale abilities to a less favourable range after two months. The difference remained highly significant in favour of group I ($p=0.0001$).

The results of the MABC-2 balance subscale demonstrated a significantly notable effect of tDCS on balance in children and adolescents with ASD, with effects persisting longer than those achieved through neurological rehabilitation training alone. Furthermore, when comparing the percentage of change between the two groups post-intervention, the total score percentage in group I was 125.42, whereas the percentage of change in group II was only 28.12. The percentage of change in the MABC-2 balance subscale follow-up for group I was 133.25, whereas for group II, it was only 25.12, indicating highly significant difference ($p=0.0001$). These results suggest a more substantial and rapid improvement in the balance subscale, as well as significant maintenance of effect in group I, utilizing tDCS as a non-invasive brain stimulation method in children and adolescents with autism. The comparison of group II's scores on the QNST pre-intervention ranged from 8 to 59, with a mean of 29.30 ± 13.53 , indicating a suspicious level of neurological coordination soft signs deficits. Post-intervention, following 10 sessions of tDCS over 2 weeks and a neuro-rehabilitation programme, scores returned to normal neurological levels, with a range of 1 to 35 and a mean of 7.46 ± 3.59 , reflecting a highly significant positive percentage change of approximately 80.65%.

During the 2-month follow-up period, the scores remained within the normal range (less than 25), specifically between 2 and 42, with a mean of 12.20 ± 9.90 , indicating sustained improvement ($p=0.001$) with a highly significant difference. Conversely, in group II, the pre-intervention scores for the QNST ranged from 9 to 45,

with a mean of 29.50 ± 11.83 , suggesting a suspicious level of neurological coordination soft signs deficit (26–50).

Post-intervention, the scores showed a slight improvement, ranging from 8 to 37, with a mean of 24.71 ± 9.24 . After 2 months, the follow-up scores ranged from 9 to 40, with a mean of 26.93 ± 10.0 , demonstrating a highly significant difference ($p=0.0001$) in the maintenance of improvement, although the scores remained at a suspicious level of neurological dysfunction (26–50). A comparison of the percentage of change in QNST scores post-intervention and during follow-up between group I and group II revealed that the range of improvement in group I was from -80.56 to -28.81 , with a mean of -61.11 ± 14.00 , whereas in group II, the range was from -11.11 to 0 , with a mean of -6.99 ± 4.61 ($p=0.0001$). These results indicate a very high significance, suggesting that the combined effect of tDCS and rehabilitation was almost ten times more effective than neurological rehabilitation alone, both post-intervention and during follow-up.

Consistent with recent controlled trials, promising results have been observed regarding the use of tDCS in ASD [14, 26]. Although the current study employed a tDCS intensity of 1 mA, whereas Mahmoodifar et al. utilized an intensity of 1.5 mA, the efficacy of tDCS in the present study demonstrated comparable outcomes. Both studies applied tDCS to the primary motor cortex [6].

Consistent with the findings of the current study, Mahmoodifar et al. demonstrated that autistic children aged 6 to 14 years who received both actual transcranial direct current stimulation (tDCS) and motor skill training exhibited significantly better balance compared to those who received sham tDCS and motor skill training [6]. Other studies applied anodal tDCS to the left dorsolateral prefrontal cortex. It was observed that anodal tDCS significantly improved the abnormal motor-related functions associated with autism spectrum disorder (ASD), extending beyond socio-behavioural dysfunction and repetitive motor mannerisms. These improvements included enhancements in gait abnormalities, gross and fine motor function impairments, basic motor control deficits, and reduced postural stability [10, 26, 35].

The observed effects of anodal tDCS may be attributed to its ability to reduce gamma-amino butyric acid (GABA) levels within the primary sensory-motor cortices. These cortices are crucial in the context of motor learning dysfunction and behavioural abnormalities in children with autism [23, 25, 33].

GABA and glutamic acid are the main inhibitory and excitatory neurotransmitters in the brain respectively, which have an important role in physiological processes

[36]. A recent research revealed that glutamic acid levels were increased in areas stimulated by tDCS [37].

There was an association between glutamatergic plasticity and the long-term effects of anodal tDCS on the primary motor cortex (M1) [38]. Another study revealed that application of anodal tDCS to the left primary sensorimotor area elevated glutamic acid concentrations significantly in the precentral gyrus and increased the functional connectivity in this area [39].

N-acetyl aspartate (NAA) affects neuronal and axonal integrity and acts as an indicator of neuronal connectivity [40]. In autistic cases, brain metabolites such as N-acetyl aspartate, Creatine, and myo-inositol levels were significantly increased following anodal tDCS [41].

Additionally, it has been suggested that the benefits of tDCS may include the enhancement of glial cell activity, modulation of mirror neurons, or the adjustment of the atypical excitation/inhibition balance in the autistic brain [14, 26, 27].

Studies have also indicated that the application of a weak electric current can alter the membrane potential of neurons, leading to spontaneous firing rates and changes in the neurons' discharge threshold [26].

The tDCS improves motor abilities and motor skill by modifying the neuronal resting membrane potential, strengthening synaptic plasticity, and enhancing and the functional connectivity of neural networks [42], which enhances regional cerebral blood flow (rCBF) leading to activation and enhancement of specific brain regions, and liberating excitatory neurotransmitters [43]. It modifies the polarity of neuronal membrane in the cerebral cortex [44].

It has been observed tDCS enhances motor skill function in children with ASD, thereby improving their social cognition and imitation functions, which positively influences their social interaction and sociability [10]. As an alternative therapeutic tool for children with ASD, tDCS facilitates more appropriate motor behaviours, such as body gestures and meaningful facial expressions, which are essential for successful social interaction. These behaviours are based on properly coordinated movement and integrated sensory-motor and balance abilities [22, 25, 29, 31, 35].

Recent research indicates that tDCS is a promising intervention for mitigating symptoms of ASD, as well as enhancing both motor skills and neuropsychological functions [25, 26, 45]. Positive outcomes from tDCS studies involving children with ASD demonstrate that the neuroplastic effects of tDCS over the motor and prefrontal regions persist for 6 months post-treatment, correlating with improvements in the severity of autistic symptoms [27, 35].

Other previous researches have indicated that tDCS may confer benefits that persist for up to 1 year, thereby reducing the severity of autistic symptoms in the affected population [14, 27]. Furthermore, the application of anodal tDCS in conjunction with conventional rehabilitation has been associated with more rapid improvements in motor, cognitive, and behavioural domains among children with autism spectrum disorder (ASD) [14, 26–28].

Conclusion

tDCS is a non-invasive new adjuvant therapeutic approach in ASD. The current study revealed that severe autistic symptoms are associated with greater motor deficits. Immediately after applying tDCS sessions alongside neurorehabilitation programme; balance subscales and neurological deficits improved significantly more than applying neurorehabilitation programme alone and this effect continued in the follow-up after 2 months of the intervention.

Recommendation

These preliminary findings indicate that transcranial direct current stimulation (tDCS) may enhance motor skills training in children with autism spectrum disorder (ASD). However, further research involving larger sample sizes, encompassing participants with varying levels of autism severity, is necessary. Additionally, a comprehensive assessment of motor skills, correlated with cognitive, social, and emotional aspects beyond the motor functions of individuals with ASD, is required. This should be conducted using diverse tDCS stimulation modalities to substantiate the practical application of this non-invasive brain stimulation in children with autism and other neurodevelopmental disorders.

Limitation of the study

Despite the special needs care centre being a tertiary facility with an autism rehabilitation unit that handles numerous cases, only 60 participants consented to partake in the study. This limited sample size is attributed to the fact that tDCS is not yet a widely recognized therapeutic approach in Egypt. Furthermore, the study was conducted as a single-centre clinical trial.

Abbreviations

ASD	Autism spectrum disorder
CARS	Childhood Autism Rating Scale
DCD	Developmental Coordination Disorder
DSM-5	Diagnostic and Statistical Manual of Mental Disorders—Fifth Edition
MABC-2	Movement Assessment Battery for Children-2

NSS	Neurological soft signs
QNST	Quick Neurological Screening Test
tDCS	Transcranial direct current stimulation

Acknowledgements

We would like to acknowledge Marwa Alazizy for applying Vineland and CARS to the studied participants, Asmaa Msfer, and Doaa Elsayy for applying the neurorehabilitation program to the studied participants. We acknowledge and thank all participants and their families in the current study for their valuable time.

Clinical trial registry

The application of this study to Pan African Clinical Trial Registry has been accepted. The study's unique identification number for the registry is PACTR202507542338595.

Authors' contributions

Omnia A. Abubakr (OA) contributed to the study concept and design, clinical assessment, designing of rehabilitation program, gathered all data, and writing and editing of the manuscript. Manal M. Mahdi Omar (MO) contributed to the study concepts and design, analysis and interpretation of results, and writing and editing the manuscript. Sara Ali (SA) recruited the studied cases, clinical psychiatric assessment and diagnosis. Dina Y. Elalfy (DE) contributed to the study concept and design, gathered some data, and formed the results, analysis and interpretation of results, writing and editing the manuscript. All authors have read and approved the manuscript.

Funding

We did not receive any funding for this research.

Data availability

Not available

Declarations

Ethics approval and consent to participate

Approval of the Faculty of Medicine, Ain Shams University Ethical Committee to conduct the study prior to its commencement (FMASU R144/2024). A written informed consent was obtained from the parents after explanation of the aim of the study and its benefits for their children and an oral consent was taken from the child.

Consent for publication

All authors agreed to publish this manuscript in the journal after reviewing the final version.

Competing interests

The authors declare no competing interests.

Author details

¹Department of Rheumatology, Rehabilitation and Physical Medicine, Faculty of Medicine, Ain Shams University, Cairo, Egypt. ²Department of Medical Studies for Children, Faculty of Postgraduate Childhood Studies, Ain Shams University, Cairo, Egypt. ³Department of Medical Studies for Children, Faculty of Postgraduate Childhood Studies, Ain Shams University, Cairo, Egypt. ⁴Department of Medical Studies for Children, Faculty of Postgraduate Childhood Studies, Ain Shams University, Cairo, Egypt.

Received: 7 August 2025 Accepted: 30 September 2025

Published online: 02 December 2025

References

- Kamp-Becker I, Smidt J, Ghahreman M, Heinzel-Gutenbrunner M, Becker K, Remschmidt H (2010) Categorical and dimensional structure of autism spectrum disorders: the nosologic validity of Asperger syndrome. *J Autism Dev Disord* 40(8):921–929. <https://doi.org/10.1007/s10803-010-0939-5>

2. Ruggeri A, Dancel A, Johnson R, Sargent B (2020) The effect of motor and physical activity intervention on motor outcomes of children with autism spectrum disorder: a systematic review. *Autism* 24(3):544–568. <https://doi.org/10.1177/1362361319885215>
3. Fournier KA, Hass CJ, Naik SK, Lodha N, Cauraugh JH (2010) Motor coordination in autism spectrum disorders: a synthesis and meta-analysis. *J Autism Dev Disord* 40(10):1227–1240
4. Nuntanee S, Daranee S (2019) Effect of motorized elephant-assisted therapy program on balance control of children with autism spectrum disorder. *Occup Ther Int* 2019:5914807. <https://doi.org/10.1155/2019/5914807>
5. Date S, Munn E, Frey GC (2024) Postural balance control interventions in autism spectrum disorder (ASD): a systematic review. *Gait Posture* 109:170–182. <https://doi.org/10.1016/j.gaitpost.2024.01.034>
6. Mahmoodifar E, Sotoodeh MS (2020) Combined transcranial direct current stimulation and selective motor training enhances balance in children with Autism Spectrum Disorder. *Percept Mot Skills* 127(1):113–125. <https://doi.org/10.1177/0031515219888072>
7. Woods AJ, Antal A, Bikson M, Boggio PS, Brunoni AR, Celnik P, Cohen LG, Fregni F, Herrmann CS, Kappenman ES, Knotkova H, Liebetanz D, Miniussi C, Miranda PC, Paulus W, Priori A, Reato D, Stagg C, Wenderoth N, Nitsche MA (2016) A technical guide to tDCS, and related non-invasive brain stimulation tools. *Clin Neurophysiol* 127(2):1031–1048
8. Araujo MO, Tاملain P, Duarte NA, Comodo AC, Ferreira GO, Queir6ga A, Oliveira CS, Collange-Grecco LA (2023) Transcranial direct current stimulation to facilitate neurofunctional rehabilitation in children with autism spectrum disorder: a protocol for a randomized, sham-controlled, double-blind clinical trial. *J Front Neurol* 14:2023. URL=<https://www.frontiersin.org/journals/neurology/articles/>. <https://doi.org/10.3389/fneur.2023.1196585>. ISSN=1664–2295
9. Reis J, Robertson EM, Krakauer JW, Rothwell J, Marshall L, Gerloff C, Wassermann EM, Pascual-Leone A, Hummel F, Celnik PA, Classen J, Floel A, Ziemann U, Paulus W, Siebner HR, Born J, Cohen LG (2008) Consensus: can transcranial direct current stimulation and transcranial magnetic stimulation enhance motor learning and memory formation? *Brain Stimul* 1(4):363–369. <https://doi.org/10.1016/j.brs.2008.08.001>
10. Hadoush H, Nazzal M, Almasri NA, Khalil H, Alafeef M (2020) Therapeutic effects of bilateral anodal transcranial direct current stimulation on prefrontal and motor cortical areas in children with Autism Spectrum Disorders: a pilot study. *Autism Res* 13(5):828–836. <https://doi.org/10.1002/aur.2290>
11. Qiu J, Kong X, Li J, Yang J, Huang Y, Huang M, Sun B, Su J, Chen H, Wan G, Kong J (2021) Transcranial direct current stimulation (tDCS) over the left dorsal lateral prefrontal cortex in children with autism spectrum disorder (ASD). *Neural Plast* 2021:6627507. <https://doi.org/10.1155/2021/6627507>
12. Amatachaya A, Auvichayapat N, Patjanasoontorn N, Suphakunpinoy C, Ngernyam N, Aree-Uea B, Keeratitanont K, Auvichayapat P (2014) Effect of anodal transcranial direct current stimulation on autism: a randomized double-blind crossover trial. *Behav Neurol* 2014:173073. <https://doi.org/10.1155/2014/173073>
13. Amatachaya A, Jensen MP, Patjanasoontorn N, Auvichayapat N, Suphakunpinoy C, Janjarasjitt S, Ngernyam N, Aree-uea B, Auvichayapat P (2015) The short-term effects of transcranial direct current stimulation on electroencephalography in children with autism: a randomized crossover controlled trial. *Behav Neurol* 2015:928631. <https://doi.org/10.1155/2015/928631>
14. Salehinejad MA, Ghanavati E, Gliniski B, Hallajian AH, Azarkolah A (2022) A systematic review of randomized controlled trials on efficacy and safety of transcranial direct current stimulation in major neurodevelopmental disorders: ADHD, autism, and dyslexia. *Brain Behav* 12(9):e2724. <https://doi.org/10.1002/brb3.2724>
15. Griff JR, Langlie J, Bencie NB, Cromar ZJ, Mittal J, Memis I, Wallace S, Marcillo AE, Mittal R, Eshraghi AA (2023) Recent advancements in non-invasive brain modulation for individuals with autism spectrum disorder. *Neural Regen Res* 18(6):1191–1195. <https://doi.org/10.4103/1673-5374.360163>
16. American Psychiatric Association, DSM-5 Task Force (2013) Diagnostic and statistical manual of mental disorders: DSM-5™ (5th ed.). American Psychiatric Publishing, Inc. <https://doi.org/10.1176/appi.books.9780890425596>
17. Nazario PF, Ferreira L, Both J, Vieira JLL (2021) Movement assessment battery for children-second edition: theoretical adequacy of a motor assessment instrument. *Revistapaulista de pediatria : orgao oficial da Sociedade de Pediatria de Sao Paulo* 40:e2020205. <https://doi.org/10.1590/1984-0462/2022/40/2020205>
18. Schopler E, Reichler RJ, DeVellis RF, Daly K (1980) Toward objective classification of childhood autism: childhood autism rating scale (CARS). *J Autism Dev Disord* 10(1):91–103
19. Bielski J, Getahun V (2008) Vineland Adaptive Behavior Scales. Second Edition. <https://doi.org/10.1002/9780470373699.speced2174>
20. Mutti, Margaret (1974) QNST: Quick Neurological Screening Test. Experimental ed. San Rafael, Calif: Academic Therapy Publications. Print.
21. Roşca AM, Rusu L, Marin MI, EneVoiculescu V, EneVoiculescu C (2022). Physical activity design for balance rehabilitation in children with autism spectrum disorder. *Children* (Basel, Switzerland) 9(8):1152. <https://doi.org/10.3390/children9081152>
22. Cho AB, Otte K, Baskow I et al (2022) Motor signature of autism spectrum disorder in adults without intellectual impairment. *Sci Rep* 12:7670. <https://doi.org/10.1038/s41598-022-10760-5>
23. Miller HL, Licari MK, Bhat A, Aziz-Zadeh LS, Van Damme T, Fears NE, Cermak SA, Tاملain PM (2024) Motor problems in autism: co-occurrence or feature? *Dev Med Child Neurol* 66(1):16–22. <https://doi.org/10.1111/dmnc.15674>
24. Gowen E, Earley L, Waheed A, Poliakoff E (2023) From "one big clumsy mess" to "a fundamental part of my character." Autistic adults' experiences of motor coordination. *PloS one* 18(6):e0286753. <https://doi.org/10.1371/journal.pone.0286753>
25. Angius L, Pascual-Leone A, Santarnecchi E (2018) Brain stimulation and physical performance. *Progress Brain Res* 240:317–339. <https://doi.org/10.1016/bs.pbr.2018.07.010>
26. García-González S, Lugo-Marín J, Setien-Ramos I, Gisbert-Gustemps L, Arteaga-Henríquez G, Díez-Villoria E, Ramos-Quiroga JA (2021) Transcranial direct current stimulation in autism spectrum disorder: a systematic review and meta-analysis. *Eur Neuropsychopharmacol* 48:89–109. <https://doi.org/10.1016/j.euroneuro.2021.02.017>
27. Auvichayapat P, Intayot K, Udomchat C, Suphakunpinoy C, Patjanasoontorn N, Keeratitanont K, Tunkamnerdthai O, Jensen MP, Humbert AT, Auvichayapat N (2023) Long-term effects of transcranial direct current stimulation in the treatment of autism spectrum disorder: a randomized controlled trial. *Dev Med Child Neurol* 65(6):811–820
28. Zemestani M, Hoseinpanahi O, Salehinejad MA, Nitsche MA (2022) The impact of prefrontal transcranial direct current stimulation (tDCS) on theory of mind, emotion regulation and emotional-behavioral functions in children with autism disorder: a randomized, sham-controlled, and parallel-group study. *Autism Res* 15(10):1985–2003. <https://doi.org/10.1002/aur.2803>
29. Wieting J, Baumann MV, Deest-Gaubatz S, Bleich S, Eberlein CK, Frieling H, Deest M (2024) Structured neurological soft signs examination reveals motor coordination deficits in adults diagnosed with high-functioning autism. *Sci Rep* 14(1):16123. <https://doi.org/10.1038/s41598-024-66723-5>
30. Ilyukhina VA, Kozhushko NY, Matveev YK, Ponomareva EA, Chernysheva EM, Shaptilai MA (2005) Transcranial micropolarization in the combined therapy of speech and general psychomotor retardation in children of late preschool age. *Neurosci Behav Physiol* 35(9):969–976. <https://doi.org/10.1007/s11055-005-0153-7>
31. Ferrucci R, Bocci T, Cortese F, Ruggiero F, Priori A (2016) Cerebellar transcranial direct current stimulation in neurological disease. *Cerebellum Ataxias* 3(1):16. <https://doi.org/10.1186/s40673-016-0054-2>
32. Kozhushko N I.u, Shaitor VM, Ponomareva EA, Berezhnaia NF (2007) Zhurnalnevologii i psikiatriiimeni S.S. Korsakova 107(10):47–51
33. Kuo MF, Chen PS, Nitsche MA (2017) The application of tDCS for the treatment of psychiatric diseases. *Int Rev Psychiatry* (Abingdon, England) 29(2):146–167. <https://doi.org/10.1080/09540261.2017.1286299>
34. Finisguerra A, Borgatti R, Urgesi C (2019) Non-invasive brain stimulation for the rehabilitation of children and adolescents with neurodevelopmental disorders: a systematic review. *Front Psychol* 10:135. <https://doi.org/10.3389/fpsyg.2019.00135>
35. Lefacheur JP, Antal A, Ayache SS, Benninger DH, Brunelin J, Cogiamanian F, Cotelli M, De Ridder D, Ferrucci R, Langguth B, Marangolo P, Mylius V, Nitsche MA, Padberg F, Palm U, Poulet E, Priori A, Rossi S, Schecklmann M, Vanneste S, Ziemann U, García-Larrea L, Paulus W (2017) Evidence-based

- guidelines on the therapeutic use of transcranial direct current stimulation (tDCS). *Clin Neurophysiol* 128(1):56–92
36. Li Y, Sun H, Chen Z, Xu H, Bu G, Zheng H (2016) Implications of GABAergic neurotransmission in Alzheimer's disease. *Front Aging Neurosci* 8:31. <https://doi.org/10.3389/fnagi.2016.00031>
 37. Marquardt L, Kusztrits I, Craven AR, Hugdahl K, Specht K, Hirnstein M (2021) A multimodal study of the effects of tDCS on dorsolateral prefrontal and temporo-parietal areas during dichotic listening. *Eur J Neurosci* 53(2):449–459. <https://doi.org/10.1111/ejn.14932>
 38. Patel HJ, Romanzetti S, Pellicano A, Nitsche MA, Reetz K, Binkofski F (2019) Proton magnetic resonance spectroscopy of the motor cortex reveals long term GABA change following anodal transcranial direct current stimulation. *Sci Rep* 9(1):2807. <https://doi.org/10.1038/s41598-019-39262-7>
 39. Antonenko D, Thielscher A, Saturnino GB, Aydin S, Ittermann B, Grittner U, Flöel A (2019) Towards precise brain stimulation: is electric field simulation related to neuromodulation? *Brain Stimul* 12(5):1159–1168. <https://doi.org/10.1016/j.brs.2019.03.072>
 40. Ben Salem D, Walker PM, Bejot Y, Aho SL, Tavernier B, Rouaud O, Ricolfi F, Brunotte F (2008) N-acetylaspartate/creatine and choline/creatine ratios in the thalami, insular cortex and white matter as markers of hypertension and cognitive impairment in the elderly. *Hypertens Res* 31(10):1851–1857. <https://doi.org/10.1291/hyres.31.1851>
 41. Auvichayapat N, Patjanasoontorn N, Phuttharak W, SuSuphakunpinyo C, Keeratanont K, Tunkamnerdthai O, Aneksan BB, Klomjai W, Boonphongsathian W, Sinkueakunkit A, Punjaruk WW, Tiamkao S, Auvichayapat P (2020) Brain metabolite changes after anodal transcranial direct current stimulation in autism spectrum disorder. *Front Mol Neurosci* 13:70. <https://doi.org/10.3389/fnmol.2020.00070>
 42. Qi S, Cao L, Wang Q, Sheng Y, Yu J, Liang Z (2024) The physiological mechanisms of transcranial direct current stimulation to enhance motor performance: a narrative review. *Biology* 13(10):790. <https://doi.org/10.3390/biology13100790>
 43. Stagg CJ, Antal A, Nitsche MA (2018) Physiology of transcranial direct current stimulation. *J ECT* 34(3):144–152. <https://doi.org/10.1097/YCT.0000000000000510>
 44. Bhattacharya A, Mrudula K, Sreepada SS, Sathyaprabha TN, Pal PK, Chen R, Udupa K (2022) An overview of noninvasive brain stimulation: basic principles and clinical applications. *Can J Neurol Sci / Journal Canadien des Sciences Neurologiques* 49(4):479–492. <https://doi.org/10.1017/cjn.2021.158>
 45. Rothärmel M, Moulier V, Vasse M, Isaac C, Faerber M, Bendib B, Mirea-Grivel I, Opolczynski G, Rosier A, Guillin O (2019) A prospective open-label pilot study of transcranial direct current stimulation in high-functioning autistic patients with a dysexecutive syndrome. *Neuropsychobiology* 78(4):189–199. <https://doi.org/10.1159/000501025>

Publisher's Note

Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.