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Effects of Aquatic Exercise and Transcranial Direct Current Stimulation on Motor Skills and Cognitive Functions in Children with Autism Spectrum Disorder

Hanieh. Akbarimehr[1], Mahboubeh. Ghayour Najafabadi[2*], Hassan. Gharayagh Zandi[2], Daryoush. Khajavi[2, 3]

[1] Department of Behaviour and Cognitive Sciences in Sports, Faculty of Alborz Campus, University of Tehran, Tehran, Iran
[2] Department of Behavioural and Cognitive Sciences in Sports, Faculty of Sport Sciences and Health, University of Tehran, Tehran, Iran
[3] Department of Motor Behavior and Sport Psychology, Faculty of Sport Sciences, University of Arak, Arak, Iran

*** Corresponding author email address**: m.ghayournaj@ut.ac.ir

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A B S T R A C T

Objective: Children with autism spectrum disorder (ASD) experience distinctive neurophysiological characteristics associated with impairments in motor coordination, balance, and executive function. In recent years, aquatic exercise (hydrotherapy) and transcranial direct current stimulation (tDCS) have been introduced as promising non-invasive interventions targeting these deficits. While each approach has shown therapeutic potential when used independently, the combined effects of these interventions remain underexplored. This study aimed to examine the integrated impact of aquatic exercise and tDCS on motor performance and cognitive flexibility in children with ASD.
Methods and Materials: This quasi-experimental study included 30 children aged 7–10 years diagnosed with ASD, randomly assigned to either an experimental group (aquatic exercise + tDCS; n=15) or a sham control group (n=15). The intervention lasted six weeks and comprised 18 sessions. Motor performance was assessed using the Bruininks–Oseretsky Test of Motor Proficiency (BOT-2), and cognitive flexibility was evaluated through the Wisconsin Card Sorting Test (WCST). Data were analyzed using analysis of covariance (ANCOVA) to compare pre- and post-test differences between groups.
Result: The analysis revealed significant post-intervention improvements in both static and dynamic balance, as well as cognitive flexibility, in the experimental group compared with the sham group ($P<0.05$). These findings suggest that the combined intervention effectively enhanced both motor and executive functions in children with ASD.
Conclusion: The results indicate that combining aquatic exercise with transcranial direct current stimulation can produce synergistic effects, improving balance and cognitive flexibility in children with autism spectrum disorder. This integrated, non-invasive approach may represent a valuable adjunct to conventional rehabilitation methods, though larger-scale studies with follow-up assessments are recommended to confirm long-term efficacy.
Keywords: *Neuroplasticity; Executive Function Enhancement; Motor Learning; Neurorehabilitation in Autism*

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1. Introduction

Autism Spectrum Disorder (ASD) was first described in 1943 by Leo Kanner as a complex and lifelong neurodevelopmental disorder characterized by deficits in social communication, restricted interests, and repetitive behaviors (1). ASD typically emerges in early childhood and is associated with a broad range of cognitive, behavioral, and sensory abnormalities (2). According to the latest surveillance data from the U.S. Centers for Disease Control and Prevention, approximately one in 36 children is diagnosed with ASD, with boys being almost four times more likely to be affected than girls (3). Children with ASD frequently exhibit difficulties in motor coordination, executive functioning, and social participation, which may affect their daily independence and quality of life. They also experience associated conditions such as atypical eating behaviors and metabolic disorders (4). Given the complex and heterogeneous nature of ASD, therapeutic approaches generally include pharmacological and non-pharmacological strategies. Biological interventions can be classified as (a) non-specific therapies, which are applied to all individuals with autistic symptoms, and (b) targeted interventions based on specific neurobiological or behavioral profiles (5). Among non-pharmacological interventions, physical exercise has gained increasing attention for its ability to promote neuroplasticity, improve motor and cognitive functions, and enhance social behaviors. Several clinical trials have shown that structured exercise programs can produce positive and consistent effects in children and adolescents with ASD (6). However, further studies are needed to explore the optimal type, duration, and intensity of exercise protocols, particularly for subpopulations with more severe symptoms or comorbidities.

In recent years, two promising non-invasive interventions—transcranial direct current stimulation (tDCS) and aquatic exercise—have been studied for their ability to modulate neural activity and improve behavioral outcomes (7, 8). tDCS is a safe, low-intensity brain stimulation technique that can alter cortical excitability and promote neuroplasticity, while aquatic exercise provides a supportive environment that enhances motor learning, postural control, and social engagement. Studies have shown that aquatic therapy can improve balance, coordination, and executive functioning in children with ASD (9-11). The buoyancy and resistance of water reduce the effects of gravity, allowing participants to practice movements more easily, while the aquatic setting also facilitates social interaction. Similarly, evidence from neuroscience suggests that tDCS applied over the motor cortex can enhance motor skill acquisition and cognitive performance (12). Research has also reported potential improvements in social communication and executive function following tDCS in individuals with ASD (13). Nevertheless, the precise mechanisms and optimal stimulation parameters remain unclear, and studies examining combined intervention protocols are limited.

To date, few studies have explored the synergistic use of tDCS and aquatic training. While both techniques independently show beneficial effects, their combination may produce additive or even synergistic outcomes through enhanced neuroplasticity and multisensory engagement. However, there is currently a lack of empirical evidence regarding this combined approach in children with ASD. Therefore, the present study aimed to examine the effects of a combined program of aquatic exercise and transcranial direct current stimulation on motor and cognitive functions in children with Autism Spectrum Disorder. This study seeks to determine whether the integration of these two non-invasive interventions can accelerate improvements in motor coordination and cognitive flexibility compared to single-modality approaches.

2. Methods and Materials

2.1 Participants and Design

This study employed a quasi-experimental pretest–posttest design with a sham group. A total of 30 children diagnosed with Autism Spectrum Disorder (ASD) participated (15 in the intervention group and 15 in the sham group). Participants were recruited from specialized autism rehabilitation centers and met the inclusion criteria of (a) clinical ASD diagnosis according to DSM-5, (b) age range 7–12 years, and (c) absence of neurological or orthopedic comorbidities. Participants were randomly assigned to either the intervention or sham group using a computer-generated simple randomization procedure. Allocation concealment was ensured by an independent researcher who was not involved in the intervention or assessment phases. All participants' parents provided written informed consent prior to inclusion. The study protocol was approved by the Ethics Committee of the University of Tehran.

2.2 tDCS Protocol

The transcranial direct current stimulation (tDCS) intervention was administered using the Active Doss 2 device. Two non-metallic sponge electrodes (5×5 cm²), soaked in saline solution, were positioned according to the international 10–20 EEG system:

- Anodal electrode: over the F3 area (primary motor cortex of the dominant hemisphere)
- Cathodal electrode: over the contralateral supraorbital region.

A direct current of 1 mA was applied for 20 minutes during each session, three times per week for six weeks (total of 18 sessions). The current intensity was ramped up gradually at the beginning and tapered off over the final 10 seconds to minimize discomfort. In the sham group, stimulation was delivered for only 30 seconds and then discontinued; ensuring participants were unaware of the absence of current throughout the remainder of the session. To maximize potential neuroplastic effects, tDCS stimulation was applied immediately before each aquatic training session. No stimulation occurred outside the designated treatment period (14).

2.3 Aquatic Training Program

Aquatic exercise was implemented using the Halliwick 10-point method, which emphasizes motor control, balance, and independence in water. Training sessions were held three times weekly for six consecutive weeks, each lasting approximately 45 minutes in a swimming pool maintained at 30–32°C. The instructor-to-child ratio was 1:2 to ensure safety and individualization. The program incorporated the four fundamental phases of the Halliwick approach:

1. Adaptation to water (breathing control, buoyancy, and confidence building)
2. Rotation control (lateral, longitudinal, and combined)
3. Movement control (propulsion and stability)
4. Independent movement (basic swimming skills such as crawl stroke, head-to-side rotation, and forward flips)

Each child's program was individually tailored to accommodate differences in motor ability and sensory response, combining structured drills and play-based activities to enhance engagement and motivation (10).

2.4 Outcome Measures

Motor performance was evaluated using the Bruininks–Oseretsky Test of Motor Proficiency, Second Edition (BOT-2), including its short form. This standardized tool comprises 8 subtests assessing fine and gross motor skills, static and dynamic balance, and coordination in individuals aged 4–20 years. Cognitive flexibility and executive function were assessed using the computerized Wisconsin Card Sorting Test (10, 15, 16). All assessments were conducted by trained examiners blinded to group allocation.

2.5 Statistical Analysis

Data analysis was performed by an independent statistician using $SPSS_{26}$. An intention-to-treat approach was used to handle missing data by substituting repeated measures from previous evaluations. Normality of data distribution was confirmed via the Shapiro–Wilk test. Parametric variables were analyzed using ANCOVA with pre-test scores as covariates, and nonparametric data were compared using appropriate nonparametric tests. Results are presented as mean ± standard deviation (SD) or median (interquartile range) as appropriate. Effect sizes (η^2) and 95% confidence intervals (CI) were reported for all comparisons. A significance threshold of $p < 0.05$ was adopted for all analyses.

3. Results

Table 1 presents the study timeline and procedural overview, along with baseline demographic and descriptive characteristics of the participants. A total of 30 children diagnosed with Autism Spectrum Disorder (ASD), aged 7–10 years, and were included in the study. Participants were recruited from autism-specialized schools and rehabilitation clinics. The intervention group consisted of 15 children (12 boys and 3 girls), and the sham control group included 15 children (12 boys and 3 girls).

Table 1. Descriptive characteristics of participants

Group	Number	Mean and SD of age (year)	Mean and SD of height (Cm)	Mean and SD of weight (Kg)
Experimental	15	7.75±0.71	125.85± 2.53	24.75± 3.82
Sham	15	7.85±0.67	124.65±2.08	25.100±2.42

According to Table 1, the mean age of participants in both groups was 7 years. The average height was 125 cm in the experimental group and 124 cm in the sham group, while the average weight was 24 kg and 25 kg, respectively. These values demonstrate that the two groups were comparable in their baseline demographic characteristics. Prior to performing inferential analyses, the normality of the data distribution was assessed using the Shapiro–Wilk test. Results confirmed that all variables followed a normal distribution (P>0.05), supporting the use of parametric statistical procedures. Furthermore, independent-samples t-tests revealed no significant differences between groups in age, gender distribution, or baseline motor and cognitive scores (P>0.05), indicating equivalence between the experimental and sham conditions before the intervention.

3.1 *Balance Outcomes*

Analysis of covariance, controlling for pre-test scores, revealed significant improvements in both static and dynamic balance in the experimental group compared to the sham group (P<0.05). Specifically, the experimental group showed increases in static balance from 2.01 ± 1.50 to 3.20 ± 1.60 and in dynamic balance from 1.00 ± 0.60 to 2.20 ± 1.60, whereas the sham group showed minimal changes. These results indicate that the combined aquatic exercise and tDCS intervention effectively enhanced balance in children with Autism Spectrum Disorder (Table 2).

Table 2. ANCOVA results for static and dynamic balance

Variable	Group				F coefficient	p-value
	T		Con			
	Pre-test	Post-test	Pre-test	Post-test		
Static balance	2.01±1.50	3.20±1.60	2.00±1.15	1.01±0.6	43.79	0.001*
Dynamic Balance	1.00±0.6	2.20±1.60	0.76±0.50	0.88±0.59	47.01	0.001*

3.2 *Cognitive Function Outcomes*

Analysis of covariance controlling for pre-test scores, revealed a significant difference between the experimental and sham groups in cognitive flexibility (P<0.05). Children who received the combined aquatic exercise and tDCS intervention demonstrated substantial improvements in correct responses, conceptual responses, and a reduction in perseverative errors compared to the sham group. These findings suggest that the multimodal intervention effectively enhances cognitive flexibility in children with ASD (Table 3).

Table 3. ANCOVA results for flexibility variable

Variable	Group				F coefficient	*p-value*
	T		Con			
	Pre-test	Post-test	Pre-test	Post-test		
Correct response	19.06±6.70	28.05±7.61	19.90±7.01	19.99±6.90	3.70	0.002*
Conceptual responses	0.36±0.29	2.03±1.19	1.39±0.49	1.87±0.79	0.32	0.001*
Perseverative Errors	20.12±6.89	18.30±7.18	20.47±7.09	19.99±6.99	1.46	0.003*

4. Discussion and Conclusion

This study examined the combined effects of aquatic exercise and transcranial direct current stimulation (tDCS) on motor skills and cognitive flexibility in children with Autism Spectrum Disorder (ASD). The results revealed that the integrated intervention significantly improved both static and dynamic balance, as well as cognitive flexibility, compared with the sham group (*P*<0.05). These findings support the hypothesis that combining environmental and neurophysiological interventions can produce synergistic therapeutic benefits for children with ASD.

The analysis of covariance indicated that children in the experimental group achieved significant improvements in both static and dynamic balance after the six-week intervention, even after controlling for pre-test scores (Table 2). These results are consistent with previous studies showing that aquatic exercise enhances postural control and motor coordination by stimulating proprioceptive and vestibular systems through the water's buoyancy and hydrostatic pressure (17-19). The water environment reduces gravitational load, enabling children to practice movements safely and confidently, which strengthens balance-related neural pathways and core muscles (20). Aquatic exercise targets deep stabilizing muscles such as the abdominals and back, which are crucial for maintaining equilibrium.

In parallel, tDCS facilitates neuroplasticity and modulates cortical excitability in brain regions associated with motor control, particularly the cerebellum and motor cortex. It has been shown to influence neurotransmitter balance—enhancing γ-aminobutyric acid (GABA) activity and reducing excessive glutamatergic signaling—thereby improving sensorimotor integration (21-23). When applied in combination, aquatic training and tDCS amplify each other's benefits: tDCS enhances neural responsiveness, while aquatic exercise strengthens muscular and sensory systems, leading to greater gains in balance performance (11, 19, 24). Moreover, aquatic exercise, being enjoyable and relaxing, can reduce anxiety and stress levels, which further facilitates cortical engagement and cognitive participation during motor tasks (21).

In addition to motor benefits, the combined intervention significantly improved cognitive flexibility, as demonstrated by higher correct and conceptual response scores and fewer perseverative errors on the Wisconsin Card Sorting Test (Table 3). These results indicate that the integration of tDCS and aquatic training supports executive functioning in children with ASD. Previous research has suggested that tDCS enhances prefrontal cortex efficiency and facilitates adaptive cognitive control through improved cerebellar–prefrontal communication. Aquatic exercise complements this process by promoting arousal regulation, emotional stability, and attentional engagement, thereby creating optimal neurocognitive conditions for learning. Consistent with our results, Elmaghraby et al. (2025) reported that reduced prefrontal excitability in individuals with ASD is associated with improved cognitive flexibility, suggesting that neuromodulators interventions like tDCS can normalize atypical cortical activity (25). Similarly, Chen et al. (2021) found that integrating aquatic therapy with tDCS improved physical independence and health outcomes in children with cerebral palsy, supporting the cross-condition applicability of this dual-modality approach (11). The observed synergy between aquatic exercise and brain stimulation may stem from concurrent modulation of sensory-motor feedback and cortical excitability. Aquatic therapy provides continuous proprioceptive feedback, while tDCS enhances synaptic efficacy within motor and prefrontal networks. Together, they strengthen neural connectivity involved in both motor coordination and executive control. Furthermore, neurotrophic factors such as brain-derived neurotrophic factor (BDNF) may increase following exercise and tDCS, supporting synaptic growth and functional reorganization (21). This dual mechanism may underlie the improvements in both balance and cognitive flexibility observed in this study.

This study is among the first experimental investigations to examine the combined effects of aquatic exercise and transcranial direct current stimulation (tDCS) on motor and cognitive outcomes in children with autism spectrum disorder (ASD). The use of validated assessment tools, a controlled design, and random group allocation contributed to the methodological robustness of the study. However, some limitations should be acknowledged. The relatively small sample size (n = 30) may limit the generalizability of the results, and the absence of separate intervention arms (aquatic-only or tDCS-only) restricts the ability to determine the specific contribution of each component. In addition, the lack of follow-up assessments prevents conclusions about the durability of observed improvements. Because of the nature of the interventions, participant blinding was not feasible, and variability in motivation, sensory responses, or baseline motor ability could have influenced performance. Environmental factors such as water temperature and instructor consistency were also not completely standardized, which may have introduced minor variations in intervention delivery.

These findings highlight the therapeutic potential of combining aquatic exercise and tDCS for motor-cognitive rehabilitation in children with ASD. The integrated approach offers a safe, engaging, and non-pharmacological method to enhance functional independence and social participation. Clinicians may apply these findings to design structured intervention protocols within multidisciplinary rehabilitation frameworks. Future studies should include larger randomized controlled trials with multiple intervention arms, long-term follow-up evaluations, and neuroimaging or electrophysiological monitoring to elucidate underlying mechanisms and optimize intervention parameters (11, 14, 21).

In conclusion, the combination of aquatic exercise and transcranial direct current stimulation represents an innovative, non-invasive, and effective approach to improving motor skills and cognitive flexibility in children with ASD. Aquatic training enhances proprioceptive feedback, vestibular activation, and muscular strength, while tDCS modulates cortical excitability, promotes neuroplasticity, and regulates neurotransmitter balance. Together, these complementary mechanisms produce synergistic effects that enhance executive functioning and motor control. This integrated intervention not only supports the development of balance and cognitive flexibility but also offers a promising strategy to improve the overall quality of life for children with ASD.

Authors' Contributions

All authors equally contributed to this study.

Declaration

In order to correct and improve the academic writing of our paper, we have used the language model ChatGPT.

Transparency Statement

Data are available for research purposes upon reasonable request to the corresponding author.

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Declaration of Interest

The authors report no conflict of interest.

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Ethical Considerations

The study protocol adhered to the principles outlined in the Helsinki Declaration, which provides guidelines for ethical research involving human participants. This study was approved by the Research Ethics Committee of Tehran University, under the ethical code IR.UT.SPORT.REC.1403.131.

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