ORIGINAL ARTICLE

# The Effect of Transcranial Direct Current Stimulation on M1 with and without Mirror Visual Feedback on Range of Motion and Hand Grip Strength of the Affected Upper Limb in Children with Spastic Hemiplegic Cerebral Palsy

Pegah Farzamfar [1]; Ali Heirani, PhD [1]; Ehsan Amiri, PhD [2]; Mustafa Sedighi, PhD [3]; Daniel Gomes da Silva Machado, PhD [4]

[1] Department Motor behavior and Corrective Exercises. Faculty of Sport Sciences. Razi University, Kermanshah, Iran
[2] Exercise Metabolism and Performance lab (EMPL), Department of Exercise Physiology, Faculty of Sport Sciences, Razi University, Kermanshah, Iran
[3] Department of Pediatric Neurology, Kermanshah University of Medical Sciences, Kermanshah, Iran
[4] Research Group in Neuroscience of Human Movement (NeuroMove), Department of Physical Education, Federal University of Rio Grande do Norte, Natal, RN, Brazil

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## ABSTRACT

### Objectives

This study investigated the effects of transcranial direct current stimulation (tDCS) before and during the mirror visual feedback (MVF) on hand grip strength (HGS) and range of motion of the affected hand in children with spastic hemiplegia cerebral palsy (SHCP).

### Materials & Methods

Twelve children with SHCP participated in this randomized, crossover, and double-blind study. They were randomly exposed to one of four intervention conditions, including 1) a-tDCS-offline, 2) s-tDCS-offline, 3) a-tDCS-online, and 4) s-tDCS-online, with a one-week interval. Participants in the online condition received either anodal or sham tDCS during MVF, while those in the offline condition received tDCS before performing MVF. The tDCS was applied over the M1 area of the affected hemisphere for 20 minutes at 1 mA intensity. The HGS and range of motion of the wrist and elbow (ROM-W and ROM-E) of the affected limb were measured before (pre) and immediately after (post) interventions in each session.

### Results

The results showed that the HGS was significantly higher under a-tDCS-offline ($p=0.001$), s-tDCS-offline ($p=0.004$), and s-tDCS-online ($p=0.005$) compared to the a-tDCS-online. Moreover, the ROM-W was significantly higher under a-tDCS-offline ($p=0.034$), s-tDCS-offline (0.011), and s-tDCS-online ($p=0.027$) compared to the a-tDCS-online. Eventually, the ROM-E was significantly higher under a-tDCS-offline, s-tDCS-offline, and s-tDCS-online compared to the a-tDCS-online ($p<0.001; p<0.001; p=0.01$, respectively).

### Conclusion

The results might have practical implications regarding the timing of the application of tDCS in conjunction with MVF in children with SHCP.

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****Corresponding Author:*** Heirani A, PhD. Department Motor behavior and Corrective Exercises. Faculty of Sport Sciences. Razi University, Kermanshah, Iran. Email: pfarzam76@yahoo.com

## Introduction

Cerebral palsy (CP) is a group of permanent, non-progressive neuromotor disorders that affect the tone and structure of the muscles and motor development of the affected person (1, 2). The most prevalent form of CP is hemiplegia spastic cerebral palsy (SHCP). This is thought to result from the developmental neuroplastic effects and abnormalities related to the corticospinal tract (CST) and primary motor cortex (M1) in one hemisphere of the brain (3, 4). The imbalance between the inhibitory processes of the two hemispheres of the brain results in reducing the activity of the primary motor cortex (M1) in the affected hemisphere, which, in turn, leads to functional limitations in the lower and upper limbs of the opposite side (5-7). A disturbance in the one-handed capacity of the affected upper limb (AUL) has been observed to result in a reduction in hand grip strength (HGS) and fine motor skills of the affected upper limb in children with CP (1, 8, 9). It is more suitable for them to use the healthy side of the body when engaging in the activity (9). The cerebral cortex must be reorganized to compensate for the learned non-use in the affected side and improve the one-handed capacity of the affected upper limb(10).

In this context, Wingert et al. (2009) posited that one of the efficacious compensatory approaches to enhance the performance of these children is to consider the presence of the injured limb while undertaking the task, utilizing visual adaptation (11). Mirror visual feedback (MVF) is a non-invasive, common, and economical method involving placing a mirror in the sagittal plane of the patients and instructing them to focus on the reflection of healthy body movements in the mirror, creating a visual illusion of AUL movement (9). In recent years, transcranial direct current stimulation (tDCS) has gained popularity as a non-invasive method with no side effects and low cost. It is now used in various fields of treatment, rehabilitation, and sports (12-18). In this method, a low and constant intensity electrical direct current is applied to cortical areas through small electrodes placed on the scalp, modifying the excitability of the underlying region (15, 19). The effects of tDCS on target areas are contingent upon several variables, including the polarity, electrode placement, intensity, and duration of stimulation (20). In children with SHCP, the stimulation is applied with a specific polarity and location. The anode is used to increase excitability in the M1 region of the affected hemisphere, while the cathode is used to reduce excitability in the M1 region of the healthy hemisphere (21).

Using a multimodal approach involving the application of more than one intervention has recently gained prominence in clinical conditions (22). Prior research has demonstrated the efficacy of tDCS when used in conjunction with other interventions (23). In this approach, tDCS can be employed either concurrently with another intervention (online-tDCS) or prior to or following administrating another intervention (offline-tDCS) (8, 24). Notably, previous studies have documented the beneficial effects of MVF and tDCS as standalone interventions in children with SHCP (21, 25). For example, Chan et al. (2009) demonstrated that training the affected limb by combining sensory feedback (visual, electrical, and the like.) results in effective treatment protocols for these patients (26). Furthermore, Farzamfar et al. (2017) have also reported that MVF improved gross motor skills in children with SHCP (27). Moreover, Tang et al. (2022) proposed that tDCS could be an efficacious intervention for children with SHCP (21). The distinct effects of MVF and tDCS on children with SHCP prompt the intriguing question of whether the combination of these two strategies yields additional or synergistic effects in children with SHCP. To our knowledge, no study has hitherto investigated this effect. Furthermore, examining the motor performance of children with SHCP, it is crucial to ascertain the optimal timing for the design of combined protocols, given the disparate outcomes linked to using online and offline tDCS. Moura et al. offered further backing for this argument (2017), indicating that utilizing online tDCS yielded results contrary to those observed in the study by Jilik et al. (2018), in which offline tDCS was employed (8, 24).

To address the aforementioned shortcomings in the existing literature, the present study was designed to pursue two distinct objectives: the first was to investigate the synergistic effects of MVF and tDCS on the HGS and range of motion (ROM) of the affected upper limb in children with SHCP , and the second was the effects of online and offline tDCS in combining MVF on HGS and ROM of the affected upper limb in children with SHCP were compared.

## Materials & Methods

Ten patients with SHCP participated in this within-group, randomized, counterbalanced, double-blind, and sham-controlled study. The sample size was calculated using G*Power software (version 3.1.9.2, Kiel, Germany) as follows: test family = F tests; Statistical test = ANOVA: repeated measurements, within group. Error probability $\alpha = 0.05$; statistical power (1-$\beta$ err prob) = 0.80; Effect size f = 0.4 (equivalent to 0.65 in Cohen’s d) (28). Given the expected dropout rate of 20% based on findings from similar studies, a sample size of 12 participants was chosen to be involved in this research. Initially, 14 children presenting symptoms of SHCP were invited. Two participants were excluded from the study following the electroencephalogram (EEG) recording due to the emergence of seizure symptoms, while two others withdrew from the study before completing the evaluations.

In conclusion, ten affected children participated in this research and completed the full experimental procedures. The selected children were between the ages of 6 and 12 years. The participants were at levels 1 and 2 of the manual ability cassification system (MACS) and had normal vision, allowing them to perform the assigned exercises during the sessions. Additionally, each subject underwent an EEG to monitor for signs of a convulsion, with the results being analyzed by a neurologist. By the criteria mentioned above, children who had experienced a convulsion, were diagnosed with attention deficit hyperactivity disorder, or had any metal implants in the brain were excluded from the research. This research was approved by the institutional ethics committee *(approval number: IR.RAZI.REC.1402.049)* and was conducted under the Declaration of Helsinki. This research was registered in *(IRCT ID: IRCT20230728058946N1; registration date: 9 November 2023)*.

### Procedure

The participants attended the clinic *(Sepid Neurology Clinic* in Kermanshah, Iran*)* on five separate occasions. The first session was designed to complete the relevant questionnaires (Personal Information Questionnaire - Edinburgh Hand Excellence Questionnaire), familiarize the participants with the procedure, and instruct them on performing the interventions and tests. In the first session, the parents also gave their written consent to participate in the research. In sessions 2 to 5, the participants were randomly exposed to one of four intervention conditions:

1. Anodal-tDCS before MVF *(a-tDCS-offline)*,
2. Sham-tDCS before MVF *(s-tDCS-offline)*,
3. Anodal-tDCS during MVF *(a-tDCS-online)*,
4. Sham-tDCS during MVF *(s-tDCS-online)*.

In each experimental session, the study variables, including the HGS and ROM of the affected upper limb, were first measured. Subsequently, the participants were randomly exposed to one of the experimental conditions. The study variables were reassessed at the end of the given experimental condition in each session. The participants and assessor were blinded to the tDCS montage used in each experimental session, employing a double-blind approach. A seven-day interval was maintained between experimental sessions to prevent the cumulative increase in the excitability of the participant's cerebral cortex. All sessions were conducted at a consistent time of day for each participant. The complete experimental procedure is illustrated in Figure 1.

### Transcranial Direct Current Stimulation (tDCS)

tDCS was applied using a battery-based stimulator (NeuroStim 2, Medina Tab Gostar, Tehran, Iran) with an intensity of 1 mA for 20 minutes. Two carbon electrodes (5 x 5 cm and 7 x 5 cm) with sponge pads soaked in a salt solution were employed as the anode and cathode, respectively. A 64-channel EEG cap was utilized to ascertain the location of the target area (M1) on the scalp, followingthe international EEG 10-20 system. The anodal electrode was positioned on C3 or C4 (depending on the affected hemisphere) to enhance the motor capabilities of the participants, while the cathodal electrode was placed on the contralateral supra-orbital region (Fp1 or Fp2). The current intensity was increased, raised from 0.1 to 1 mA over 30 seconds, and then kept at that level for 20 minutes. Finally, the intensity was decreased from 1 mA to 0.1 in 30 seconds. In the case of sham tDCS (s-tDCS), the electrodes were positioned in the same location as in the a-tDCS. At the outset of the stimulation, the current was increased for 30 seconds, after which it was allowed to return to zero over the subsequent 20 minutes. The sham tDCS procedure effectively keeps participants unaware of the stimulation they receive (14-16, 18).

### Mirror Visual Feedback (MVF)

The MVF interventions were conducted over 20 minutes, comprising four distinct segments, each lasting five minutes (4 segments × 5 minutes each). Each segment comprised four 30-second periods of mirror training, with a 30-second rest interval between each. The sequence mentioned above was repeated four times, with a 90-second interval permitted between each segment (Figure 1). Further details regarding the MVF can be found in another publication (27).

### Measurement of Motor Function

Joint passive range of motion (PROM) is a comprehensive process involving a a trained physiotherapist conducting measurements and recording the wrist and elbow PROM results using a standardized universal goniometer. Each joint's PROM was recorded as the average of three consecutive measurements to reduce the potential for measurement error (29). Using a goniometer has yielded high intra- and inter-examiner reliability (r = 0.91). A digital dynamometer device was utilized to measure the subject's HGS. The digital pinch/grip analyzer (MIE, MIE

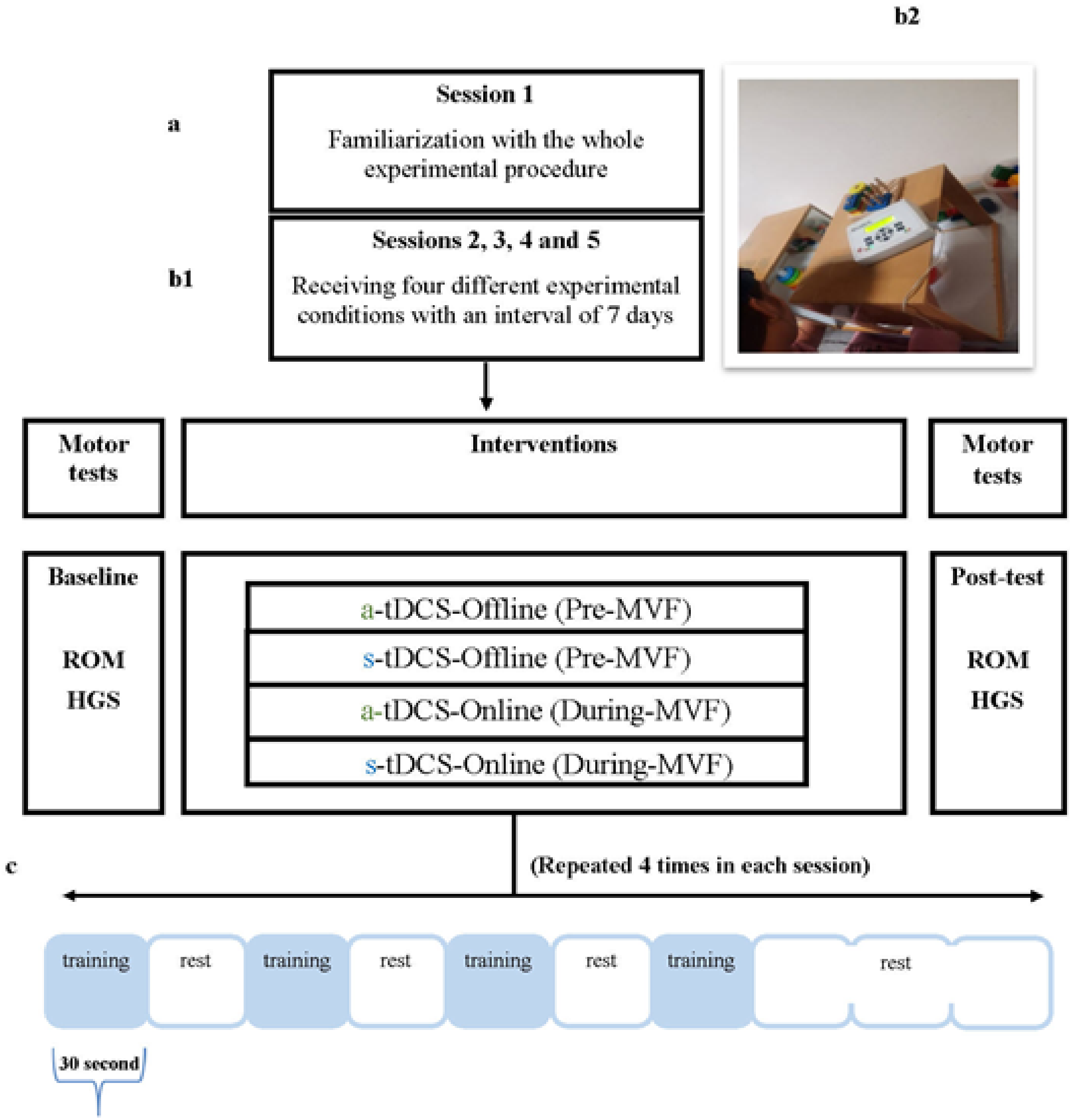

**Figure 1.** Experimental setup and design. All participants were studied in 5 separate sessions. In the first session, all participants completed all relevant questionnaires(a). In sessions 2 to 5, the participants were randomly exposed to one of four intervention conditions, including Condition 1:(a-tDCS-offline) first 20 minutes of a-tDCS, then 20 minutes of MVF training. Condition 2: (s-tDCS-offline), first 20 minutes of s-tDCS, then 20 minutes of MVF training. Condition 3: (a-tDCS-online) 20 minutes of simultaneous a-tDCS and MVF training. Condition 4: (s-tDCS-online) 20 minutes of simultaneous s-tDCS and MVF training(b1). Placing the mirror in front of the midline (sagittal) of the patient's body and performing exercises with the healthy hand in front of the mirror creates the illusion of the affected hand's movement. The healthy hand was placed in a mirror box that prevented direct viewing of the healthy hand but allowed indirect viewing via the mirror(b2) to provide MVF during healthy hand motor training. MVF interventions lasted for 20 minutes in four 5-minute segments. The sequence of each 5-minute section includes 30 seconds of exercise and 30 seconds of rest, and the final section consists of 90 seconds of rest(c). For details, see text

Medical Research Ltd, Leeds, UK) was employed under the standard methodology set forth by the American Society of Hand Therapists. For evaluation, the participants were positioned in a chair of an appropriate height. The shoulder of the limb being evaluated was placed in adduction (without any rotation), the elbow was bent at a 90-degree angle, the forearm was positioned midway, and the wrist was placed in a neutral position. The dynamometer was positioned in the participant's hand in a perpendicular orientation relative to the forearm, and the participant was instructed to exert maximum force within the pain-free range (9). The assessment was conducted thrice for each participant with an interval of 60 seconds, and the mean of the three repetitions was documented as the participant's maximum grip strength.

### Statistical Analysis

The data are presented as the mean ± standard deviation (M ± SD). The normality of each data set was evaluated using the Shapiro-Wilk test. A two-way repeated measures ANOVA (4 × 2 factorial design; four experimental conditions and two time points) was employed to analyze the data pertaining to HGS and ROM at each time point. In the case of a significant "condition × time" interaction effect, the Bonferroni post hoc test was used for the pairwise comparisons. Partial eta squared ($\eta^2_p$) was used as a measure of the effect size for the ANOVAs and interpreted as small (0.01–0.059), medium (0.06 to 0.139), or large (≥0.14). Cohen's d calculation of the effect size was also used for pairwise comparison and interpreted as small (0.20–0.49), medium (0.50–0.79), or large (≥ 0.80). Furthermore, the percentage change of the variables from the pre-test to the post-test in each experimental condition was calculated and reported as a percentage change (Δ%). The statistical analyses were performed using SPSS 27 (SPSS Inc., Chicago, IL, USA), and $p<0.05$ was adopted.

## Results

Participants reported no adverse side effects related to tDCS but experienced the expected itching/needling sensation on the skin when the current was slowly increased to 1 mA. Table 1 presents the mean and standard deviation of HGS and ROM of the affected upper limb in four different conditions.

### Hand Grip Strength (HGS)

The results showed significant main effects of time ($F_{(1,9)} = 34.69$, $p = 0.0001$, $\eta^2_p = 0.794$, *Power = 0.999*), condition ($F_{(3,27)} = 11.82$, $p = 0.0001$, $\eta^2_p = 0.568$, *Power = 0.999*), and "conditions×time" interaction ($F_{(3,27)} = 59.33$, $p = 0.0001$, $\eta^2_p = 0.747$, *Power = 1.000*) on the

**Table 1.** The mean values of HGS , ROM of the wrist, and ROM of the Elbow

| Experimental Conditions Variable | a-tDCS offline Mean ( SD) | | s-tDCS offlin Mean ( SD) | | a-tDCS onlin Mean ( SD) | | s-tDCS onlin Mean ( SD) | |
|---|---|---|---|---|---|---|---|---|
| | pre | post | pre | post | pre | post | pre | post |
| HGS | 25.70<br>(6.36) | 31.30<br>(6.89) | 24.80<br>(7.17) | 28.00<br>(8.05) | 24.60<br>(6.20) | 22.00<br>(6.56) | 25.10<br>(5.99) | 26.9<br>(6.57) |
| ROM W | 66.80<br>(8.57) | 74.30 (8.49) | 71.60 (8.78) | 75.80<br>(9.28) | 70.70<br>(6.86) | 68.30<br>(8.17) | 69.50<br>(7.12) | 73.20<br>(7.49) |
| ROM E | 73.60<br>(11.18) | 79.30<br>(10.66) | 72.50<br>(9.83) | 76.50<br>(8.84) | 70.40<br>(9.53) | 67.10<br>(8.59) | 71.90<br>(8.46) | 74.30<br>(8.43) |

SD: Standard Deviation; a-tDCS: Anodal-Transcranial Direct-Current Stimulation; s-tDCS: Sham-Transcranial Direct-Current Stimulation; HGS: Hand Grip Strength; ROM-W: Range of motion of the wrist; ROM-E: Range of Motion of the Elbow

HGS. Considering the significant "condition × time" interaction effect, pairwise comparisons were applied, and the results revealed that at post-test, the HGS was significantly higher in the a-tDCS-offline condition compared to the a-tDCS-online and s-tDCS-online conditions *($P = 0.001$, $p = 0.025$; respectively)*. The results also showed that the HGS was significantly higher in the s-tDCS-offline condition than the a-tDCS-online condition *($p = 0.004$)* at the post-test. Besides, the HGS was significantly higher under the s-tDCS-online condition compared to the a-tDCS-online condition *($p = 0.005$)* at the post-test. Furthermore, the results showed that in the a-tDCS-offline and s-tDCS-offline conditions, the HGS was significantly increased from pre-test to post-test *($P <0.001$, $\Delta = 21.79\%$, $d = 0.84$; $P = 0.001$, $\Delta = 12.90\%$, $d = 0.42$, respectively)*. The same trend was also observed in the HGS from pre-test to post-test under the s-tDCS-online condition *($P = 0.003$, $\Delta = 7.17\%$, $d = 0.28$)* while the HGS was significantly decreased from pre-test to post-test under a-tDCS-online condition *($P = 0.003$, $\Delta = -10.57\%$, $d = 0.40$)*, see Figure 2.

**Range of Motion of the Wrist (ROM-W)**

The results demonstrated significant main effects of time ($F_{(1,9)} = 35.20$, $p = 0.0001$, $\eta^2_p = 0.796$, *Power = 0.999*), condition *($F_{(3,27)} = 2.88$, $p = 0.05$, $\eta^2_p = 0.243$, Power = 0.623)* and also "condition × time" interaction *($F_{(3,27)} = 14.80$, $p = 0.0001$, $\eta^2_p = 0.622$, Power = 1.000)* on the

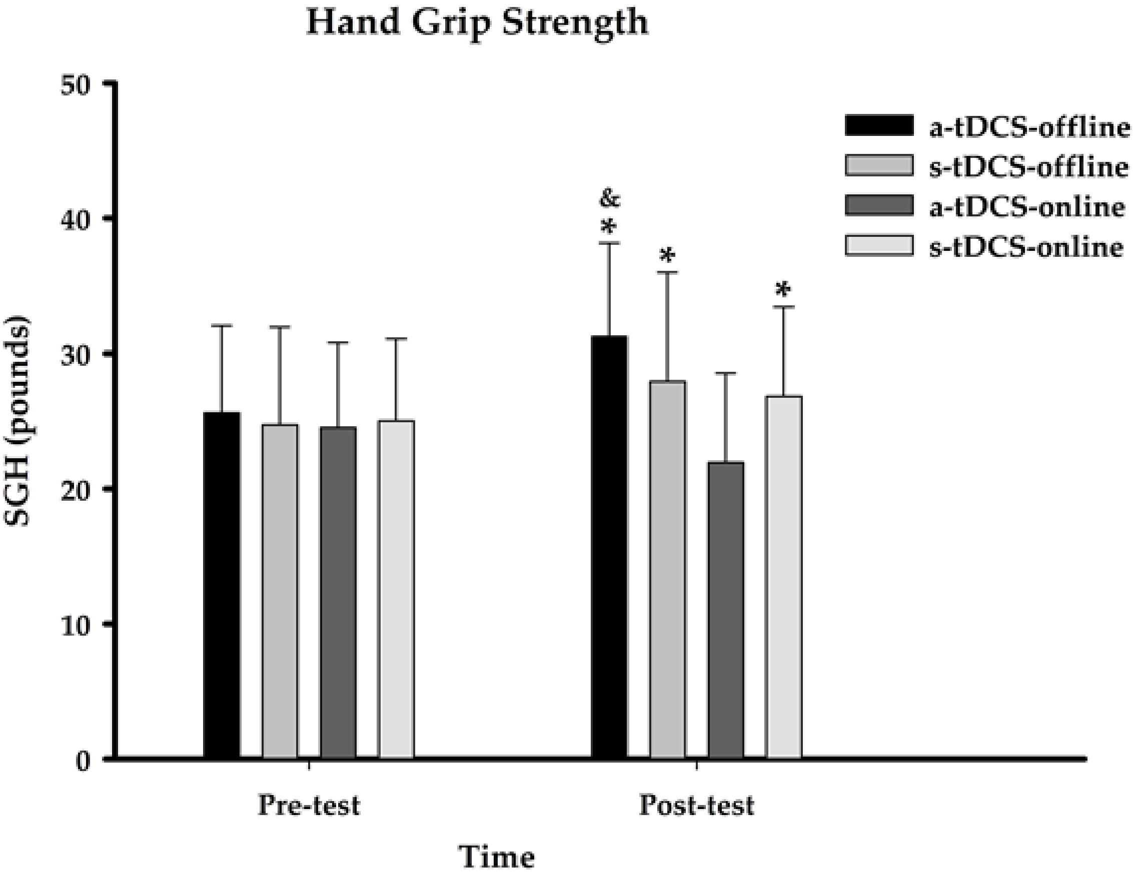

**Figure 2.** Comparison of four conditions of tDCS in pre-and post-tests (HGS)

*= Significant difference with the a-tDCS-online

&= Significant difference with the s-tDCS-online

ROM-W. According to the significant interaction effect, pairwise comparisons were employed, and the results indicated that at post-test, the ROM-W was significantly higher under a-tDCS-offline *($p = 0.034$)*, s-tDCS-offline *($p = 0.011$)*, and s-tDCS-online *($p = 0.027$)* conditions compared to the a-tDCS-online condition. In addition, the results showed that in the a-tDCS-offline and s-tDCS-offline conditions, the ROM-W was significantly increased from pre-test to post-test *($p = 0.001$, $Δ = 11.23\%$, $d = 0.87$; $p = 0.004$, $Δ = 5.87\%$, $d = 0.46$, respectively)*. The same trend was also observed in the ROM-W from pre-test to post-test under the s-tDCS-online condition *($p <0.001$, $Δ = 5.32\%$, $d = 0.50$)* while the ROM-W was significantly decreased from pre-test to post-test under a-tDCS-online condition *($p = 0.014$, $Δ = -3.39\%$, $d = 0.31$),* see Figure 3.

**Range of Motion of the Elbow (ROM-E)**

The obtained results on the ROM-E revealed that there were significant main effects of time *($F_{(1,9)} = 13.62$, $p = 0.005$, $η^2_p = 0.602$, Power = 0.906)*, condition ($F_{(3, 27)} = 8.402$, $p = 0.0001$, $η^2_p = 0.483$, Power = 0.984), and "condition × time" interaction *($F_{(3,27)} = 15.92$, $p = 0.0001$, $η^2_p = 0.639$, Power = 1.000)*. Based on the significant "condition × time" interaction, pairwise comparisons were used, and the results showed that at post-test, the ROM-E was significantly higher under a-tDCS-offline, s-tDCS-offline, and s-tDCS-online conditions compared to the a-tDCS-online condition *($p < 0.001$; $p < 0.001$; $p = 0.01$, respectively)*. Also, the results showed that the ROM-E was significantly increased from pre-test to post-test under a-tDCS-offline *($p = 0.0001$, $Δ = 7.74\%$, $d = 0.52$)*, s-tDCS-offline *($p = 0.002$, $Δ = 5.52\%$, $d =$*

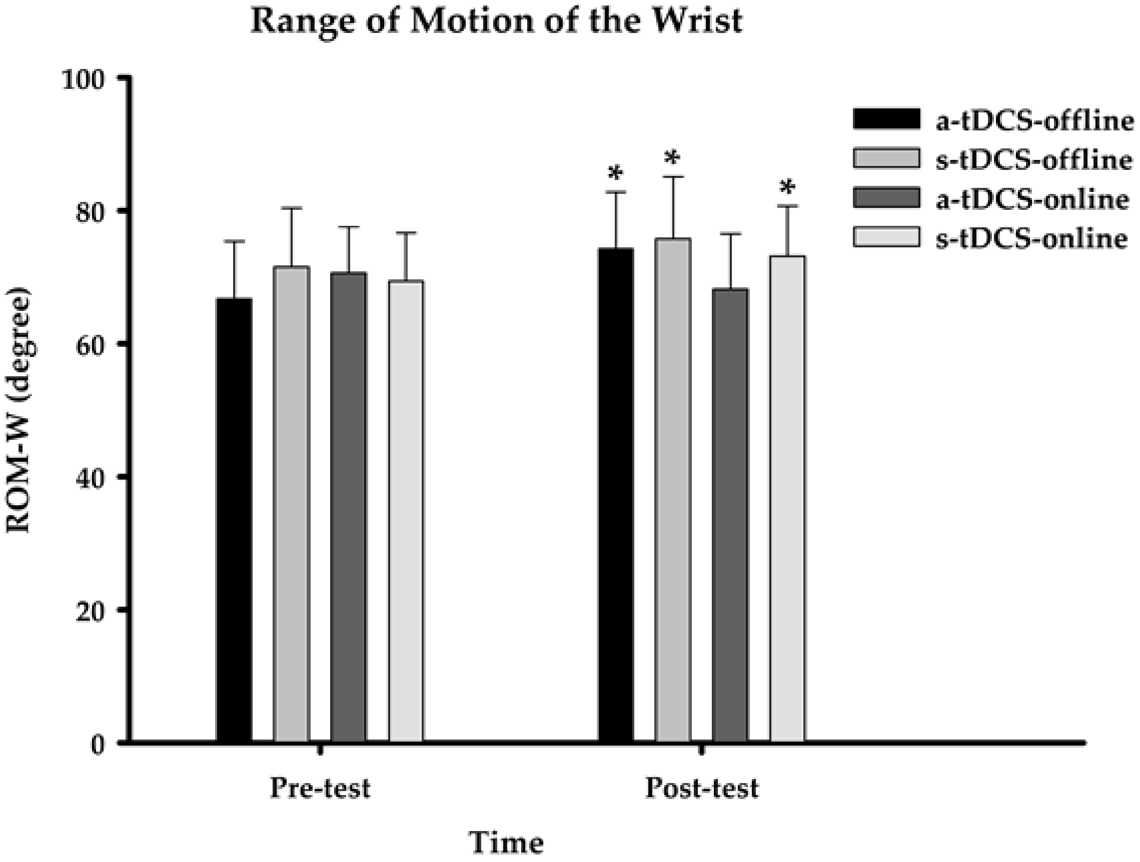

**Figure 3.** Comparison of four conditions of tDCS in pre- and post- tests (wrist range of motion)

*= Significant difference with the a-tDCS-online

*0.42)*, and s-tDCS-online *(p = 0.001, Δ = 3.34%, d = 0.28)*, while no significant difference from pre-test to post-test was observed under a-tDCS-online condition *(p = 0.054),* see Figure 4.

## Discussion

This study was the first to compare the effect of tDCS before (offline) and during (online) MVF on HGS and ROM of the affected upper limb in children with SHCP. The results indicated that the application of tDCS during the MVF (online-tDCS) resulted in a decrement in HGS and ROM, representing a novel finding of the present study. The presence of permanent spasms in the flexor muscles and the weakness of the extensor muscles have impaired mobility of the upper limbs in children with SHCP. In contrast to the typical growth patterns observed in healthy individuals, these children's muscle strength and functionality do not follow a typical trajectory with age. In light of these considerations, several intervention strategies have been employed to enhance the motor functions of the affected limbs in individuals with SHCP. MVF has been demonstrated to be an efficacious strategy for enhancing motor function in individuals with SHCP. In this context, Palomo et al. demonstrated that practicing with a mirror significantly improved HGS in the affected limb (9). The study reported that MVF increases the activity of M1, thus facilitating the transmission of descending motor commands from the brain to the muscles of the affected limb and ultimately enabling the use of a greater number of motor units in the muscles. These findings are consistent with previous studies (7, 30). The rationale behind utilizing MVF is based on the distinction between

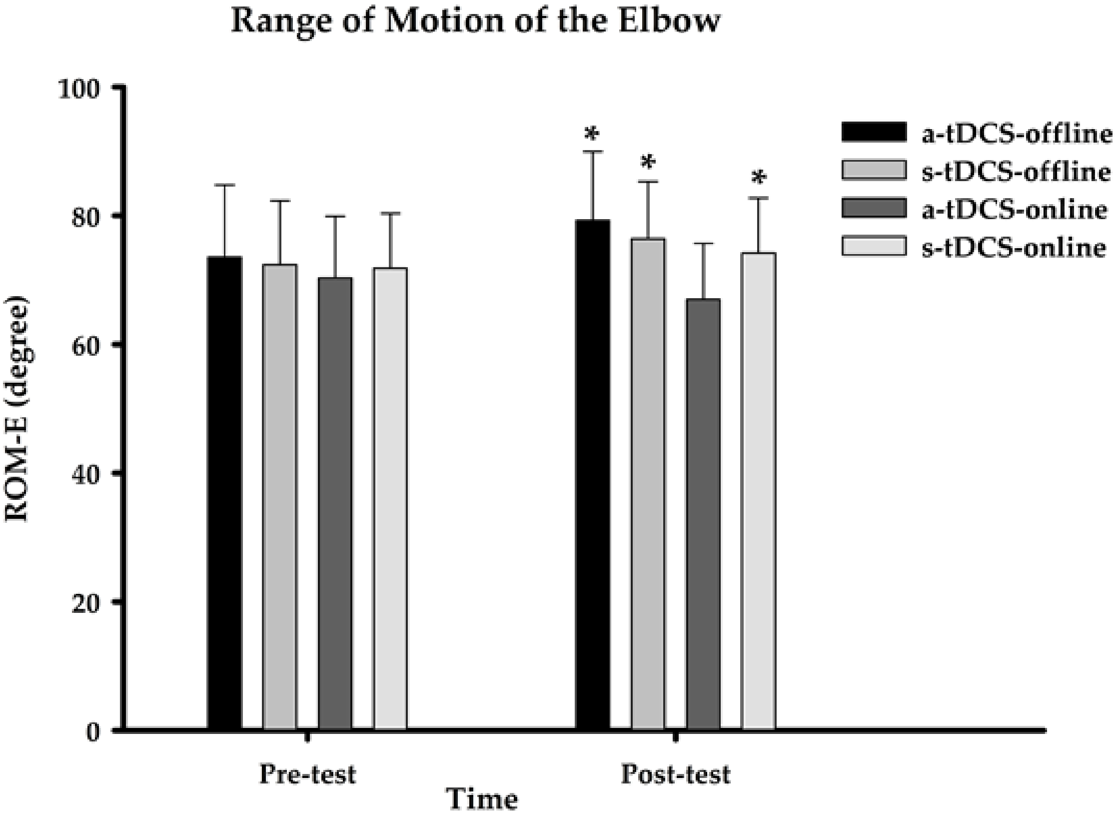

**Figure 4.** Comparison of four conditions of tDCS in pre-and post-tests (Elbow range of motion)

*= Significant difference with the a-tDCS-online

motor and mirror neurons. The mirror neuron system of the motor cortex is activated by the mechanism of mirror therapy (4). Subsequently, active neurons transmit impulses to motor neurons via the CST, facilitating the transmission of motor commands to the affected limb's muscles (30). Ultimately, the reorganization of M1 results in the adjustment of interhemispheric inhibition and the coupling of two organs. Our previous research aimed to investigate the impact of motor exercises in the mirror on gross motor skills in the affected hand of children with hemiplegic CP. The findings indicated that the MVF method was more effective and efficient in enhancing motor skills in the affected hand than the control group(27).

In this study, despite no statistically significant difference between offline anodal and sham tDCS, a larger effect size was observed in the anodal tDCS conditions than in the sham tDCS on HGS and ROM of the affected upper limb. Neurophysiological studies have demonstrated that the low excitability of the motor cortex in children with SHCP results in impaired motor control (8). Consequently, the impact of anodal tDCS on M1 enhances corticospinal excitability for up to 90 minutes post-stimulation, promoting brain flexibility (21). In the study by Moura et al., an improvement in upper limb motor function was reported following a single session of anodal tDCS to the M1 of the affected hemisphere in children with SHCP (8). Given the clear benefits of anodal tDCS over sham tDCS and the positive effects of MVF in the baseline state, electrical stimulation evidently improves motor performance (31) but does not activate cognitive aspects of performance. Undoubtedly, the cerebral cortex's practical organization and motor performance improvement occur when both motor and cognitive aspects are considered. MVF, in conjunction with electrical stimulation, constitutes an efficacious intervention for enhancing cognitive aspects, specifically awareness of the affected limb. Consequently, substituting visual feedback from the healthy limb in the mirror results in the formation of the impression of movement from the affected limb for the patient and the stimulation of the cerebral cortex in the damaged area (9). The results of the studies conducted by Von Rien et al. (2015), Hoff et al. (2015), Horiba et al. (2019) and Jin et al. (2019), as well as the study by Segal et al. (2020), have demonstrated that the combination of MVF and tDCS synergistically and additively affect the improvement of motor performance (12, 13, 32, 33).

The findings also indicated that the HGS and ROM were higher under offline anodal tDCS than online tDCS. This suggests an interference effect between tDCS and MVF when performed concurrently. In the a-tDCS-online mode, an additional stimulus (electrical stimulus) was presented during mirror exercises (receiving visual stimulus), and the combination of these two stimuli (visual and electrical) was applied with the assumption of synergistic motor performance. However, some results were obtained that were contrary to the research hypothesis. When analyzing the results, it becomes evident that the practice structure plays a pivotal role in determining the success of motor learning. As some studies have also demonstrated that the concurrent presentation of two stimuli with disparate motor programs results in a phenomenon termed the contextual interference effect (CI), the sequence in which the stimuli are administered is a crucial determinant of the strength of the CI (34).

The results of this study indicate a clear trend towards a reduction in performance with the application of a-tDCS-online, as evidenced by the decline in the HGS and ROM of the affected upper limb. Seemingly, the observed pattern involves different learning mechanisms. Although the competition of cognitive-motor stimuli for control of the injured upper limb in these children resulted in a decline in motor performance, some neuroimaging studies have demonstrated the impact of cognitive-motor interference on prefrontal cortex (PFC) activation (35). The PFC region is of significant importance concerning motor learning and memory formation. Three distinct types of motor learning have been identified: These three stages of motor learning are 1) execution (during practice), 2) maintenance (maintaining the learned skill for a certain period), and 3) transfer (the effect of the individual's previous experience on learning a new skill) (34). Porter and Magill's studies demonstrated that reducing background interference in stimulus presentation enhanced performance across all three stages of motor learning. These are the maintenance and transfer stages of motor skill learning (36).

Moreover, a study by Jin et al. (2019) demonstrated that sustained optimization of motor learning is possible with longer interventions. The long-term effects of dual time-dependent interaction (tDCS) and mirror therapy on hemiplegic upper limbs in patients with chronic stroke were studied. The results demonstrated that the a-tDCS-online group exhibited a notable enhancement in the Action Research Arm Test (ARAT) and the Fugl-Meyer Assessment-Upper Extremity (FMA-UE) in comparison to the s-tDCS and a-tDCS-offline groups at the post-test stage. Apparently, the simultaneous combination of tDCS and MVF is more beneficial and time-efficient over a longer period (13). As the simultaneous effect of tDCS and MVF on children with SHCP has yet to be investigated, the present research examined the effects of one session of the desired interventions, conducted simultaneously and consecutively. However, the results in the simultaneous conditions (online) did not demonstrate the desired improvement in performance in these children. In light of the findings of Porter and Magill regarding the reduction of performance in the acquisition phase and the improvement of performance in the retention and transfer phase during the simultaneous application of stimuli, the results of this research can be used as a basic protocol for the application of longer interventions to improve the HGS and ROM of the affected upper limb in these children. Therefore, one possible recommendation for future studies is to explore the impacts of retention and transfer.

## Limitations

One of the limitations of the present research was the relatively small number of participants and the decision to evaluate the intervention immediately after its completion. The restricted sample size precludes any determination of whether a-tDCS-online conditions can enhance HGS and ROM over the long term. Because the present study is the inaugural investigation to assess the impact of visual feedback in conjunction with tDCS on the upper limb functionality of children with SHCP, it is recommended that future studies investigate the long-term effects of this intervention, as well as the memory effect, at one-and three-month intervals following the research. Moreover, the results of studies conducted in the field of tDCS have demonstrated that due to the existence of differences in stimulation characteristics, including stimulation technique, intensity, frequency, location, and period of stimulation, the design of an effective protocol for the recovery process of these children has been a significant challenge.

## In Conclusion

This research aimed to evaluate the HGS and ROM among children with SHCP. The findings indicated that observing the healthy hand in a mirror evoked a kinesthetic representation of the injured hand in the patient. Furthermore, the findings indicated that combining MVF brain stimulation in a sequential (offline) manner is more effective than the simultaneous (online) combination of both in the execution stage. As this type of intervention was not previously conducted in conjunction with this specific demographic, the findings of this research serve as a foundation for enhancing the performance of these children. Therefore, proposedly, considering the role of time in motor learning, an acute online training protocol may prove an effective means of improving upper limb performance.

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## Authors' Contribution

Farzamfar Pegah conceptualized and designed the study. PF conducted the experiments. PF, Heirani Ali and Ehsan Amiri participated in the formal analysis. Farzamfar Pegah and Heirani Ali wrote the original draft of the manuscript. Ehsan Amiri, Sedighi Mustafa, and Daniel Gomes da Silva Machado reviewed and edited the manuscript. All authors approved the final version of the manuscript.

## Conflict of Interest

The author declares that they have no conflict of interest.

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