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Modulating Neuronal Networks to Enhance Postural Control: A Review of Transcranial Direct Current Stimulation Approach

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Abstract

Context: Postural stability is essential for performing everyday activities. The central nervous system (CNS) must modify balance control to provide stability to intrinsic and external perturbations. Methods considered as the main candidates for ultimate promotion of neural plasticity could be used for rehabilitation to enhance motor performance. The Transcranial Direct Current Stimulation (tDCS) as a non-invasive brain stimulation tool is applied over the cortex to accentuate and/or accelerate neural effects on network connectivity.
Objectives: This study aimed to address the impact of tDCS intervention on balance recovery. We postulated that tDCS induces neuroplasticity that is fundamental for refining motor behaviors such as postural stability during rehabilitation.
Methods: The present review discusses the tDCS application over the important areas of the CNS that are responsible for the sensorimotor processing of balance-relevant information. We searched ProQuest, PubMed, Science Direct, Cochrane, and Google Scholar for randomized, controlled trials that assessed the efficacy of tDCS intervention in improving balance impairment following neurologic disorders and enhancing postural stability in a healthy population.
Results: Recent studies provide insights into the effects of tDCS on postural stability. Based on the defined criteria, there is a positive response to tDCS, but the underlying neural mechanisms are yet unknown. We suggest that interventions promoting more neural plasticity are crucial for better balance training outcomes and improved effectiveness of rehabilitation programs.
Conclusions: Balance recovery after tDCS needs to be more investigated. The tDCS might be considered as an adjunct preventive strategy to provide functional recovery and reduce the adverse effects of balance impairment.

Keywords: Transcranial Direct Current Stimulation, Balance, Cerebral Cortex, Neurologic Disorders, Neuronal Plasticity, Posture, Functional Mobility, Rehabilitation

1. Introduction

Postural control is the main concern in functional rehabilitation programs. To ensure postural steadiness, the central nervous system (CNS) integrates sensory information obtained from various sources in order to initiate appropriate motor actions (1). The higher regions of the CNS are responsible for modifying the postural context-specific reactions (1). The term “neuroplasticity” describes non-pathological changes in the structure of the adult brain to construct adaptive modifications related to the structure and function of the nervous system (2). Neuroplasticity is responsible for neurobiochemical changes in neuronal network connectivity. Neuroplasticity exerts a significant ameliorative function during normal aging and health, as well as in different brain diseases (3). Therefore, rehabilitation protocols need to boost cortical reorganization providing the greatest potential for recovery (4).

Balance impairment is one of the main causes of disability in people with neurological disorders, despite the extensive use of physical therapy for stability rehabilitation. However, these protocols are burdened with poor sufficiency to promote stability (5). New neuroplasticity-based approaches for balance recovery are emerging to develop the principles of harnessing plasticity mechanisms in the adult brain. Experimental evidence demonstrates that strategies inducing neuroplasticity may lead to greater motor and functional recovery than traditional rehabilitation. Transcranial Direct Current Stimulation (tDCS) uses scalp electrodes to produce low-magnitude direct currents to penetrate the cortex and alter neuronal

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excitability (6). The excitatory effect of the anodal electrode and the inhibitory effect of the cathodal electrode produces neuromodulatory effects in the neuronal network (7). Although the exact mechanisms of action for tDCS are unclear, the long-term potentiation-like plasticity created by tDCS may rely on NMDA receptor-dependent glutamatergic neurons that vary depending on the location of the stimulation (8). A very recent study illustrated subcortical structure facilitation resulting from enhanced cortico-reticular drive following tDCS. They postulated that the faster onset of postural reactions after stimulation indicates the robust evidence of impressing subcortical structures, especially the reticular formation to produce stability. This evidence for reticulospinal compensation may be promising for neurorehabilitation protocols (9). The tDCS has shown to promote neuroplasticity, thereby improving motor and cognitive functions and facilitating motor learning in different populations (10). In healthy adults, tDCS can accelerate the sensory feedback mechanisms in line with modulating the excitability of the responsible cortical area during a motor task (11).

Recently, a meta-analysis study investigated the efficiency and safety of tDCS in the restoration of lower extremities in stroke patients. The evidence demonstrated the significant effect of tDCS on mobility and muscle strength of lower limbs (12). It is worth considering that very few research has reported the effects of tDCS on posture and balance. The role and efficacy of tDCS in balance control and fall prevention have not been well established. Among a wide variety of training methods used to improve balance and postural stability, tDCS is a safe and low-cost technique with little transient adverse effects compared to other modern adjunct therapies. In fact, tDCS is an appealing intervention to boost neuroplasticity. An update of the effects of tDCS on balance control is warranted given the number of new trials published, addressing theoretical gaps and variability in the efficacy of stimulation in obtaining stability. No previous study directly reviewed balance adaptation in accordance with tDCS application. This is the first study that deals with postural control enhancement with a noninvasive brain stimulation approach, i.e., tDCS. This review may have important implications in making decisions about long-term clinical relevance and obtaining information to design future trials.

2. Methods

2.1. Data Sources and Study Selection

A systematic review was performed following PRISMA guidelines using keywords (neuroplasticity, tDCS, balance, posture, and rehabilitation) in ProQuest, PubMed, Science Direct, Cochrane, and Google Scholar, which resulted in 102 articles. This review addressed the randomized controlled trials (RCTs) in healthy adults or adults with neurological disorders receiving tDCS stimulation in comparison with sham tDCS with measuring balance control outcomes (PICOS). Animal studies and studies assessing other neuromodulatory techniques were excluded. Two authors independently performed reviews and data extraction. Discrepancies were resolved by consensus. Additionally, more specific searches were conducted for different CNS locations, including the motor cortex and cerebellum. Our comprehensive search also covered the "grey literature," such as international theses and dissertations and congress proceedings. We also examined the references cited in the retrieved articles and reviews. Finally, we searched clinicaltrials.gov for additional RCTs. Then, based on a targeted selective approach, we selected articles reporting on any outcome related to the balance and posture from among articles written in English. The process of study selection is presented in Figure 1.

2.2. Data Extraction

We assessed the methodological quality of each trial by determining whether (1) the study was correctly randomized and/or the authors reported the randomization method, (2) the study used a control group (sham tDCS), and (3) the study reported the anode and cathode positioning. Two reviewers independently extracted data and resolved disagreements. The quality of the studies was evaluated using a checklist based on the CONSORT statement for clinical trials.

3. Results

After initial screening and removing irrelevant studies, 83 studies were chosen for the analysis. Proper interventions were selected according to the outcome using a targeted selection approach.

Further screening removed papers (104 subjects) that scored $< 40\%$ on CONSORT and were not compatible with the study objective. During this process, 22 articles (537 subjects) were selected as the main articles for the review. The kappa level of agreement between the two review authors for the CONSORT assessment was 0.81. Since studies could not be pooled, we considered a qualitative analysis (selective outcome reporting). In this systematic review, we used the Cochrane risk of bias tool for component approach.

Randomization was sufficient in all trials; however, three articles did not clearly explain data analysis following the intention-to-treat principle. Only two randomized trials used following-ups for three months.

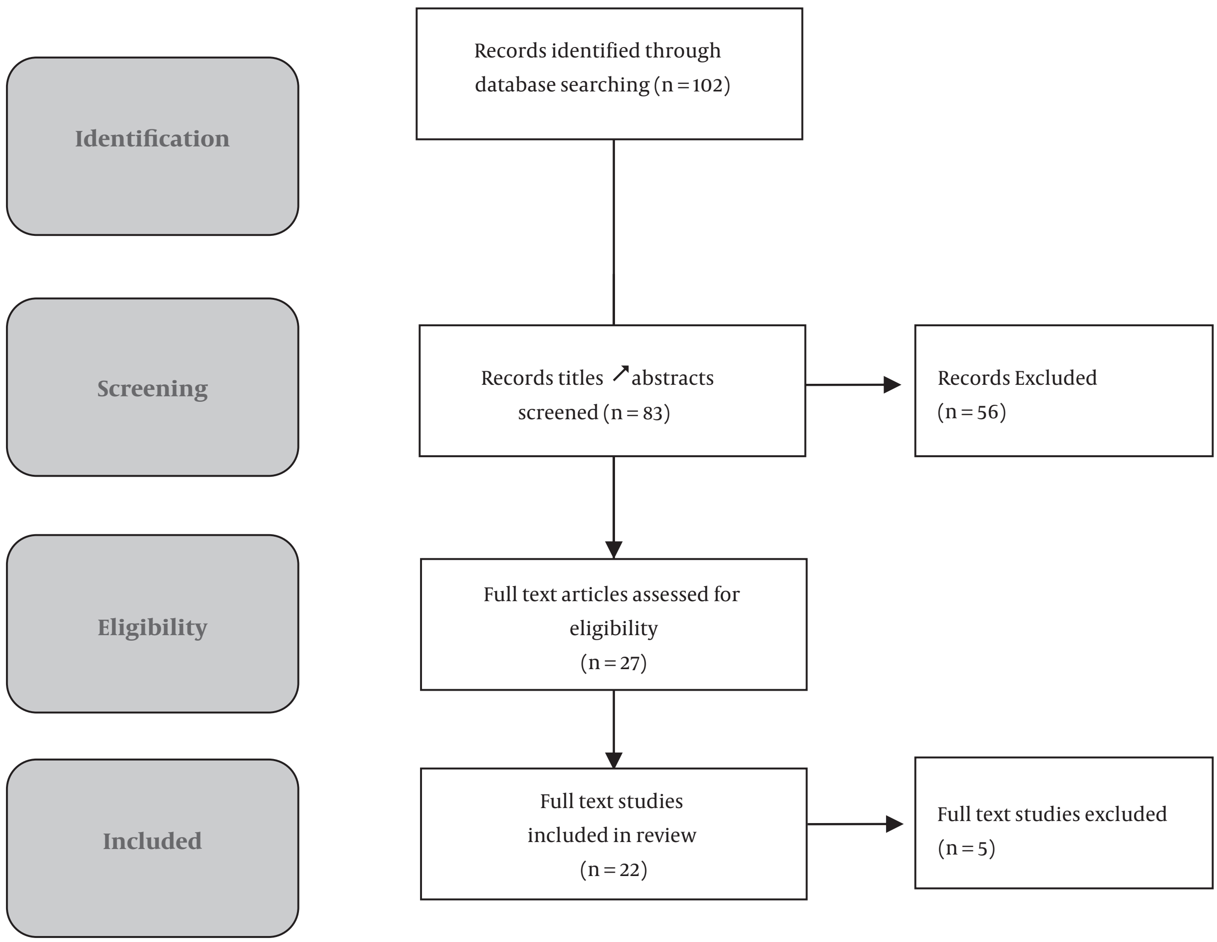

Figure 1. Study selection flow diagram

3.1. Impact of tDCS on Neuroplasticity and Balance in Individuals with Neurological Disorders

Despite progress in functional rehabilitation, balance recovery remains challenging in neurologic disorders. Balance after stroke is one of the most important issues addressed in stroke recovery. Stroke is a worldwide health problem, and the main leading cause of disability (13). Increased postural sway and asymmetrical weight distribution with disturbance of stance phase stability characterize postural impairment in hemiplegic stroke patients (14). The rationale of cortical stimulation using tDCS following stroke is to harnessing plasticity that depends on the interaction between the damaged hemisphere and healthy hemisphere (15). Bihemispheric tDCS intervention aims at either elevating ipsilesional primary motor cortex (M1) excitability or reducing contralesional M1 excitability, or both at the same time. Nevertheless, the other controversial findings depend on the functional status of the brain cortex (16). The tDCS over the leg motor area has also been demonstrated to modulate the excitability of leg muscles in stroke survivors (17). Evidence indicates that the motor cortex leg area is strongly involved in postural control strategies (18) and tDCS is capable of enhancing upright standing (19). In a study, a single anodal tDCS session was applied over the leg area of ipsilesional M1 in 11 acute stroke patients. The results showed improvement in locomotion and the lower extremity force of the affected side (20). Combination therapies, such as adding concomitant rehabilitation programs, are potent to further drive motor recovery. Combined tDCS and weight-supported treadmill training (BWSTT) were investigated in individuals suffering from a stroke. The anode was applied in the front of Cz, and the cathode was applied over the inion (1 mA, 20 minutes). The tDCS applied to the somatosensory area (SMA) confirmed the improved postural control during BWSTT (21).

Postural instability is common in Parkinson's disease (PD). PD upsets the basal ganglia functions, which supply both cortical and brainstem motor areas. Individuals with PD fail to respond adequately to different perturbations (22). This rigidity in the ability to properly recruit motor pathways explains why individuals with PD choose a restricted stance, and it may contribute to postural instability (23). The role of brain plasticity changes in motor rehabilitation has been proven in patients with brain damage such as PD patients. At present, efforts are being made to augment cortical neuroplasticity combining rehabilitation with tDCS to target motor tasks specifically. Regarding balance intervention in PD, Hadoush et al. demonstrated in a sham-controlled study that bilateral anodal tDCS could diminish fear of falling and improve balance in this population (24). Verheyden et al. conducted a double-blind, experimental crossover study with 20 PD patients on either active (1 mA, 15 minutes) or sham tDCS. The anode was placed over the M1 of the dominant hemisphere and the cathode over the contralateral supraorbital region. Participants' baseline clinical measures included timed-sit-to-stand test, functional reach test, standing start 180° turn test, timed up and go test, and 10-m walk test. The outcome measures were collected again after the stimulation. The authors reported no significant recovery with active tDCS in any outcome (25).

Another study suggested that anodal tDCS (a-tDCS) on the left DLPFC and the cathodal tDCS on the right orbitofrontal cortex (Fp2) could support motor function in individuals with PD and recover the balance and functional motion in comparison with sham tDCS ($P < 0.05$). They contended a significant difference between groups in the Berg Balance Scale (BBS) score ($t = -5.399$; $P \leq 0.001$) with an a-tDCS montage, demonstrating better functioning (42.82 ± 12.17) than the sham tDCS (41.06 ± 12.28) (26). Recent work has also shown deficits in other brain regions necessary for ambulation in PD. In particular, researchers have recently paid attention to the spinal cord and closely focused on brainstem areas that are recognized as essential for regulating gait and postural tone (27). Recent results indicate that this region may represent a new location promising for brain stimulation to prevent falls in this target group (28).

3.2. Impact of tDCS on Postural Stability in Older Adults

Standing postural control is complex. Evidence has documented a decline in balance control during aging. In healthy older individuals, age-related balance decline can rely on abnormal balance adjustment as a form of motor learning (29).

Recent tDCS studies have raised the opportunity to observe the benefits of cortical stimulation in the balance rehabilitation process for fall prevention in older adults. Kaminski et al. investigated the impact of tDCS applied over the leg motor area on balance task learning of healthy elderly in a whole-body dynamic balance task (DBT). Relevant kinematic variables such as velocity, acceleration, jerk, and the number of zero crossings and learning performance were assessed. They concluded that the concurrent application of tDCS over the leg motor area did not facilitate DBT learning enhancement in older adults (30). Considering balance impairment in older adults, a study reported minimal online effects on postural measurement in the experimental tDCS group in eyes-open condition. They concluded that the value of tDCS on stability was too weak to affect postural responses to environmental perturbation (31).

Contrary to these findings, the results from the a-tDCS study supported the efficiency of intervention in ameliorating static and dynamic levels of stability in older fallers (32). Zhou et al. examined the complexity of static postural stability after tDCS intervention. The results showed that real tDCS was more effective than sham on augmenting standing postural sway complexity in the dual-task condition ($P = 0.02$) (33). Accordingly, a-tDCS over the SMA showed the decreased Center of Pressure (CoP) sway path length immediately and 15 minutes after stimulation compared to pre-intervention, implying an improvement in anticipatory postural adjustments (APAs) (34).

3.3. tDCS Modulates Postural Stability in Healthy Young Individuals

There is an increasing interest in conducting sound studies dealing with the effectiveness of tDCS in enhancing balance performance and motor learning in healthy adults. Reis et al. reported that a-tDCS over the motor cortex amended motor skill acquisition three months following the stimulation (35). In this regard, Lee et al. were the first who conducted research on tDCS efficacy in balance in healthy adults. They randomized 30 subjects to receive active or sham tDCS (2 mA) for 20 minutes. The anode was placed at Cz, and the cathode was attached to the supraorbital area. The balance overall stability index (OR), anterior-posterior stability index (AP), and medial-lateral stability index (ML) were the outcome measures. Balance stability significantly increased following active tDCS (36).

In a very recent study, 14 healthy participants were recruited in a double-blind study to perform motor imagery practice (MIP) alone or combined with tDCS during postural control. The CoP was measured using a Wii Balance Board. The findings showed that a slight MIP combined with tDCS might be sufficient to improve performance on a weight-shifting task during postural control and it had a slightly better performance than both MIP and sham tDCS. These results lasted for one month after the intervention. They suggest that tDCS in combination with traditional treatment, may play an adjuvant role in rehabilitation (37). For removing the effects of tDCS on combined cognitive and postural tasks, 20 adults (22 ± 2 years) completed two separate double-blind active or sham tDCS (1.5 mA) locating in the left dorsolateral prefrontal cortex. Gait and postural control were assessed before and after interventions. Standing postural sway speed (P = 0.01) and area (P = 0.01) decreased when the subjects performed a serial-subtraction task. Active tDCS also significantly diminished (P < 0.01) the dual-task cost on each of these outcomes (38). Another study on a standing balance task showed that the motor cortex anodal tDCS improved the maximum CoP excursions but not the return reaction time in healthy participants (39). Kaminski et al. examined anodal tDCS over the M1 leg area, facilitated 26 healthy young subjects who underwent stimulation. Highly-skilled participants, such as sportsmen were not enrolled in this study. The subjects completed the DBT during 20 minutes of tDCS, which was administered over the bilateral leg area. Improved dynamic balance performance and decreased error scores were obtained only after active tDCS intervention (40). As mentioned before, their study on older adults failed to support a beneficial effect on motor performance. These conflicting results may be due to a "ceiling effect" and can be explained by the optimal level of neuronal plasticity in young adults (29). In order to modulate cortical excitability in 20 young adults, a very recent study particularly targeted the SMA by a-tDCS. The cathode was placed over the right supraorbital area. During applying real tDCS, subjects performed significantly enhanced choice reaction time and faster balance task when compared to the sham tDCS (41).

Taken together, tDCS effects are highly variable and seem to be dependent on a wide variety of factors ranging from study sampling qualities to outcome parameters used to assess the effects of postural control. In spite of variations in tDCS intensity, electrode setup, and the type of balance task being used in these studies, these findings are promising for improving standing balance performance.

3.4. Impact of Cerebellar tDCS on Postural Stability

The cerebellum plays an important role in postural adjustments, motor learning, and stability, especially in "remembering" the accurate assignment of situation and error feedback learning (40). The cerebellum has a complex structure with an extensive neuronal network. The cerebello-thalamo-cortical inhibitory projections can be modulated by cerebellar tDCS (42). Available studies obtained evidence that tDCS could alter motor tasks and non-motor cerebellar performance in healthy humans (43). In a very recent study, participants received cerebellar a-tDCS (1.5 mA, 20 minutes). The BBS significantly enhanced in the active cerebellar a-tDCS group. Immediately after cerebellar a-tDCS, postural sway significantly reduced in static and dynamic postural tasks (44). Steiner et al. revealed that cerebellar tDCS did not improve balance learning in a dynamic balance task (DBT). They tried different cerebellar tDCS montages, with stimulation (2.8 mA) applied 2 cm below the inion. Neither mean platform angle deviation nor mean balance time differed before and after the intervention (45).

Inukai et al. examined a cathodal tDCS to the cerebellum in a randomized study. The tDCS (2 mA, 20 minutes) was applied over the scalp 2 cm below the inion in 16 healthy subjects. The results showed a significantly modified body sway (velocity). Total sway length and sway length per second changed significantly after the cathodal stimulation (46). In another study, 15 healthy, right-handed individuals were enrolled to receive a cathodal cerebral tDCS. The results reflected impaired static balance in healthy individuals receiving the cathodal cerebral tDCS, in particular, a significant impairment in the left Athlete Single Leg test, in comparison with sham stimulation (P = 0.04) (47). The cerebellum dysfunction consequences in a larger pathway of CoP in static balance were compared with healthy subjects. There are only primary data on the utilization of cerebellar tDCS in stroke. The effect of cathodal tDCS on chronic stroke was recently described in 15 patients during standing balance. They administered a-tDCS on the contra-lesional cerebellar hemisphere or ipsilesional cerebellar hemisphere compared to sham stimulation (1.5 mA, 20 minutes) in three sessions. Contra-lesional cerebellar tDCS showed potentials for recovery standing balance stability (48). Although the small group size was used in these studies, we considered that young, healthy individuals may have near peak adjusted levels of neuroplasticity and performance (49). The results propose that the tDCS effects on postural stability seem to be highly reliant on the targeted brain region and the sample group. Moreover, these results should be interpreted with great caution due to a large diversity in the tDCS setups.

3.5. Limitations

One of the main limitations of this review was the small sample size. The reviewed studies had used a wide variety of outcome measures. Nevertheless, the advantages of the present study were the comprehensiveness of the literature review and the application of precise inclusion criteria. The findings were promising, and the subject deserves to be explored comprehensively.

4. Conclusions

Standing postural control plays a crucial role in everyday activities. The tDCS is a safe, low-cost, easily manageable technique to modulate cortical excitability. Few studies have addressed the effects of tDCS on the impaired balance in individuals suffering from stroke and even on postural control augmentation in healthy individuals. Overall, it seems that tDCS is potent for use in the neural control of movement and postural stability in neurological disorder patients and even healthy adults. The clinical modifications yielded by tDCS may intensely vary according to methodological and neuroanatomical aspects. The effects of tDCS on cortical excitability in different subjects are dependent on the preserved cortical function and between-individual variations. Participants may respond differently, depending on the extent of pre-existing excitability, brain anatomy, age, and gender (49).

Ultimately, tDCS effects may have been neglected because of the small sample size. The results need to be confirmed in large clinical trials using larger sample sizes with prolonged follow-ups. As a new promising technique, using tDCS combined with rehabilitation awaits further clarification on how to implement tDCS in rehabilitation settings.

Footnotes

Authors' Contribution: Fariba Yadolahi constructed the idea for research, performed literature review, and wrote the paper. Mohammad Mohsen Roostayi and Minoo Khalkhali-Zavieh supervised the paper. Abbas Rahimi and Masoud Mehrpour supervised the manuscript drafting.

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