

Wearable Non-Invasive Brain Stimulation for Parkinson's Disease: Current Evidence, Clinical Applications, and Future Perspectives

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Abstract:

This review explores the emerging and significant role of wearable non-invasive brain stimulation (NIBS) technologies, with a focus on transcranial direct current stimulation (tDCS), in the management of Parkinson's disease (PD). While current PD therapies, including medication and deep brain stimulation, have limitations and risks, wearable NIBS offers a non-surgical, accessible alternative. The paper outlines the principles of tDCS, its methodology, and recent evidence supporting its efficacy for both motor (gait, balance) and non-motor (cognitive, mood) symptoms in PD. Meta-analyses show that tDCS, particularly when combined with rehabilitation, can significantly improve mobility, executive function, and depressive symptoms. However, the clinical impact remains moderate and variable, with optimal protocols still under investigation. The review discusses the ongoing development of wearable NIBS devices, their advantages, limitations, and future prospects for personalized, at-home therapy. These technologies have the potential to complement existing treatments, enhancing the quality of life for people with Parkinson's disease.

Keywords: Parkinson's disease, non-invasive brain stimulation, transcranial direct current stimulation, wearable devices.

1. Introduction

Parkinson's disease (PD) is a progressive brain disorder causing movement problems like tremors, stiffness, slow movement, and balance difficulties. PD also causes non-motor symptoms. Medication such as Levodopa is the main treatment for these

movement problems. However, long-term use can cause side effects, including movement fluctuations and involuntary movements. Serious issues like walking or balance trouble in advanced PD often do not improve significantly with medication. Deep brain stimulation (DBS) can help with PD motor

symptoms but requires surgery and carries risks like brain bleeding. Because of these challenges, researchers are seeking non-surgical treatments. Non-invasive brain stimulation (NIBS) methods, such as transcranial magnetic stimulation (TMS), transcranial direct current stimulation (tDCS), and transcranial ultrasound, may alter brain activity without surgery. Wearable NIBS devices are being developed for patient self-use, making long-term therapy more accessible outside the hospital [1].

Building on these new technologies, recent research finds early evidence that NIBS may improve PD symptoms. For example, repetitive TMS and tDCS have shown efficacy in improving motor function in some PD trials [1]. Various non-invasive devices for PD are in development, including wearable vibrotactile cueing devices (providing rhythmic stimulation to improve gait or tremor), transcutaneous nerve stimulators, and low-intensity focused ultrasound [2]. These mainly aim to relieve motor symptoms such as tremor, gait freezing (FOG), and balance problems. Most remain investigational: by 2022, almost no non-invasive PD device had FDA approval or CE marking despite positive randomized trial results [1]. This highlights both the promise and challenge in bringing wearable neuromodulation to practice.

Among these NIBS modalities, tDCS has garnered significant interest for PD therapy due to its portability, safety, and low cost. tDCS delivers a weak direct current (typically 1–2 mA) between scalp electrodes to modulate cortical excitability [3]. It can be administered with a lightweight battery-powered stimulator and headgear. This makes it well-suited for wearable or home use. Patients or caregivers can self-administer tDCS devices, which have been used in home-based rehabilitation [4]. Preliminary studies suggest tDCS may improve aspects of PD. For example, anodal tDCS over the motor cortex may improve gait and balance when paired with training [5]. Prefrontal tDCS may benefit cognitive function and mood [6]. However, results across studies have been mixed. This is likely due to varying stimulation parameters and patient populations [7]. In summary, as NIBS technologies advance, tDCS remains a key focus for potential clinical application in PD. Given the need for safer, more accessible PD treatments, wearable tDCS (and related non-invasive stimulators) represent a compelling therapeutic avenue. They offer continuous or frequent neuromodulation without surgery. This feature may complement medication and physical therapy to better manage PD's motor and non-motor symptoms. For this reason, the present review focuses on wearable non-invasive brain stimulation systems for Parkinson's therapy, with emphasis on tDCS as a representative technology. The article first introduces the principles and methodology of tDCS in PD. It then reviews recent prog-

ress applying tDCS to motor symptoms (gait, balance) and to non-motor symptoms (cognition, mood). Representative studies and results are highlighted, including examples of devices and integration with rehabilitation. Finally, current limitations of wearable NIBS for PD and future research and clinical translation outlooks are discussed.

2. Theoretical analysis

2.1 Transcranial Direct Current Stimulation (tDCS) Principles

tDCS is a type of non-invasive brain stimulation that uses constant, low-amplitude direct current applied through surface electrodes on the head. In a typical setup, at least two electrodes—an anode and a cathode—are placed over target regions such as the motor cortex or prefrontal cortex, with a saline-soaked sponge serving as the interface. During stimulation, current flows from the anode through the scalp and brain to the cathode, inducing electric fields that modulate neuronal membrane potentials. The effects depend on electrode polarity: anodal tDCS causes slight depolarization, increasing neuron excitability and raising the likelihood of firing, while cathodal tDCS hyperpolarizes neurons and reduces cortical excitability [6]. These polarity-specific effects lead to functional changes; for example, anodal stimulation over the primary motor cortex (M1) can boost motor output by lowering motor neuron thresholds, whereas cathodal stimulation can inhibit motor function. The neuromodulatory effects may last beyond the stimulation session due to neuroplastic changes. Anodal tDCS can induce long-term potentiation-like effects through NMDA receptor activation and calcium-dependent plasticity, while cathodal stimulation may induce LTD-like effects. Importantly, tDCS is subthreshold: unlike TMS, it does not directly cause action potentials, but instead primes neural circuits by modulating ongoing activity [6].

2.2 Stimulation Parameters

Key tDCS parameters include current intensity, electrode size, the placement montage, session duration, and session frequency. Typical protocols use a current of 1–2 mA for 10–30 minutes per session [7]. Current density is determined by dividing the applied current by the electrode area. For example, 2 mA over a 25 cm² pad yields about 0.08 mA/cm². Most studies limit current density to 0.04–0.1 mA/cm² to prevent skin irritation or tissue damage [8]. This falls within safety guidelines. Electrode montages target specific cortical regions involved in PD. For motor symptoms, a common setup places the anode over the pri-

mary motor cortex (M1) or premotor cortex, and the cathode on the forehead or opposite hemisphere. For cognitive or mood symptoms, anodal tDCS is often applied over the left dorsolateral prefrontal cortex (DLPFC), with a reference electrode on the forehead. Placement determines which brain circuits get the strongest stimulation. tDCS effects can extend to interconnected subcortical structures. For example, anodal M1 stimulation may raise activity in motor networks and promote dopamine release in basal ganglia circuits [7].

Session length and repetition are key to tDCS effectiveness. Research shows longer sessions (20–30 minutes) and more sessions (at least 5–10) give more robust, lasting results. For example, a recent meta-analysis found 10 or more sessions led to greater cognitive improvements [6]. Stimulation strength also matters. Using 2 mA usually leads to stronger changes than 1 mA. Most PD studies use 2 mA, as evidence shows it improves motor cortex plasticity more consistently, though results on intensity are mixed. Intensities above 2 mA are rarely studied in PD.

2.3 Evaluation Metrics and Data Sources

In studies of tDCS for PD, researchers use both clinical scales and objective tests to assess outcomes. Common motor metrics include the Unified Parkinson's Disease Rating Scale Part III (UPDRS-III) for motor function. Gait speed tests, like the 10-meter or 6-minute walk test, and measures such as stride length and cadence, are also used. The Timed Up and Go (TUG) test assesses mobility. Balance assessments, like the Pull Test or Berg Balance Scale, are common [5]. Freezing of gait is often measured by the Freezing of Gait Questionnaire (FOG-Q). Wearable motion sensors, such as accelerometers and inertial measurement units (IMUs), increasingly provide quantitative data on gait and balance [9]. For example, limb-worn sensors can show stride consistency or postural stability improvements after tDCS. Non-motor outcomes are tracked with neuropsychological tests of executive function, memory, attention, and language, such as verbal fluency, the Stroop test, and digit span. Mood is measured using scales like the Hamilton Depression Rating or the Geriatric Depression Scale. Quality of life is often rated by the PDQ-39 questionnaire. In tDCS trials, these metrics are compared between real and sham stimulation to measure efficacy. Many studies combine tDCS with behavioral therapy, such as physical or cognitive training, to enhance results. For instance, a PD gait study may apply anodal tDCS over M1 while the patient practices walking exercises. This primes the motor cortex for relearning [5]. Outcomes may include clinical scales before and after intervention, retention of motor learning, and neurophys-

iological measures, such as TMS-induced motor evoked potentials or neuroimaging of connectivity.

2.4 Wearable tDCS System Design

A wearable tDCS system typically has a portable current stimulator and a headset or cap for electrode placement. The stimulator is a battery-powered constant-current source. Modern devices are set up for remotely supervised tDCS, so patients can receive stimulation at home. Telemonitoring of adherence and safety, such as video supervision, is sometimes used. tDCS equipment is simple, often limited to a few buttons or a smartphone interface. This simplicity makes home use feasible. Safety features are built in to limit current and to ramp the current on/off gradually for comfort. Some research prototypes integrate closed-loop control, which can adjust stimulation intensity based on feedback like tremor or EEG readings. These features are experimental. Overall, the wearable aspect means the device is lightweight and unobtrusive. For example, it might include a soft cap or integrated electrode headbands so the patient can move during stimulation. This enables stimulation alongside exercise, such as treadmill training or dancing. The methodology aims to optimize parameters and delivery for benefit, while keeping safety and ease of use.

3. tDCS for Motor Symptoms in Parkinson's Disease

A 2024 systematic review and meta-analysis examined tDCS impacts on gait in PD. The figure 1 shows the pooled effect on gait cadence (steps per minute), comparing real tDCS vs sham. The blue diamond shows a significant overall reduction in cadence with tDCS. This means PD patients took fewer steps per minute—slower cadence—after tDCS than controls. This positive result is counterintuitive. Reduced cadence usually means longer stride length and better gait efficiency in PD, as patients often have fast, shuffling steps. In this meta-analysis, tDCS, especially when combined with gait training, produced a meaningful cadence improvement with a large, highly significant effect size [5]. Other gait measures, like average walking speed and stride length, showed trends favoring tDCS but did not reach significance (possibly due to heterogeneity between studies). Cadence emerged as the gait metric most robustly improved by tDCS. This matches individual trials, which reported increased stride length and reduced step frequency after anodal motor cortex stimulation. These findings suggest tDCS can normalize gait patterns in PD by combating the short, rapid steps typical of Parkinsonian gait [10].

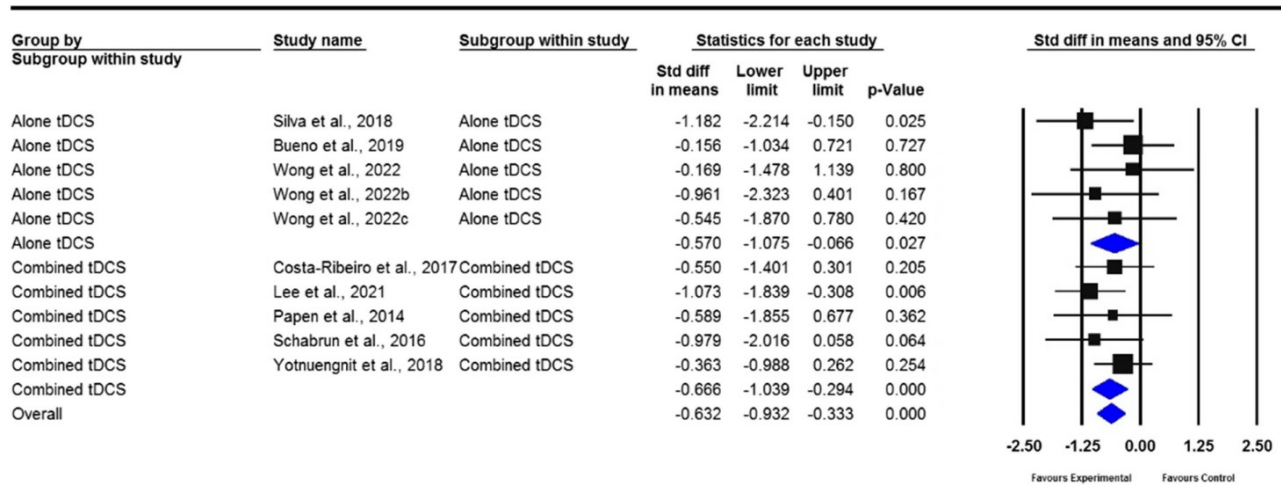


Fig. 1 tDCS effects on gait in PD – Meta-analysis of Cadence [10].

The Timed Up and Go (TUG) is a functional mobility test. Lower times indicate better balance and agility. The figure 2 (from the same 2024 meta-analysis) shows tDCS effects on TUG performance [10]. Lower (negative) values mean improvement (faster completion). The pooled result favors the tDCS group. Patients who received real tDCS (alone or with physical therapy) performed the TUG faster than those who received sham. The standardized mean difference was about -0.29 , which is significant. Many included studies in the analysis gave tDCS alongside exercise or physical therapy. Subgroup analysis showed that combined interventions tended to yield larger improvements than tDCS alone. For example, Kaski et al. (2014) found

that anodal tDCS over the motor cortex during 15 minutes of balance and gait training significantly improved gait velocity and pull-test balance recovery. tDCS without physical training had no isolated benefit. The meta-analysis shows several combined tDCS-plus-training studies (blue squares) with greater effect sizes than trials of tDCS alone. Overall, the evidence suggests that tDCS by itself yields modest motor benefits. Integration with rehabilitative training amplifies mobility and balance improvements. tDCS can prime neural circuits to be more plastic and responsive to training. This may lead to better outcomes when combined with physiotherapy, such as using a wearable stimulator cap during treadmill practice [7].

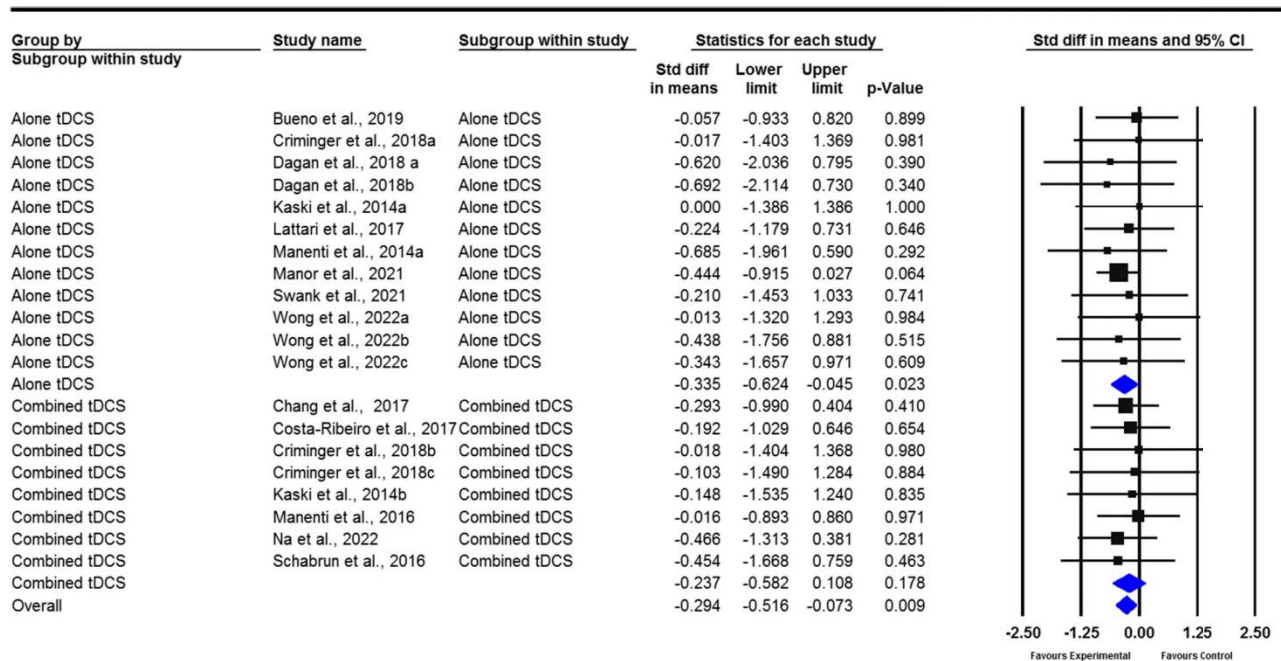


Fig. 2 tDCS effects on balance and mobility – Timed Up & Go test [10].

Beyond cadence and TUG, tDCS has shown positive effects on certain motor symptoms in specific studies. For

tremor, tDCS is less frequently studied than methods such as TMS or peripheral nerve stimulation. Some reports suggest that cathodal stimulation over the motor cortex or cerebellum can reduce tremor amplitude for a short time, although results are inconsistent. A 2021 review found insufficient evidence for significant tremor improvement in PD overall. Freezing of gait is difficult to treat, but some tDCS trials using frontal or cerebellar stimulation have reported fewer FOG episodes or improved questionnaire scores; meta-analysis shows a moderate benefit. Small RCTs examining tDCS for bradykinesia and motor scores (typically UPDRS-III) have found mixed results: while some studies report improvements with repeated tDCS, meta-analyses generally find no significant overall benefit compared to sham. Liu et al. (2021), after reviewing 21 studies, found tDCS did not significantly improve UPDRS motor scores or gait/balance overall but did note trial variability, likely due to protocol differences and small sample sizes. More recent evidence suggests that specific gait and mobility outcomes improve under certain tDCS protocols, especially when paired with exercise. Thus, protocol optimization is important; targeted regimens like anodal M1 or cerebellar tDCS with gait training may yield benefits for PD motor function, even though tDCS alone is not a solution for all symptoms [7].

In summary, wearable tDCS shows promise in addressing PD motor deficits like impaired gait and balance. As described throughout the preceding sections, the non-invasive stimulation can be delivered through a simple cap or headset during movement training, potentially enhancing neurorehabilitation. The improvements observed, though moderate, are valuable, since gait freezing, falls, and mobility problems greatly reduce quality of life in PD and are not fully addressed by medication. Looking forward, refining stimulation parameters (such as optimal cortical targets and timing relative to training) and using objective sensor data to personalize tDCS could further increase its impact on motor function. Notably, other wearable stimulator approaches are also being explored for motor symptoms, complementing the potential of tDCS. For example, transcutaneous spinal cord stimulation and vibrotactile cueing devices have shown reductions in freezing episodes and improvements in walking speed. Among these, tDCS stands out for its ease of application

to cortical targets involved in motor control and its ability to broadly promote cortical plasticity. As attention shifts toward non-motor symptoms in the following section, the next part will examine how tDCS and related techniques have been applied to address PD's cognitive impairment and mood symptoms, thereby continuing the discussion of these equally important therapeutic targets [1].

4. tDCS for Cognitive and Other Non-Motor Symptoms

Cognitive decline is a common non-motor feature of Parkinson's, ranging from mild executive dysfunction to dementia in later stages. The figure 3 is a forest plot from a 2025 meta-analysis of 23 studies evaluating tDCS for PD cognitive outcomes [6]. It shows the overall effect of tDCS on global cognition, measured by composite cognitive test scores. The pooled result favors the tDCS group with a standardized mean difference +0.73, indicating a large and highly significant improvement compared to sham. In practical terms, this means patients receiving tDCS did better on neuropsychological tests of memory, attention, language, and related skills. The analysis also looked at multiple cognitive subdomains. Executive function (planning, task switching) improved significantly in the short term (SMD $\sim$ -0.32 for reaction time-based executive tasks, where a negative score indicates faster/better performance). Language function, such as verbal fluency, showed a medium positive effect (SMD $\sim$ +0.5). However, tDCS did not significantly improve some domains like memory and attention in this meta-analysis (effect sizes were small and non-significant). The best cognitive benefits were seen in executive processes and language. This matches the common use of anodal DLPFC tDCS in these studies, targeting frontal executive networks. Meta-regression found that higher-dose protocols (2 mA intensity, $\geq$ 25 min session length, and $\geq$ 10 sessions total) were linked to larger cognitive gains. This suggests a dose-response effect, and trials with longer or repeated stimulations saw more robust improvements. Overall, Figure 3 supports tDCS as a way to meaningfully enhance cognition in PD patients, at least in the short term. This suggests a possible role for home-based tDCS as an adjunct to cognitive training or as a therapy for mild cognitive impairment in PD.

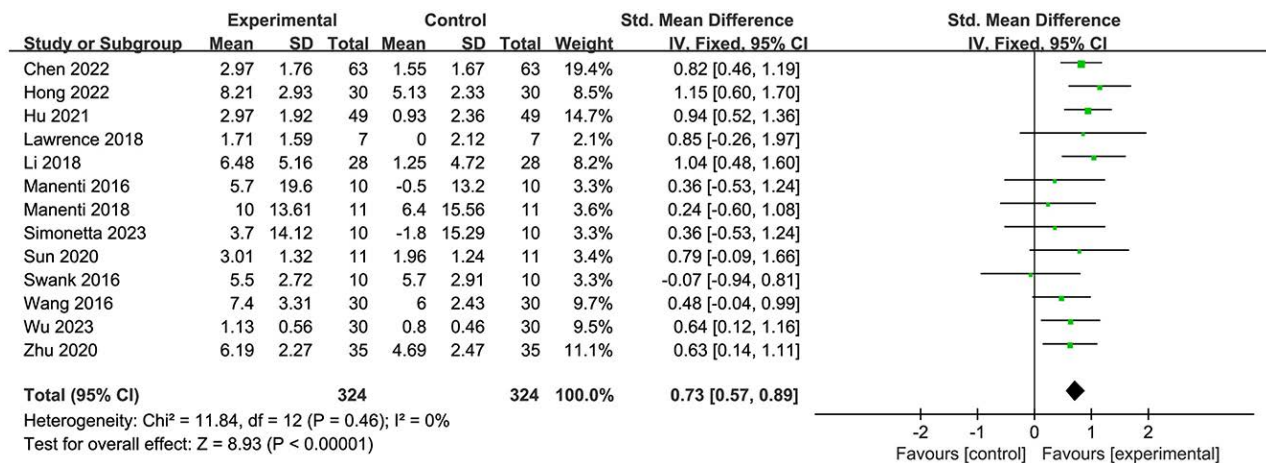


Fig. 3 tDCS effects on global cognitive function in PD [6].

Aside from cognitive deficits, many PD patients suffer from depression or apathy. The figure 4 focuses on depression outcomes from tDCS studies [6]. It pools four randomized trials that specifically measured changes in depression scales after tDCS vs sham. The combined result (diamond) shows a moderate antidepressant effect: the standardized mean difference is -0.46 favoring real tDCS. In other words, PD patients who received active tDCS reported significantly lower depression scores (improved mood) compared to those who received sham, with an effect size nearly half a standard deviation. Notably, all four studies used anodal tDCS over the left DLPFC (a common montage for treating depression in psychiatric research). The consistency across studies suggests a reliable effect of frontal tDCS on mood in PD. This is an encouraging

finding, as depression in PD is often undertreated and contributes greatly to reduced quality of life. Non-invasive stimulation offers a means to directly modulate cortical mood-regulating circuits. The meta-analysis did not find significant improvement in PD patients' quality of life (QoL) questionnaires from tDCS alone, likely because QoL is multifaceted and may require larger functional gains to change. However, by improving specific domains – cognitive performance, executive function, and depressive symptoms – tDCS could indirectly enhance overall well-being. It is also worth noting that tDCS is generally well-tolerated in these populations, with only minimal side effects (e.g. mild tingling at the electrode), which is important for any therapy targeting mood or cognition [8].

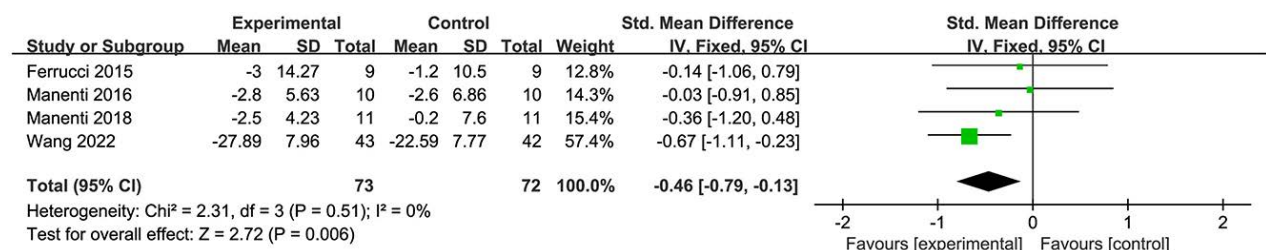


Fig. 4 tDCS effects on depressive mood in PD [6].

Overall, studies show that wearable tDCS can help with some non-motor symptoms of PD, especially thinking and mood problems. People with PD who use tDCS regularly often do better on tasks like memory exercises or word fluency and report better mood. These effects make sense because stimulating the DLPFC can boost activity and connections in the front part of the brain, which helps with thinking. It can also affect brain chemicals like dopamine and glutamate that play a role in both thinking and mood. For example, anodal tDCS over the left DLPFC can increase blood flow and brain activity in that area, linking to better planning skills. There is also evidence that tDCS

can improve how different parts of the brain work together, which may help with mental flexibility and apathy [7]. It is important to note that not all thinking skills respond equally to tDCS. Memory and attention improvements have varied. This may be because typical electrode placements do not target memory-specific brain areas, or because the tests used may not pick up small changes. Some studies that added mental exercises to tDCS found larger gains, suggesting that a combined approach may work better. Another research direction is using high-definition tDCS with more electrodes to focus on memory circuits; early results are still being studied. Still, tDCS gives mod-

erate to large improvements in overall thinking and planning, which is notable since no drug has clearly improved thinking in PD [6].

5. Limitations and Future Outlooks

5.1 Limitations

Wearable NIBS in PD holds promise but faces key limitations, chiefly modest clinical efficacy compared to invasive options like DBS. Effect sizes from non-invasive devices are often moderate or inconsistent: for example, tDCS produces statistically significant but limited benefits, and some meta-analyses fail to show significant impact [7]. These inconsistencies are due to heterogeneous study methods—varied targets, protocols, and small sample sizes—making it difficult to establish optimal treatment parameters. Patient differences further complicate results, and improvements are often transient, requiring frequent sessions and raising adherence concerns. Practical issues remain: advanced PD patients may find device setup challenging or experience skin irritation, and blinding is imperfect due to stimulation sensations. Safety is generally high but not absolute; adverse events such as skin burns or seizures, though rare, have occurred with improper use. Research currently focuses on symptom management, without evidence for altering disease progression, and most studies are short-term. Unknowns about long-term effects, dosing, habituation, and patient selection persist. In summary, wearable NIBS shows potential, but efficacy is limited and further robust data are needed before clinical impact rivals DBS [8].

5.2 Future Outlooks

Wearable brain stimulation for Parkinson's shows significant future promise, with key directions being personalized, adaptive neuromodulation and integration with complementary therapies. Future devices may tailor stimulation to patient characteristics or operate in real-time with closed-loop systems. Combination therapies and multi-modal approaches could amplify benefits, while improvements in device design may enhance usability. Regulatory approvals and insurance coverage could bring these devices into standard care [11]. Research is also beginning to explore possible disease-modifying effects of early, repeated neuromodulation. In summary, the next decade will likely bring smarter, more individualized wearable brain stimulation, with the potential to make non-invasive symptom management more effective and convenient for people with Parkinson's.

6. Conclusion

Wearable non-invasive brain stimulation systems offer a promising way to improve Parkinson's disease treatment without surgery. This review emphasized that tDCS, a portable neuromodulation technique, produces measurable benefits in PD: enhanced gait, balance, cognitive function, and reduced depressive symptoms. Numerous studies have shown that tDCS can safely modulate brain circuits in PD, resulting in faster mobility (such as quicker Timed-Up-and-Go) and improved executive function compared to sham stimulation. While improvements are moderate and optimization continues, these findings show that non-invasive stimulation can benefit both motor and non-motor aspects of PD. Combining wearable tDCS with rehabilitation brings greater functional gains, underscoring the devices' synergistic value.

The main takeaway is that wearable NIBS technologies could become pivotal adjuncts to conventional PD treatments. They provide a low-risk, user-friendly means to continuously engage and retrain neural pathways affected by Parkinson's, addressing gaps that medication and standard therapies may miss. This approach is significant for its accessibility—enabling patients at home to maintain mobility and mental sharpness through regular brain stimulation using a simple device. As larger trials confirm efficacy and future developments refine these systems, wearable brain stimulators (like tDCS headsets or vibrotactile cueing devices) may complement pharmacotherapy to personalize and enhance PD care. Harnessing non-invasive neurostimulation in a wearable format directly supports the broader goal of empowering patients with adaptive, at-home treatments that enhance quality of life. Ongoing research and innovation will shape the extent to which this vision becomes reality for those living with Parkinson's disease.

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