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Review

Exploring the Impact of Electroencephalography-Based Neurofeedback (EEG NFB) on Motor Deficits in Parkinson's Disease: A Targeted Literature Review

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Abstract: Parkinson's disease (PD) is a progressive neurodegenerative disorder, with pharmacological treatments predominantly focusing on dopaminergic therapies. In the early stages of PD, symptoms may also be alleviated through non-pharmacological interventions. One such non-invasive technique is electroencephalogram neurofeedback (EEG NFB), which has shown promising results in improving the cognitive and motor functions of PD patients. The aim of our study was to assess the existing evidence, identify key trends and determine potential opportunities for future research in the field of EEG NFB for PD. This analysis explores the impact of EEG NFB on motor deficits in PD and identifies key factors for the successful implementation of EEG NFB as evidenced in the literature. The synthesis includes findings from five relevant studies, including one case study, one pilot study and three randomized controlled trials. Study selection followed the PICO framework to ensure relevance and rigor. The results suggest a correlation between sensorimotor rhythm (SMR) and beta rhythms, with increases in SMR (13–15 Hz) and beta (12–15 Hz) rhythms linked to improvements in balance, mobility and stability in PD patients. However, limitations such as small sample sizes, brief intervention durations and lack of follow-up warrant a cautious interpretation. Future research should prioritize robust protocols, larger samples and extended neurofeedback training to fully assess EEG NFB's potential for PD management.

Keywords: Parkinson's disease; motor deficits; biofeedback; neurofeedback; electroencephalography

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1. Introduction

Parkinson's disease (PD) is a progressive neurodegenerative disorder that is primarily treated with pharmacological approaches targeting the dopaminergic system [1]. These treatments, such as levodopa [2,3] or dopamine receptor agonists [4,5], aim to alleviate motor symptoms and slow the progression of the disease. Although effective in the short term, their benefits often diminish over time, accompanied by side effects and limited efficacy in treating non-motor symptoms [2]. Advanced treatments such as intrajejunal levodopa infusion, deep brain stimulation or gene therapy are often reserved for later stages when oral medications lose their effectiveness [6].

In this context, non-pharmacological interventions are gaining increasing attention due to their potential to complement existing therapies. Neurofeedback (NFB), a non-invasive method developed over 60 years ago [7], is one such intervention. NFB provides real-time feedback on subconscious neural activity, enabling self-regulation through sensory

cues such as visual or auditory stimuli [8–12]. This method operates on the principles of instrumental conditioning, reinforcing desired neural activity patterns [13,14]. Over time, participants learn to regulate neural activity and apply these skills in everyday settings, resulting in cortical changes [9,10,15].

Various NFB methods have been developed, including the following:

Electroencephalographic Neurofeedback (EEG-NFB): Measures electrical brain activity via scalp electrodes [11].

Functional Magnetic Resonance Imaging Neurofeedback (fMRI-NFB): Detects changes in blood oxygenation and flow during brain activity, with high spatial resolution [16].

Deep Brain Stimulation Neurofeedback (DBS-NFB): Involves implanted electrodes that regulate excessive neural activity, often used with pharmacological treatments [17].

Functional Near-Infrared Spectroscopy Neurofeedback (fNIRS-NFB): Utilizes near-infrared light to assess brain hemodynamics, showing promise in conditions like ADHD and stroke recovery [18,19].

Magnetoencephalographic Neurofeedback (MEG-NFB): Measures magnetic fields from neural activity with high temporal and spatial resolution, beneficial in ADHD treatment [20,21].

While promising, the underlying mechanisms of NFB remain partially understood. Davelaar [22] proposed a multilevel computational model to describe its effects, comprising three phases. In the initial "exploration" phase", individuals test strategies—such as focused breathing or recalling positive memories—to alter, for example, EEG signals and receive positive feedback. In this phase, frontal–striatal connectivity is strengthened as participants identify effective strategies. In the subsequent "reinforcement" phase, these strategies are consolidated through instrumental learning, strengthening connections between the striatum and thalamus and stabilizing EEG patterns. Finally, in the "awareness" phase, participants develop an internal representation of the targeted brain state that enables them to maintain improvements without external feedback.

Given its potential to influence neural plasticity, NFB represents a promising avenue for treating motor deficits in PD. This review examines the role of EEG-based NFB in improving motor symptoms and addresses critical gaps in its application and efficacy in PD patients.

EEG Neurofeedback

EEG-NFB uses electroencephalography to detect neural activity through electrical signals generated by neurons [23]. These signals, captured by scalp electrodes, record synchronized activity from pyramidal neurons and classify brain waves based on frequency and amplitude [10]. Treatment protocols commonly target specific brain waves, such as alpha, beta, or theta, to achieve desired physiological effects (Table 1). During training, participants receive real-time feedback about their brain activity, enabling them to practice and modify their neural responses over time.

Table 1. An overview of neurofeedback training protocol. The table describes which NFB protocols are used to alleviate certain health problems (summarized from [10,11,24]).

Brain Waves	Frequency [Hz]	Training Protocols
Delta	1–4	Reduce pain, relieves headache, traumatic brain injuries, improve sleep.
Theta	4–8	For treatment of depression, anxiety and attention disorders.
Alpha/theta	7–8.5	To reduce stress, depression, addiction and anxiety.
Alpha	8–13	Relief pain, reduce stress and anxiety, improve memory and motor performance.
Low alpha	8–10	Relief stress and anxiety
High alpha	10–13	Deep relaxation, reduction of stress, sleep improvement, relief of symptoms of depression, increase attention and concentration.
SMR (sensorimotor rhythm)	13–15	Reduce anxiety, anger and fear.
Beta	15–20	To improve attention and concentration. Improve reading skills. In the treatment of anxiety, obsessive compulsive disorder, alcoholism and insomnia. Reduce fatigue and stress.
High beta	20–32	To treat anxiety and stress.
Gamma	32–100	To stimulate cognition, reducing the migraine attacks.

In recent years, the use of EEG NFB and the number of studies in this area have increased. Positive effects have been observed in alleviating sleep problems, often associated with anxiety and depression [25]. Improvements in sleep quality have also been reported in individuals with schizophrenia [26], where EEG NFB was shown to alleviate symptoms of varying degrees of schizophrenia, whereas medications are effective only in the initial stage. Additionally, EEG NFB has been effective in alleviating panic attacks that occurred during the COVID-19 pandemic [27] and has shown promising results in the treatment of depression [28] and attention disorders [29]. All these studies emphasize that therapy needs to be tailored to the individual, as a uniform approach does not work the same for all patients.

A study by Kopanska et al. [27]. demonstrated the durability of EEG NFB's effects with follow-up measurements conducted six months after the treatment. Participants reported sustained improvements in well-being, speech, muscle control and organizational abilities. All these studies conducted in recent years suggest that EEG NFB can be a very effective method in alleviating various health issues. Furthermore, the effectiveness and application of this method are also evident in the field of sports, for example, to improve the reaction time of judokas [30]. Participants in the experimental group showed a significant improvement in results compared to the control group, confirming the effectiveness of the method in different situations and among different participants.

2. Methods

This study investigates the impact of EEG NFB on improving motor deficits in patients with PD and identifies the key factors for successful implementation and broader adoption of this method.

To formulate research questions and establish inclusion and exclusion criteria, we utilized the PICO method [31,32].

Our main research questions were as follows:

1. Can EEG NFB influence motor deficits in patients with PD, and if so, how?
2. What key factors for the successful implementation and broader adoption of the EEG NFB method can be identified in the literature?

Based on existing evidence that suggests improvements in attention and concentration through EEG NFB, we hypothesize that improvements in motor symptoms of PD patients could also be observed, more specifically, enhancing movement (gait), tremor control and balance issues. We also anticipate identifying general brainwave patterns or regions that respond best to the applied method.

To address the research questions, we conducted a targeted literature review following the PRISMA-S strategy [33].

The inclusion criteria for study selection were developed using the PICO method:

P (Population): We included studies involving participants diagnosed with Parkinson's disease who used experimental EEG NFB to improve motor abilities. We included randomized control studies, clinical trials, pilot and sham-controlled studies, age-matched studies and case studies. We excluded studies that did not utilize the EEG NFB method or did not apply it to alleviate motor deficits. Additionally, studies not written in English or Slovenian, animal studies, unfinished studies and observational and narrative studies were excluded.

I (Intervention): We analyzed studies where the EEG NFB method was used to alleviate motor deficits in PD patients.

C (Comparison): In this targeted literature review, we compared studies that employed the EEG NFB method.

O (Outcome): We specifically analyzed tests that were used to assess motor abilities.

We retrieved studies published up to October 2023 from PubMed, Scopus, Web of Science and Europe PMC, as these databases provide open access to a wide range of research relevant to our interests. We included randomized control studies, clinical trials, pilot studies, sham-controlled studies, age-matched controlled studies and case studies. All included studies were peer-reviewed and written in English. Studies in foreign languages, those conducted on animals, observational studies and narrative studies were excluded. We also reviewed the reference lists of the retrieved studies for a broader literature overview. Participants in these studies, except for control groups, were individuals diagnosed with Parkinson's disease who had difficulty performing motor movements. A detailed overview of the study selection process is presented in the PRISMA-S flow diagram (see Figure 1). A more detailed search string is explained in Appendix A.

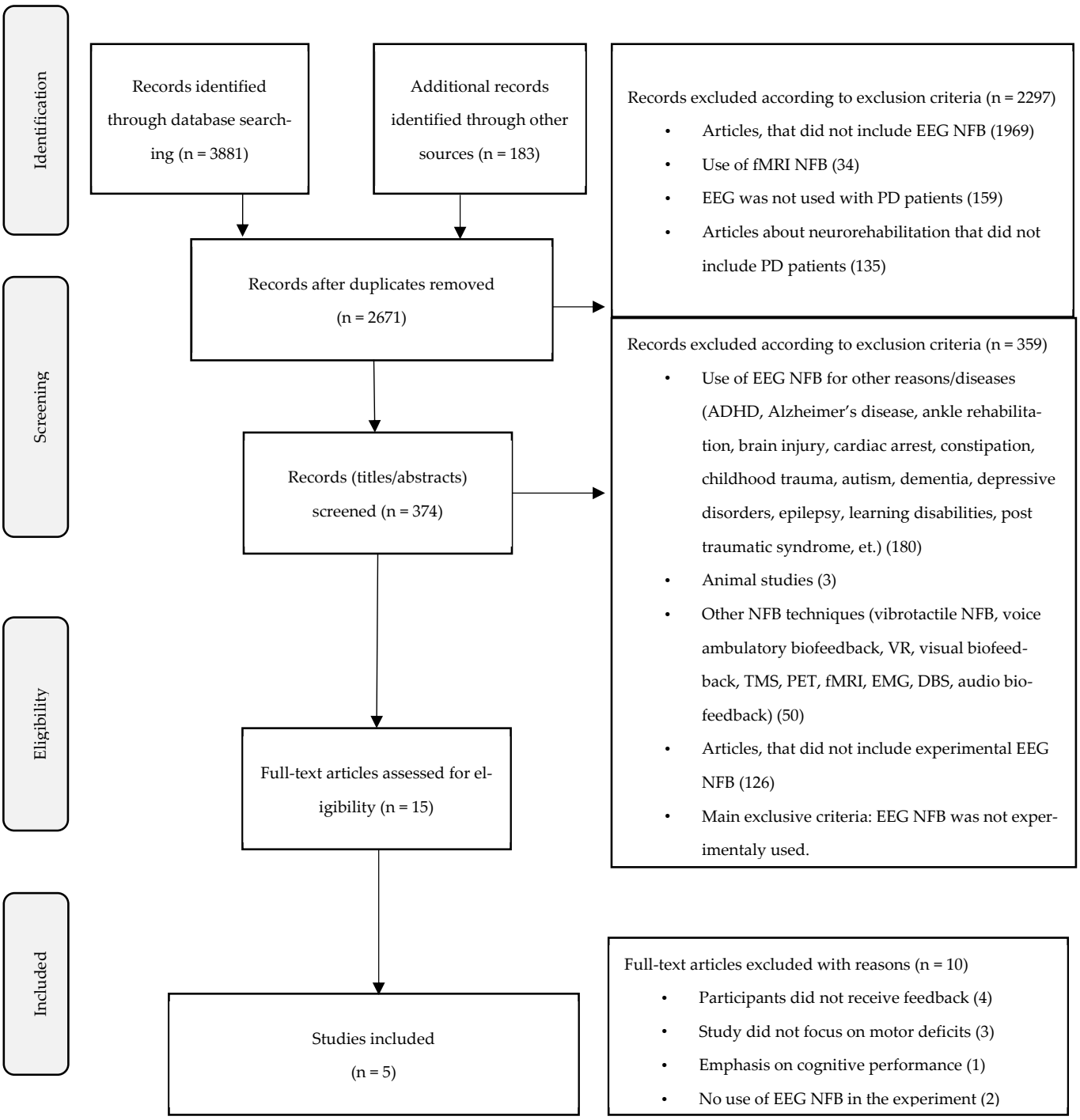

Figure 1. PRISMA—S flow diagram, which shows the entire literature collection process. The reason for exclusion and the number of studies that were excluded are also described.

3. Results

Five studies that met all our inclusion criteria were thoroughly reviewed and analyzed. The main findings of the studies are presented in Tables 2 and 3 in chronological order. Table 2 highlights the key results of individual studies, the design of the NFB method, descriptions of the EEG method, descriptions of control groups and the target frequency of the studies and their limitations. Table 3 provides a more detailed description of the type of NFB and the number of NFB training sessions. Descriptive results are provided below the tables.

Table 2. Key results and methodologies of reviewed studies.

Studies/ Criteria	Design, Population	EEG NFB Method and Control Group	Target Frequency	Measured Results	Results	Limitation
Thompson and Thompson (2002) [34]	Case study HY = ND N = 1 Avg. age = 47 100% F 10–20 system FCz—PCz	4+ month 42x 1 h; 1–2x/week ND	↑ SMR (13–15 Hz) + breathing exercises	Descriptive results	Reduction of uncontrollable movements, improvement of walking unaided, control of freezing of gait	Case study, descriptive results, double blind research
Erickson-Davis et al. (2012) [35]	RTC HY = ND N = 9 (4/5) Avg. age. = 55.83 55.56% F 10–20 system C3–C4	12–14 weeks; 24x 30 min NFB SHAM group	↑ 8–15 Hz; ↓ 4–8 Hz; ↓ 23–34 Hz	AIMS, PD home diary, qEEG, HY, UPDRS	AIMS, UPDRS, HY—nonsignificant results; Significant results in qEEG measurements in spectral EEG topography	Age differences, small sample size, small dyskinesia difference between experimental and control groups.
Azarpaikan et al. (2014) [8]	RTC HY = 1.5–2 N = 16 (8/8) Avg. age. = 74.7 50% F 10–20 system O1–O2	2.5 weeks 3x/week 30 min SHAM and control group	↑ beta1 (12–15 Hz); ↓ theta (4–7 Hz)	Biodex test (level 8), BBS	Biodex, BBS—statistically significant results	No long-term follow-up of the participants; PB with more severe disease stage according to the HY scale.
Cook et al. (2021) [36]	Pilot study HY = 2 N = 2 (1/1) Avg. age = middle 50 NP% F 256-channel system C3–C4	2 consecutive days 2x NFB 1 h ND	SMR (12–17 Hz)	UPDRS-III	UPDRS-III mixed results, second day improvement in rigidity and walking.	No long-term follow-up of the participants; a small number of participants, a small number of NFB.
Shi et al. (2023) [37]	RTC HY = 2–3 N = 21 (7/7/7) Avg. age = 61.72 76.19% F ND C3–C4	2 weeks 5x NFB; 13 min SHAM group	SMR (13–15 Hz) + breathing exercises	UPDRS II, UPDRS III, BBS, TUG, HRSD	EEG training ↑ BBS; ↓ TUG; beta regulation (enhancement); Multimodal group: ↑ depression, theta regulation	Gender differences, no long-term follow-up of participants.

Note: HY—Hoehn–Yahr scale, ND—no data, N—number of participants, avg. age. = age average of the participants, RTC—randomized control study, SHAM—SHAM control group, EEG NFB—electroencephalograph based neurofeedback, SMR—sensorimotor rhythm, UPDRS—MDS Unified Parkinson's Disease Rating Scale, BBS—Berg balance scale, TUG—Timed up and go test, AIMS—Modified abnormal involuntary movement scale, HRSD—Hamilton depression scale, Biodex test—center of gravity control test, ↑—increase, ↓—decrease.

Table 3. Comparison of neurofeedback types and training sessions.

		Study	Thompson and Thompson (2002) [34]	Erickson-Davis et al. (2012) [35]	Azarpaikan et al. (2014) [8]	Cook et al. (2021) [36]	Shi et al. (2023) [37]
Intervention	Type of NFB	Form of neurofeedback	EEG NFB	EEG NFB	EEG NFB	EEG NFB	EEG NFB
		Form of feedback	Video and audio	Audio	Game stopped	Color chart and points	Color column and reward points
		Electrode placement	10–20 system, FCz-CPz	10–20 system, C3–C4	10–20 system, O1–O2	256-channel EEG, C3–C4	C3–C4
		Target frequency	SMR (13–15 Hz) + breathing exercise	↑ 8–15 Hz, ↓ 4–8 Hz in 23–34 Hz	↑ beta 1 (12–15 Hz), ↓ theta (4–7 Hz)	SMR (12–17 Hz)	SMR (13–15 Hz) + breathing exercise
	Number of NFB trainings	Duration	6 months	12–15 weeks	2.5 weeks	2 days	2 weeks
		Number of NFB	30	24	8	2	5
		With medicine	YES	ND	YES	YES	YES
		Without medicine	NO	ND	NO	YES	NO
		Duration of NFB	1 h	30 min	30 min	1 h	13 min

Note: ND—no data, EEG NFB—electroencephalograph based neurofeedback, SMR—sensorimotor rhythm, ↑—increase, ↓—decrease.

Thompson and Thompson (2002) [34] presented one of the first studies on the use of EEG biofeedback for movement disorders, specifically in a patient with dystonia and Parkinson's disease. Their six-month case study involved a 47-year-old woman who completed 30 one-hour NFT sessions, aiming to increase sensorimotor rhythm (SMR, 13–15 Hz) activity and practice diaphragmatic breathing. Motor improvements were observed after 12 sessions, with control over freezing episodes restored by the end of training. Erickson-Davis et al. (2012) [35] conducted a pilot study assessing the efficacy of NFT for dyskinesia induced by levodopa in PD patients. Nine participants underwent 24 half-hour sessions targeting increased alpha and low-beta activity (8–15 Hz) and reduced theta (4–8 Hz) and high-beta (23–34 Hz) activity. Although there were no statistically significant changes in motor symptoms (AIMS, UPDRS), quantitative EEG (qEEG) analysis revealed a decrease in high-beta power and an increase in alpha power post-training. Azarpaikan et al. (2014) [8] explored the effects of NFT on balance in 16 PD patients, with an average age of 74.23 years in the experimental group. They were assessed for static and dynamic balance before NFT. Participants sat in front of a computer screen while playing video games designed to increase beta1 (12–15 Hz) and reduce theta (4–7 Hz) activity. After eight 30 min sessions over 2.5 weeks, the experimental group showed significant improvement in both static and dynamic balance tests (Biodex, BBS). The control group received random feedback but showed no significant changes. Cook et al. (2021) [36] conducted a single-case feasibility study targeting SMR (12–17 Hz) in a PD patient in the 50s. He underwent NFT both with and without medication. The patient completed NFT over two days, and his motor skills were assessed with the UPDRS-III scale. Although the patient's ability to regulate SMR improved during training, the results on the UPDRS-III were statistically insignificant, though there were improvements in rigidity and walking by the second day. Lastly, Shi

et al. (2023) [37] explored the effects of multimodal biofeedback on motor and nonmotor symptoms in PD patients. This study involved 21 participants, divided into three groups: a multimodal (MM) experimental group (feedback from EEG, electrocardiogram (ECG), photoplethysmogram (PPG) and respiratory feedback (RSP)), an EEG-only experimental group and an SHAM control group. Each participant completed five training sessions over 14 days, assessing motor and nonmotor symptoms with various scales (UPDRS II, III; BBS; TUG; HRSD). The results showed that the EEG group showed significant improvement in motor symptoms, while the MM group showed significant improvement in nonmotor symptoms.

4. Discussion

The analysis of selected studies provides insights into the impact of EEG NFB on motor deficits in PD, addressing both of our research questions.

First, as to whether EEG NFB can affect motor deficits in PD, the findings suggest that EEG NFB can indeed improve balance, coordination and mobility in individuals with PD. Although the long-term effects are still unclear, there is evidence that EEG NFB can improve quality of life, particularly in the early stages of the disease. This is consistent with the observed correlation between increasing SMR (13–15 Hz) and beta (12–15 Hz) rhythms and improvements in balance, mobility and stability, as indicated by motor performance tests.

- **Improvement in balance:** Two of the selected studies aimed to improve balance issues using EEG NFB. This was tested using the Berg Balance Scale and the Biodex Test. In the randomized controlled trials by Azarpaikan et al. [8] and Shi et al. [37], statistically significant improvements in balance were observed. Descriptive results of improved balance were also reported by Thompson and Thompson in their case study.
- **Improvement in mobility and stability:** The same studies also used scales to assess progress in mobility and stability. Both the TUG test and the Biodex test showed statistically significant improvements in the results measured after EEG NFB in PD patients. A case study also demonstrated improvements in mobility and stability through descriptive results.

The selected studies varied in design, including case studies, pilot studies and randomized controlled trials, each offering distinct levels of reliability and generalizability The study by Thompson and Thompson [34] was a case study, while Cook et al. [36] conducted a pilot study. The remaining three studies by Erickson-Davis et al. [35], Azarpaikan et al. [8] and Shi et al. [37] were randomized controlled trials. While case studies provide detailed individual outcomes, their results are descriptive and not easily replicable. In contrast, RCTs provide higher scientific reliability but still face challenges such as limited sample sizes.

Variability was also evident in the rating scales used across studies and on increasing frequencies. Three of the five studies assessed the general motor abilities of PD patients using the UPDRS-III scale, but, contrary to expectations, the results did not indicate an improvement in motor abilities. This suggests that this scale may not detect minor progress in a short period, as it is designed to assess a broader range of motor symptoms, potentially reducing sensitivity.

Studies that focused on increasing beta frequency showed promising results in improving coordination and balance, similar to those directed at SMR frequencies. Similarly, alterations in beta–gamma phase–amplitude coupling have been identified as potential biomarkers for motor symptom severity and monitoring therapeutic outcomes in PD patients (for the review please see Hodnik et al. [38]). On the other hand, a decrease in theta frequencies in one of the two studies led to a deterioration in general well-being.

Secondly, when asked which key factors are crucial for the successful implementation and wider application of EEG NFB, several important considerations can be found in the literature. Questions remain about the optimal protocols, such as the targeted frequencies, the duration of therapy, the form of feedback and the most effective NFB methods, which makes comparison between different studies difficult. It is emphasized that an individualized approach is needed, although clear guidelines for personalized protocols are still lacking. Although the long-term efficacy is still uncertain, there is a growing consensus that combining EEG NFB with other therapeutic approaches, such as physiotherapy or pharmacological treatments, may increase its potential. These factors—such as the standardization of protocols, the individualization of treatment plans and the integration of EEG NFB into multidisciplinary treatment regimens—are essential for a broader acceptance and successful implementation of EEG NFB in clinical practice.

5. Study Limitations

One of the main challenges in studies on EEG NFB focused on motor deficits in people with PD is the small sample size of participants and the lack of long-term follow-up, making it difficult to assess the method's sustainable effectiveness. Additionally, most participants had a low disease stage according to the Hoehn–Yahr scale [39], limiting the generalization of findings to patients in later stages of the disease. Inconsistencies in intervention protocols, measurement tools and data reporting further restricted the comparability of results, underscoring the need for standardized study designs. Age and gender imbalances among participants and unclear descriptions of medication use also made it difficult to interpret the results. Another major problem is that, due to our specific inclusion criteria, we could only analyze five studies published before October 2023. Due to the small number of studies, this review should be considered preliminary and point to an even greater need for studies on this topic.

6. Advantages and Limitations of EEG NFB

EEG NFB is a non-invasive and painless method that does not require medication or surgery. Although the mechanism underlying neurofeedback training protocol is still not fully understood, the research indicates potential benefits, including improved attention, concentration, sleep quality, reduced anxiety and headaches [40]. It shows positive outcomes in conditions such as autism spectrum disorders, attention deficit hyperactivity disorder (ADHD) and other mental health disorders [18–21,41]. Despite these promising results, NFB has limitations. Key issues include insufficient data on long-term effects and whether learned positive behavioral patterns transfer to other behaviors [40]. Some studies suggest that positive effects may last up to 12 months for ADHD, but more research is needed to confirm these findings and understand their applicability to different NFB forms [40]. Furthermore, there is a lack of studies on behavioral patterns outside controlled settings and uncertainties about why NFB benefits are inconsistent across participants, possibly related to brain structure, putamen size and trust in the technology [40]. Additionally, the absence of control groups complicates distinguishing genuine effects from placebo responses. One of the main limitations is that not everyone is suitable for EEG NFB. For example, people with severe cognitive impairment cannot participate.

Potential side effects of NFB include headaches, fatigue, nausea, dizziness, insomnia, agitation or anxiety [9].

7. Practical Implications and Future Development of the Method

In exploring NFB, we discovered several knowledge gaps crucial for the future development of this therapy. An accurate and precise understanding of its mechanisms of

action remains limited. Questions remain regarding optimal protocols, including target frequencies, therapy duration, feedback form and the most effective neurofeedback methods, complicating cross-study comparisons. The need for an individualized approach is emphasized, though clear guidelines for personalized protocols are still lacking. Long-term effectiveness and combining neurofeedback with other therapeutic approaches require further exploration. Machine learning algorithms could enhance personalized EEG NFB protocols by identifying optimal frequencies for specific symptoms. Integrating virtual reality (VR) or augmented reality (AR) technologies could offer immersive, real-life training scenarios, making neurofeedback therapies more accessible and engaging. For successful clinical integration, proper training for healthcare professionals will be essential.

8. Conclusions

Based on a targeted review of EEG NFB studies that focused on motor deficits in patients with PD, we found evidence supporting its potential to alleviate motor symptoms in PD patients, particularly in improving balance and stability. However, the observed progress was often too subtle to be detected as statistically significant by traditional assessment scales, highlighting the need for more sensitive evaluation tools. Future EEG NFB research should focus on specific symptoms to produce more pronounced results and facilitate the development of optimized treatment protocols.

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Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

The keywords for database searching were neurofeedback and Parkinson disease, biofeedback and Parkinson disease, neuro feedback and Parkinson disease, EEG biofeedback and Parkinson disease, brainwave training and Parkinson disease, qEEG and Parkinson disease, neuro feedback therapy and Parkinson disease, neurofeedback therapy and Parkinson disease and neurorehabilitation and Parkinson disease. With those keywords and inclusion criteria, we obtained 302 articles from PubMed, 608 from Scopus, 762 from Web of Science and 2209 from Europe PMC. After that, the doubles were excluded.

Table A1. Overview of the number of studies found during the searches, including the inclusion criteria—clinical studies, randomized control studies, studies in English or Slovenian, studies conducted on humans and final studies. For further search of studies, we used studies that included at least one of the criteria. Using the inclusion criteria, we obtained 3881 articles from four different bata bases. Duplicate articles have not yet been removed. The keyword "PD" was written in its full form—Parkinson disease.

Search String/ Databases	Neurofeedback and PD	Biofeedback and PD	Neuro Feedback and PD	EEG Biofeedback and PD	Brainwave Training and PD	qEEG and PD	Neuro Feedback Therapy and PD	Neurofeedback Therapy and PD	Neurorehabilitaion and PD	∑
PubMed	7	30	27	7	5	1	23	7	195	302
Scopus	63	94	17	5	1	52	2	22	352	608
Web of Science	23	53	24	2	1	313	4	4	338	762
Europe PMC	94	262	615	42	9	64	294	44	785	2209
∑	187	439	683	56	16	430	323	77	1670	

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