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Neurofeedback for motor networks: A comparative systematic review of fMRI, fNIRS, and EEG protocols, neural mechanisms, and functional transfer

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Abstract

Introduction: Neurofeedback (NF) enables volitional modulation of neural activity, yet the comparative clinical utility of electroencephalography (EEG)-, functional Magnetic Resonance Imaging (fMRI)-, and functional Near-Infrared Spectroscopy (fNIRS)-based NF for motor rehabilitation remains uncertain.

Materials and Methods: We systematically searched MEDLINE, Scopus, Embase, Web of Science, and PsycINFO (2010-2025) for studies pairing NF with motor-system targets, using combinations of "neurofeedback", imaging modality, and "motor cortex". Forty-six studies met the inclusion criteria (22 fMRI-NF, 17 EEG-NF, 7 fNIRS-NF).

Results: All three modalities up-regulated activity in primary motor, premotor, and supplementary motor areas, demonstrating short-term neuroplasticity. Sustained behavioral gains, however, appeared chiefly in multi-session EEG-NF and fNIRS-NF protocols, whereas most single-session fMRI-NF studies showed limited functional transfer. The evidence base is constrained by small samples, heterogeneous outcomes, and frequent absence of sham controls.

Conclusion: Robust, multi-arm trials with larger cohorts, extended follow-up, and rigorously blinded comparators are needed to clarify dose-response relationships and optimize NF protocols for motor rehabilitation.

Keywords: Electroencephalography, Functional magnetic resonance imaging, Functional near-infrared spectroscopy, Motor cortex, Neurofeedback

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Introduction

Movement disorders such as stroke, Parkinson's disease, and other conditions affecting the sensorimotor system remain a leading cause of long-term disability, and a substantial proportion of patients are left with

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persistent motor impairment even after standard rehabilitation (1). Conventional interventions - physical and occupational therapy, pharmacological management, and, where indicated, surgical or device-based approaches - can improve function, but their benefits frequently plateau despite prolonged, intensive treatment, and full recovery of motor function is uncommon. This gap between clinical need and the limited efficacy of existing interventions has motivated growing interest in approaches that act directly on the neural circuits underlying movement, rather than solely on its peripheral expression.

Neurofeedback (NF) is a form of operant conditioning in which individuals learn to self-regulate specific features of their brain activity by receiving real-time physiological feedback (2). The feedback, delivered through auditory, tactile, or visual channels, indicates the extent to which the participant is succeeding in modulating a predefined neural signal, most often derived from Electroencephalography (EEG), functional Magnetic Resonance Imaging (fMRI), or functional Near-InfraRed Spectroscopy (fNIRS) (3). Because it allows direct, non-invasive modulation of activity within motor and sensorimotor networks, NF has emerged as a candidate strategy for rehabilitation after stroke and other movement disorders, in addition to its more established use for symptoms of neurological and psychiatric conditions such as attention-deficit/hyperactivity disorder and epilepsy (4). Its outcomes, however, are variable and are influenced by non-specific factors such as attention, motivation, and mood, which are difficult to standardize across sessions. Recent methodological advances aim to reduce this variability, including the integration of NF with high-resolution imaging, the use of comprehensive behavioral test batteries, longer follow-up, and stricter inclusion and exclusion criteria (5,6).

The three modalities most commonly used to implement NF for motor rehabilitation differ substantially in what they offer and what they cost. In EEG-based NF (EEG-NF), the ongoing electroencephalographic signal is analyzed in real time and fed back to the participant; most protocols reinforce changes in band-limited power or amplitude, although other features such as peak frequency, inter-site coherence, or phase synchrony can also serve as training targets (7). EEG-NF is inexpensive, portable, and temporally precise, but it offers limited spatial specificity for deep or small cortical targets. fMRI-based NF (fMRI-NF) instead offers millimeter-scale spatial resolution, allowing a region of interest, or the functional connectivity between regions, to be defined a priori and fed back to the participant as a dynamic display (8,9); this precision, however, comes with high cost, limited accessibility, and logistical demands that constrain both session number and setting. fNIRS-based NF (fNIRS-NF) uses cortical hemodynamics as an indirect measure of brain activation (10,11) and occupies an intermediate position: better spatial resolution and motion tolerance than EEG, and substantially lower cost and greater portability than fMRI, at the expense of reduced depth sensitivity and spatial precision relative to fMRI. Because no single modality is uniformly superior across cost, portability, spatial resolution, and temporal resolution, a direct comparison of their efficacy for motor rehabilitation is needed.

Brain areas involved in movement

Studies in humans and non-human primates show that skilled motor behavior depends on a distributed cortico-subcortical network that spans the pre-Supplementary Motor Area (pre-SMA), SMA, dorsal Premotor Cortex (dPM), primary motor cortex (M1), primary somatosensory cortex, superior parietal lobule, thalamus, basal ganglia, and cerebellum (12). The Posterior Parietal Cortex (PPC), together with its interconnected frontal regions, plays a pivotal role in sensorimotor transformations, supporting motor planning, action selection, forward state estimation, and the encoding of spatial information in relative coordinates (13). These sensorimotor transformations provide scaffolds for preparatory motor activity. Classic single-unit recordings in macaques trained to push a lever after a warning cue showed a ramp-up of firing in M1 during the delay period, well before movement onset (14). Sequential movement preparation depends on the supplementary motor complex: the pre-SMA is strongly recruited while a new sequence is being learned, whereas the SMA proper predominates once the sequence is executed from memory (12). Anatomical tracing reinforces this functional split as SMA projects directly to M1 and the spinal cord, whereas pre-SMA connects mainly with prefrontal cortex. These connections are consistent with a division between motor implementation and

higher-order sequence selection (15). Preparatory activity is not confined to the SMA complex. Arm- and eye-movement studies reveal parallel engagement of the dPM, Frontal Eye Fields (FEF), superior colliculus, and interconnected thalamic nuclei (16). Disrupting right dPM with transcranial magnetic stimulation selectively impairs on-line trajectory adjustments, underscoring its role in dynamic action control (17). Complementary evidence from intracortical microsimulation in humans and optogenetic silencing in rodents shows that the premotor cortex orchestrates planning, whereas M1 governs execution (18). Together, these findings illustrate that each node in the motor network makes a distinct yet cooperative contribution to skilled movement. Precisely how these areas interact over time and in what sequence remains an important question for future work.

Prior systematic reviews have each examined NF within a single modality or a single clinical context - for example, EEG-based protocols across disorders (7), the reporting and effects of fMRI-NF in clinical populations (9), or NF specifically for post-stroke motor rehabilitation (1) - but none has directly compared EEG-, fMRI-, and fNIRS-based NF for motor-system targets within a single synthesis.

Even the most recent contributions remain confined to a single modality or a single trial: a systematic review and meta-analysis of EEG-NF for Parkinsonian motor symptoms (19), a systematic review and meta-analysis of EEG-NF for motor performance (20), a randomized trial of combined EEG-fMRI NF for post-stroke upper-limb recovery (21), and a study of fNIRS-guided NF for supplementary motor area training in Parkinson's disease (22). Emerging multimodal-fusion approaches that combine EEG with fMRI (23,24) or with fNIRS (25) likewise aim to merge signals from two modalities within a single system, rather than to compare EEG-, fMRI-, and fNIRS-based NF as distinct, interchangeable clinical options. Consequently, it remains unclear which modality yields the most robust and durable clinical effects on motor function, whether efficacy depends on the neural network engaged, and how the relative strengths and limitations of each technique should guide modality selection in a given clinical setting.

In this review we address this gap by evaluating how neurofeedback modulates the neural circuits underlying movement, comparing the three most widely used modalities - fMRI-, fNIRS-, and EEG-based neurofeedback - to determine which yields the most robust and durable gains in motor performance.

Materials and Methods

Search strategy

On 1st October 2025 we systematically searched MEDLINE (Ovid), Embase (Ovid), Scopus, Web of Science, and PsycINFO for papers published from 1 January 2010 to 1st October 2025. In each database we queried the abstract field (syntax adapted as required) with three concept blocks: 1. “neurofeedback” AND “EEG” AND “motor cortex”, 2. “neurofeedback” AND “fNIRS” AND “motor cortex”, and 3. “neurofeedback” AND “fMRI” AND “motor cortex”. The blocks were combined with the Boolean operator “OR” to maximize retrieval. All search outputs were exported to Zotero for de-duplication and subsequent screening.

Inclusion

1. Population: Human participants of any age, either healthy or with clinical diagnoses.
2. Intervention: Real-time neurofeedback delivered via EEG, fNIRS, or fMRI with the explicit goal of modulating motor-system activity.
3. Outcomes: At least one neural or behavioral measure of motor function (e.g., regional brain activity, connectivity or clinical motor scores).
4. Study design: Peer-reviewed original research employing randomized, non-randomized, or single-arm designs.
5. Language: Published in English.

Exclusion

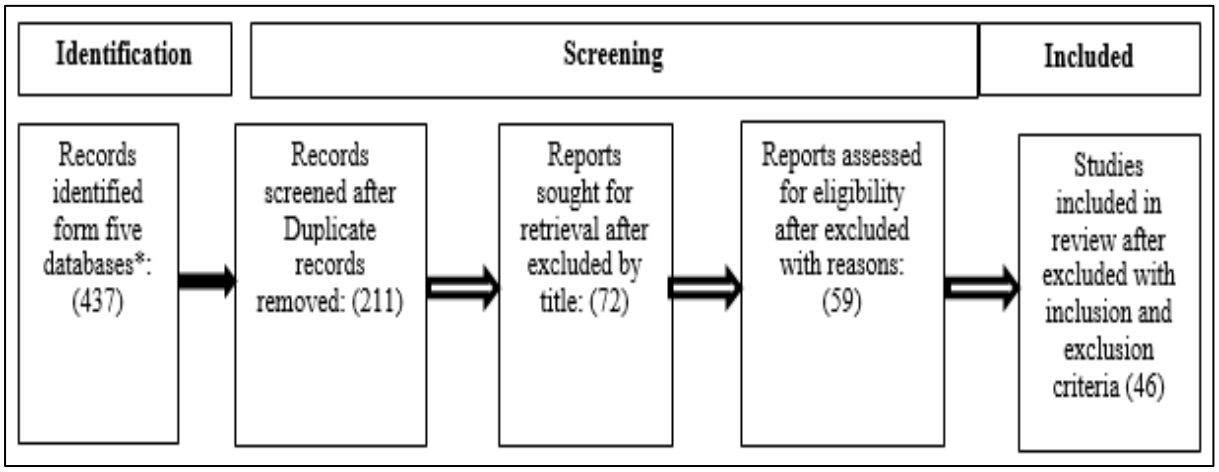
We excluded review articles, editorials, conference abstracts, case reports, animal studies, and investigations that used simultaneous EEG-fMRI neurofeedback, the latter to allow a clearer modality-specific comparison.

Data extraction

Two reviewers independently populated a piloted spreadsheet with the following items: publication year, country, participant characteristics, neurofeedback modality, session parameters, targeted brain region, control condition, follow-up duration, primary and secondary outcomes, and main findings. Any discrepancies were resolved by discussion until consensus was reached (Fathi. M, Poormohammad. A).

Results

Database searching identified 437 records: MEDLINE (n= 207), Scopus (n= 98), Embase (n= 62), Web of Science (n= 51) and PsycINFO (n= 19). After automated and manual de-duplication, 211 unique records remained and were screened by title and abstract. One hundred thirty-nine records were excluded because they did not employ real-time neurofeedback or the targeted brain regions were unrelated to motor function. Seventy-two full texts were sought; 13 could not be retrieved and another 13 failed the eligibility criteria at full-text review, yielding 46 studies for qualitative synthesis. The PRISMA 2020 flow diagram summarizes this selection process (Figure 1, Appendix A).



Note: the Klein et al. (22) row was added post hoc as a directly relevant recent study; it was published in 2026, after the original 2010-2025 search window, and is included here as a notable update rather than a result of the original systematic search

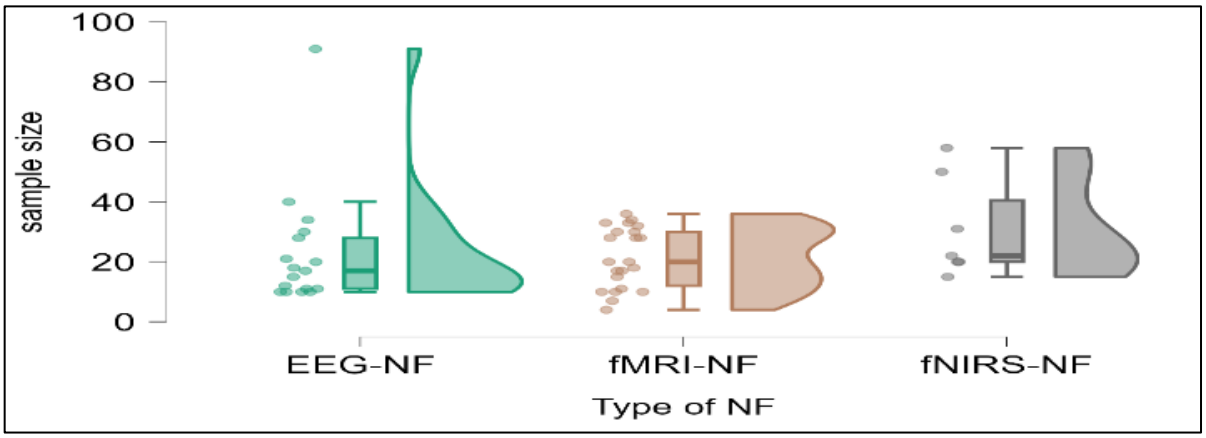


Figure 1. Flow diagram of the selection process used in this study, based on the Prisma guidelines.
***** Medline (207), Scopus (98), Embase (62), Web of Science (51), and PsycINFO (19) databases

The data extraction results are summarized in Table 2 (23 fMRI-NF studies) and Table 3 (25 studies: 8 fNIRS-NF, 17 EEG-NF), presented in full on separate pages at the end of the manuscript.

Across the 46 included studies, 22 used fMRI-NF, 17 EEG-NF and 7 fNIRS-NF. Among the fMRI trials, 17 recruited healthy adults, two addressed Parkinson's disease, and one each targeted stroke, Huntington's disease and autism. Although field strength (1.5 T-7 T) and real-time processing pipelines differed widely, most groups relied on low-motion paradigms like finger tapping or kinesthetic motor imagery to minimize movement artefact. Only three fMRI studies enrolled older adults (26-28), limiting age-related generalizability. Dosing was also sparse: 20 of the 22 fMRI studies delivered≤ 5 sessions (typically one or two), whereas the two provided≥ 6 sessions (29,30). target regions clustered in M1, SMA, dPM and broader sensorimotor cortex, areas with robust, easily localized BOLD responses. Collectively, the fMRI-NF literature shows that rapid neural modulation of motor circuits is feasible, but heterogeneity in methodology, modest session

doses and an adult-centered evidence base constrain the strength and generalizability of current findings. Seven studies employed fNIRS-NF: one enrolled stroke survivors (31), and the remaining six investigated healthy adults. Most tasks were imagery or motor tasks to elicit corresponding motor area in contralateral area activity. Only the stroke study included older adults; the others examined younger cohorts. Session dose exceeded that of most fMRI-NF work; two trials delivered eight sessions, two delivered six, one provided two and two offered a single session, reflecting the greater portability and lower set-up demands of fNIRS. Four studies targeted classical motor regions (M1, SMA or premotor cortex), two trained DLPFC, and one focused on the parietal cortex.

Among the EEG-NF studies, 11 recruited healthy participants and 6 enrolled patients with stroke. Training almost invariably targeted primary motor or premotor cortex, using hand-movement tasks or kinesthetic motor imagery, paradigms chosen to enhance upper-limb function in both healthy volunteers and stroke survivors. Four trials involved older adults, whereas the remainder focused on younger cohorts. Session dose was highly variable: six studies delivered more than five sessions, whereas four provided only a single session. Figure 2 plots sample size against session count for all three NF modalities. Finally, 14 of the 46 included studies satisfied two key quality criteria, a sample size equal or more than 30 and the presence of a sham or active control arm, marking them as the most methodologically robust and warranting detailed discussion (32,33).

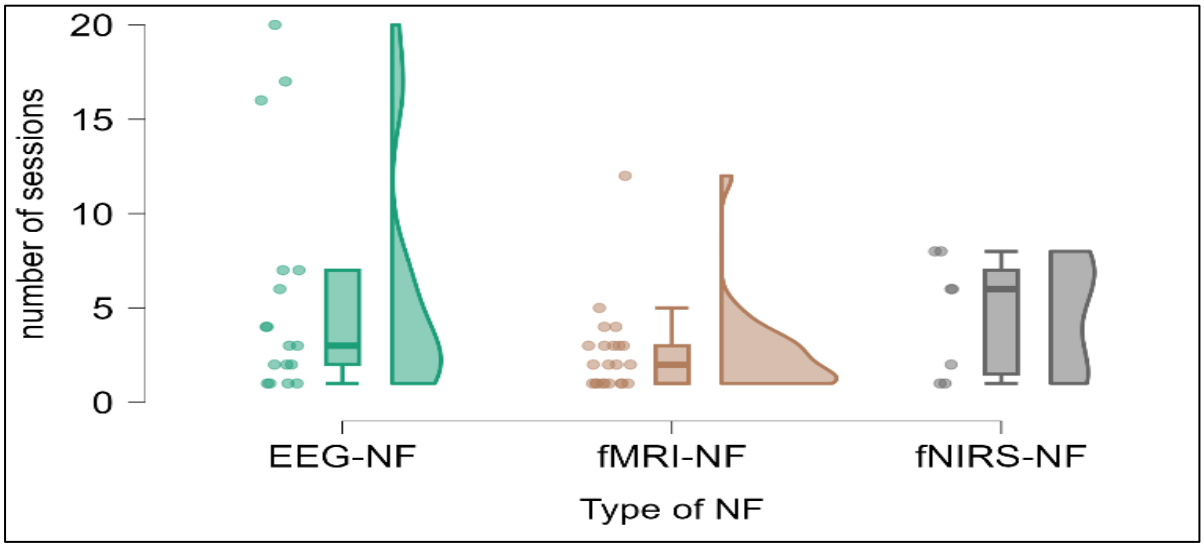


Figure 2. Sample size and number of sessions across the three neurofeedback modalities investigated in this study

Table 1. Appendix A. Revised PRISMA 2020 flow diagram wording

PRISMA 2020 label	Count
Records identified from: databases (Medline, Scopus, Embase, Web of Science, PsycINFO)	n= 437
Records after duplicates removed	n= 211
Records screened	n= 211
Records excluded	n= 139
Reports sought for retrieval	n= 72
Reports not retrieved	n= 13
Reports assessed for eligibility	n= 59
Reports excluded, with reasons	n= 13
Studies included in qualitative synthesis	n= 46

Table 2. Summary of some data extracted from articles about fMRI-NF

Year/ Author	Participants/ Number, (male or female, mean years old)	type of NF/ protocols	Target networks	Key findings
2011, Subramaniam, et al. (26)	10 people with PD (6 M / 4 F; 39-75 y, mean ≈ 63.7 y) Randomized to 5 EG (feedback) / 5 CG (sham)	fMRI-NF/ using left-hand Mi. 2 sessions (each: SMA localizer + 2 NF runs) separated by 2-6 months; daily home imagery practice between sessions; CG received no contingent feedback	SMA, downstream activation observed in STN, GPi, thalamus, and cerebellum	EG learned to up-regulate SMA to the same level as overt movement; this co-activated STN and GPi. After 2 months, EG showed 37 % improvement on UPDRS-III and faster finger-tapping, while CG showed no SMA control or clinical change
2012, Berman et al. (41)	15 healthy adults (7 M / 8 F; mean 29.7 ± 7.9 y; all right-handed)	fMRI-NF/ training of overt right-hand finger-tapping and hand-Mi tasks. 1 single scanner session was done.	M1, NF also engaged premotor, parietal, thalamic and visuomotor attention regions	All participants learned to up-regulate M1 during finger-tapping NF, independent of tap amplitude; however, no significant M1 modulation occurred during Mi despite robust activation of the classic imagery network. Results imply M1 output is tightly coupled with overt movement.
2012, Mark Chiew, et al. (42)	18 healthy, 13 EG (7 M / 6 F, 27 ± 3 y) vs 5 CG (2 M / 3 f; 24 ± 3 y)	Single fMRI-NF/ 4 sequential hand imagery NF training runs, each separated by 1–2 min of rest. Each run consisted of 12 NF trials. Each trial lasted 45 s.	M1, downstream engagement of premotor, SMA, BG, thalamus, and parietal areas.	Just 6 of the 13 trainees managed to raise the laterality index, mostly by dialing down activity in the motor cortex on the same side instead of boosting the opposite side. They also activated attention-related areas more strongly, whereas the rest looked like the sham group. Reaction times didn't improve,
2014, Hui, et al. (43)	28 healthy, right-hand-dominant adults, 15 EG (6 M, 22 ± 1.6 y) vs 13 CG (8 M, 23 ± 1.7 y)	Single fMRI-NF/ training of right dorsal PMA during kinesthetic hand-grasp imagery. It contained 4 feedback runs, each 7.5 minutes long.	Dorsal PMA with network analysis of left PPL, M1/S1 and cerebellum	A single session let healthy adults raise right-dorsal PMA activity and tap 20 % faster. Larger dorsal PMA boosts paired with weaker PMA-parietal coupling during motor imagery, while faster taps aligned with stronger cerebellum - motor-cortex links
2015, Marins, et al. (44)	28 healthy adults;14 NF (9 F / 5 M, 27 ± 4.7 y) vs 14 CG (9 F / 5 M, 27 ± 6.4 y)	Single fMRI-NF/ training of left PMA during kinesthetic right-hand finger-tapping imagery. 3 × 48-s MI feedback runs after a ME baseline	SMA, bilateral PMA, BG, cerebellum	NF group progressively up-regulated left PMA. Final run showed broader co-activation of SMA, ipsilateral PMA, BG & cerebellum and a 3-fold greater overlap between imagery and execution maps. Results supported the rehabilitative potential of fMRI-NF.
2015, Megumi, et al. (38)	33 healthy adults (23 M, 10 F, 19-43 y). 12 EG, 12 CG (sham), and 9 tapping-imagery group.	fMRI-NF/ 4 days (20×14 s trials in a day)	left M1, visuospatial network, left LPC, DMN	The NF group alone turned the usual anti-correlation between left M1 and left parietal cortex into a zero or slight positive link, which in turn strengthened overall motor–default-mode coupling—and this new pattern lasted for at least two months.
2016, Liew, et al. (45)	4 subjects (2 F, 49 ± 5.9y), chronic stroke	fMRI-NF/ 2 sessions, 2-hour NF within 1 week. Continuous sliding-window of 12 s, feedback updated every 1.5 s to increase BOLD in regions of interest.	Ipsilesional M1, motor cortico-thalamic circuit	3/4 patients learned to raise cortico-thalamic connectivity. Gains transferred to no-feedback runs and boosted resting-state M1–thalamus coupling; larger improvements were seen in those with greater baseline motor impairment.
2015, Scharnowski et al. (29)	7 subjects (1 M, 23-26 y). healthy	fMRI-NF/12-22 runs over 4-6 days (4 training runs every day). The training composed of three 45 s up-regulation blocks and three 45 s down-regulation blocks	SMA and PHC	Using fMRI-NF, participants mastered dual-site control, driving SMA up while damping PHC or the reverse, and the modulation was behavior-specific: higher SMA speed motor reactions, while lower PHC during encoding enhanced later memory, confirming that fMRI-

				NF can causally shape distinct cognitive functions
2016, Subramania n, et al. (27)	30 subjects (27 M, 65y), 15 MOT+NF, 15 MOT. PD	fMRI-NF/ 3 sessions to up-regulate SMA over 10 weeks (weeks 2, 6, 12) + daily imagery homework. assessments after 4 and 10 weeks.	SMA within cortico-basal-ganglia motor loop	Volitional boosting of SMA activity fMRI-NF produced clinically meaningful (20% improvement), transfer-ready motor gains and engaged basal-ganglia nodes, indicating a feasible mechanistic route to augment motor circuits.
2018, Papoutsi, et al. (28)	10 n (7 F, 51 ± 9 y). HD	fMRI-NF/ 3–4 visits over 8 weeks; each visit 4 runs of continuous feedback. Mi was used to up-regulate BOLD in an individually localized SMA	SMA and cortico-striatal loop	Patients learned to raise SMA activity across sessions; those who succeeded showed increase in pre-SMA grey-matter volume, activation in left putamen, and stronger SMA–putamen functional connectivity, which together predicted better motor and cognitive scores.
2017, Ramot, et al. (46)	17 ASD, (M, 15-25 y)/ 10 CG	fMRI-NF/ 4 sessions, over 8 days & 5-56 weeks later follow-up. Real-time "puzzle-piece" reward whenever BOLD trends in two targets matched.	Left STS, left S1, right IPL.	15/17 ASD participants learned to boost STS–S1 connectivity while weakening STS/S1–IPL coupling; gains generalized to rest and were largely retained up to a year. This change correlated with improvement on Social Responsiveness Scale.
2018, Auer, et al. (30)	32 healthy adults: EG = 16 (10 M, 26 ± 3 y) vs CG = 16 (7 M, 27 ± 3 y)	fMRI-NF/ 12 sessions (24 runs) across 4 weeks. Mi of right/left hand; real-time bar showed changes in BOLD between left & right SenMA	Effects tracked in SMA and its connectivity with cingulate cortex and frontal pole	Training boosted contralateral SMA activity and raised SMA-frontal/cingulate coupling during transfer. 75 % of trainees could up-regulate SenMA without feedback.
2019, Lee, et al.	10 healthy adults. EG (7 M, 20 - 35 y) 10 CG (8 M, 21 -31 y).	fMRI-NF/ One 13-min NF embedded in a virtual-navigation task between two mental-practice sessions; EG watched feedback decoded from bilateral M1, CG repeated the same imagery without feedback	Bilateral M1. effects evaluated in the broader motor-imagery network and DMN.	NF raised classification accuracy and trial-by-trial pattern consistency in M1, whereas controls showed no change. It simultaneously boosted Mi network and suppressed DMN connectivity, changes that correlated with the stability of local activation patterns.
2019, Kober · et al (47)	11 healthy adults (4 M, 7 F; 29 ± 5.6 y)	fMRI-NF/ 2sessions. One functional localizer with two 10-trial NF runs. Visual thermometer displayed signal change in left lateral pre-central gyrus. Mi of saliva-swallowing used to raise the bar.	Left pre-central gyrus within the distributed swallowing motor network (insula, SMA, BG, cerebellum)	Mi and overt swallowing activated broadly overlapping networks. During NF, participants significantly up-regulated left pre-central BOLD; gains exceeded offline-MI and co-recruited insula, SMA, putamen, cerebellum.
2019, Marinsa, , et al. (34)	36 healthy volunteers, EG: 19 (7 M, 27.7 ± 4.0 y), sham group: 17 (7 M, 27 ± 5.8 y	fMRI-NF/ 60-min training (3 Mi runs) that rewarded brain-wide similarity to an ME pattern; double-blind, sham-controlled	Sensorimotor network (M1/PMC/SMA), white-matter sensorimotor corpus-callosum, and DMN	NF but not sham raised FA in the sensorimotor corpus callosum and boosted SenMA and DMN functional connectivity immediately after training.
2019, Mehler et al. (48)	17 healthy adults (9 M, 8 F; 26.6 ± 5.5 y)	fMRI-NF/ a single session: 5 runs training the same participants to up/down-regulate either the hand-knob of M1 or SMA using kinesthetic Mi, with thermometer feedback for low vs high signal change in target levels.	M1 and SMA	NF gave participants graded, voluntary control over SMA. they pushed its BOLD signal higher in "high target" blocks, but the same imagery drove M1 below baseline and could not raise it. This contrast showed that premotor hubs such as SMA are trainable, whereas M1 proves a poor up-regulation candidate.

2020, Alwasity, et al. (23)	20 healthy adults. EG: 10 (5 M, 5 F; 26 ± 5 y) vs Sham = 10 (7 M, 3 F; 23 ±3 y)	fMRI-NF/ seven runs in 1 session, continuous thermometer feedback of percent-signal-change in individually localized SMA was used while participants performed complex whole-body Mi. Sham group viewed prerecorded signal	SenMA	NF trainees showed a run-by-run rise in SMA activity while controls did not. Only the NF group exhibited faster right-hand reaction times in a Go/No-Go test. Thus, results underscored SMA's promise as a neuro-rehabilitation target.
2021, Long, et al. (49)	28 right-handed adults: EG: 15 (6 M, 9 F; 22 ± 1.6 y) vs Sham:13 (8 M, 5 F; 23 ± 1.7 y)	3 fMRI-NF/ four 7.5-min runs of NF to up-regulate the right dorsal PMA during kinesthetic Mi; sham group viewed yoked prerecorded signal	Dorsal PMA, cognitive networks and DMN.	NF trainees boosted dorsal PMA run-by-run and, at post-test ME tasks. DMN strengths were negatively correlated with both dorsal PMA up-regulation and faster right-hand tapping. Thus, successful PMA self-regulation refined motor output, whereas mismatched sham feedback left networks unchanged.
2021, Sampaio-Baptista, et al. (50)	20 healthy right-handed adults (5 M, 15 F; 22–38 y) split into EG: 10 subjects vs Sham: 10 subjects	fMRI-NF/ two × 20-min sessions: "Association" session that boosted sensorimotor strip, "Dissociation" session that boosted contralateral and suppress ipsilateral sensorimotor strip; sham watched replay.	Ipsilateral and contralateral sensorimotor strip and callosal fibers linking the two hemispheres.	Real NF produced opposite BOLD shifts in ipsilateral sensorimotor strip for the two conditions, and within 24 h induced matching bidirectional FA changes in the corpus callosum, a promising lever for motor rehabilitation.
2021, Yang, et al. (51)	30 healthy volunteers (16 M / 14 F), 23.9 ± 3.1 y. Randomly split into two equal groups (15 subjects) matched for sex.	fMRI-NF/ one group received BOLD signals from their left M1, another from their left PMv by executing or imagining a right-hand clenching movement. 6 runs in 1 session were performed.	M1, PMv	During Mi, PMv-group significantly up-regulated PMv while de-activating M1 but M1-group showed no M1 increase. During ME, both groups up-regulated their respective targets; M1-group achieved the largest NF Scores. The efficacy and direction of modulation depend on which motor-area is fed back; contralateral M1 is a poor target for imagery-based NF, whereas PMv supports imagery modulation
2022, De Filippi et al. (35)	33 healthy adults: EG: 17 (6 M / 11 F, 27.4 ± 3.5 y), Sham: 16 (7 M / 9 F, 27.3 ± 5.8 y)	fMRI-NF/ 1 session. Mi task contained 3 training runs; each run: 8 × 40 s blocks (20 s Mi task/ 20 s stop task)	SenM areas .	A single motor-imagery fMRI-NF tightened whole-brain dynamics: an effective-connectivity machine-learning classifier distinguished pre- vs post-training only in the EG group with 75 % accuracy.
2023, Nunes JD, et al. (52)	34 subjects/ (38.4 ± 13.2 y). healthy	fMRI-NF/ 6 sessions. Three tasks were performed: ME through finger tapping; Mi; and MI training with motor observation (participants observed the virtual avatar arm moving while instructed to imagine the movement).	Frontal, parietal and occipital cortices	MI-Motor observation task elicited stronger brain activation compared with a MI task. It recruited large portions of the parietal and occipital cortices in addition to the somato-motor and premotor cortices, including the mirror neuron system that could be explored for more effective neurorehabilitation protocols.
2025, Butet et al. (14)	30 chronic stroke survivors (NF n=15, MI n=15), FMA-UE>21	Bimodal EEG-fMRI-NF/ multi-session upper-limb motor imagery training, vs. motor imagery (MI) without feedback	Ipsilesional M1, SMA	FMA-UE improved significantly only in the NF group (p=0.003 vs p=0.633 for MI); between-group difference p=0.048, supporting bimodal EEG-fMRI-NF for post-stroke upper-limb motor recovery

Note: the Butet et al. (14) row was added post hoc as a directly relevant 2025 study and falls within the original 2010-2025 search window.

Table 3. Summary of data extracted from articles about fNIRS-NF / EEG-NF

Year/ Author	Participants/Number, (male or female, mean years old)	Type of NF/feedback /protocols	Target networks	Key findings
2011, Pichiorri F, et al. (53)	10 subjects (6 F, 30 ± 7 y) healthy.	EEG-NF/6–8 training sessions of SMR-based BCI training were done for 1 month. TMS was performed prior to and after the BCI training session. 2 subjects underwent MRI for modeling of the head structures.	Hand/foot- M1 were targeted. SMR over centroparietal area and TMS excitability thresholds were measured.	Findings revealed that practicing Mi of hand grasping leads to changes in brain network topology. These results showed that BCI technology can be used to monitor and support brain plasticity driven by Mi, suggesting its potential as an effective tool for stroke rehabilitation.
2021, Xin Hou (39)	50 healthy, EG: 30 (15 M / 15 F), Sham: 20 (10 M / 10 F); 18–25 y	fNIRS-NF/ 8 sessions across 9 days. Each session contained 6 runs of 30 s up-regulation vs 25 s rest. EG aimed to increase HbO in target, sham viewed feedback from an irrelevant region	LPC	EG learned to up-regulate LPC activity by session 5; controls showed no change. Spatial-memory precision rose significantly after training only in the NFB group with no working memory gains beyond practice effects.
2013, Mihara, et al. (31)	20 chronic subcortical strokes. EG: 10 (8 M / 2 F), sham: 10 (4 M / 6 F); 58.1 ± 8.3 y.	fNIRS-NF/ 6 sessions over 2 weeks. Each session: 10 min video-guided Mi+ 10 min kinesthetic Mi with a color-bar display; sham saw random signal	Ipsilesional PMA	EG up-regulated PMA and gained larger hand/finger scores vs sham group. Benefit held even in severely impaired patients; PMA activation increases correlated with hand recovery. The sham showed no neural or behavioral change.
2017, Fujimoto et al. (54)	20 healthy adults (7 M / 13 F), 28.1 ± 4.6 y; each person completed both real and sham sessions.	fNIRS-NF/ 2 sessions were done. Measures were extracted from 16 trials of 5 s "raise-the-bar" up-regulation alternating with 8–15 s rest. Sham used prerecorded not real-time data	SMA	fNIRS-NF raised HbO in SMA and improved whole-body postural stability, while sham feedback produced no neural or balance gains; however, neither real nor sham training altered fine hand dexterity on the 9-hole peg test.
2017, Lapborisuth et al. (55)	22 subjects (14 f / 8 M, 24.5 ± 7.8 y; healthy	fNIRS-NF/1 session. participants performed 15 second blocks of right-hand squeezing (active) or imagined squeezing, alternated with 15 s rest; a colored map of HbO changes over the left motor cortex updated every 1 s served as feedback.	Left PM, M1 and SMA (contralateral hand-related area)	Neurofeedback significantly increased motor-cortex activation during both active and imagined tasks; imagined squeezing recruited motor areas only when NF was present, demonstrating that fNIRS-based NF can up-regulate task-relevant activity without extensive training and is promising for brain–machine-interface applications.
2020, Ota et al. (40)	31 n (17 m / 14 f; 25.4 ± 0.7 y). EG 16 n; 9 M/7 F) CG 15 n, 8 M/7 F) healthy	fNIRS-NF/ 6 × 20-min sessions over 2 weeks. Each session: 10 min video-guided Mi, then 10 min Mi with fNIRS-NF. EG saw a color bar updated every 250 ms by HbO values over the aPFC. CG received replayed, randomized traces.	left PM, M1, S1, and SMA	NF produced greater aPFC activation than sham and a larger improvement in motor task. HbO gain in aPFC correlated with performance gain. Post-training, real group showed increased hemodynamic activity in left PM, M1 and S1 whereas sham showed SMA activation only. HbO in Lateral M1 predicted dexterity gains, supporting an aPFC-to-S1 pathway that facilitates hand skill learning.
2020, He et al. (56)	20 subjects (10 F), 18-21 y. healthy	EEG-NF. Each 4 s trial showed a "basketball" whose vertical drop was driven in real time by β-burst detection over SenMA. 4 training & 4 "no-training" blocks per session, repeated for both hemispheres over 3 separate days.	SenMA	EEG-NF enabled significant voluntary suppression of β-burst rate and accumulated duration versus sham. Training that specifically suppresses pre-movement β bursts causally speeds movement initiation, supporting β-burst modulation as a feasible EEG-based therapeutic target for motor rehabilitation.

2021, Grigorev et al. (57)	10 subjects (6 F/ 4 M), (22.5 ± 2.3 y). healthy	EEG-NF/ In 4 sessions, subjects learned kinesthetic hand-Mi that produced sensorimotor μ/β desynchronization, then performed the same Mi task under 3 conditions: no feedback, vibrotactile pulses every 0.5 s; and identical pulses when a 500 ms EEG window was classified as left-M1, right-M1, or rest. Corticospinal excitability was probed by TMS.	SenMA	Coupling MI with vibrotactile feedback causally enhances sensorimotor desynchronization over C3 and C4 and motor-cortex excitability. Feedback increased MEP amplitudes in 7 / 10 subjects, indicating plastic changes beneficial for post-stroke or other motor-rehab applications.
2024, Godet. et al. (58)	15 healthy adults (9 F / 6 M), (28.7 ± 7.2 y)	fNIRS-NF/ 8 sessions of training of bilateral DLPFC over 4 weeks. Real-time vertical gauge showed HbO levels; 30 s NF / 30 s rest, 15 cycles per run; no sham. fMRI acquired in sessions 1 and 8	DLPFC and its connectivity with PCC, caudate, putamen and insula	NF enabled most of the 15 participants to raise dlPFC oxygenation. fMRI scans revealed stronger PCC-to-DLPFC FC/dorsal-striatum links and weaker DLPFC - insula coupling—signatures of enhanced executive-control circuitry. Training could reliably up-regulate DLPFC and reinforce fronto-striatal networks, highlighting its promise for treating impulse-control issues.
2024, Yang et al. (36)	58 healthy participants. (EG: 31, sham: 27), (mean age: 21 y)	fNIRS-NF/ 1session, 4 runs of 25 s rest vs regulation blocks. HbO level in left DLPFC was presented as feedback.	DLPFC, and anterior insula	NF group learned to up-regulate left DLPFC across runs; during a subsequent N-back task they showed higher bilateral DLPFC activity and reduced left DLPFC–left anterior-insula connectivity, while accuracy/RT were unchanged.
2024, Hanna et al. (59)	91 n (44 M / 47 F), 18–40 y (24 ± 4 y)	EEG-NF/ a single 30-min session (3 × 9 min blocks) aiming to down-regulate mu (8–12 Hz) at C4; compared with pure Mi blocks, and an alternating Mi + NF protocol.CG watched recorded NF screens.	Right primary SenMA	Mi alone improved sequence accuracy only briefly; mu-rhythm neurofeedback alone did nothing. Combining imagery with real-time mu down-regulation produced the strongest performance gains, and deeper mu desynchronization predicted bigger gains; showing neurofeedback boosts motor consolidation only when paired with imagery.
2014, Mottaz, et al. (60)	10 healthy adults (6 F / 4 M), 25–31 y (mean: 27.4 y). 1 chronic stroke patient, 57 y.	EEG-NF / alpha-band fc training. Mi. 1 session for CG and 7 sessions for the patient for 1 month.	Hand-related M1	7 / 10 healthy participants raised motor-cortex α-coherence within a single session. Stroke patient progressively increased α-coherence across sessions, limited to the trained cortex and frequency band, without altering α-power. Patient's motor function improved and gains lasted ≥ 6 weeks.
2019, Tsuchimoto , et al. (61)	17 subjects (14 m, 58±10y), post-stroke severe chronic hemiplegic including Sham and EG	EEG-NF /2 sessions. Paretic hand Mi with NF, robot-aided sensorimotor stimulation, and neuromuscular electrical stimulation. In training, whenever SMR attenuated, sensorimotor stimulation was provided for EG, but not for sham.	M1, PMA, S1 and motor cortices in the ipsilesional hemisphere	Findings indicated that contingent EEG-SMR NF of the affected hand resulted in significant increases in fc in CG not in the sham group. Furthermore, SMR-based NF induced greater ipsilesional compared to contralesional sensorimotor activity.
2020, Andreas M. Ray, et al. (20)	30 subjects, 16 in EG and 14 in CG (49.8 ± 12.4). 18 M/12 F Stroke.	EEG-NF with the help of BCI translated changes in the SMR into movement of the arm and hand orthosis only in the EG. Each subject performed 17 sessions of training within a period of up to 6 weeks.	SenMA activity measured by alpha and beta oscillation.	The results indicated that patients gain control over the orthoses to link brain oscillatory activity and upper limb movement. Their success rebalancing ipsilesional/contralesional activity plays an important role in impairment reduction.

2018, Mottaz, et al. (62)	10 chronic stroke (5 M / 5 F), 57.1 (40–71 y. each patient received both real and sham training.	EEG-NF/ resting-state alpha-band feedback was used. Two 4-week blocks separated by 1-mo wash-out; each block = 8 sessions (2 × week); each session = 50×45 s trials with bar-height feedback updated every 300 ms	Ipsilesional hand M1 alpha connectivity was used. Control condition trained the contralesional prefrontal cortex activity.	EG up-regulated alpha-band functional connectivity of their spared ipsilesional hand M1 significantly, while sham training left it unchanged. This neural gain translated into a larger improvement in upper-limb motor ability.
2019, Vukelic, et al. (63)	21 healthy adults (14 M / 7 F), 25.9 ± 3.7 y; 12 right-handers, 9 left-handers	Single-session EEG-NF: 2 × 48 kinesthetic-Mi trials (left & right finger extension). Beta desynchronization drove passive hand opening via robotic orthosis in a randomized cross-over design	Contralateral SenMA	Sensorimotor beta-band activity can be robustly modulated by Mi and proprioceptive feedback in both hemispheres, independent of handedness. However, right and left-handers show different oscillatory entrainment of cortical alpha-band networks during neurofeedback.
2020, Hayashi, et al. (64)	12 subjects, healthy male (21-30 y)	EEG-NF/ 4 groups. Each group performed 4 Mi-NF sessions: shoulder-ipsilateral/contralateral MI training, hand-ipsilateral/contralateral MI training aimed at lateralizing to the related SenMA.	ipsilateral/contralateral SenMA associated with the shoulder and hand areas	During shoulder Mi-NF, both the contralateral and ipsilateral desynchronization of SMR increased. Conversely, ipsilateral desynchronization of SMR did not increase during hand MI indicating that the amount of corticospinal projection from the ipsilateral hemisphere can constrain the laterality of brain activity. NF showed great potential to facilitate the shaping of the neural remodeling process
2015, Vukelić, et al. (65)	11 healthy adults (7 M / 4 F), 25.8 ± 3.1 y; each completed both feedback modes in a randomized cross-over design	EEG-NF/ single session: 3 runs × 16 trials (6 s kinesthetic Mi of right-hand opening and 6 s rest). β-band desynchronization had to cross adaptive thresholds to trigger either a visual BCI cursor or a proprioceptive robotic hand opening	SenMA	When participants felt a robotic hand open in response to their brain signals, they could hold the desired beta rhythm longer and more reliably, their beta activity "snapped back" more strongly during rest, and their motor cortex synced up better with other brain areas.
2023, Kevin Kern, et al. (66)	18 chronic stroke patients with finger-paralysis (13 M / 5 F), 60.4 ± 9.9 y	EEG-NF/ single screening session (2 s prep then 6 s kinesthetic hand-opening imagery, then 8 s rest); beta desynchronization over ipsilesional SenMA drove a robotic orthosis; subgroup (n = 8) then did 4-week, 20-session training.	SenMA and frontoparietal area	Subgroup who was trained by NF to increase FPI showed significantly higher improvement in wrist movement than those without FPI and got better scores on the Fugl-Meyer test.
2023, Zulauf-Czajaeet al. (67)	10 subjects (7 f/ 3 M), 28.4 ± 8.4 y	EEG-NF/ data was source analyzed with real-time sLORETA derived from EEG channels. Visual view of the leg area of M1 refreshed every 1.25 s; participants performed 20 s "on" / 20 s "off" single-leg kinesthetic Mi. Two sessions were done: Mi without feedback and Mi with feedback from the desynchronized SMR	M1, PMA, SMA and S1	Mi produced bilateral/contralateral alpha desynchronization on prefrontal regions, reflecting proprioceptive imagery. In feedback group beta-band activity increased in ipsilateral/bilateral M1, while alpha activity in sensory areas decreased, and overall shift toward operant conditioning of the leg motor area. Study showed single-leg, source-level EEG-NF is feasible and may prime early lower-limb rehabilitation
2023, Toolis et al. (68)	28 subjects (22 ± 2 y), pair-matched into	EEG-NF/ Six 30-min sessions (10 × 3-min blocks each) training frontal-midline-theta up-regulation while athletes dry-fired	medial prefrontal / ACC	NF reliably boosted theta during training but did not improve live-fire shooting accuracy, speed, or sustained theta post-training. Results

	EG vs. CG. Biathletes	their rifles; control group continued regular training only.		indicated that EEG-NF alone was not a profitable stand-alone tool for motor enhancement in elite biathletes.
2023, Kodama et al. (69)	40 subjects (33 M; (24.6 ± 8.3 y). healthy.	EEG-NF / a single 30-min SMR-based NF during kinesthetic mi of right-finger movement; (5 blocks, verum feedback from contralateral SenMA versus sham placebo)	Contralateral SenMA, SMA, inter-hemispheric motor pathways via corpus callosum	EG learned to amplify SMR desynchronization and out-performed placebo; showed short-term increase of gray-matter volume in ipsilateral SenMA and SMA and decrease in FA in corpus callosum. Structural plasticity was seen after a single neurofeedback sess.
2025, Decker et al. (70)	34 healthy participants, two groups of 17 subjects; quiet-rest and documentaries group (18-35 y, mean:25 y)	EEG-NF/ 3 kinesthetic Mi sessions across 2 days; each session: 1 training run + 2 EEG-NF runs guiding a 2-D ball with contralateral μ/β desynchronization while imagining bilateral finger-tapping. Post-Mi condition differed: 10-min quiet rest vs. 2 × 30-min nature-documentary viewing.	SenMA	In this study, EEG-NF increased μ/β desynchronization only during individual runs and produced no cumulative neural or behavioral improvement across sessions; break content (quiet rest vs. nature documentaries) had no impact, suggesting that under the tested parameters NF offered no added motor benefit beyond passive rest.
2025, Cha et al. (71)	15 subjects (13 M / 2 F, 66.5 y) sub-acute stroke	EEG-NF/each participant completed 2 matched NF and sham sessions in which rest and grasp tasks bracketed a 3-min intervention: feedback updated by the participant's own mu-rhythm suppression (real) or by another person's data (sham).	Ipsilesional SenMA and bilateral parietal cortices	EEG-NF produced significantly greater mu suppression in target cortices during training, and a progressive increase during subsequent grasp attempts. larger gains in patients with lower Fugl-Meyer assessment scores supported its promise as an adjunct to stroke rehabilitation
2026, Klein et al. (15)	54 subjects in 3 groups (n=18 each): PD-NFB, healthy-NFB, healthy control	fNIRS-NF/ 4 sessions, feedback on decreased Δ[HbR] (increased activity) during motor imagery of whole-body movements	SMA	NFB groups showed feedback-guided modulation of SMA activity; protocol was feasible and manageable in PD, supporting fNIRS-guided SMA-NFB as a proof-of-concept approach for PD motor rehabilitation

Abbreviations of words in Table 1, 2: NF: neurofeedback, PD: Parkinson's disease, M: male, F: female, Y: years, EG: experimental group, CG: control group, Mi: motor imagery, SMA: supplementary motor area, STN: subthalamic nucleus, GPi: globus pallidus internus, UPDRS: Unified Parkinson's Disease Rating Scalen, M1: primary motor area, BG: basal ganglia, PMA: premotor area, PPL: posterior parietal lobe, S1: somatosensory cortex, ME: motor execution, LPC: lateral parietal cortex, DMN: Default mode network, PHC: para hippocampal cortex, MOT: motor training, HD: Huntington's disease, BOLD: Blood-Oxygenation-Level-Dependent, ASD: autism, STS: Superior Temporal Sulcus, IPL: Inferior Parietal Lobe, SMR: sensory motor rhythms SenMA: sensory-motor area, min: minutes, PMv: ventral premotor cortex, BCI: brain computerized interface, TMS: transcranial magnetic stimulation, FA: fractional anisotropy, HbO: oxygenated hemoglobin, aPFC: anterior prefrontal cortex, MEP: motor evoked potential, DLPFC: dorsolateral prefrontal cortex, PCC: posterior cingulate cortex, fc: functional connectivity, FPi: fronto-parietal integration, sLORETA: Standardized Low-Resolution Electromagnetic Tomography, ACC: anterior cingulate cortex.

Discussion

This review assessed the effectiveness of neurofeedback across three modalities: EEG, fMRI, and fNIRS. After careful inspection, a common methodological theme emerged; small samples, brief interventions and minimal follow-up constraints. Most trials enrolled young adults for a single laboratory visit or a short multi-day schedule, a design that leaves little head-room for extra improvement on simple tasks such as finger-tapping or N-back (34-36). Consequently, genuine gains maybe be missed and false positives inflated. Clinical studies were rare but more illustrative. Ray in 2020 applied 17 EEG-BCI sessions to a group of severe chronic-stroke patients and, thanks to a double-blind yoked-sham control, linked larger alpha-related desynchronization to meaningful motor improvements (37). Subramanian in 2016 delivered just three real-time fMRI-NF sessions to 15 people with Parkinson's disease per arm; although it showed motor advantages they failed to reach significance, demonstrating how small samples and imperfect controls can dilute clinical signals (27). Durability remains an open question. Only Megumi in 2015 followed participants for two months, confirming sustained network changes (38), and Subramanian in 2016 reassessed motor function at ten weeks with borderline results. Most others stopped at same-day or ≤ 24hrs

assessments, so the longevity of most neural shifts is unknown. Behavioral outcomes, on the other hand, were mixed. More studies reported no significant behavioral benefit probably because the protocols were single-session, under-powered, ceiling-limited, or lacked proper sham arms. Three well-designed trials did achieve robust gains in clinically relevant stroke recovery by multi-session EEG-NF (37), improvement in spatial-memory by 8 sessions of fNIRS-NF (39), and improvement of reaction time in pegboard speed by 6-8 sessions of fNIRS-NF (40). These successes paired higher session numbers with strict blinding or behaviorally aligned tasks, suggesting a recipe for future efficacy. For modalities, each approach offers unique advantages and challenges, suggesting that the rational selection of neurofeedback depends on several factors and cost-utility varies by context. EEG-NF offers the cheapest, portable and even remote-deployable setup and supported the largest clinical win (37). fNIRS-NF occupies a mid-cost niche yet produced two of the strongest behavioral effects (39,40). fMRI-NF provides rich mechanistic insight but remains expensive and logistically demanding. EEG-NF is well-suited for motor rehabilitation and cognitive training, especially when combined with brain-computer interfaces or robotic devices. fMRI-NF, with its superior spatial resolution, is ideal for targeting deeper brain regions and complex networks, making it effective for conditions like Parkinson's disease, although its cost and infrastructure needs may limit its accessibility. fNIRS-NF strikes a balance between spatial and temporal resolution and provides a portable and cost-effective option for motor and cognitive training, particularly valuable in clinical settings. All included articles were published in peer-reviewed journals, yet the lack of standardization across studies made cross-study comparisons challenging. Many investigations employed small sample sizes, limiting the generalizability of their findings. In addition, substantial heterogeneity in study designs, target populations, feedback protocols and training durations complicate direct comparisons of modality-specific efficacy. Finally, most studies lacked long-term follow-up, a gap that hampers assessment of the sustained impact of neurofeedback on motor recovery and neural plasticity.One further determinant is target-strategy matching. Yang in 2021 showed that kinesthetic motor imagery up-regulates ventral premotor cortex but can suppress M1 (51) and Hanna in 2024 likewise found no finger-tapping benefit from pure mu-suppression over M1 unless the feedback was coupled with explicit motor imagery (59). These illustrate how mismatched targets waste learning potential. Future research should focus on addressing the current limitations by increasing sample sizes, standardizing protocols, and conducting long-term follow-up studies. This would improve the reliability and clinical applicability of neurofeedback techniques, ultimately enhancing outcomes for patients with motor impairments.

Conclusion

Across modalities, NF reliably alters motor-system activity in the short term, but durable functional gains emerge only when protocols combine adequate sample size, multi-session dosing, rigorous sham or active controls, and a cognitive strategy matched to the neural target. To move beyond proof-of-concept, future trials should recruit larger clinical cohorts, extend follow-up into multi-week or multi-month ranges, and maintain precise target-strategy pairing. Meeting these design benchmarks will determine whether the striking neural plasticity already demonstrated can translate into reliable, generalizable rehabilitation benefits. The rational choice of the neurofeedback method depends on aligning each modality’s unique advantages with specific patient needs, desired outcomes, and available resources to ensure personalized and effective interventions. From a translational standpoint, EEG-NF currently yields the best cost-benefit, fNIRS-NF shows promise for sustained training, and fMRI is best reserved for exploratory mapping.

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Authors' Contributions

The first author conducted the systematic literature search, performed data extraction and synthesis, and drafted the initial version of the manuscript. The corresponding author conceptualized and supervised the study, verified data integrity, interpreted the results, and critically revised the manuscript for important intellectual content. The principal investigator provided clinical and methodological oversight, guided the study design, and approved the final version of the manuscript for submission. The other co-authors contributed to literature screening, data tabulation, critical review of neurofeedback mechanisms, and final editing of the manuscript. All authors reviewed and approved the final version and agreed to be accountable for all aspects of the work.

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