

Advancing fNIRS-Driven Stroke Recovery: From Quantitative Assessment to Closed-Loop Interventions

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ABSTRACT Stroke is a cerebrovascular disease with high disability rates, necessitating effective strategies for functional assessment and rehabilitation. However, current research and clinical workflows still lack a closed-loop framework linking objective assessment to adaptive intervention. Functional near-infrared spectroscopy (fNIRS) is a non-invasive neuroimaging technique that monitors cerebral hemodynamics and provides practical biomarkers for evaluating post-stroke impairment and guiding rehabilitation. This review systematically summarizes recent fNIRS-based stroke research across three dimensions: assessment paradigms, analytical methodologies, and intervention strategies. This review first addresses the rationale for selecting regions of interest and designing experimental paradigms to support greater standardization of stroke assessment. It then summarizes widely used analytical methods and quantitative indices, with emphasis on how different approaches capture local activation, inter-regional connectivity, and network-level reorganization. Finally, it examines the use of fNIRS in evaluating peripheral and central interventions, highlighting its potential to objectively monitor therapeutic efficacy and clarify the neural mechanisms underlying functional recovery. fNIRS provides a promising bridge between quantitative assessment and adaptive rehabilitation in stroke. Continued progress will depend on improving methodological standardization, deepening multimodal and network-level analysis, and integrating into closed-loop systems.

KEYWORDS Functional near-infrared spectroscopy; Stroke; Assessment; Intervention; Rehabilitation

1 Introduction

Stroke remains a leading cause of death and long-term disability worldwide [1]. Survivors often show motor [2], cognitive [3], and language impairments [4]. Although rehabilitation assessment still relies mainly on clinical scales that lack objective physiological markers for precise, individualized evaluation [5]. In addition, many treatment protocols use fixed parameters and do not adapt to the patient's changing neural state. Objective monitoring tools are therefore needed to support individualized rehabilitation.

Neuroimaging is an important approach for post-stroke functional reorganization [6]. Functional near-infrared spectroscopy (fNIRS) measures relative changes in oxygenated hemoglobin (HbO) and deoxygenated hemoglobin (HbR) through the modified Beer-Lambert Law [7]. Compared with functional magnetic resonance

imaging (fMRI) and electroencephalography (EEG), fNIRS is more portable, relatively motion tolerant, and well suited to monitoring superficial cortical metabolic responses during rehabilitation [8,9]. Because stroke is a vascular disease, this link to neurovascular activity is especially relevant clinically [10].

Several issues still limit broader clinical use of fNIRS. Studies vary widely in assessment paradigms, analytical methods, and uses of fNIRS within closed-loop interventions. In experimental design, substantial heterogeneity remains. Although models such as inter-hemispheric competition stress the balance between affected and unaffected hemispheres [11], no broad consensus on regions of interest (ROIs) selection for stroke assessment. Channel placement and cortical coverage therefore differ markedly across studies [12], and inconsistent probe-task mapping hampers baseline comparison and standard development.

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Similar limitations appear in data analysis. Most fNIRS studies still use the general linear model (GLM) to quantify regional activation, which can't fully exploit the physiological information in the signals [13]. Functional connectivity (FC) [14] and brain network analysis [15] have characterized inter-regional interactions, but they are often built on static Pearson correlation alone, with limited attention to dynamic coupling. More robust analytical frameworks are needed to capture the high-dimensional features of post-stroke neural reorganization.

Intervention studies show similar breadth and complexity. Stroke rehabilitation includes peripheral approaches such as robotic exoskeleton training [16] and electrical stimulation [17], as well as central neuromodulation methods such as transcranial magnetic stimulation (TMS) and transcranial direct current stimulation (tDCS) [18]. fNIRS can objectively read out the hemodynamic responses evoked by these interventions. However, the literature still lacks a clear synthesis of their physiological differences. A more systematic review is needed to organize these pathways and clarify how fNIRS can support closed-loop rehabilitation strategies.

This review examines how fNIRS-derived information is used in post-stroke rehabilitation. Here, fNIRS-driven describes a progression from quantitative assessment and treatment monitoring during recovery to the potential use of validated markers as feedback variables. This review proceeds from the influence of ROI and task design on signal acquisition, through the conversion of signals into quantitative markers, to the interpretation of intervention responses and their potential role in adaptive rehabilitation.

2 Fundamentals of ROI Selection and Experimental Paradigms

Reliable functional assessment depends on aligning anatomical targets with task design. Current fNIRS stroke

studies still vary substantially in sensor layout and experimental paradigm, limiting reproducibility and cross-study comparison [19]. This section links the anatomical rationale for ROI selection with the sensorimotor, cognitive and language, and non-execution paradigms used to assess post-stroke function.

2.1 Rationale for ROI selection

The cerebral cortex contains functionally distinct regions, commonly described with Brodmann's cytoarchitectural map [20], as shown in Fig. 1A. For fNIRS studies, these anatomical boundaries must be translated into practical sensor layouts. Because optode placement usually follows the international 10-10 system, scalp landmarks must be mapped accurately to the underlying cortex [21]. Fig. 1B illustrates this correspondence, and Table 1 links the cortical regions addressed below to their functional roles in post-stroke assessment.

The anterior frontal regions, particularly the frontopolar cortex (FPC) and dorsolateral prefrontal cortex (DLPFC), are closely linked to executive functions such as working memory, decision-making, and attentional control, and are therefore commonly targeted in cognitively demanding paradigms [15,22]. The posterior frontal regions form the main cortical network for motor control. The premotor cortex (PMC) contributes to motor planning and movement sequencing, the supplementary motor area (SMA) is involved in movement initiation and coordination, and primary motor cortex (M1) is most directly related to motor execution. Motor assessment studies often assess all these regions [23,24]. The parietal cortex integrates somatic sensory input, including touch, pain, and proprioception. Somatosensory cortex (S1) is a common target in sensory dysfunction [25]. Since S1 and M1 are anatomically close and functionally related, many studies refer to them together as the sensorimotor cortex (SMC) [26]. This region also follows a clear somatotopic arrangement, with lower-limb and foot representations

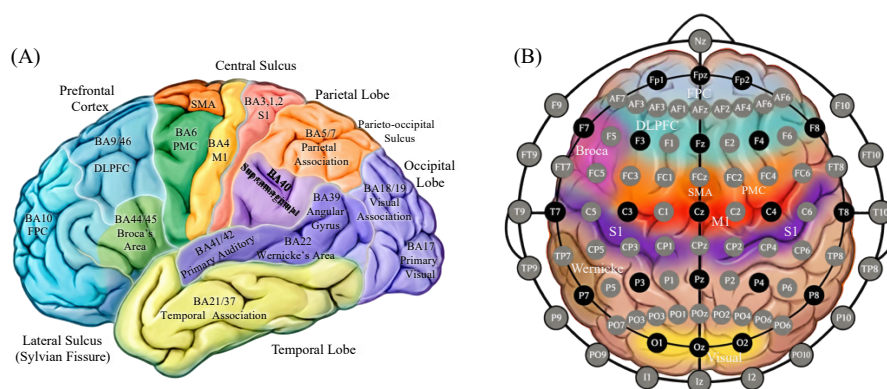


Table 1 Anatomical locations and functional roles of key regions of interest for fNIRS stroke assessment.

Functional domain	Brain region	10-10 location	Functional role in stroke rehabilitation
Cognitive	Frontopolar Cortex (FPC)	Fp1-Fp2	Multitasking, strategic planning, high-order branching control
	Dorsolateral Prefrontal Cortex (DLPFC)	F7-F8, FC5-FC6	Executive control, working memory, attention allocation, problem-solving
Motor	Premotor Cortex (PMC)	FC3-FC4	Motor planning, sensory guidance of movement, spatial coordination
	Supplementary Motor Area (SMA)	FC1-FC2	Sequence initiation, bimanual coordination, postural control
	Primary Motor Cortex (M1)	C5-C6	Voluntary motor execution, fine motor control, hand dexterity
	Somatosensory Cortex (S1)	CP5-CP6	Proprioception, tactile processing, sensorimotor integration
Language	Broca's Area	F7, FT7, FC5	Speech production, syntactic processing, articulatory planning
	Wernicke's Area	CP5, P5, TP7, P7	Phonological processing, speech decoding, auditory comprehension
Vision	Occipital Cortex (V1)	O1-O2	Visual perception, motion detection, visuospatial processing

located around C1/C2 [27] and upper-limb and hand representations around C3/C4 [28].

Language assessment mainly targets the temporal lobe and adjacent cortical regions, including Broca's area for speech production and Wernicke's area for semantic comprehension [19], which usually show clear left-hemispheric lateralization during language tasks [29,30]. The occipital lobe is the main cortical region for visual processing. It is less frequently used as a primary target, but it is often included in paradigms involving visual stimulation or visual feedback [31].

2.2 Design of experimental paradigms

Because the hemodynamic response is delayed, most fNIRS studies use block designs alternating task and rest to quantify relative hemoglobin changes. Task blocks commonly last about 10–30 s and are followed by rest periods of about 20–40 s, allowing the HbO/HbR response to rise and partially return toward baseline. For post-stroke assessment, the paradigms considered below are organized according to the function being probed and the feasibility of overt task performance: sensorimotor, cognitive and language, and non-execution. Fig. 2 illustrates these categories. Task design should nevertheless be matched to the clinical or experimental question. For example, Formica et al. [32] combined gripping, tapping, and tactile exploration (Fig. 2D) to evaluate the multidimensional effects of mirror therapy.

2.2.1 Sensorimotor paradigm

Motor assessment paradigms mainly assess hand function, upper-limb movement, gait, balance, and swallowing. Hand function is commonly assessed with three tasks. Grip task (Fig. 2A [23]) relates grip strength to cortical activation [33]. Finger tapping (Fig. 2B [34]) probes fine motor control and finger individuation.

Positioning tasks (Fig. 2C [35]) require precise object placement and are often used to assess hand-eye coordination and spatial planning. Upper-limb paradigms mainly use three movement types. Single-joint tasks, such as isolated elbow flexion (Fig. 2G [36]), isolate specific muscle groups. Task-oriented training (Fig. 2H [37]) emphasizes coordinated, goal-directed multi-joint movement and is widely used because it better reflects activities of daily living [38–41]. Bilateral arm training (Fig. 2F [21]) examines inter-limb coordination and inter-hemispheric interaction during synchronous or alternating movement.

Locomotor function is usually assessed with walking tasks performed over a set duration or distance. Common options include overground walking (Fig. 2E [27]) and treadmill walking (Fig. 2I [42]). Comparative studies suggest that both can produce similar cortical activation patterns [43]. Balance is often examined with two simple paradigms. The eyes-open/close task (Fig. 2J [13]) probes stability under changing visual input, whereas the sit-to-stand task (Fig. 2K [44]) evaluates postural control and dynamic weight shifting during transitional movement.

Swallowing tasks are comparatively simple and usually involve swallowing saliva or liquid (Fig. 2L [45]). Some recent studies have added sensory modulation, such as sour taste stimulation, which appears to increase activation in the DLPFC, PMC, and S1, although its clinical value still needs further validation [25].

2.2.2 Cognitive and language paradigm

Cognitive function is commonly evaluated with three paradigms. The verbal fluency task (VFT) (Fig. 2O [46]) requires word generation under semantic or phonemic constraints and is often used to probe lexical access and executive control. The repetition task (Fig. 2P [30]) assesses the phonological loop and working memory. The sorting task (Fig. 2M [22]) examines cognitive flexibility

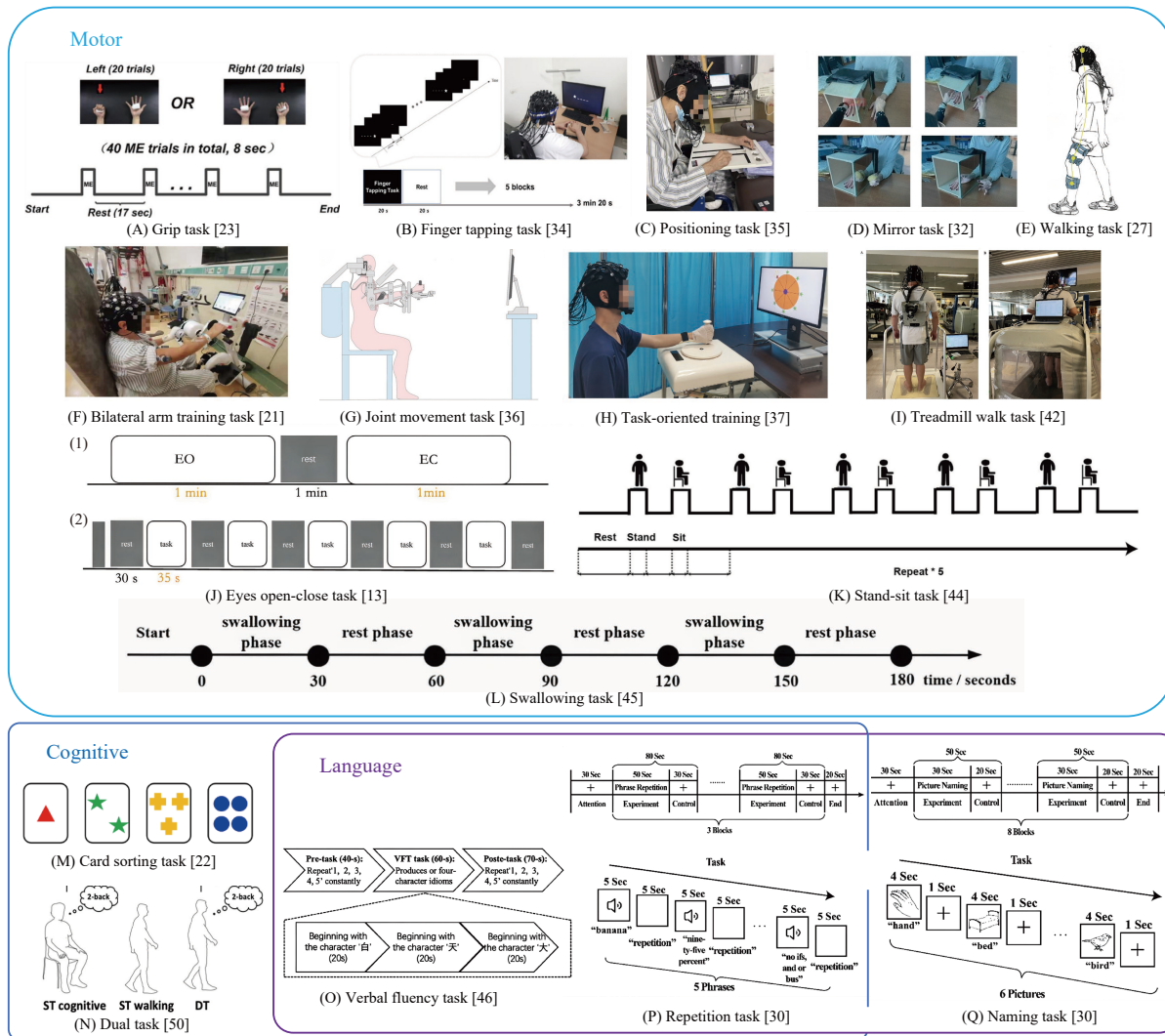


Fig. 2 Experimental paradigms for fNIRS-based post-stroke assessment.

by asking participants to classify items according to predefined rules. In post-stroke cognitive impairment (PSCI), the hemodynamic responses evoked by these tasks are often compared with standardized scales such as the MoCA and MMSE [46–49].

An important extension of stroke assessment is the dual-task paradigm (Fig. 2N [50]), which combines motor and cognitive demands to quantify cognitive-motor interference. Compared with single-task conditions, dual-task performance usually requires greater prefrontal recruitment, which likely reflects the added cost of divided attention [51]. Since fNIRS can be used during natural movement, it is well suited to dual-task assessments involving walking, balance, or other rehabilitation-related activities.

Assessment of post-stroke aphasia (PSA) overlaps partly with cognitive testing, since tasks such as VFT and

repetition can also probe lexico-semantic processing. At the same time, more language-specific tasks, especially confrontation naming (Fig. 2Q [30]), are used to isolate lexical retrieval deficits. Together, these paradigms provide a broader view of speech production, comprehension, and semantic access [52].

2.2.3 Non-execution paradigm

Non-execution paradigms are especially useful for patients with severe motor deficits or flaccid paralysis. Resting-state measurement provides a passive option for patients unable to complete voluntary tasks by focusing on spontaneous hemodynamic fluctuations, intrinsic FC, and baseline neurovascular status [53]. Motor imagery (MI) offers another alternative, recruiting networks that partly overlap with those involved in actual movement [54].

3 Analytical Frameworks and Metrics for Assessment

Quantitative assessment links fNIRS measurement with rehabilitation decision-making. This section reviews the main fNIRS frameworks used in the field, including the GLM, laterality index (LI), functional and effective connectivity (FC/EC), graph-theoretical analysis, and multimodal coupling. Together, these measures support the evaluation of functional status and treatment response and, after sufficient validation, may also provide state variables for adaptive rehabilitation.

3.1 General linear model (GLM)

GLM is the standard framework for decomposing continuous hemodynamic time series into task-related components. In this model, the observed signal Y is represented as a linear combination of explanatory variables X plus an error term ε :

$$Y = X\beta + \varepsilon \quad (1)$$

where Y represents the time-series vector of hemoglobin concentration changes; X denotes the design matrix, constructed by convolving the experimental event timing with a canonical HRF; ε is the residual noise; and β represents the magnitude of the hemodynamic response under each condition.

Longitudinal changes in β can be used to track neuroplasticity. For example, increased ipsilesional β values during motor or cognitive tasks are often associated with better functional scores and may reflect recovery-related recruitment of neural resources [32,35]. GLM-based measures have been used in studies of motor execution, swallowing [45], and language recovery [49,52]. It can also be relevant for closed-loop paradigms that adjust intervention intensity according to cortical responses. Standard implementations are available in widely used toolboxes such as Homer3 [55] and MNE-NIRS [56].

3.2 Laterality index (LI)

LI is a quantitative metric designed to assess the functional asymmetry between homologous brain regions, serving as a proxy for inter-hemispheric balance. It is typically calculated as:

$$LI = \frac{A_{\text{left}} - A_{\text{right}}}{A_{\text{left}} + A_{\text{right}}} \quad (2)$$

where A represents the magnitude of the hemodynamic response within the ROI, quantified as mean HbO concentration or GLM β -values. The index ranges from -1 to 1 , with positive values indicating left-hemispheric

dominance and values near zero reflecting bilateral symmetry.

Many patients show a shift toward the contralesional hemisphere, either because of compensatory recruitment or reduced transcallosal inhibition [57]. Over time, a return toward greater symmetry is often interpreted as a sign of adaptive reorganization and functional recovery. Some studies calculate LI using GLM coefficients [58], wavelet-based amplitude or phase features [59], making it possible to quantify inter-hemispheric balance over time.

3.3 Functional and effective connectivity (FC/EC)

Connectivity analysis is central to studying post-stroke network reorganization. FC describes statistical dependence between regions and is usually interpreted as undirected communication. Clinically, reduced inter-hemispheric FC may indicate impaired communication between bilateral motor or cognitive networks, whereas increased contralesional or frontoparietal connectivity may reflect compensatory recruitment during recovery. EC, by contrast, aims to infer the direction and causal structure of information flow from ipsilesional motor regions to downstream networks is weakened or whether alternative contralesional pathways are being recruited. Although both are commonly represented as connectivity matrices, they capture different aspects of neural organization, as summarized in Table 2.

Within FC analysis, Pearson correlation remains the most common measure of linear synchronization between channels. Fisher's Z-transformation is often applied before group analysis. Time-frequency methods such as wavelet phase coherence and phase locking value provide complementary information about oscillatory synchronization. In stroke studies, reduced inter-hemispheric FC is a common finding and is often interpreted as network disruption.

For EC analysis, Granger causality remains a common starting point. Under this framework, one signal is said to exert directional influence if its past values improve prediction of another signal. Partial directed coherence extends this idea into the frequency domain. Dynamic Bayesian inference is used when time-varying causal interactions are of interest. Clinically, these measures help describe how stroke disrupts large-scale brain organization and whether alternative contralesional pathways are being recruited during recovery.

3.4 Brain network analysis

Brain network analysis describes the topology of stroke-related network reorganization by treating channels or ROIs as nodes and functional or effective connections as edges. After thresholding the connectivity matrix,

Table 2 Summary of mathematical definitions and characteristics of FC and EC methods.

Type	Method	Mathematical formula	Key parameters	Core characteristics	Related studies
FC	Pearson correlation	$\frac{\sum_{i=1}^n (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^n (x_i - \bar{x})^2 \cdot \sum_{i=1}^n (y_i - \bar{y})^2}}$	x_i, y_i : time series $\bar{x}, \bar{y}$: mean value n : sample size	Evaluate the linear correlation of the data	[21,28,44,60–65]
	Pearson correlation and Fisher-Z	$z = \frac{1}{2} \ln\left(\frac{1+r}{1-r}\right)$	r : Pearson coefficient z : normalized score	Calibrate data to normal distribution and improve group comparisons	[15,25,29,33,36,38,41,53,66–68]
	Wavelet phase coherence	$\frac{ S[s^{-1} \sum W_x^*(f) W_y(f)] ^2}{S[s^{-1} W_x(f) ^2] \cdot S[s^{-1} W_y(f) ^2]}$	W_x, W_y : wavelet transforms S : smoothing operator s : scale parameter f : frequency	Assess synchronicity in time-frequency domain	[42,59,69–73]
	Phase locking value	$\left \frac{1}{N} \sum_{n=1}^N e^{j[\phi_x(n) - \phi_y(n)]} \right $	ϕ_x, ϕ_y : phase values N : sample size	Assess phase synchronization in the frequency domain	[48,62,74]
EC	Granger causality	$G_{Y \rightarrow X} = \ln\left(\frac{\sigma^2(X X^-)}{\sigma^2(X X^-, Y^-)}\right)$	$\sigma^2(X X^-)$: conditional variance X^-, Y^- : past time series	Infer directed causal relationships from predictive improvement	[73,75]
	Partial directed coherence	$\pi_{i \leftarrow j}(f) = \frac{ A_{ij}(f) }{\sqrt{\sum_{k=1}^m A_{kj}(f) ^2}}$	$A_{ij}(f)$: MVAR coefficients m : number of channels f : frequency	Frequency-domain extension of Granger causality	[76]
	Dynamic Bayesian inference	$P(\theta D) \propto P(D \theta) \cdot P(\theta)$	θ : model parameters D : observed data $P(\theta)$: prior $P(D \theta)$: likelihood	Infer causal interactions under time-varying conditions	[37,77,78]

measures of network integration, segregation, and nodal importance can be extracted from the resulting sparse network, although their values may depend on the thresholding strategy. The graph-theoretical metrics used for these purposes are summarized in Table 3.

Global network metrics mainly describe how efficiently information can be exchanged across the whole brain. Global efficiency reflects long-range integration and parallel information transfer, and reductions in this measure are often interpreted as evidence of impaired large-scale coordination after stroke [80]. Local efficiency and the clustering coefficient describe local segregation and fault tolerance, and

therefore capture the density of local information processing [81]. Small-worldness reflects the balance between integration and segregation relative to a random network. When this balance is altered after stroke, the network may become less efficient overall.

Nodal centrality measures identify network hubs. Betweenness centrality captures how often a node lies on shortest paths between other nodes and therefore indicates potential bridge regions. Eigenvector centrality weights a node according to the importance of the nodes to which it connects. Tracking these measures over time can help identify compensatory hubs in contralesional or perilesional regions.

Table 3 Definitions and interpretations of graph-theoretical metrics for brain network topology.

Method	Mathematical expression	Key parameters	Core characteristics	Related studies
Global efficiency	$GE_N = \frac{1}{n} \sum_{i \in N} \frac{\sum_{j \in N, j \neq i} d_{ij}^{-1}}{n-1}$	N : set of all nodes d_{ij} : shortest path n : number of nodes	Indicate integration, coordination ability, and communication efficiency of the network	[15,17,29,37,39,68,69,77,78]
Local efficiency	$LE_i = \frac{\sum_{j,k \in G_i, j \neq k} d_{jk}^{-1}}{k_i(k_i-1)}$	G_i : neighbor subgraph d_{jk} : shortest path k_i : node degree	Reflect modularity and fault tolerance	[15,17,37,39,68,69,75,77,79]
Clustering coefficient	$C_i = \frac{\sum_{j,k \in N, j \neq k} (\omega_{ij}, \omega_{jk}, \omega_{ik})^{\frac{1}{3}}}{k_i(k_i-1)}$	N : set of all nodes ω_{ij} : weight of edge k_i : node degree	Reflect communication efficiency in local brain areas	[15,17,29,37,39,68,69,77,79]
Small-worldness	$S = \frac{C_{\text{brain}}/C_{\text{rand}}}{L_{\text{brain}}/L_{\text{rand}}}$	C : avg clustering coeff L : characteristic path length	Balance segregation and integration relative to random networks	[15,39,68,77,79]
Eigenvector centrality	$EVC_i = \frac{1}{\lambda} \sum_j \omega_{ij} EVC_j$	λ : maximum eigenvalue of adjacency matrix ω_{ij} : weight of edge	Measure node importance and impact	[17,75]
Betweenness centrality	$BC_i = \frac{2}{(n-1)(n-2)} \sum_{j \neq k \neq i} \frac{\sigma_{jk,i}}{\sigma_{jk}}$	n : number of nodes σ_{jk} : shortest-path count $\sigma_{jk,i}$: paths through node i	Indicate the bridge or hub role in information processing	[37,74,78]

Together, these metrics extend assessment beyond local activation to whole-network organization. In stroke rehabilitation, reduced global efficiency may indicate impaired integration, whereas shifts in local topology or nodal centrality may help identify adaptive reorganization in contralesional or perilesional regions.

3.5 Multimodal coupling analysis

Multimodal physiological coupling analysis combines fNIRS with electrophysiological or muscular signals to examine coordinated activity across physiological systems. fNIRS has also been integrated with other imaging and physiological techniques; within the post-stroke rehabilitation literature synthesized here, the coupling evidence is concentrated in two frameworks: neurovascular coupling (NVC) assessed with fNIRS and EEG, and corticomuscular coupling (CMC) assessed with fNIRS and surface electromyography (sEMG). Accurate temporal synchronization is essential in both cases because the signals arise from different physiological processes and operate on different time scales [9,82].

3.5.1 fNIRS-EEG integration for neurovascular coupling (NVC)

NVC describes the relationship between neuronal electrical activity and the accompanying hemodynamic response by integrating EEG and fNIRS [83]. Because the two modalities are closely linked in time [26], this combination is well suited to quantifying NVC and examining how neural activity relates to vascular response [84].

More recent work has extended this approach. Lin et al. used cross-layer EEG-fNIRS connections to derive NVC-related measures of neural reorganization [85]. fNIRS-informed EEG source imaging is used to improve source localization by introducing hemodynamic priors [86]. In addition, Li et al. combined multimodal signals with a linear time-invariant model to study brain network controllability [23]. These approaches may be useful for interventions that need real-time estimates of cortical state, including non-invasive brain stimulation and brain-computer interfaces (BCIs).

3.5.2 fNIRS-sEMG integration for corticomuscular coupling (CMC)

CMC reflects the functional interaction between cortical motor hemodynamics and peripheral muscle activity, which allows central-peripheral relationships to be quantified during motor tasks [21]. Task-based studies

suggest that some stroke-related impairments may reflect reduced central-peripheral transmission efficiency rather than complete loss of motor pattern organization [87,88].

To quantify this transmission, transfer entropy (TE) is widely favored over traditional coherence methods [89,90]. Clinical applications show that TE strength from the ipsilesional motor cortex to the paretic limb is significantly reduced in stroke, reflecting weakened central drive and impaired information transfer between the central and peripheral nervous systems [79,91].

By quantifying cortex-muscle interaction, CMC measures such as TE provide a practical way to assess the descending motor pathway. They may also help drive peripheral closed-loop interventions, for example by adjusting exoskeleton assistance or functional electrical stimulation (FES) timing according to the patient's current CMC state.

4 fNIRS-Informed Rehabilitation and Interventions after Stroke

Rehabilitation promotes stroke recovery through repeated, task-oriented practice that stimulates neural activity and supports circuit reorganization [43,66,92]. In relation to their role in the rehabilitation pathway, the interventions examined below are organized as peripheral interventions and stimulation, non-invasive brain stimulation, and feedback-based therapies, as summarized in Fig. 3. Across these groups, fNIRS is used mainly to measure treatment-related cortical changes; it enters the control loop only when its features trigger or adjust feedback. Before interpreting stimulation-induced fNIRS responses, intervention paradigms should generally include sham or control conditions to reduce potential confounding from non-specific cortical, peripheral vascular, or scalp-related hemodynamic responses.

4.1 fNIRS assessment of peripheral rehabilitation interventions

4.1.1 Robot-assisted exoskeleton rehabilitation

Robot-assisted exoskeleton rehabilitation is widely used in stroke rehabilitation because it can provide intensive, standardized, and quantifiable sensorimotor training [16]. Although robotic assistance may initially increase cognitive load [93], it can also provide consistent proprioceptive input that supports functional recovery. fNIRS studies generally show that exoskeleton training increases cortical activation in the affected hemisphere and supports functional reorganization [94–96].

One advantage of exoskeleton systems is that training

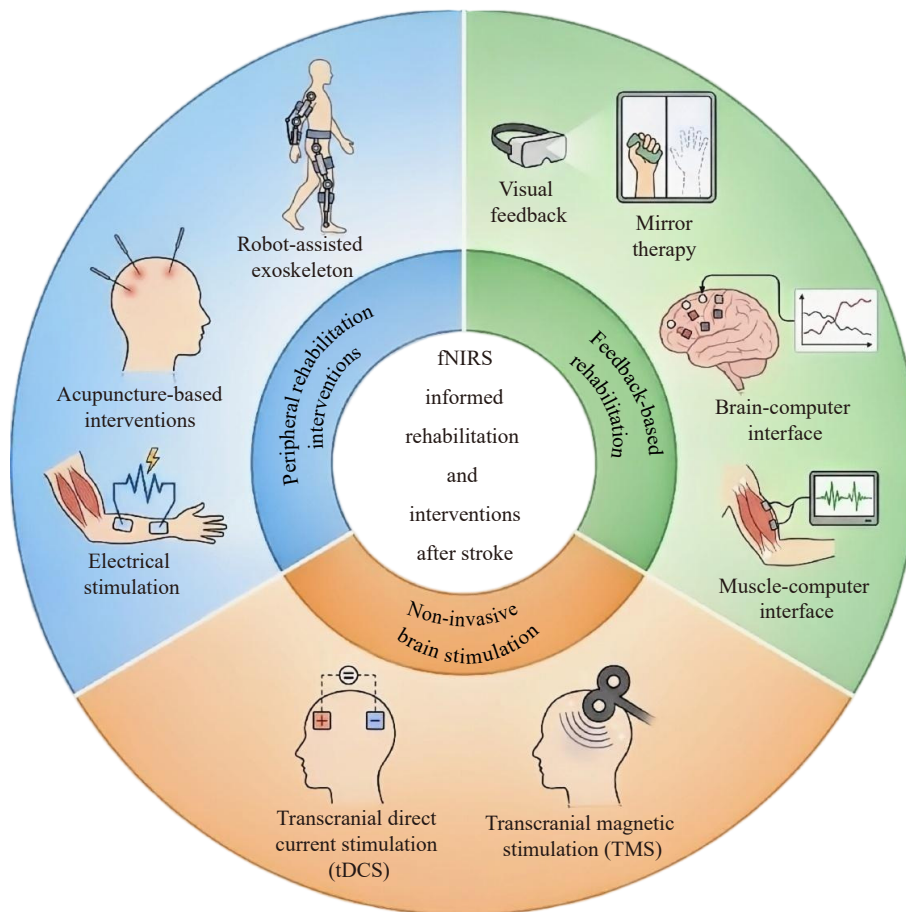


Fig. 3 fNIRS-informed rehabilitation and intervention for stroke.

mode can be adjusted to different impairments [71]. In bimanual paradigms, the unaffected hand can assist the paretic hand through a rehabilitation glove, and fNIRS studies suggest that this may enhance inter-hemispheric coupling [97]. Lower-limb exoskeleton-assisted gait training recruits the PMC and SMA [98], while static isotonic upper-limb robot training may produce broader cortical activation than dynamic training [99].

Training intensity should also match impairment severity. Assisted or passive modes are often necessary for severe deficits [73], whereas active participation is preferred for mild or moderate impairment. fNIRS studies show that voluntary effort tends to evoke stronger cortical activation and is generally associated with better rehabilitation outcomes [100]. For patients who cannot perform overt movement, MI can evoke activation patterns similar to active movement [36].

4.1.2 Electrical stimulation

Neuromuscular electrical stimulation (NMES) uses surface electrodes to activate motor nerves and induce muscle contraction, thereby increasing proprioceptive

input. fNIRS studies suggest that this input can alter cortical excitability and connectivity. In PSA, median-NMES can enhance FC in language-related networks [72]. In closed-loop designs, stimulation of the paretic hand can be triggered by activity of the unaffected hand, which may further strengthen inter-hemispheric coupling, particularly in the SMC [63].

FES can coordinate muscle contractions to restore functional movements such as gait. fNIRS reveals that stroke patients engaging in FES-assisted walking require the compensatory recruitment of the SMC–SMA–PMC cortical network [27]. However, the hemodynamic response varies across protocols; while some enhance activation in the contralateral SMA and PMC, others may reduce M1 activation due to improved neural efficiency [101]. These fNIRS findings support fNIRS-based optimization of stimulation parameters and future protocols that adapt FES or NMES intensity to cortical state.

4.1.3 Acupuncture-based interventions

Acupuncture is also used as an adjunct to stroke

rehabilitation. fNIRS studies suggest that specific acupoints can evoke measurable cortical hemodynamic responses [75]. In PSCI, scalp acupuncture is associated with frontal and parietal activation and improved MoCA scores [102]. In PSA, stimulation over the projection of Broca's area has been linked to local activation and language improvement [103]. In motor recovery, both body and auricular acupuncture are associated with increased M1 activation [76,104], while electroacupuncture may strengthen PMC and in swallowing-related networks [105]. These findings suggest that fNIRS may be useful for monitoring response to acupuncture-based interventions.

4.2 fNIRS monitoring of non-invasive brain stimulation

4.2.1 Transcranial direct current stimulation (tDCS)

tDCS modulates cortical excitability by applying weak currents that alter resting membrane potentials. Anodal stimulation generally increases excitability, whereas cathodal stimulation reduces it [106]. fNIRS can track the associated hemodynamic response over time. Longitudinal studies suggest that cortical activation may rise early and then decline, with stable after-effects appearing after sufficient stimulation [74].

fNIRS has also been used to assess the network-level effects of specific tDCS protocols. In PSCI, anodal stimulation over the DLPFC at 2 mA for 30 minutes has been associated with increased activation in the left superior temporal gyrus and stronger FC, alongside improved cognitive performance [46]. To improve spatial focality, high-definition tDCS (HD-tDCS) uses a multi-electrode array. Studies monitored with fNIRS suggest that HD-tDCS over the ipsilesional PMC at 1 mA for 20 minutes can alter local hemoglobin concentrations and may help restore inter-hemispheric balance [34].

These findings indicate that tDCS affects not only local activation but also broader functional networks. They also suggest that fNIRS monitoring may help refine stimulation parameters in future adaptive or closed-loop protocols.

4.2.2 Transcranial magnetic stimulation (TMS)

Repetitive transcranial magnetic stimulation (rTMS) modulates neuronal activity through electromagnetic induction, and its effects depend on stimulation frequency. Low-frequency stimulation (below 1 Hz) is generally inhibitory, whereas high-frequency stimulation (above 5 Hz) is excitatory [107]. fNIRS has been used to characterize these responses and to support individualized targeting [108]. In motor recovery, high-frequency stimulation of ipsilesional M1, especially with bilateral

arm training, has been associated with increased local hemoglobin concentration and improved inter-hemispheric balance [69,78]. Conversely, low-frequency stimulation of contralesional M1 may suppress maladaptive hyperactivation [85]. Individual responses remain variable and may depend on neurovascular characteristics [70].

Outside motor rehabilitation, fNIRS has also been used to study cognitive and language networks. High-frequency rTMS over the left DLPFC has been linked to stronger frontoparietal connectivity and improved working memory [109], whereas stimulation of Broca's area may recruit language-related networks in aphasia [19,29].

Intermittent theta-burst stimulation (iTBS) can induce plastic changes within a shorter period [64]. fNIRS studies suggest that iTBS produces activation patterns similar to high-frequency rTMS but with greater time efficiency. fNIRS has also been used to compare stimulation schemes such as combined cerebellum-SMA stimulation for balance-related networks [67]. These results support fNIRS monitoring during protocol optimization.

4.3 fNIRS in feedback-based rehabilitation

4.3.1 Visual feedback

Visual feedback forms a behavioral loop in which patients adjust movement using visual information about task performance. In most fNIRS studies, this feedback is not generated from fNIRS signals; fNIRS instead measures the accompanying cortical response. Increased ipsilesional M1 activation and stronger connectivity with prefrontal regions suggest recruitment of motor, attentional, and error-monitoring processes [61]. Visual context may also modulate these responses [40], but fNIRS-derived markers are rarely used to adapt feedback online.

4.3.2 Mirror therapy

Mirror therapy uses the visual illusion of paretic limb movement to compensate partly for impaired proprioception [32]. fNIRS studies show that observing mirrored movement can evoke cortical responses resembling active execution [110], particularly in ipsilesional M1 and may help restore inter-hemispheric balance without paretic-limb movement [58]. Combining mirror therapy with exoskeleton assistance may produce stronger cortical effects than passive mobilization [31].

4.3.3 Brain-computer interface (BCI)

BCI represents the pinnacle of central-intervention

strategies, decoding MI signals to drive external assistive devices. By bypassing damaged efferent pathways to mechanically execute the intended movement, BCI reinforces the “intention-action” link via Hebbian learning [111].

Within BCI-based rehabilitation, fNIRS can assess training effects or serve as a signal source. fNIRS studies indicate that BCI-triggered training often produces stronger and more focused cortical activation than open-loop MI or passive training, together with better motor scores [112]. As a signal source, fNIRS-based BCI uses hemodynamic features such as the slope and amplitude of HbO signals to classify movement intention [54]. Some studies suggest that successful BCI use is accompanied by strengthening of frontopolar control networks [49], implying that functional gains reflect genuine network reorganization rather than only peripheral adaptation. However, existing fNIRS-based BCI studies have rarely focused on real-time closed-loop decoding because of the intrinsic hemodynamic delay of fNIRS.

4.3.4 Muscle-computer interface (MCI)

In MCI, sEMG closes the feedback loop by converting muscle activity into visual or tactile cues. fNIRS assesses the associated cortical response. Combined fNIRS-MCI studies suggest that accurate biofeedback can increase contralateral M1 and PFC activation, linking peripheral training with central motor planning [91]. Longitudinal work also report improved inter-hemispheric balance and reduced antagonist co-contraction [113]. Inaccurate feedback may instead dampen cortical activation and interfere with learning [114], emphasizing the need for reliable signal processing.

5 Discussion

5.1 Methodological considerations for fNIRS-based assessment

The results of fNIRS are significantly influenced by the selection before signal analysis. ROI selection determines the cortical area for sampling, while task design determines the functional process represented by the hemodynamic response. Motor tasks may recruit different cortical regions depending on movement complexity, effort, and compensatory behavior, so the same experimental paradigm may provide different information across patients. Resting-state and MI paradigms can be extended to patients who cannot perform explicit movement, but their results describe different aspects of cortical function.

The analytical methods reviewed in this work also provide related but non-equivalent information. GLM describes regional task responses, whereas LI summarizes interhemispheric asymmetry. FC/EC and brain network analysis focus on interactions and brain organization. An increase in cortical activation doesn't necessarily indicate better recovery, as this may reflect additional neural recruitment, greater task effort, or inefficient processing. Similarly, a shift toward hemispheric symmetry may be consistent with functional reorganization, but its significance depends on lesion location, recovery stage, and task performance. Therefore, when multiple indicators present a consistent pattern and imaging changes are examined simultaneously with behavioral performance, the results will be more reliable.

Methodological standardization remains necessary for comparison across studies. Common procedures for optode localization, channel-quality assessment, preprocessing, and task reporting can reduce avoidable variability. At the same time, differences in head anatomy, lesion distribution, and residual function may require individualized cortical coverage or task difficulty. Such adjustments should be predetermined and recorded rather than introduced after examination of the results. For longitudinal studies, consistent probe placement and task execution are particularly important, because small differences between sessions may resemble physiological change. Using the same subject design and repeated measurements can improve interpretation, but their value depends on whether the recorded channels sample comparable cortical regions over time.

5.2 Clinical implications of fNIRS in stroke rehabilitation

In stroke rehabilitation, fNIRS is mainly used to assess treatment-related cortical change. Across robot-assisted training, electrical stimulation, acupuncture, non-invasive brain stimulation, and feedback-based therapies, it can show whether an intervention is accompanied by changes in regional activation, hemispheric balance, or FC. This information may help explain why patients with similar behavioral improvement exhibit different patterns of cortical reorganization. It may also identify physiological changes that are not fully represented by a single clinical scale. However, the results of fNIRS should be regarded as complementary to, rather than a replacement for, established clinical assessments. Cortical responses alone cannot establish whether an intervention has produced a clinically meaningful therapeutic effect.

Several practical features support its use in rehabilitation. fNIRS is portable, non-invasive, relatively tolerant of motion, and is suitable for upper-limb training, gait, balance tasks, and robotic assistance. During the

rehabilitation process, measurements can be repeated without being limited by space and operational procedures as in fMRI. Compared with EEG, fNIRS provides spatial information about cortical hemodynamics and is less affected by electromagnetic interference, which facilitates measurements during electrical or magnetic stimulation. These features allow researchers to study cortical responses under conditions closer to conventional treatment. However, relative movement tolerance cannot eliminate motion artifacts, and higher practicality alone is not sufficient to ensure that the measurement results have clinical significance.

The significance of fNIRS changes depends on its relationship with patient characteristics and functional outcomes. Increased activation after training may indicate an enhanced recruitment of the affected hemisphere, which may also indicate increased effort. Reduced activation may represent limited engagement or improved neural efficiency. These situations cannot be differentiated solely based on hemodynamic data. Therefore, the characteristics of the lesion, impairment severity, time after stroke, task completion, and changes in clinical scores should be considered together. Currently, most research evidence is based on group comparisons, while rehabilitation decisions involve individual patients. More consistent associations between fNIRS measures and clinically meaningful change are needed before these measures can support patient-level treatment selection or adjustment. At present, the most appropriate use is to strengthen treatment monitoring and physiological interpretation alongside established clinical outcomes.

5.3 Challenges and future directions

Technical and physiological factors limit the interpretation of fNIRS. The signal is mainly sensitive to superficial cortical tissue, while the effects related to deep lesions are indirectly manifested through changes in connected cortical regions. Stroke-related vascular damage and altered NVC may change the relationship between neural activity and HbO or HbR responses [7,84]. Dynamic tasks introduce motion artifacts, optode displacement, scalp blood-flow changes, and systemic physiological fluctuations. Therefore, reliable longitudinal measurement requires stable channel configurations, reproducible optode placement, documented individual adjustments, and predefined signal-quality criteria [14]. Sham or control conditions are also needed in intervention studies because observed responses may arise from task repetition, sensory input, attention, or spontaneous variation rather than the intended treatment.

Multimodal measurement may help separate these physiological components. EEG-fNIRS integration links electrical activity with hemodynamic response and provides a basis for assessing NVC [115]. fNIRS-sEMG integration relates cortical hemodynamics to peripheral muscle activity and can characterize changes in CMC [116]. These methods may help distinguish changes in cortical recruitment function from impaired vascular responses or low central-peripheral conduction efficiency. However, their value depends on accurate synchronization, analysis methods suited to different time scales, and maintaining stable coupling metrics in multiple experiments. Therefore, multimodal signals should be integrated around specific physiological problems rather than simply combined for the purpose of increasing available features.

Future directions may involve combined interventions and adaptive rehabilitation systems. Combining robot training or electrical stimulation with tDCS or rTMS may achieve a linkage from lower sensory-motor input to upper cortical regulation [71,100]. Any additional benefit needs to be compared with each component separately, as the improvements after the combined approach do not necessarily imply a synergistic effect. Closed-loop systems also face similar challenges. Currently, most fNIRS applications rely on offline classification or comparisons before and after intervention, whereas true closed-loop systems require the use of physiological information to adjust assistance, stimulation, feedback, or task difficulty during the same session [117]. EEG may support rapid detection of motor intention, while fNIRS may track slow changes in cortical recruitment or fatigue. Progress depends on reproducible individual-level measures, external validation, and evidence that signal-guided adaptation improves meaningful functional outcomes rather than classification performance alone.

6 Conclusions

This review has outlined an fNIRS-informed pathway for stroke rehabilitation. ROI and paradigm design determine what cortical activity is sampled; analytical methods convert hemodynamic signals into measures of regional recruitment, connectivity, and network organization; and intervention studies test whether these measures are sensitive to treatment-related change. fNIRS currently functions mainly as a quantitative cortical readout for assessment and treatment monitoring. Its use as a feedback variable for online parameter adjustment remains limited by biomarker reliability and hemodynamic delay. Multimodal recording and combined central-peripheral interventions may broaden

physiological interpretation, but they do not by themselves establish closed-loop control. Progress toward fNIRS-driven rehabilitation therefore depends on validating markers that are reproducible at the individual level, sensitive to clinically meaningful change, and suitable for use within adaptive treatment protocols.

Data availability The datasets used and/or analyzed during the current study are available from the corresponding author upon reasonable request.

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Competing Interests Honghai Liu is an Editorial Board Member for *ENGINEERING Health and Rehabilitation Engineering*. The paper was handled by another Editor and has undergone a rigorous peer review process. Honghai Liu was not involved in the Journal's peer review or decisions related to this manuscript. All other authors declare that they have no conflict of interest or financial conflicts to disclose.

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