The following publication Y. Gong et al., "The Use of Functional Near-Infrared Spectroscopy (fNIRS) for Monitoring Brain Function, Predicting Outcomes, and Evaluating Rehabilitative Interventional Responses in Poststroke Patients With Upper Limb Hemiplegia: A Systematic Review," in IEEE Journal of Selected Topics in Quantum Electronics, vol. 31, no. 4: Adv. in Neurophoton. for Non-Inv. Brain Mon., pp. 1-10, July-Aug. 2025, Art no. 6800210 is available at https://doi.org/10.1109/JSTQE.2025.3563153.

The Use of Functional Near-Infrared Spectroscopy (fNIRS) for Monitoring Brain Function, Predicting Outcomes, and Evaluating Rehabilitative Interventional Responses in Poststroke Patients with Upper Limb Hemiplegia: A Systematic Review

Yongan Gong*, Ruixuan Lin*, Murat Can Mutlu, Lukas Lorentz, Usman Jawed Shaikh, Joscha D Graeve, Niloufar Badkoubeh, Roy Rongyue Zeng, Franziska Klein, Michael Lührs, Klaus Mathiak, Jack Jiaqi Zhang#, David MA Mehler#

***Abstract* —Functional near-infrared spectroscopy (fNIRS) has been increasingly applied in poststroke research. The accumulated evidence in this area warrants a comprehensive review systematically investigating the utility of fNIRS in poststroke rehabilitation, specifically focusing on upper limb motor recovery. The target of this systematic review was the use of fNIRS for monitoring brain function, predicting outcomes, and evaluating rehabilitative interventional responses in poststroke patients with upper limb hemiplegia. A literature search was carried out using PubMed, Web of Science, EMBASE, Medline, and IEEE Explore, to identify studies that applied fNIRS in stroke survivors. A total of 52 studies were included, with 23 cross-sectional studies, 8 longitudinal studies and 21 interventional studies. The majority of the included fNIRS studies displayed a bilateral activation pattern in patients after stroke during paretic upper limb movement. The change in hemispheric laterality, measured by oxygenated hemoglobin concentration changes (Δ[HbO]) levels in different corticomotor regions, has been found to be correlated with motor recovery following a stroke. Various rehabilitation interventions, such as exercise-based, stimulation-based, and neurofeedback techniques, improved recovery outcomes by increasing Δ[HbO] levels in the ipsilesional sensorimotor and secondary motor areas. These interventions also recruit different brain regions connected to the ipsilesional sensorimotor area, thereby strengthening their connectivity. In conclusion, outcomes derived from fNIRS demonstrate promise in monitoring brain function, predicting outcomes, and evaluating responses to interventions in patients after stroke. Future fNIRS research can be enhanced by adhering to best practice checklists, utilizing the latest experimental setup and analysis protocols, and recruiting large sample sizes.**

***Index Terms*— Stroke; Functional Near-Infrared Spectroscopy; Upper limb; Neuroplasticity; Rehabilitation**[1]

I. INTRODUCTION

Stroke is the second leading cause of death and disability worldwide [1]. Over 85% of stroke survivors experience upper limb dysfunction [2], and around 65% of those who have survived a stroke retain residual upper extremity deficits six months or more after the onset of the stroke [3]. As a type of cerebrovascular disease, poststroke brain physiology is primarily characterized by pathological changes in cerebral hemodynamics. Therefore, hemodynamic signals can offer valuable information for monitoring brain function, predicting prognosis, and guiding poststroke rehabilitation interventions [4]. Magnetic resonance imaging (MRI) has been extensively utilized to evaluate cerebral blood flow following stroke [5]. For example, arterial spin labelling has been used as one of MRI techniques for the detection of cerebral perfusion deficit and ischemic penumbra. The outcome indicator offers reliable monitoring of cerebral blood flow and valuable insights for prognostic prediction following an acute stroke [6].

In addition to cerebral perfusion imaging, functional MRI (fMRI) provides unique insight into the recovery in poststroke patients [7, 8]. Poststroke recovery can be understood through two key conceptual models: the hemispheric rivalry model and the vicariation model [9, 10]. The hemispheric rivalry model describes that the recovery following stroke is linked to the rebalance of the bilateral hemispheric activities, with the decrease in the hyperinhibitory flow from the contralesional hemisphere to the ipsilesional hemisphere, while the vicariation model describes that the recovery after stroke is associated with

---

[1] This study was partially supported by the National Natural Science Foundation of China (NSFC): Young Scientists Fund (ref No. 82402987), Start-up Fund for Research Assistant Professors under the Strategic Hiring Scheme, The Hong Kong Polytechnic University (ref No. P0048866) and Advanced Research Opportunities Program (AROP) Fellowship, RWTH Aachen University to JZ, The RWTH Junior Principal Investigator (JPI) fellowship funded by the Excellence Strategy of the Federal Government and the Laender (Grant No. JPI074-21) to DMAM; the China Scholarship Council PhD Studentship to YG (ref No.20230808183); and the RGC-DAAD Germany-Hong Kong Joint Research Scheme to JZ, DMAM, LL, UJS, and KM (ref No. G-PolyU508/24).
Yongan Gong, Murat Can Mutlu, Joscha Graeve, Niloufar Badkoubeh, Franziska Klein, Klaus Mathiak, and David MA Mehler are affiliated with the Department of Psychiatry, Psychotherapy and Psychosomatics, University Hospital RWTH Aachen, Aachen, Germany. Ruixuan Lin, Roy Rongyue Zeng, Jack Jiaqi Zhang are affiliated with the Department of Rehabilitation Sciences, The Hong Kong Polytechnic University. Lukas Lorentz and Usman Jawed Shaikh are affiliated with Division of Clinical Cognitive Sciences, Department of Neurology, University Hospital RWTH Aachen. Michael Lührs is affiliated with the Faculty of Psychology and Neuroscience, Maastricht University and Brain Innovation B.V., Maastricht, The Netherlands.David MA Mehler is also affiliated with Institute of Translational Psychiatry, Medical Faculty, University of Münster, Münster, Germany, and Cardiff University Brain Research Imaging Centre (CUBRIC), School of Psychology, Cardiff University, Cardiff, UK. Franziska Klein is also affiliated with Biomedical Devices and Systems Group, R&D Division Health, OFFIS—Institute for Information Technology, Oldenburg, Germany.

*Yongan Gong and Ruixuan Lin contributed equally to this article and share first authorship. Jack Jiaqi Zhang and David MA Mehler contributed equally and share senior authorship. #Corresponding authors: Jack Jiaqi Zhang (jack-jiaqi.zhang@polyu.edu.hk) and David MA Mehler (dmehler@ukaachen.de).

the capacity of the contralesional hemisphere in substituting for the function of the ipsilesional hemisphere, especially when the ipsilesional hemisphere is severely damaged [11]. Longitudinal fMRI studies have revealed a shift occurs from initial activation in the contralesional hemisphere during paretic hand movement execution to later activation returning to the ipsilesional hemisphere, indicating a rebalancing of bilateral hemispheric activity during motor recovery following a stroke [12, 13]. According to a meta-analysis of fMRI studies, the level of activation in the ipsilesional primary motor (M1) and premotor cortex (PMC) during movement execution with affected upper limb was associated with a favorable recovery outcome [14]. In addition, another study showed that increased activation in contralesional M1 and PMC was associated with functional recovery in severely affected stroke survivors [15]. Therefore, these fMRI studies have provided empirical evidence to support both conceptual models of poststroke recovery.

Motor recovery following stroke is also closely associated with neural reorganization in the connectivity and network levels [16]. For instance, some longitudinal fMRI studies have shown that changes in interregional connectivity between the bilateral SMC correlate with improvements in motor functions of the affected upper limb in patients with stroke [17-19]. In addition, brain network analysis based on graph theory has been increasingly applied in fMRI studies with poststroke patients in outcome evaluation and prognostic prediction [20].

Further, neural correlates of motor recovery processes have been targeted via real-time fMRI neurofeedback training with the aim of promoting functional reorganization of disturbed brain activity and inducing neuroplasticity [21]. For instance, cortical target brain areas for real-time fMRI neurofeedback training included the supplementary motor area (SMA) [22], and its activity was entrained using a graded kinesthetic motor imagery (MI) paradigm. A more recent randomized controlled trial (RCT) targeted the laterality index (LI) of the M1 during a motor execution task [23].

To date, neuroscientific and clinical mechanistic research in poststroke recovery has primarily been supported by(f)MRI or fMRI-based real-time neurofeedback. However, the use of (f)MRI is often limited by its high cost, accessibility issues, patient discomfort, sensitivity to motion, and the complexity of data interpretation. Functional near-infrared spectroscopy (fNIRS) on the other hand, is a more mobile and cost-effective hemodynamic optical neuroimaging modality, compared to fMRI, making it an ideal neuroimaging solution for real-world clinical applications [24, 25]. fNIRS detects changes in the concentrations of oxygenated hemoglobin (Δ[HbO]) and deoxygenated hemoglobin ([ΔHbR]) associated with neuronal activity [26]. Compared to fMRI, fNIRS measurements can be conducted in an upright position and without physical restraints during task execution, or even during walking (as it is less susceptible to motion artifacts) [27]. Therefore, it is much easier to use fNIRS in various functional task conditions to evaluate task-specific hemodynamic changes in relevant brain regions. [28]. Over the past decade, fNIRS has rapidly emerged as a functional neuroimaging tool in neuroscience and rehabilitation research [29].

Several reviews were published on the utility of fNIRS in stroke [30-35], majority of which were narrative reviews [30, 32-35]. These narrative reviews outlined the fundamental knowledge and analytical methods of fNIRS, with limited coverage of research studies related to stroke. A systematic review published in 2019 [31] examined the research scope of fNIRS in stroke rehabilitation, focusing on its applications in brain monitoring, as a brain-computer interface (BCI) for interventions, and additional applications such as assessing stroke risk during surgery and monitoring muscle metabolic indices. However, this review did not include a focused discussion on the utility of fNIRS for upper limb hemiplegia after stroke. Moreover, the review did not include an assessment of technical fNIRS specifications that would allow us to evaluate aspects such as data quality. To fill this gap, we conducted a systematic review to analyze the scope and progress of fNIRS applications in post-stroke rehabilitation, with a focus on upper limb motor recovery. As illustrated in Figure 1, the aim of this review was to address the following research questions: (1) How do cerebral hemodynamic responses, measured by continuous-wave (CW) fNIRS, differ between the two hemispheres in stroke patients compared to healthy individuals? (2) Can cerebral hemodynamic responses measured at baseline, or changes in hemodynamics across recovery, as measured by fNIRS, serve as a predictor of future motor functional outcomes in stroke patients? (3) Are cerebral hemodynamics measured by fNIRS during or after treatment correlated with clinical outcomes in poststroke survivors?

II. METHODS

This systematic review has been prospectively registered on the online platform PROSPERO (ID: CRD42024606647). We followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses statements (PRISMA) in the reporting of the current review [36].

A. Search Strategy

A comprehensive literature search was conducted in multiple databases, including PubMed, MEDLINE, Web of Science, EMBASE and IEEE Explore., covering studies from their inception through 21 May 2024. The search was based on the Title/Abstract using the following combination of keywords: (stroke OR cerebrovascular disorder OR cerebrovascular disease OR cerebrovascular accident OR cerebral infarction OR cerebral hemorrhage OR cerebral hemorrhage) AND (NIRS OR near-infrared spectroscopy). Medical Subject Heading Terms were applied when searching PubMed. Three groups of two authors (YG, RL; MCM, JG; UJS, and LL) independently scanned all titles, read the abstracts, and identified relevant studies. A manual screening was also conducted to identify target articles in the reference lists of previous relevant reviews.

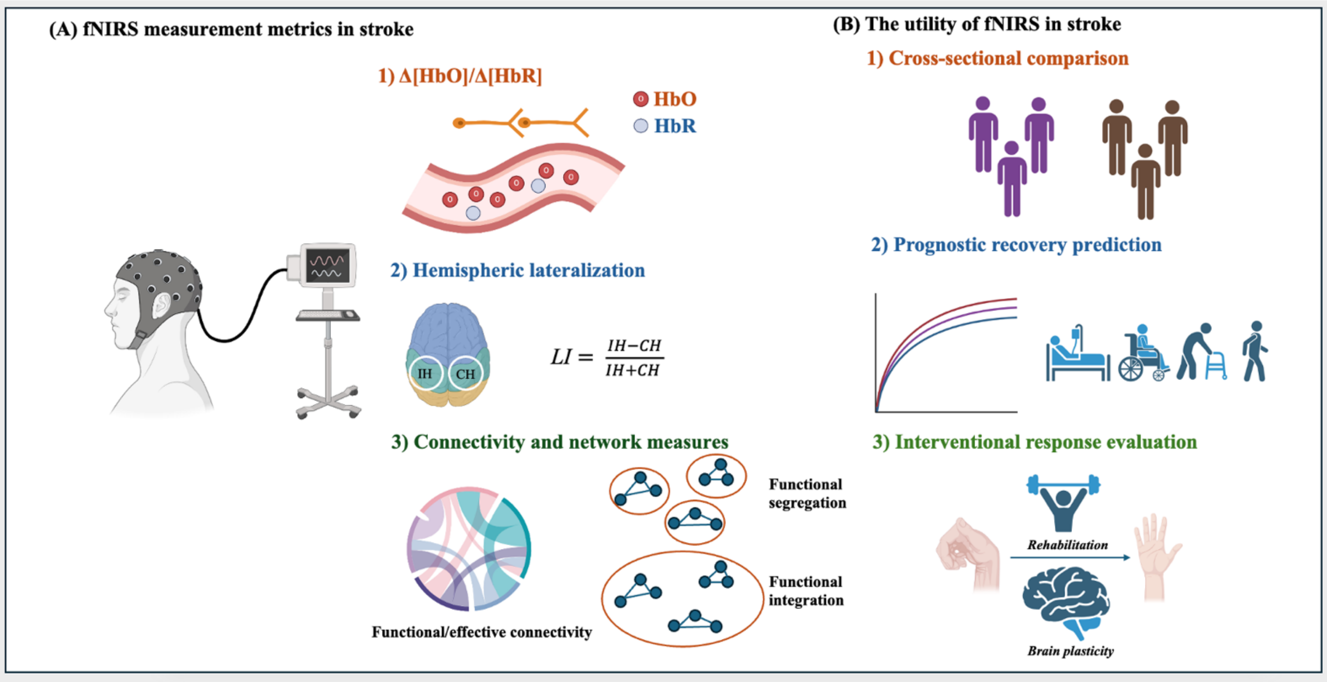


Figure 1: Conceptual framework of the review. (A) Different types of fNIRS metrics in stroke research. (B) The utility of fNIRS in stroke research. Figure created with BioRender.com/s91w503 (Agreement Number: QY27LQ6NFJ) and Microsoft PowerPoint. Abbreviations: fNIRS: Functional near-infrared spectroscopy. LI: Laterality index; IH: Ipsilesional hemisphere; CH: Contralesional hemisphere.

B. Selection criteria

Study selection was carried out according to the inclusion and exclusion criteria. After study selection, two authors (YG and RL) concluded the list of included studies. Any discrepancy was resolved by a senior author (JZ).

Inclusion criteria:

Population: adult patients with upper limb hemiplegia who have had a stroke.

Measurement outcomes: Changes in concentration of oxygenated hemoglobin (Δ[HbO]) and deoxygenated hemoglobin (Δ[HbR]) measured by CW-fNIRS. Any outcome calculated based on Δ[HbO] and/or Δ[HbR], such as LI, functional or effective connectivity (FC/EC) and network measures, were also considered. An inclusion criterion was that the studies had to use a standardized task related to the upper extremities for the fNIRS measurements such as MI, action observation, or execution of movements.

Study type: We included observational studies (both cross-sectional and longitudinal studies), as well as interventional studies (including single group studies without a control group, non-randomized and randomized controlled studies).

Intervention: Among the interventional studies that we screened, we included all types of nonpharmacological, rehabilitative interventions targeting the hemiparetic poststroke upper limb, including but not limited to exercise-based interventions, peripheral/central neural stimulation modalities, and BCI/neurofeedback/biofeedback, etc.

Exclusion criteria:

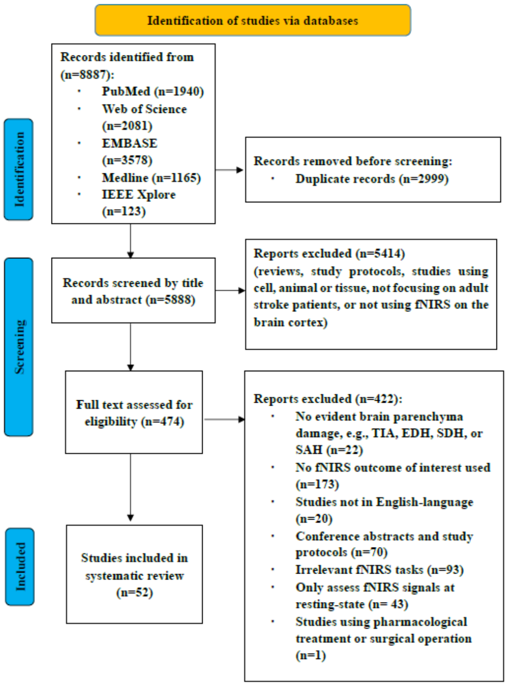
Studies meeting any of the following criteria were excluded: 1) the study only enrolled participants with other neurological diseases excluding stroke; 2) the study was published as conference abstracts, dissertations, or in books; 3) among the interventional studies, pharmacological or surgical operation was applied as the main treatment; 4) fNIRS signal was only recorded and analyzed during resting-state, or an irrelevant task state (e.g., cognitive or emotional tasks), or 5) the study was not published in English language.

C. Methodological quality assessment

The Physiotherapy Evidence Database (PEDro) scale [37] was used to assess the methodological quality of the randomized controlled trials included in this review. Two authors (YG and RL) independently evaluated the quality of the studies. In cases of discrepancies, a senior author (JZ) discussed the evaluations with the two authors to reach a consensus.

D. Data extraction

We categorized the included studies into three groups: (1) Cross-sectional studies that compared fNIRS outcomes between stroke patients and healthy individuals, or within a group of stroke patients. (2) Longitudinal studies have assessed the predictive value of fNIRS outcomes for poststroke recovery during the first three months, a period in which spontaneous biological recovery, rather than rehabilitative training protocols, predominantly influences functional improvement. These studies should investigate the predictive value of baseline fNIRS data in relation to functional recovery poststroke and explore the parallel changes between fNIRS data and motor function over time. (3) Interventional studies that explored the impact of rehabilitative interventions on fNIRS outcomes in poststroke patients. Characteristics of each study, including demographics and clinical information of participants, information related fNIRS task, and main results, were extracted. Additionally, we summarized technical information related to the fNIRS device (number of fNIRS channels, manufacturer), as well as some key aspects related to data analysis, the use of short-distance channels (SDC) to remove or correct signals stemmings fromextracerebral tissue, head motion artefacts correction algorithms, and localization methods employed during fNIRS measurement. These methodological aspects are key aspects to ensure high data quality and can have a substantial impact on reported results [38-40].



III. RESULT

Searching results

The online literature search on the five databases identified 8887 citations. After screening the records according to the inclusion and exclusion criteria, 52 articles met the inclusion criteria [41-92], with 23 cross-sectional studies [41-63] (Table 1 in the Appendix), 8 longitudinal studies [64-69, 73, 82] (Table 2 in the Appendix), and 21 interventional studies [70-72, 74-81, 83-92] (Table 3 in the Appendix). Figure 2 shows the flowchart of study selection.

Figure 2: Flowchart of study selection. Abbreviations: EDH: Epidural hematoma; SDH: Subdural hematoma; SAH: Subarachnoid hemorrhage; TIA: Transient ischemic attack; fNIRS: Functional near-infrared spectroscopy.

A. Results of cross-sectional study

In this category of studies, the primary focus was to compare the differences in cerebral hemodynamics between stroke patients and healthy individuals, as well as the variations in hemodynamics between the two hemispheres in poststroke patients with different severities and types (Table 1).

The majority of the included studies reported an increase in Δ[HbO] across various brain regions, such as sensorimotor cortex (SMC), PMC, SMA, and prefrontal cortex (PFC), in patients after stroke during upper limb movement (either affected or unaffected upper limb movement) [41-63]. Some studies have shown that stroke patients typically exhibit an increase in Δ[HbO] over the bilateral SMC during paretic hand/upper limb movement, while their healthy counterparts demonstrate unilaterally dominant increase in Δ[HbO] over the contralateral hemisphere [41, 43, 46, 48, 49, 61]. In some of these studies, this was characterized by a LI toward the contralesional side (ipsilateral to the moving hand), or close to zero (indicating bilateral activation) in poststroke patients, compared to an LI toward the contralateral side in healthy controls [49, 53, 62, 63]. These findings support the assumption of contralesional involvement during paretic upper limb movement in poststroke patients. Furthermore, the degree of Δ[HbO] increase was associated with task intensity; specifically, greater force exerted by the affected hand corresponded to higher levels in Δ[HbO] of the bilateral SMC [44]. Providing sensory feedback during movement execution, such as vibration or visual cues, resulted in a greater HBbO concentration in the corresponding SMC and SMA of the ipsilesional side [45, 46, 50, 52, 56], in comparison to movement execution condition without sensory feedback . Similarly, providing visual observational feedback during MI also led to a greater increase in Δ[HbO] in the corresponding SMC and SMA of the ipsilesional side, compared to that induced by MI alone [50]. One MI study showed that, compared to left hemispheric stroke patients, right hemispheric stroke patients show lower Δ[HbO] in the bilateral PFC and SMC during imagery [56].

Some studies have indicated between-group differences in brain connectivity metrics when comparing stroke patients and healthy individuals, however, the results seemed not fully consistent. Compared to healthy controls, stroke survivors exhibited a lower FC value measured by Pearson's correlation between bilateral M1 and PFC [48] In another study, the EC value was higher as measured by transfer entropy between M1 and PFC [47]. A study found that patients with severe stroke had more widespread FC in the bilateral PFC and in themotor and occipital areas during assistive movement of the affected upper limb than patients with moderate stroke [51]. Using network measures, post-stroke patients showed a reduced clustering coefficient (CC, a measure of functional segregation) and global efficiency (GE, a measure of functional integration) based on the connectivity among the bilateral SMA, SMC and M1 [53, 61], compared to their healthy counterparts. Furthermore, it has been shown that the network during movement execution can be strengthened if excitatory repetitive transcranial magnetic stimulation (rTMS) [57, 58]. Some studies reported a correlation between CC and GE (M1 and PFC areas) and hemiplegic upper limb motor functions in poststroke patients [53, 54, 61]. Overall, it should be noticed that the sample sizes were rather small in most studies, with only six out of 23 cross-sectional observational studies including at least 20 patients (max n = 35).

B. *Result of longitudinal study*

Eight longitudinal studies investigated the relationship between cerebral hemodynamics and recovery of upper limb function in a timespan ranging from one week to 3 months in stroke patients [64-69, 73, 82], as summarized in Table 2. In these studies, four indicated that patients received conventional rehabilitation, such as occupational or physical therapy, during the observational period [65, 66, 68, 69]. Two studies specified the training protocols as mirror therapy [73] or task-oriented training [82], in combination with conventional rehabilitation, while the interventions were not specified in the other two studies [64, 67]. Two of these studies found a positive correlation between changes in the LI and the extent of functional recovery after stroke, indicating that increased activation in the ipsilesional hemisphere is associated with a favorable motor outcome [64, 65]. In contrast, one study found that a shift of activation towards the contralesional SMC was positively correlated with improvements in functional performance measured by the action research arm test in poststroke patients with moderate to severe upper limb hemiparesis [66]. Another study indicated that the LI of the bilateral SMA measured at baseline was associated with upper limb prognosis, with an activation towards the contralesional

SMA correlating with a favorable recovery outcome [69]. Another experiment also indicated that participants who can exhibit a PC activation pattern similar to that of healthy individuals, with increased activation on the ipsilesional side and decreased activation on the contralesional side, are more likely to benefit from mirror therapy [73]. In one study, improvements in upper limb motor function were also found to be related to a decrease in cortical metabolic cost over the bilateral SMC (calculated by the area under the curve of Δ[HbO]) [67]. Additionally, one study found that activation in the ipsilesional SMC during movement execution with the affected hand was increased after three weeks compared with that measured after one week in moderate and severe stroke; however, the correlation between hemodynamic changes and clinical outcome was not investigated [68]. Another study has also demonstrated similar conclusions, revealing reduced activation in the ipsilesional PMC and PFC four weeks after patients performed tasks on the affected side and also showed improvements in clinical motor test scores for all participants [82]. Three of the six studies included at least 20 patients (Table 2).

C. Result of interventional study

A total of 21 interventional studies used fNIRS as the outcome measure [70-72, 74-81, 83-92]as summarized in Table 3. Among the included studies, the types of intervention can be categorized into exercise-based [70, 74, 78, 85, 87-89], peripheral/central electrical/magnetic stimulation [71, 75, 76, 81, 84, 90-92], and BCI, neurofeedback or biofeedback [72, 77, 79, 80, 83, 86] intervention studies.

Seven studies used the exercise-based intervention, this kind of intervention included constraint-induced therapy, mirror therapy, robot-assisted therapy, task-oriented training, and traditional rehabilitation therapy, which include physiotherapy or occupational therapy. Most of the studies have demonstrated that these interventions led to increased Δ[HbO] in the ipsilesional PMC, M1, SM1 and PFC after intervention [74, 78, 85, 88, 89]. Additionally, some studies reported a change in LI after intervention, specifically a shift of activation towards the ipsilesional SMC and PMC after intervention [70, 87-89]. Moreover, using connectivity measures, enhancements in FC have also been observed after intervention, such as the FC between bilateral PFC and M1, as well as between the bilateral M1 [87].

Eight studies applied peripheral/central stimulation, including functional electrical stimulation (FES), neuromuscular electrical stimulation (NMES), rTMS, transcranial direct current stimulation (tDCS), and transcutaneous auricular vagus nerve stimulation (taVNS) as the intervention [71, 75, 76, 81, 84, 90-92]. Similar to studies using exercise-based intervention, changes in LI were observed after stimulation, particularly a shift in activation from the contralesional hemisphere to the ipsilesional side [71, 75, 76, 84, 92]. Furthermore, stimulation-based interventions also strengthened brain connectivity. For instance, contralaterally controlled NMES was shown to enhance FC between ipsilesional M1 and contralesional M1 and S1, and between ipsilesional PFC and contralesional M1 and S1 [81], while tDCS was shown to increase FC between the ipsilesional M1 and PMC [90]. The change in network properties (node strength and CC) of the ipsilesional hemisphere were found to be correlated with the improvement of upper extremity function in a rTMS study [84].

Six studies used BCI, neurofeedback, or biofeedback as the intervention [72, 77, 79, 80, 83, 86]. The results demonstrated an improvement of the upper limb function and an increase in the cortical activation in the bilateral M1 and PFC as well as the ipsilesional PMC [72, 79, 80, 83, 86]. Biofeedback training has also shown to have the potential to rebalance the brain, which was characterized by a shift in LI towards the affected SMC and approaching zero, i.e., a more balanced activation pattern after intervention [77]. Overall, only six out of 21 interventional studies included a sample size of at least 20 patients (Table 3).

D. Result of technical aspects of the included fNIRS studies.

Table 4 in the Appendix presents an overview of the technical aspects of all fNIRS studies included in this review. Digital methods of optode localization, the use of SDCs to regress out cutaneous blood signals, and motion artifact correction are key elements to ensure data quality in fNIRS analysis pipelines. While their use is considered best practice [93], a consensus with regards to optimal parameter settings and approaches remains to be established. Most studies (36 out of 52) followed the standardized EEG 10-20 cap placement alone for probe placement without using digitizer or individual MRI. A 3D digitizer was used for digitizing optode positions in 11 studies, while individual MRI was utilized in only 2 studies.

Only one study employed SDCs during data collection. Motion artifact correction was applied in 25 out of the 52 papers.

E. Result of methodological quality assessment of the include RCTs

Table 5 in the appendix presents the results of the methodological quality assessment based on the PEDro scale [37], which was performed for the ten randomized controlled trials (RCTs) included in this review. The mean quality score was 7.4 out of 10, with individual scores ranging from 7 to 10, indicating high reporting quality and methodological rigor of the included RCTs.

V. DISCUSSION

The current review investigates the use of fNIRS for monitoring brain function, predicting outcomes, and evaluating responses to rehabilitative interventions in poststroke patients with upper limb hemiplegia. The main findings can be summarized as follows: (1) In line with previous fMRI findings, fNIRS studies confirmed that poststroke patients exhibit a bilateral activation pattern during the execution of movement with the paretic hand [41, 43, 46, 48, 49, 53, 61-63]. The addition of sensory feedback during movement execution increases activation in the ipsilesional corticomotor region (primary and secondary motor areas) [45, 46, 50, 52, 56],. Impaired network and connectivity patterns in the corticomotor areas were also observed in these patients using fNIRS. [47, 48, 51, 53, 54, 61]. (2) Hemispheric laterality in different corticomotor regions, such as M1 or SMA, has been found to be paralleled with or predictive of motor recovery after stroke [64-67]. (3) Various rehabilitation interventions, including exercise, stimulation, and BCI/neurofeedback/biofeedback, have shown the potential to improve rehabilitation outcomes by modulating cortical activation in the ipsilesional SMC and secondary motor regions [70-80, 82-89, 92]. The intervention was able to recruit different brain regions, such as PFC or secondary motor areas, to support the functioning of the ipsilesional SMC, by strengthening their connectivity [81, 84, 87, 90].

A classic pathological change observed in poststroke brains is the overactivation of bilateral corticomotor regions when patients move the paretic upper limb. This phenomenon has been consistently documented in fMRI studies involving ischemic subcortical stroke patients [94, 95]. A shift in activation toward the ipsilesional hemisphere is associated with the recovery of upper limb function [95]. We also observed these classic bilateral activation patterns in several fNIRS studies included in the present systematic review. Furthermore, the LI measured by fNIRS correlated with motor recovery and was influenced by rehabilitation interventions [64-67]. This consistency between fNIRS and fMRI findings indicates that fNIRS may be a viable alternative to fMRI for mechanistic studies of brain function in stroke rehabilitation, particularly in the context of the cortical recovery model.

It is noteworthy that all included studies used Δ[HbO] as the primary outcome indicator in their analyses, even though Δ[HbR] was typically measured simultaneously. It has been documented that changes in Δ[HbR are associated with the blood-oxygen-level-dependent signal, detected in fMRI [96]. Also, the reporting of both Δ[HbO] and Δ[HbR] has been recommended [25, 97] to better understand the underlying neurovascular coupling process. Noteworthy, only one study used SDCs. SDCs are created with a source-detector distance of less than 1 cm (ideally 8 mm for adults) [98, 99]. These shorter distances limit the penetration depth of the source signal and primarily capture extracerebral contributions, such as signals from the scalp and skull. Therefore, SDCs provide a way to measure and correct for these extracerebral signals, improving the accuracy of cerebral hemodynamic measurements in fNIRS studies [98]. SDCs hence capture local estimates of physiological noise that can be regressed out from the fNIRS signal time series to avoid contaminations and yield more precise and accurate measurements [100]. Among the studies that did not utilize SDCs, we found that no alternative algorithmic approaches—such as common averages, principal component analysis, or global component removal [101]—was used to exclude the impact of cutaneous blood flow on the neural signal captured by fNIRS. Furthermore, although motion artifacts are a significant source of noise in fNIRS, several studies have not implemented any motion artifact correction algorithms in their data analysis pipelines. Future research should follow reporting checklists [93, 102, 103], including protocol preregistration to ensure more transparent and comprehensive study planning and reporting [40, 104, 105], and employ preprocessing techniques and hardware developments that allow to enhance the utility of fNIRS in stroke research [101, 106]. Current work of the fNIRS research community also provides easy access to a glossary of relevant concepts and developments in the fNIRS field [107]. Moreover, larger sample sizes are needed to yield more robust effect size estimates and a higher chance for conclusive findings [108].

As stroke is a heterogeneous disease, the type, severity, and chronicity of stroke may influence the cerebral hemodynamic response. However, most of the included studies enrolled a mixed sample of stroke patients, likely due to the challenges in recruiting a very specific poststroke cohort. The impact of clinical profiles regarding stroke on fNIRS outcomes has not been thoroughly investigated, although a few studies have compared the effects of stroke side and severity on fNIRS results [51, 53, 56, 91]. Investigating these confounding effects could be a valuable area for future research.

Limitations: This review is qualitative in nature and no meta-analysis was conducted due to the heterogeneity among studies regarding design, outcome measures, and other factors. To allow for more specific conclusions regarding the reported neural correlates, the scope of this review was focused on fNIRS applications related to upper limb motor tasks. Consequently, the use of fNIRS in other areas, such as lower limb rehabilitation, cognition, and emotion in stroke recovery, was not considered. Additionally, we acknowledged the potential confounding effects due to the heterogeneity of stroke types on the results concerning varying cortical activation and intercortical connectivity, as the majority of the included studies enrolled a mixed group of stroke patients. Lastly, this review may include potential publication bias, exclusion of non-English language studies, and differences in the quality and methodology of the reviewed studies, which could affect the generalizability of the results.

IV. CONCLUSION

There is growing evidence supporting the use of fNIRS for monitoring brain function, predicting outcomes, and evaluating responses to interventions in patients after a stroke. Future fNIRS research can be improved by following best practice checklists, utilizing the latest experimental setup and analysis protocols, and recruiting large sample sizes.

VI. APPENDIX

Table 1. Characteristics of the included cross-sectional studies

Table 2. Characteristics of the included longitudinal studies

Table 3. Characteristics of the included interventional studies

Table 4. Technical aspects of included studies

Table 5. Methodological quality assessment of included randomized controlled trials

ACKNOWLEDGEMENT

The authors thanks Ms Bella Bingbing Zhang (Hong Kong Polytechnic University) for her help in preparation of the visualization.

CONFLICT OF INTEREST

ML is COO of Brain Innovation B.V., Maastricht, The Netherlands. This has not affected the content or quality of this work. All other authors declare no conflict of interest.

REFERENCES

[1] V. L. Feigin *et al.*, "Global, regional, and national burden of stroke and its risk factors, 1990ñ2019: a systematic analysis for the Global Burden of Disease Study 2019," *Lancet Neurol.,* vol. 20, no. 10, pp. 795-820, 2021.

[2] P. Raghavan, "Upper Limb Motor Impairment After Stroke," *Phys Med Rehabil Clin N Am N.,* vol. 26, no. 4, pp. 599-610, 2015, doi: 10.1016/j.pmr.2015.06.008.

[3] B. H. Dobkin, "Rehabilitation after Stroke," *Engl. J. Med.,* vol. 352, no. 16, pp. 1677-1684, 2005, doi: doi:10.1056/NEJMcp043511.

[4] A. S. Salinet, V. J. Haunton, R. B. Panerai, and T. G. Robinson, "A systematic review of cerebral hemodynamic responses to neural activation following stroke," *J. Neurol. y,* vol. 260, pp. 2715-2721, 2013.

[5] E. H. Lo, T. Dalkara, and M. A. Moskowitz, "Mechanisms, challenges and opportunities in stroke," *Nat. Rev. Neurosci.,* vol. 4, no. 5, pp. 399-414, 2003/05/01 2003, doi: 10.1038/nrn1106.

[6] A. A. ElBeheiry, M. A. Hanora, A. F. Youssef, A. A. M. Al Neikedy, A. Elhabashy, and H. M. Khater, "Role of arterial spin labeling magnetic resonance perfusion in acute ischemic stroke," *Egypt J Radiol Nucl Med,* vol. 54, no. 1, p. 43, 2023/02/23 2023, doi: 10.1186/s43055-023-00980-8.

[7] N. S. Ward, M. M. Brown, A. J. Thompson, and R. S. J. Frackowiak, "Neural correlates of motor recovery

after stroke: a longitudinal fMRI study," *Brain,* vol. 126, no. 11, pp. 2476-2496, 2003, doi: 10.1093/brain/awg245.

[8] C. Calautti and J.-C. Baron, "Functional neuroimaging studies of motor recovery after stroke in adults: a review," *Stroke,* vol. 34, no. 6, pp. 1553-1566, 2003.

[9] N. Murase, J. Duque, R. Mazzocchio, and L. G. Cohen, "Influence of interhemispheric interactions on motor function in chronic stroke," *Ann Neurol,* vol. 55, no. 3, pp. 400-409, 2004.

[10] C. Butefisch *et al.*, "Recruitment of contralesional motor cortex in stroke patients with recovery of hand function," *Neurology,* vol. 64, no. 6, pp. 1067-1069, 2005.

[11] G. Di Pino *et al.*, "Modulation of brain plasticity in stroke: a novel model for neurorehabilitation," (in eng), *Nat Rev Neurol,* vol. 10, no. 10, pp. 597-608, Oct 2014, doi: 10.1038/nrneurol.2014.162.

[12] Y. Kim, S. You, Y. Kwon, M. Hallett, J. Kim, and S. Jang, "Longitudinal fMRI study for locomotor recovery in patients with stroke," *Neurology,* vol. 67, no. 2, pp. 330-333, 2006.

[13] D. Tombari *et al.*, "A longitudinal fMRI study: in recovering and then in clinically stable sub-cortical stroke patients," *Neuroimage,* vol. 23, no. 3, pp. 827-839, 2004.

[14] I. Favre, T. A. Zeffiro, O. Detante, A. Krainik, M. Hommel, and A. Jaillard, "Upper Limb Recovery After Stroke Is Associated With Ipsilesional Primary Motor Cortical Activity," *Stroke,* vol. 45, no. 4, pp. 1077-1083, 2014/04/01 2014, doi: 10.1161/STROKEAHA.113.003168.

[15] A. K. Rehme, G. R. Fink, D. Y. von Cramon, and C. Grefkes, "The Role of the Contralesional Motor Cortex for Motor Recovery in the Early Days after Stroke Assessed with Longitudinal fMRI," *Cerebral Cortex,* vol. 21, no. 4, pp. 756-768, 2010, doi: 10.1093/cercor/bhq140.

[16] A. G. Guggisberg, P. J. Koch, F. C. Hummel, and C. M. Buetefisch, "Brain networks and their relevance for stroke rehabilitation," *Clin Neurophysiol,* vol. 130, no. 7, pp. 1098-1124, 2019/07/01/ 2019, doi: https://doi.org/10.1016/j.clinph.2019.04.004.

[17] Y. Zhang *et al.*, "Relationship between functional connectivity and motor function assessment in stroke patients with hemiplegia: a resting-state functional MRI study," *Neuroradiology,* vol. 58, pp. 503-511, 2016.

[18] H. Liu, T. Tian, W. Qin, K. Li, and C. Yu, "Contrasting evolutionary patterns of functional connectivity in sensorimotor and cognitive regions after stroke," *Front Behav Neurosci,* vol. 10, p. 72, 2016.

[19] X. Zheng *et al.*, "The plasticity of intrinsic functional connectivity patterns associated with rehabilitation intervention in chronic stroke patients," *Neuroradiology,* vol. 58, pp. 417-427, 2016.

[20] M. N. Hallquist and F. G. Hillary, "Graph theory approaches to functional network organization in brain disorders: A critique for a brave new small-world," (in eng), *Netw Neurosci,* vol. 3, no. 1, pp. 1-26, 2019, doi: 10.1162/netn_a_00054.

[21] T. Wang, D. Mantini, and C. R. Gillebert, "The potential of real-time fMRI neurofeedback for stroke rehabilitation: A systematic review," *Cortex,* vol. 107, pp. 148-165, 2018.

[22] D. M. Mehler *et al.*, "Graded fMRI neurofeedback training of motor imagery in middle cerebral artery stroke patients: a preregistered proof-of-concept study," *Frontiers in human neuroscience,* vol. 14, p. 226, 2020.

[23] Z.-B. Sanders *et al.*, "Self-modulation of motor cortex activity after stroke: a randomized controlled trial," *Brain,* vol. 145, no. 10, pp. 3391-3404, 2022.

[24] A. von Lühmann *et al.*, "Toward Neuroscience of the Everyday World (NEW) using functional near-infrared spectroscopy," *Curr Opin Biomed Eng,* vol. 18, p. 100272, 2021.

[25] F. Klein, S. H. Kohl, M. Lührs, D. M. Mehler, and B. Sorger, "From lab to life: challenges and perspectives of fNIRS for haemodynamic-based neurofeedback in real-world environments," *Philosophical Transactions B,* vol. 379, no. 1915, p. 20230087, 2024.

[26] F. Scholkmann *et al.*, "A review on continuous wave functional near-infrared spectroscopy and imaging instrumentation and methodology," *Neuroimage,* vol. 85, pp. 6-27, 2014.

[27] P. Thönnessen, L. C. Bollheimer, M. Lührs, U. Habel, B. Sorger, and C. Huppertz, "(Interfering) Cortical mechanisms of standing balance and cognition in old-age depression: A functional near-infrared spectroscopy (fNIRS) study," *Psychiatry Research: Neuroimaging,* vol. 345, p. 111905, 2024.

[28] Y. Hoshi and M. Tamura, "Detection of dynamic changes in cerebral oxygenation coupled to neuronal function during mental work in man," *Neuroscience letters,* vol. 150, no. 1, pp. 5-8, 1993.

[29] P. Pinti *et al.*, "The present and future use of functional near infrared spectroscopy (fNIRS) for cognitive neuroscience," *Annals of the new York Academy of Sciences,* vol. 1464, no. 1, pp. 5-29, 2020.

[30] X. Sun *et al.*, "Current implications of EEG and fNIRS as functional neuroimaging techniques for motor recovery after stroke," *Medical Review,* 2024, doi: doi:10.1515/mr-2024-0010.

[31] M. Yang, Z. Yang, T. Yuan, W. Feng, and P. Wang, "A Systemic Review of Functional Near-Infrared Spectroscopy for Stroke: Current Application and Future Directions," (in eng), *Front Neurol,* vol. 10, p. 58, 2019, doi: 10.3389/fneur.2019.00058.

[32] J. Chen *et al.*, "fNIRS-EEG BCIs for Motor Rehabilitation: A Review," (in eng), *Bioengineering (Basel),* vol. 10, no. 12, Dec 6 2023, doi: 10.3390/bioengineering10121393.

[33] M. A. Rahman, A. B. Siddik, T. K. Ghosh, F. Khanam, and M. Ahmad, "A Narrative Review on Clinical Applications of fNIRS," (in eng), *J Digit Imaging,* vol.

33, no. 5, pp. 1167-1184, Oct 2020, doi: 10.1007/s10278-020-00387-1.

[34] M. Mihara and I. Miyai, "Review of functional near-infrared spectroscopy in neurorehabilitation," (in eng), *Neurophotonics,* vol. 3, no. 3, p. 031414, Jul 2016, doi: 10.1117/1.NPh.3.3.031414.

[35] C. Huo *et al.*, "A review on functional near-infrared spectroscopy and application in stroke rehabilitation," *Med Nov Technol Devices,* vol. 11, p. 100064, 2021/09/01/ 2021, doi: https://doi.org/10.1016/j.medntd.2021.100064.

[36] D. Moher, A. Liberati, J. Tetzlaff, and D. G. Altman, "Reprint—Preferred Reporting Items for Systematic Reviews and Meta-Analyses: The PRISMA Statement," *Physical therapy,* vol. 89, no. 9, pp. 873-880, 2009, doi: 10.1093/ptj/89.9.873.

[37] S. K. Bhogal, R. W. Teasell, N. C. Foley, and M. R. Speechley, "The PEDro scale provides a more comprehensive measure of methodological quality than the Jadad Scale in stroke rehabilitation literature," *J Clin Epidemiol,* vol. 58, no. 7, pp. 668-673, 2005, doi: 10.1016/j.jclinepi.2005.01.002.

[38] M. D. Pfeifer, F. Scholkmann, and R. Labruy®®re, "Signal processing in functional near-infrared spectroscopy (fNIRS): methodological differences lead to different statistical results," *Front Hum Neurosci,* vol. 11, p. 641, 2018.

[39] F. Klein and C. Kranczioch, "Signal processing in fNIRS: a case for the removal of systemic activity for single trial data," *Front Hum Neurosci,* vol. 13, p. 331, 2019.

[40] M. Yücel *et al.*, "The fNIRS Reproducibility Study Hub (FRESH): Exploring Variability and Enhancing Transparency in fNIRS Neuroimaging Research," 2024.

[41] H. Kato, M. Izumiyama, H. Koizumi, A. Takahashi, and Y. Itoyama, "Near-infrared spectroscopic topography as a tool to monitor motor reorganization after hemiparetic stroke: a comparison with functional MRI," *Stroke,* vol. 33, no. 8, pp. 2032-6, Aug 2002, doi: 10.1161/01.str.0000021903.52901.97.

[42] S. Leistner *et al.*, "Non-invasive simultaneous recording of neuronal and vascular signals in subacute ischemic stroke," (in eng), *Biomed Tech (Berl),* vol. 56, no. 2, pp. 85-90, Apr 2011, doi: 10.1515/bmt.2011.002.

[43] M. Hatakenaka, I. Miyai, M. Mihara, H. Yagura, and N. Hattori, "Impaired motor learning by a pursuit rotor test reduces functional outcomes during rehabilitation of poststroke ataxia," *Neurorehabil Neural Repair,* vol. 26, no. 3, pp. 293-300, Mar-Apr 2012, doi: 10.1177/1545968311412053.

[44] S. B. Lim and J. J. Eng, "Increased Sensorimotor Cortex Activation With Decreased Motor Performance During Functional Upper Extremity Tasks Poststroke," *J Neurol Phys Ther,* vol. 43, no. 3, pp. 141-150, Jul 2019, doi: 10.1097/NPT.0000000000000277.

[45] Z. Bai and K. N. K. Fong, "“Remind-to-Move” Treatment Enhanced Activation of the Primary Motor Cortex in Patients with Stroke," *Brain topography,* vol. 33, no. 2, pp. 275-283, 2020, doi: 10.1007/s10548-020-00756-7.

[46] U. M. Bello, C. C. H. Chan, and S. J. Winser, "Task Complexity and Image Clarity Facilitate Motor and Visuo-Motor Activities in Mirror Therapy in Post-stroke Patients," *Front Neurol,* vol. 12, pp. 722846-722846, 2021, doi: 10.3389/fneur.2021.722846.

[47] C. Jian, H. Liu, L. Deng, X. Wang, T. Yan, and R. Song, "Stroke-induced alteration in multi-layer information transmission of cortico-motor system during elbow isometric contraction modulated by myoelectric-controlled interfaces," *J Neural Eng,* vol. 18, no. 4, Aug 25 2021, doi: 10.1088/1741-2552/ac18ae.

[48] Q. Chu *et al.*, "Cortical reorganization pattern of stroke patients under upper limb multi-joint linkage task," presented at the 2022 12th International Conference on CYBER Technology in Automation, Control, and Intelligent Systems (CYBER), 2022.

[49] C. L. Friesen, M. Lawrence, T. G. J. Ingram, and S. G. Boe, "Home-based portable fNIRS-derived cortical laterality correlates with impairment and function in chronic stroke," *Front Hum Neurosci,* vol. 16, pp. 1023246-1023246, 2022, doi: 10.3389/fnhum.2022.1023246.

[50] K. Fujiwara, R. Shimoda, M. Shibata, Y. Awano, K. Shibayama, and T. Higashi, "A Method for Using Video Presentation to Increase Cortical Region Activity during Motor Imagery Tasks in Stroke Patients," (in eng), *Brain Sci,* vol. 13, no. 1, Dec 23 2022, doi: 10.3390/brainsci13010029.

[51] C. Huo *et al.*, "fNIRS-based brain functional response to robot-assisted training for upper-limb in stroke patients with hemiplegia," *Front Aging Neurosci,* vol. 14, p. 1060734, 2022, doi: 10.3389/fnagi.2022.1060734.

[52] W. Xia *et al.*, "Cortical mapping of active and passive upper limb training in stroke patients and healthy people: A functional near-infrared spectroscopy study," *Brain Res,* vol. 1788, p. 147935, Aug 1 2022, doi: 10.1016/j.brainres.2022.147935.

[53] Z. Yuan *et al.*, "Task-State Cortical Motor Network Characteristics by Functional Near-Infrared Spectroscopy in Subacute Stroke Show Hemispheric Dominance," *Front Aging Neurosci,* vol. 14, p. 932318, 2022, doi: 10.3389/fnagi.2022.932318.

[54] L. Bu, J. Qu, L. Zhao, Y. Zhang, and Y. Wang, "A neuroergonomic approach to assessing motor performance in stroke patients using fNIRS and behavioral data," *Applied ergonomics,* vol. 109, pp. 103979-103979, 2023, doi: 10.1016/j.apergo.2023.103979.

[55] Q. Chu *et al.*, "Stroke-Related Alterations in the Brain's Functional Connectivity Response Associated with Upper Limb Multi-Joint Linkage Movement,"

Brain Sci, vol. 13, no. 2, Feb 16 2023, doi: 10.3390/brainsci13020338.

[56] K. Fujiwara, M. Shibata, Y. Awano, N. Iso, K. Shibayama, and T. Higashi, "Differences in Cortical Area Activity and Motor Imagery Vivid-Ness during Evaluation of Motor Imagery Tasks in Right and Left Hemiplegics," *Brain Sci,* vol. 13, no. 5, Apr 29 2023, doi: 10.3390/brainsci13050748.

[57] C. Huo *et al.*, "Effect of High-Frequency rTMS combined with bilateral arm training on brain functional network in patients with chronic stroke: An fNIRS study," *Brain Res.,* vol. 1809, p. 148357, 2023/06/15/ 2023, doi: https://doi.org/10.1016/j.brainres.2023.148357.

[58] H. Li *et al.*, "Upper limb intelligent feedback robot training significantly activates the cerebral cortex and promotes the functional connectivity of the cerebral cortex in patients with stroke: A functional near-infrared spectroscopy study," *Front Neurol,* vol. 14, p. 1042254, 2023, doi: 10.3389/fneur.2023.1042254.

[59] W. Lu *et al.*, "Prefrontal cortex activity of active motion, cyclic electrical muscle stimulation, assisted motion, and imagery of wrist extension in stroke using fNIRS," *J Stroke Cerebrovasc Dis,* vol. 32, no. 12, p. 107456, Dec 2023, doi: 10.1016/j.jstrokecerebrovasdis.2023.107456.

[60] Y. Ma, Y. Yu, W. Gao, Y. Hong, and X. Shen, "Cerebral Hemodynamic Changes during Unaffected Handgrip Exercises in Stroke Patients: An fNIRS Study," *Brain Sci,* vol. 13, no. 1, Jan 13 2023, doi: 10.3390/brainsci13010141.

[61] W. Xu, Y. Tao, J. Zhu, Z. Yuan, J. Guo, and G. Wang, "Machine Learning Method Evaluates Upper-Limb Motor Function by fNIRS in Stroke Patients," presented at the 2023 IEEE 4th International Conference on Pattern Recognition and Machine Learning (PRML), 2023.

[62] Y. Zhang *et al.*, "Motor network reorganization in stroke patients with dyskinesias during a shoulder-touching task: A fNIRS study," *J Innov Opt Health Sci s,* vol. 16, no. 06, 2023, doi: 10.1142/s1793545823400035.

[63] S. Ye *et al.*, "Upper limb motor assessment for stroke with force, muscle activation and interhemispheric balance indices based on sEMG and fNIRS," *Front Neurol,* vol. 15, pp. 1337230-1337230, 2024, doi: 10.3389/fneur.2024.1337230.

[64] K. Takeda, Y. Gomi, I. Imai, N. Shimoda, M. Hiwatari, and H. Kato, "Shift of motor activation areas during recovery from hemiparesis after cerebral infarction: a longitudinal study with near-infrared spectroscopy," *Neurosci. Res.,* vol. 59, no. 2, pp. 136-44, Oct 2007, doi: 10.1016/j.neures.2007.06.1466.

[65] M. Delorme, G. Vergotte, S. Perrey, J. Froger, and I. Laffont, "Time course of sensorimotor cortex reorganization during upper extremity task accompanying motor recovery early after stroke: An fNIRS study," *Restor Neurol Neurosci,* vol. 37, no. 3, pp. 207-218, 2019, doi: 10.3233/RNN-180877.

[66] S. Kinoshita, H. Tamashiro, T. Okamoto, N. Urushidani, and M. Abo, "Association between imbalance of cortical brain activity and successful motor recovery in sub-Acute stroke patients with upper limb hemiparesis: A functional near-infrared spectroscopy study," (in English), *NeuroReport,* Article vol. 30, no. 12, pp. 822-827, 2019, doi: 10.1097/WNR.0000000000001283.

[67] N. Lamberti *et al.*, "Cortical Oxygenation during a Motor Task to Evaluate Recovery in Subacute Stroke Patients: A Study with Near-Infrared Spectroscopy," *Neurol Int,* vol. 14, no. 2, pp. 322-335, Mar 23 2022, doi: 10.3390/neurolint14020026.

[68] V. T. Nguyen *et al.*, "Evaluating interhemispheric synchronization and cortical activity in acute stroke patients using optical hemodynamic oscillations," (in eng), *J Neural Eng,* vol. 19, no. 3, Jun 10 2022, doi: 10.1088/1741-2552/ac73b4.

[69] S. Chen *et al.*, "The assessment of interhemispheric imbalance using functional near-infrared spectroscopic and transcranial magnetic stimulation for predicting motor outcome after stroke," *Front Neurosci,* vol. 17, pp. 1231693-1231693, 2023, doi: 10.3389/fnins.2023.1231693.

[70] S. W. Park, A. J. Butler, V. Cavalheiro, J. L. Alberts, and S. L. Wolf, "Changes in serial optical topography and TMS during task performance after constraint-induced movement therapy in stroke: a case study," *Neurorehabil Neural Repair,* vol. 18, no. 2, pp. 95-105, Jun 2004, doi: 10.1177/0888439004265113.

[71] Y. Hara, S. Obayashi, K. Tsujiuchi, and Y. Muraoka, "The effects of electromyography-controlled functional electrical stimulation on upper extremity function and cortical perfusion in stroke patients," *Clin Neurophysiol,* vol. 124, no. 10, pp. 2008-15, Oct 2013, doi: 10.1016/j.clinph.2013.03.030.

[72] M. Mihara *et al.*, "Near-infrared spectroscopy-mediated neurofeedback enhances efficacy of motor imagery-based training in poststroke victims: a pilot study," *Stroke,* vol. 44, no. 4, pp. 1091-8, Apr 2013, doi: 10.1161/STROKEAHA.111.674507.

[73] M. Brunetti *et al.*, "Potential determinants of efficacy of mirror therapy in stroke patients - A pilot study," *Restor. Neurol. Neurosci.,* vol. 33, no. 4, pp. 421-434, 2015, doi: 10.3233/RNN-140421.

[74] K. Saita *et al.*, "Biofeedback effect of hybrid assistive limb in stroke rehabilitation: A proof of concept study using functional near infrared spectroscopy," *PLoS One,* vol. 13, no. 1, p. e0191361, 2018, doi: 10.1371/journal.pone.0191361.

[75] N. Urushidani, S. Kinoshita, T. Okamoto, H. Tamashiro, and M. Abo, "Low-Frequency rTMS and Intensive Occupational Therapy Improve Upper Limb Motor Function and Cortical Reorganization Assessed by Functional Near-Infrared Spectroscopy in a Subacute Stroke Patient," *Case Rep Neurol,* vol. 10, no. 2, pp. 223-231, May-Aug 2018, doi: 10.1159/000492381.

[76] H. Tamashiro, S. Kinoshita, T. Okamoto, N. Urushidani, and M. Abo, "Effect of baseline brain activity on response to low-frequency rTMS/intensive occupational therapy in poststroke patients with upper limb hemiparesis: a near-infrared spectroscopy study," *Int J Neurosci,* vol. 129, no. 4, pp. 337-343, Apr 2019, doi: 10.1080/00207454.2018.1536053.

[77] F. Alnajjar *et al.*, "Self-Support Biofeedback Training for Recovery From Motor Impairment After Stroke," *IEEE access,* vol. 8, pp. 72138-72157, 2020, doi: 10.1109/ACCESS.2020.2987095.

[78] C. Jian, L. Deng, H. Liu, T. Yan, X. Wang, and R. Song, "Modulating and restoring inter-muscular coordination in stroke patients using two-dimensional myoelectric computer interface: a cross-sectional and longitudinal study," *J Neural Eng,* vol. 18, no. 3, Mar 8 2021, doi: 10.1088/1741-2552/abc29a.

[79] A. K. Matarasso, J. D. Rieke, K. White, M. M. Yusufali, and J. J. Daly, "Combined real-time fMRI and real time fNIRS brain computer interface (BCI): Training of volitional wrist extension after stroke, a case series pilot study," *PLoS One,* vol. 16, no. 5, p. e0250431, 2021, doi: 10.1371/journal.pone.0250431.

[80] Y. Dai, F. Huang, and Y. Zhu, "Clinical efficacy of motor imagery therapy based on fNIRs technology in rehabilitation of upper limb function after acute cerebral infarction," *Pak J Med Sci,* vol. 38, no. 7, pp. 1980-1985, Sep-Oct 2022, doi: 10.12669/pjms.38.7.5344.

[81] C. Guo *et al.*, "Contralaterally controlled neuromuscular electrical stimulation-induced changes in functional connectivity in patients with stroke assessed using functional near-infrared spectroscopy," *Front Neural Circuits,* vol. 16, p. 955728, 2022, doi: 10.3389/fncir.2022.955728.

[82] C. Li *et al.*, "A study of dynamic hand orthosis combined with unilateral task-oriented training in subacute stroke: A functional near-infrared spectroscopy case series," *Front Neurol,* vol. 13, p. 907186, 2022, doi: 10.3389/fneur.2022.907186.

[83] L. Liu *et al.*, "Brain-Computer Interface-Robot Training Enhances Upper Extremity Performance and Changes the Cortical Activation in Stroke Patients: A Functional Near-Infrared Spectroscopy Study," (in eng), *Front Neurosci,* vol. 16, p. 809657, 2022, doi: 10.3389/fnins.2022.809657.

[84] J. Ni *et al.*, "Effect of rTMS intervention on upper limb motor function after stroke: A study based on fNIRS," *Front Aging Neurosci,* vol. 14, p. 1077218, 2022, doi: 10.3389/fnagi.2022.1077218.

[85] S. Shin, H. J. Lee, W. H. Chang, S. H. Ko, Y. I. Shin, and Y. H. Kim, "A Smart Glove Digital System Promotes Restoration of Upper Limb Motor Function and Enhances Cortical Hemodynamic Changes in Subacute Stroke Patients with Mild to Moderate Weakness: A Randomized Controlled Trial," *J Clin Med,* vol. 11, no. 24, Dec 10 2022, doi: 10.3390/jcm11247343.

[86] Z. Wang *et al.*, "Multimodal Neural Response and Effect Assessment During a BCI-Based Neurofeedback Training After Stroke," *Front Neurosci,* vol. 16, p. 884420, 2022, doi: 10.3389/fnins.2022.884420.

[87] H. Xie *et al.*, "Effects of robot-assisted task-oriented upper limb motor training on neuroplasticity in stroke patients with different degrees of motor dysfunction: A neuroimaging motor evaluation index," *Front Neurosci,* vol. 16, p. 957972, 2022, doi: 10.3389/fnins.2022.957972.

[88] G. Xu *et al.*, "Effective brain network analysis in unilateral and bilateral upper limb exercise training in subjects with stroke," *Med. Phys.,* vol. 49, no. 5, pp. 3333-3346, May 2022, doi: 10.1002/mp.15570.

[89] C. Huo *et al.*, "Cortical response induced by task-oriented training of the upper limb in subacute stroke patients as assessed by functional near-infrared spectroscopy," *J Biophotonics,* vol. 16, no. 3, p. e202200228, Mar 2023, doi: 10.1002/jbio.202200228.

[90] H. Kim, G. Lee, J. Lee, and Y. H. Kim, "Alterations in learning-related cortical activation and functional connectivity by high-definition transcranial direct current stimulation after stroke: an fNIRS study," *Front Neurosci,* vol. 17, pp. 1189420-1189420, 2023, doi: 10.3389/fnins.2023.1189420.

[91] L. Wang *et al.*, "Transcutaneous auricular vagus nerve stimulation on upper limb motor function with stroke: a functional near-infrared spectroscopy pilot study," *Front Neurosci,* vol. 17, pp. 1297887-1297887, 2023, doi: 10.3389/fnins.2023.1297887.

[92] M. H. Wang *et al.*, "Transcutaneous auricular vagus nerve stimulation with task-oriented training improves upper extremity function in patients with subacute stroke: a randomized clinical trial," *Front Neurosci,* vol. 18, pp. 1346634-1346634, 2024, doi: 10.3389/fnins.2024.1346634.

[93] M. A. Yücel *et al.*, "Best practices for fNIRS publications," (in eng), *Neurophotonics,* vol. 8, no. 1, p. 012101, Jan 2021, doi: 10.1117/1.NPh.8.1.012101.

[94] C. Grefkes and G. R. Fink, "Reorganization of cerebral networks after stroke: new insights from neuroimaging with connectivity approaches," (in eng), *Brain,* vol. 134, no. Pt 5, pp. 1264-76, May 2011, doi: 10.1093/brain/awr033.

[95] A. K. Rehme, S. B. Eickhoff, C. Rottschy, G. R. Fink, and C. Grefkes, "Activation likelihood estimation meta-analysis of motor-related neural activity after stroke," *NeuroImage,* vol. 59, no. 3, pp. 2771-2782, 2012/02/01/ 2012, doi: https://doi.org/10.1016/j.neuroimage.2011.10.023.

[96] E. M. Hillman, "Coupling mechanism and significance of the BOLD signal: a status report," (in eng), *Annu Rev Neurosci,* vol. 37, pp. 161-81, 2014, doi: 10.1146/annurev-neuro-071013-014111.

[97] K. T. Kinder *et al.*, "Systematic review of fNIRS studies reveals inconsistent chromophore data reporting practices," (in eng), *Neurophotonics,* vol. 9,

no. 4, p. 040601, Oct 2022, doi: 10.1117/1.NPh.9.4.040601.

[98] S. Brigadoi and R. J. Cooper, "How short is short? Optimum source®Cdetector distance for short-separation channels in functional near-infrared spectroscopy," *Neurophotonics,* vol. 2, no. 2, pp. 025005-025005, 2015.

[99] I. Tachtsidis and F. Scholkmann, "False positives and false negatives in functional near-infrared spectroscopy: issues, challenges, and the way forward," *Neurophotonics,* vol. 3, no. 3, pp. 031405-031405, 2016.

[100] F. Klein, M. Lührs, A. Benitez-Andonegui, P. Roehn, and C. Kranczioch, "Performance comparison of systemic activity correction in functional near-infrared spectroscopy for methods with and without short distance channels," *Neurophotonics,* vol. 10, no. 1, pp. 013503-013503, 2023.

[101] F. Klein, "Optimizing spatial specificity and signal quality in fNIRS: an overview of potential challenges and possible options for improving the reliability of real-time applications," *Frontiers in Neuroergonomics,* vol. 5, p. 1286586, 2024.

[102] T. Ros *et al.*, "Consensus on the reporting and experimental design of clinical and cognitive-behavioural neurofeedback studies (CRED-nf checklist)," ed: Oxford University Press, 2020.

[103] S. H. Kohl, D. M. Mehler, M. Lührs, R. T. Thibault, K. Konrad, and B. Sorger, "The potential of functional near-infrared spectroscopy-based neurofeedback°™a systematic review and recommendations for best practice," *Front Neurosci,* vol. 14, p. 594, 2020.

[104] P. A. Schroeder *et al.*, "Using preregistration as a tool for transparent fNIRS study design," *Neurophotonics,* vol. 10, no. 2, pp. 023515-023515, 2023.

[105] C. Allen and D. M. Mehler, "Open science challenges, benefits and tips in early career and beyond," *PLoS biology,* vol. 17, no. 5, p. e3000246, 2019.

[106] P. Pinti, F. Scholkmann, A. Hamilton, P. Burgess, and I. Tachtsidis, "Current status and issues regarding pre-processing of fNIRS neuroimaging data: an investigation of diverse signal filtering methods within a general linear model framework," *Frontiers in human neuroscience,* vol. 12, p. 505, 2019.

[107] K. Stute *et al.*, "The fNIRS Glossary Project: A Consensus-based Resource for Functional Near-Infrared Spectroscopy Terminology."

[108] J. Algermissen and D. M. Mehler, "May the power be with you: are there highly powered studies in neuroscience, and how can we get more of them?," *J Neurophysiol,* vol. 119, no. 6, pp. 2114-2117, 2018.

Biography

Yongan Gong, M.Med.

Yongan studied Clinical Medicine at Dalian Medical University in China where he has completed residency training in neurology. He is currently a doctoral student at the Applied Computational Neuroscience lab at Uniklinik RWTH Aachen, Germany. For his doctoral study, he will look at the impact of fNIRS-based neurofeedback training for motor rehabilitation.

Ruixuan Lin, M.Sc.OT.

Ruixuan received her occupational therapy training at the Fujian University of Traditional Chinese Medicine. She later earned her Master of Science in Occupational Therapy from The Hong Kong Polytechnic University. Currently, she works as a research assistant on a research project that utilizes a brain-computer interface for neurofeedback in post-stroke rehabilitation.

Murat Can Mutlu, Ph.D.

Murat is a neuroscientist with an electronics and biomedical engineering background. He is currently a post-doctoral researcher at the Applied Computational Neuroscience lab at Uniklinik RWTH Aachen. He has previously completed postdoctoral training at the Cognitive Biology Department in OVGU, Magdeburg, where he has worked on multistable perception with fMRI and EEG-based global brain dynamics. During his Ph.D., he investigated bilingual language processing at word and sentence level with fNIRS at Boğaziçi University, İstanbul. Murat is mainly interested in analyzing brain signals from different neuroimaging modalities and in topics of neurolinguistics.

Lukas Lorentz, Dr. rer. nat.

Lukas Lorentz studied psychology and neuropsychology at the universities of Nijmegen and Maastricht. He completed his doctoral studies on the feasibility, efficacy, and neural mechanisms of Virtual Reality treatment for cognitive rehabilitation at Ruhr-University Bochum and it currently employed as a postdoctoral researcher at the University Hospital Aachen investigating the clinical applicability of Extended Reality technologies using fMRI and fNIRS.

Usman Jawed Shaikh, M.Sc.

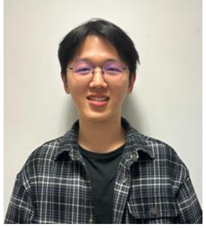
Usman Jawed Shaikh is a proficient engineer specialized in biomedical signal processing methodologies. He attained his undergraduate degree in electronics engineering from NED University of Engineering and Technology in Pakistan. Subsequently, he acquired his M.Sc. degree in Digital Communication from the University of Kiel in Germany. During his master's program, he engaged in various neuroscience projects, including EEG, TMS and MRI, thereby accumulating substantial experience in neuroimaging data analysis. He is presently undertaking his doctoral research at Uniklinik RWTH Aachen in Germany. His research endeavours concentration on the investigation of brain connectivity through the application of non-invasive brain stimulation techniques (such as TMS), along with PET, MRI, and fNIRS modalities.

Joscha D. Graeve, M.Sc.

Joscha completed an M.Sc. in biotechnology at RWTH Aachen University. For his thesis he investigated activities of neuroal networks under different cultivation conditions. He has obtained his second M.Sc. degree, specializing in education to teach chemistry and biology in schools. He is currently working as a research assistant in the Applied Computional Neuroscience lab at Uniklinik RWTH Aachen, Germany.

Niloufar Badkoubeh, B.Sc.

Niloufar Badkoubeh is currently pursuing a Bachelor of Science in Psychology (polyvalent) at RWTH Aachen University, Germany. She works as a research assistant in the Applied Computational Neuroscience laboratory. She has previously gained practical experience as a student assistant at Uniklinik RWTH Aachen, working in both the Department of Psychiatry, Psychosomatics, and Psychotherapy, and the Forschungszentrum Kinder- und Jugendpsychiatrie. Her research focuses on neuroimaging techniques, particularly fNIRS. Prior to this, she earned a B.Sc. degree in Laboratory Science from Islamic Azad University, Tehran Medical Branch, in Iran.



Roy Rongyue Zeng, M.Sc.OT.

Rongyue received his occupational therapy training at the Fujian University of Traditional Chinese Medicine. He later earned her Master of Science in Occupational Therapy from The Hong Kong Polytechnic University. Currently, he works as a research assistant on a research project that utilizes non-invasive magnetic brain stimulation in poststroke rehabilitation.

Franziska Klein, Dr. rer. nat.

Franzi is a senior researcher at OFFIS – Institute for Information Technology in Oldenburg and a postdoctoral researcher in the Applied Computational Neuroscience lab at the Unklinik RWTH Aachen. Her work focuses on the further development of real-time applications such as neurofeedback and BCIs, with a particular focus on improving and validating (real-time) signal processing and analysis of fNIRS, EEG and fMRI data as well as other physiological measures. She is a strong advocate of open science and is also passionate about data visualization and its role in scientific communication.

Michael Lührs, Ph.D.

Michael is a postdoctoral researcher at the Department of Cognitive Neuroscience, Faculty of Psychology and Neuroscience, Maastricht University, and works as a researcher and software developer at Brain Innovation B.V. His work emphasizes the development and optimization of real-time neuroimaging methods, particularly focusing on the integration of functional near-infrared spectroscopy (fNIRS) and functional magnetic resonance imaging (fMRI). He is committed to advancing precision in brain–computer interface and specifically neurofeedback applications, with a strong interest in translating these technologies into clinical settings for therapeutic interventions and cognitive rehabilitation.

Klaus Mathiak, M.D., Ph.D.
Klaus Mathiak is professor and lead-consultant for psychosomatic medicine at the Uniklinik RWTH Aachen. He develops neuroimaging methods and studies psychiatric populations to understand dysregulated brain physiology in the sensory, affective, cognitive, and motor domain. His current focus encompasses neural self-regulation using fMRI.

Jack Jiaqi Zhang, Ph.D.
Jack is a Research Assistant Professor (Neurorehabilitation and Neuroscience) in the Department of Rehabilitation Sciences at The Hong Kong Polytechnic University, Hong Kong SAR, China. His background training is in occupational therapy. His research interests focus on poststroke neurophysiology, non-invasive brain stimulation (including TMS and TES), and the integration of neurotechnology (brain-computer interfaces, robotics, and assistive rehabilitative technology) in neurological and medical rehabilitation. He has received several competitive grants, including those from the NSFC, HMRF and RGC Germany-Hong Kong Joint Research Scheme.

David MA Mehler, Dr. med., M.D., Ph.D.
David is a physician-scientist and heads the Applied Computational Neuroscience lab at Uniklinik RWTH Aachen, Germany. The research of his group focuses on non-invasive brain-computer-interfaces (neurofeedback), metaresearch for neurotechnology, as well as machine-learning based big data approaches to investigate clinical and biological markers and predictors for psychiatric and neurological diseases.