Received: 14 September 2024 | Accepted: 7 December 2024

DOI: 10.1111/dmcn.16238

SCOPING REVIEW

Assessment of cortical activity, functional connectivity, and neuroplasticity in cerebral palsy using functional near-infrared spectroscopy: A scoping review

Owais A. Khan | **Simin Rahman** | **Kanishka Baduni** | **Christopher M. Modlesky**

Department of Kinesiology, University of Georgia, Athens, GA, USA

Correspondence
Christopher M. Modlesky, Department of Kinesiology, University of Georgia, 330 River Road, Athens, GA 30602, USA.
Email: christopher.modlesky@uga.edu

Funding information
Eunice Kennedy Shriver National Institute of Child Health and Human Development, Grant/Award Number: RO1 HD090126; University of Georgia Athletic Association

Abstract

Aim: To map and critically appraise the literature on the feasibility and current use of functional near-infrared spectroscopy (fNIRS) to assess cortical activity, functional connectivity, and neuroplasticity in individuals with cerebral palsy (CP).

Method: A scoping review methodology was prospectively registered and reported following Preferred Reporting Items for Systematic review and Meta-Analysis Extension for Scoping Reviews (PRISMA-ScR) guidelines. A systematic search was conducted in four databases. Empirical studies using fNIRS to assess neural activity, functional connectivity, or neuroplasticity in individuals with CP aged 3 years or older were included.

Results: Sixteen studies met the inclusion criteria. Individuals with CP (age range = 3–43 years; 70% unilateral CP) underwent fNIRS-based assessment for task-evoked activity (studies [*n*] = 15) and/or resting-state functional connectivity (*n* = 3). Preliminary observations suggest greater magnitude, extent, and ipsilateral hemispheric lateralization of sensorimotor cortex activity in CP, while magnitude and patterns of prefrontal cortex activity in CP appear dependent on task demands. Normalization of fNIRS-based activity metrics observed postintervention (*n* = 3) paralleled improvements in functional outcomes, highlighting their potential as promising biomarkers for functional gains in CP.

Interpretation: This review details the use of fNIRS in CP, highlights research gaps and technical limitations, and offers recommendations to support fNIRS implementation for ecologically valid functional neuroimaging in individuals with CP.

A majority of children with cerebral palsy (CP) present abnormal findings on neuroradiological examinations,[1] with lesions identified through structural magnetic resonance imaging (MRI) often corresponding to patterns and distribution of sensorimotor impairments. For example, focal vascular lesions are commonly observed as perinatal stroke in unilateral CP (UCP),[2] while diffuse bilateral white matter injury (e.g. periventricular leukomalacia) is most frequent in bilateral CP (BCP), and grey matter lesions are often associated with dyskinetic CP.[3] However, at least 10% to 15% of children with CP have normal MRI,[2,4] and abnormal findings do not consistently relate to clinical outcomes in CP[5,6] because of the complex interactions between lesion type, timing, location, and extent.[7–10] The exaggerated potential for neuroplasticity in the early years of life (Kennard principle),[11,12] individual genetic constitutions[13] and epigenetic variance,[14] and lived experiences further contribute to the heterogeneity in brain structure–function relationships in CP.[15–17]

Abbreviations: BCP, bilateral cerebral palsy; CIMT, constraint-induced movement therapy; fNIRS, functional near-infrared spectroscopy; MACS, Manual Ability Classification System; MEG, magnetoencephalography; PEDI-CAT, Pediatric Evaluation of Disability Index – Computer Adaptive Test; PFC, prefrontal cortex; SMC, sensorimotor cortex; UCP, unilateral cerebral palsy.

Plain language summary: https://onlinelibrary.wiley.com/doi/10.1111/dmcn.16286

Functional neuroimaging can provide greater insights into neurophysiological dynamics during functional tasks.[18,19] The most commonly used functional neuroimaging modality in CP is functional MRI,[20] which measures changes in blood oxygenation levels (blood oxygen level dependent response) to capture brain activity during tasks (task-evoked activation; see, e.g. Phillips et al.[21]), and identify functionally connected brain regions at rest (resting-state functional connectivity; see, for example, Doucet et al.[22]). Functional MRI has been used in CP to investigate adaptive plasticity following intervention,[23,24] and resting-state functional connectivity in the sensorimotor[25,26] and language neural networks[27] and their association with clinical outcomes.[28] Alternative modalities, such as electroencephalography (EEG) and magnetoencephalography (MEG), offer superior temporal resolutions compared to MRI and directly capture electrical activity in neuronal populations. Studies using EEG in CP reported reduced activity at specific frequencies (mu-band[29]) in the ipsilesional sensorimotor cortex (SMC) during upper limb tasks (reach-to-grasp,[30] isometric wrist extension,[31] hand squeezing[32]) and heightened bilateral activity during treadmill walking.[33] Altered dynamics of the somatosensory,[34] visual,[35–37] and sensorimotor cortices[38] identified through MEG studies in CP shed light on impaired motor planning[39] and execution, with MEG outcomes potentially sensitive to change following intervention.[40,41]

Despite these promising observations, practical concerns (e.g. scanner constraints, signal noise, and high costs) limit the use of these modalities in children.[42,43] While efforts to improve scanner-based experiences have increased acceptance and completion rates,[44,45] concerns persist about the effectiveness of in-scanner strategies to reduce movement artifacts,[46] and of motion correction strategies during data processing.[47] These issues are magnified in individuals with CP, who exhibit cognitive, visuospatial, and sensorimotor impairments[48,49] that render them unable or unwilling to remain still, sustain attention, or comply with task instructions during repetitive experimental assessments.[50] For example, children with even mild manual impairments struggle to comply with simple hand-squeezing tasks during functional MRI.[32] Additionally, individuals with ataxic or dyskinetic CP who experience involuntary movements are underrepresented in neuroimaging studies,[51] resulting in selection bias and limited generalizability of neuroimaging findings.[52] These observations highlight the need for child-friendly, non-invasive functional neuroimaging tools that can incorporate engaging and ecologically valid methods.

Functional near-infrared spectroscopy (fNIRS) is a relatively inexpensive, portable, and non-invasive functional neuroimaging tool with great potential for assessing brain activity in CP. Like functional MRI, fNIRS relies on neurovascular coupling, or increased blood flow (reactive hyperemia) to active neural areas in response to metabolic demand,[53] to provide an indirect measure of neural activity.[54,55] Near-infrared light of specific wavelengths (optical window, 650–900 nm[56]) is emitted through optodes placed in contact with the scalp, typically through a flexible cap (Figure 1). This light penetrates 1 to 2 cm into the underlying tissue, being reflected, scattered, and absorbed by oxyhemoglobin and deoxyhemoglobin in the outer 5 to 10 mm rim of the cerebral cortex.[57] Emergent light is captured by detectors, and attenuation of light intensity is used to quantify relative changes in hemoglobin concentrations through the modified Beer–Lambert law.[58] Cortical activity is indirectly reflected by an increase in oxyhemoglobin and a concurrent, smaller decrease in deoxyhemoglobin concentration, with a net increase in total hemoglobin concentration.[59]

What this paper adds

- Functional near-infrared spectroscopy (fNIRS) is feasible for assessing task-evoked brain activity and functional connectivity in cerebral palsy.
- Greater sensorimotor cortex activity scales with lower gross motor and manual abilities.
- Prefrontal cortex activity patterns appear dependent on task complexity and demands.
- Changes in fNIRS-based metrics may accompany functional improvements following therapeutic intervention.
- Potential for real-world brain imaging with fNIRS remains largely untapped in cerebral palsy.

Features of fNIRS that make it particularly suited for use in children and adults with neurodevelopmental disorders such as CP are detailed in Table 1. Briefly, fNIRS provides higher spatial resolution than EEG and better temporal resolution than functional MRI, allowing accurate localization and temporal characterization of cortical activity.[60] Wireless fNIRS devices enable mobile neuroimaging in natural settings,[61] facilitating ecologically valid tasks that optimize engagement,[62] an especially important consideration in individuals with CP exhibiting cognitive and attention deficits.[48] Notably, functional task contexts provoke improved postural control[63] and altered cortical activation patterns in those with CP compared with conventional experimental tasks such as finger tapping.[64] Additionally, fNIRS offers greater methodological flexibility, customizable optode template arrangements,[65] low cost, and minimal maintenance, making it an ideal neuroimaging tool in low-resource settings of low- and middle-income countries that show greater prevalence of CP.[66]

A major drawback of fNIRS is its limited penetration depth, which prevents the assessment of neural activity below the outer 5 to 10 mm of cortical grey matter. This precludes neuroimaging of deep grey-matter structures (e.g. basal nuclei, thalami) or deeper temporal lobe structures (e.g. hippocampi) that are involved in more extensive lesions in CP.[67] Another shortcoming is the susceptibility of fNIRS signal to contamination from task-induced and/or spontaneous changes in systemic physiology such as fluctuations in heart rate, respiration, blood pressure, or

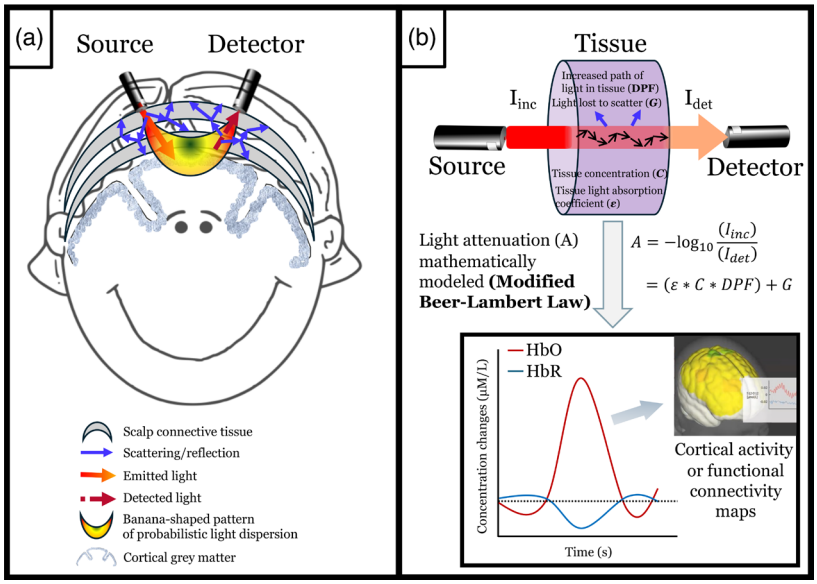

FIGURE 1 (a) Schematic illustration of the principles of fNIRS measurement. Near-infrared light passes through scalp connective tissues, undergoing scattering, reflection, and absorption along its probabilistic banana-shaped path through cortical tissue, before being reflected out to be captured by detectors placed at the scalp. (b) Decreased light intensity is mathematically modelled (modified Beer–Lambert law) using estimates of tissue concentrations (*C*) and light scattering (*G*), absorption (ε), and refraction (DPF, differential pathlength factor) to obtain estimates of relative changes in oxyhemoglobin (HbO) and deoxyhemoglobin (HbR) concentration. These changes are surrogate markers of cortical activity, with modern software providing real-time feedback of cortical activity and functional connectivity at rest or during functional task performance.

TABLE 1 Non-invasive functional neuroimaging modalities.

Modality	Typical resolution (spatial; temporal)[a]	Movement tolerance; safety; cost	Setting	Additional comments
fMRI	3–12 mm (high); 2–4 s (low)	Low;[b] high; high	Scanner-based; loud scans with limited limb motion	Indirect measure of neural activity (BOLD response with ΔHbR only). Whole-brain and white matter tractography. Can detect subcortical neural activity.
MEG	3–5 mm (high); <1 ms (very high)	Low; high; very high	Scanner-based via helmet with helium-encased sensors; silent scan	Direct measure of neural activity (ultra-minute magnetic fields, 10^{-15} T). No reference electrode. Whole-brain and subcortical neural activity detection.
EEG	≥1 cm (low); ≤1 ms (very high)	Low–moderate; high; low	Semi-mobile via cap-based using gel adhesive; silent scan	Direct measure of neural activity. Reference electrode needed; cap and gel-induced discomfort. Whole-head with high-density templates. Sensitive to contraction and motion artifact.
fNIRS	0.5–2 cm (moderate); 10 ms–1 s (moderate)	Moderate–high; very high; low	Freely mobile if via wireless cap-based optodes; silent scan	Indirect measure of neural activity (neurovascular coupling: ΔHbO and ΔHbR). Whole-head with high-density templates. Low optical penetration limits detection of activity to cerebral cortex. Discomfort[c] from cap and optode.

Abbreviations: BOLD, blood oxygen level dependent; EEG, electroencephalography; fMRI, functional magnetic resonance imaging; fNIRS, functional near-infrared spectroscopy; ΔHbO, change in oxyhemoglobin concentration; ΔHbR, change in deoxyhemoglobin concentration; MEG, magnetoencephalography.

[a]Not theoretical limits, but dependent on acquisition and processing protocols.

[b]New strategies in development to improve tolerance to movement (e.g. real-time head motion feedback in cerebral palsy[212]).

[c]System-dependent.

autonomic activity.[68] A significant portion of near-infrared light is absorbed by superficial, extracerebral tissues that are sensitive to non-neuronal physiology,[69] necessitating additional signal processing to account for this contamination. Technical challenges arise with fNIRS data collection in individuals with thick or curly hair that can hinder

TABLE 2 Systematic search components.

Component	Search criteria
Population	Children and adults diagnosed with cerebral palsy (CP) of any etiological origin; includes pre-, peri-, or postnatal stroke; all topographical and phenomenological distributions included (unilateral–bilateral; hemi–/diplegia; no restriction on spastic–ataxic–dyskinetic–hypotonic–mixed tone presence)
Concept	Any aspect of brain activity, functional connectivity, or neuroplasticity captured using functional near-infrared spectroscopy (fNIRS)
Context	All geographical locations; sexes and races/ethnicities included; clinical, academic, and/or research settings accepted; no language restrictions implemented

scalp-optode contact. Additionally, individuals with darker skin experience reduced penetration depth of near-infrared light,[70,71] potentially introducing systemic biases in fNIRS results.[72] The fNIRS community is aware of these limitations,[73] with efforts to address technical shortcoming,[74,75] improve accessibility, and tackle equity challenges in fNIRS research spurring initiatives such as the BRIGHT project, which uses fNIRS to assess neurodevelopment in infants in The Gambia.[76]

Previous reviews of neuroimaging findings in CP have primarily focused on structural brain lesions[77,78] or connectivity,[51] with task-based functional neuroimaging reviews generally limited to conventional scanner-based modalities such as functional MRI.[18,79] While several reviews have detailed the use of fNIRS in typically developing children[80] and those with other neurodevelopmental disorders,[81,82] a comprehensive review specifically addressing the potential, limitations, and applications of fNIRS in CP is lacking, which may discourage adoption of this modality in research and clinical settings.[73] To address this, this scoping review aims to map and critically appraise the literature on the feasibility and current use of fNIRS to assess cortical activity, functional connectivity, and neuroplasticity in individuals with CP.

METHOD

A scoping review was conducted to synthesize existing knowledge on the use of fNIRS neuroimaging in CP,[83,84] map current practices, and highlight research gaps.[85] In accordance with evidence-based principles,[86] five key steps were included: research question identification, literature identification, study selection, data extraction, and evidence synthesis. Results were reported following Preferred Reporting Items for Systematic review and Meta-Analysis Extension for Scoping Reviews (PRISMA-ScR) guidelines.[87] The study protocol was registered on the Open Science Framework (https://osf.io/f3u8b).

Research question(s)

How has fNIRS been used to assess cortical activity, functional connectivity, or neuroplasticity in children and adults with CP? What are the methodological characteristics (sample characteristics, experimental protocols, processing pipelines and analyses algorithms) of studies that have used fNIRS in CP? What are the feasibility, potential, and limitations related to the use of fNIRS in CP?

Identification of relevant studies

A systematic search was conducted in PubMed, Web of Science, CINAHL (via EBSCOhost), and PsycINFO (via EBSCOhost) following the JBI format[88] (Table 2). Key terms were piloted on PubMed for sensitivity in detecting relevant studies, with the search strategy (Table S1) finalized in consultation with an academic librarian and translated across databases. Hand searching strategies included reviews of reference lists and citation tracking using Google Scholar and Lens.[89] No date or language restrictions were applied, and searches were updated on 18th July 2024. In line with previous scoping reviews,[90–92] grey literature (Table S2), abstracts, conference proceedings, and opinion pieces were not included, to focus on empirical, peer-reviewed literature and prevent 'double-counting' of studies.

Study selection

Eligible reports were imported into EndNote (version 20; Clarivate, Philadelphia, PA, USA) and Rayyan.[93] Duplicates were manually removed, and titles and abstracts were independently screened by three reviewers (OAK, SR, KB). Criteria for study inclusion were: (1) empirical human studies using fNIRS to assess brain activity, functional connectivity, or neuroplasticity; (2) studies where more than 50% of the sample comprised children (aged ≥3 years, after complete myelination in infancy[94]) or adults with CP. No demographic or geographical restrictions were imposed. Studies not reporting task-evoked or resting-state fNIRS outcomes, or those focusing on neurodevelopmental disorders other than CP, were excluded. Full-texts were reviewed independently by two reviewers (OAK, SR), with disagreements resolved through discussion, or through consultation with a third reviewer (KB).

Data extraction

A data extraction table was designed before study selection and iteratively refined during full-text review to ensure completeness of extracted information.[90] Two reviewers (OAK,

SR) performed data charting with pseudo-random assignment ensuring studies from the same group were reviewed by one reviewer for consistency.[91] One reviewer (OAK) validated accuracy of data extraction for all studies.

Evidence synthesis

Data were tabulated and categorized by study background, sample characteristics, experimental procedures, fNIRS parameters, and primary findings. Research trends and clinical implications were highlighted, with recommendations proposed for future fNIRS research in CP.

Critical appraisal of included studies

In line with previous fNIRS work,[90] study quality was appraised by three reviewers (OAK, SR, KB) using the adapted 15-item Downs and Black assessment tool for non-randomized studies[95] (Table S3), with consensus achieved through discussion. Quality was rated as low (<60%), moderate (60–74%), or high (≥75%), on the basis of the proportion of criteria met.

RESULTS

From 112 studies identified through searches, 42 duplicates and 41 irrelevant studies were removed. Full-text review of 29 studies resulted in the inclusion of 16 studies for analyses. Figure S1 illustrates the study selection process.

Study quality and background

Using the modified Downs and Black checklist (Table S4), study quality scores ranged from 53% to 100%, with an average score of 84%. Three studies[98,99,109] scored 60% to 74% (moderate quality), one study[100] scored less than 60% (poor quality), and the other 12 studies scored at least 75% (high quality). The lowest scoring item assessed external validity ('Were participants representative of the population', 44%), with similarly low scores for questions assessing confounding ('Were participants recruited from the same population?', 56%) and internal validity ('Were participants recruited over the same period?', 50%).

Study background and sample characteristics

Study settings (Table S5) indicate most studies ($n = 13$) were conducted in the USA, with two studies in China[109,110] and one in Italy.[108] All studies were published during the previous 15 years (2010–2024), and were in English. Most studies ($n = 13$) were observational, with three interventional studies including pre–post assessments[106], one including a mid-intervention assessment,[108] and another with a 6-month follow-up.[99] A priori power analyses was reported in only one study,[107] while two studies[96,99] used post hoc analyses to assess fNIRS's sensitivity at detecting group differences. Attrition rates (10–33%) were reported in six studies. One study excluded 20% of data (2 out of 10 participants) post hoc owing to large lesions observed in the cortical regions of interest on structural MRI.[103]

Participants' characteristics are also detailed in Table S5. Across 16 studies, 158 individuals with CP were assessed using fNIRS (sample sizes = 2–24), with 70% displaying unilateral affection (i.e. UCP). Participants' ages ranged from 3 to 43 years, with 12 studies recruiting only children, three studies including both children and adults,[102–104] and one pilot study assessing two adults with CP.[100] Structural brain imaging confirmed brain injury in seven studies, or was inferred through inclusion/exclusion criteria.[101,105–107] Nine studies described brain pathology, with six studies specifying injury type (e.g. perinatal stroke, periventricular leukomalacia) and three studies reported lesion location (e.g. subcortical or cortical lesion).[96,97,99] Functional classification varied by type of experimental task. Seven of the 11 studies incorporating an upper limb task documented Manual Ability Classification System (MACS) levels. Most participants displayed mild impairment (MACS levels I or II: $n = 46$, 63%) or moderate impairment (MACS levels III or IV: $n = 26$, 36%), and one study included a participant with severe impairment (MACS level V).[106] Gross Motor Function Classification System (GMFCS) levels were consistently reported across studies using a lower limb or whole-body task,[101,102,104,108,110,111] with most participants displaying mild to moderate impairments (GMFCS levels I–III: $n = 71$, 87%) and severe impairments less frequently (GMFCS level IV: $n = 10$; GMFCS level V: $n = 1$).[108,110] Muscle tone abnormality (primarily spasticity) was reported in eight studies, with two studies reporting limb dystonia.[102,103] Mirror movements were documented in four studies,[97,98,102,104] with one study focusing on this phenomenon.[98]

Experimental procedures

Experimental procedures are summarized in Table S6. Most studies employed motor tasks, except for three studies that used cognitive-motor dual-tasks involving varying cognitive demands[105,106] or concurrent postural challenge.[107] Upper limb tasks included unimanual protocols such as finger tapping,[96–99] ball grasp-and-drop,[100] and shape-matching,[105–107] as well as bimanual protocols such as ball grasp-and-squeeze and simulated pouring[103] and machine-assisted arm cycling.[109] One study combined unimanual and bimanual tasks.[104] Lower limb tasks included functional mobility (treadmill walking,[101] robot-assisted gait training,[108] functional strength [progressive lateral step-up] test[111]), and seated protocols such as passive cycling,[110] active cycling,[102] and single-joint movements.[102,104] Only one study combined upper- and lower-limb tasks.[104]

Major study findings

The major research questions and primary findings of each study are presented in Table S7.

Task-evoked sensorimotor cortex activity in CP

Early fNIRS studies highlighted altered patterns of local hemodynamic activity in children with UCP, with lower time-to-peak activity[97] and time-to-peak activity/total activation duration ratios[96] consistently observed at 2 months and sensitive at distinguishing UCP from age-matched typically developing children.[96,97] The same research group identified contributions of mirror movements to bilateral SMC activity in UCP during unimanual tasks,[98] with methods proposed to isolate these signal contaminants. Age-related variability in SMC hemispheric laterality was greater in children with UCP, who displayed bilateral SMC activation, unlike contralateral SMC activity displayed by typically developing children older than 7 years.[97] Following intensive constraint-induced movement therapy (CIMT), acute changes in local hemodynamics in children with UCP were sustained at 6-month follow-up, while acute change in SMC laterality (increased contralateral SMC activity) was not maintained, and was related to better unimanual, but worse bimanual, function.[99] Heightened SMC activity was also observed in adolescents and young adults with UCP during bimanual tasks,[103] with asymmetric tasks evoking more exaggerated and lateralized SMC activity that were linked to increased muscle co-activation and better daily function on the Pediatric Evaluation of Disability Index – Computer Adaptive Test (PEDI-CAT), respectively.

Few fNIRS studies assessed SMC activity in individuals with BCP displaying bilateral affection. One exploratory study[101] reported greater SMC and superior parietal lobule activity in BCP ($n=4$) than controls during treadmill walking. Increased activity in the combined groups was related to greater variability in temporal gait parameters, suggesting heightened neural demands to maintain ongoing gait trajectories. Another study reported greater SMC activity in older adults with BCP during lower limb tasks,[102] with activity scaling with higher GMFCS levels and greater muscle activation. Increased SMC activity during non-dominant ankle dorsiflexion was also related to worse selective motor control, and lower walking ability and mobility scores on the ABILOCO and PEDI-CAT, respectively. The only study comparing SMC activity in UCP and BCP[104] reported excessive activity in both groups compared with typically developing individuals, with activity scaling with increasing functional impairment (higher MACS, GMFCS levels). Differences between groups with CP were task-dependent. During non-dominant hand squeeze, SMC activity was greatest in individuals with UCP and those with more impaired manual abilities (MACS level III), with an positive relationship observed between SMC activity and MACS level. During non-dominant ankle dorsiflexion, SMC activity was greatest in individuals with BCP and those with more impaired gross motor function (GMFCS level III), with a similar positive association observed between SMC activity and GMFCS level.

Task-evoked prefrontal cortex activity in CP

The earliest fNIRS investigation of prefrontal cortex (PFC) activity in CP reported similar temporal patterns of hemodynamic activity in two adults with BCP as neurotypical individuals during a ball-grasp and drop task.[100] However, PFC laterality differed between the groups, with both individuals with BCP exhibiting ipsilateral PFC dominance, in contrast to the bilateral-to-contralateral PFC dominance observed in the neurotypical group. In children with UCP, no hemispheric difference in PFC activity was noted during a shape-matching task,[105] although overall PFC activity was greater than controls. Group differences were more pronounced with the more-affected arm, increasing task difficulty,[105] and during dual-task conditions with a dynamic postural challenge of ball-sitting.[107] Greater PFC activity during the dual-task was also linked to greater dual-task cost in children with UCP. Following intensive CIMT,[106] reduced PFC activity in children with UCP was comparable to baseline levels in typically developing children, but links between PFC activity and functional improvements were not reported.

Recent fNIRS studies assessing PFC activity during whole-body tasks such as robot-assisted gait training[108] and functional strength (progressive lateral step-up) test[111] revealed task-dependent patterns. Perpetuini et al.[108] reported contrasting changes in PFC activity across hemispheres, but no significant changes in SMC activity following robot-assisted gait training in children with BCP. Cortical activity changes were evident only at the end of the 4-week intervention, suggesting a dose-dependent neuroplastic response in children with more severe gross motor impairment. Licea et al.[111] observed suppressed PFC activity in children with CP compared with typically developing children across all levels of a progressive lateral step-up test, even after controlling for task performance differences. However, no significant association between PFC activity and step-up task performance was observed in the group with CP.

Resting-state functional connectivity in CP

Three fNIRS studies assessed resting-state functional connectivity in CP.[99,109,110] Cao et al.[99] noted lower frequency of functional connections in the pre-, supplementary, and primary motor cortices in children with UCP following intensive CIMT, which was linked to improved functional outcomes. However, changes were observed only in those with mild–moderate manual ability impairment (MACS level II, no change in those classified in MACS level I) and were not sustained at 6 months. More recent studies[109,110] reported similar

reductions in intra- and interhemispheric functional connectivity in the PFC and SMC of children with CP at rest, during assisted arm-cycling[109] and passive leg bicycling.[110] Decreased interhemispheric SMC connectivity in UCP was also strongly related to worse gross motor ability (higher GMFCS level). Zhang et al.[109] reported greater resting-state activity in the dominant SMC which remained unchanged during passive-assisted arm cycling, unlike the increased activity observed in controls. More advanced network analyses by Xie et al.[110] also revealed decreased global and local neural network efficiency in individuals with CP, both at rest and during passive bicycling, alongside decreased strength of motor-prefrontal connections from the non-dominant motor cortex.

DISCUSSION

Settings and sample characteristics

Most studies included in this review arose from research conducted over the past 15 years, with nearly all originating from North America. No studies from low- or middle-income countries were identified, despite these regions accounting for up to 98% of the global caseload of CP in children under 5 years[112] with significantly higher CP-related morbidity.[113] These constrained study settings reflect equity challenges in fNIRS research[73], which also presents researchers with opportunities to explore collaborations with not-for-profit organizations (e.g. the Bill and Melinda Gates Foundation's Brain Imaging for Global Health [BRIGHT] Project[114,115]) and communities in more diverse settings.[76] The low cost and portability of fNIRS make it a particularly promising neuroimaging modality for use in these underserved regions.

Despite small sample sizes (range = 2–24; median = 8), individuals with CP across a wide age range (3–42 years), different topographies (UCP, BCP), and varying levels of functional impairment (GMFCS, MACS levels) were assessed, broadly supporting the feasibility of fNIRS use in CP. Spastic CP was the most frequently reported subtype across studies, with dystonia reported in two studies.[102,103] Notably, no study included individuals with the less common dyskinetic or ataxic subtypes of CP, despite their distinct clinical phenotype[116] and evidence of altered neural connectivity.[117,118] None of the studies were pre-registered,[119] and only one study reported a priori power analyses for sample size estimation,[107] possibly reflecting the incipient nature of the field. Adequate powering of neuroimaging-focused studies to detect interventional neuroplasticity in CP is an important issue, with specific sample size recommendations proposed for some MRI-based outcomes.[120] While similar guidelines for fNIRS studies are currently lacking (but see Schroeder et al.[119] for general discussion), future fNIRS research should consider adopting standardized experimental protocols,[121] consistent preprocessing pipelines,[122] and engaging in collaborative initiatives such as the ManyBabies 3 NIRS project[123] to facilitate data pooling across studies.

Additionally, only 10 individuals with significant gross motor impairment (GMFCS levels IV–V; ~6% of total participants with CP) were assessed across two studies,[108,110] despite this group comprising close to 30% of all individuals with CP.[124] This underrepresentation highlights ongoing equity challenges in neuroimaging research in CP, restricting generalizability of findings and marginalizing individuals already less likely to access and benefit from evidence-based interventions.[125] A similar issue was observed for upper limb assessments in individuals with UCP, with only four individuals classified at MACS levels IV or V included across two studies,[105,106] while MACS levels were not reported in three of 11 studies using upper limb tasks.[96,100,109] As fNIRS outcomes can vary across functional abilities on both the GMFCS and MACS,[104] future fNIRS studies in individuals with CP should include these descriptors to improve generalizability of findings and facilitate aggregation of results.

Experimental protocols

Most studies incorporated tasks that were either functional (e.g. shape-matching, seated cycling, walking) or resembled real-world behavior (e.g. simulated pouring). Only three studies incorporated whole-body tasks,[101,108,111] and upper limb tasks were performed in seated or reclined positions that may not reflect real-world behavior. Two studies employed experimental protocols with movements that were either fully passive[110] or active-assisted.[109] Functional MRI work in UCP demonstrated that passive movements evoke lower cortical activation than self-generated active movements,[126] and passive modalities do not reflect the task-focused, child-driven, and activity-based principles of evidence-based best practices for CP neurorehabilitation.[127] While the great potential of fNIRS to assess neurophysiology during real-world tasks in unconstrained environments remains largely untapped,[61] recent efforts to integrate more functional assessment protocols such as robot-assisted walking[108] and a progressive lateral step-up test[111] are promising, and may guide future fNIRS research in CP.

Sensorimotor cortex activity

Unilateral CP

Most fNIRS studies in UCP reported exaggerated SMC activity, with potential contributors including mirror movements,[98] lower functional abilities (higher MACS levels),[104] greater task complexity (asymmetric vs. symmetric bimanual or unimanual tasks),[104] and deficits in upper limb selective voluntary motor control.[103] Functional MRI studies in UCP reported similar heightened SMC activity during impaired hand movement,[126,128] including increased bilateral[126] and ipsilateral (contralesional) SMC activity,[128] with the latter related to residual hand function and strength of

mirror movements.[128] Mirror movements may reflect altered neurophysiology due to early developmental injury in UCP,[129] and may have potential clinical implications such as reduced bimanual function.[130,131] Despite early fNIRS work suggesting mirror movements contribute to increased SMC activation in UCP,[98] their presence and impact was inconsistently reported. Future studies should report clinically observable mirror movements, with quantitative tools available for more detailed analyses.[132]

Studies assessing hemispheric lateralization of SMC activity in UCP reported age-related variability,[97] bilateral activation,[99] or trends of ipsilesional SMC dominance during unimanual[104] and bimanual tasks.[103] The functional relevance of SMC lateralization in UCP was less studied, although contralesional SMC dominance during asymmetric bimanual squeezing was related to better daily function,[103] while SMC activity during non-dominant hand squeezing and ankle dorsiflexion was not related to functional outcomes.[104] Variability in activation patterns reflects methodological differences across studies and aligns with functional MRI literature in UCP that describes three main lateralization patterns:[18] bilateral dominance in motor functions, ipsilesional dominance in somatosensory functions, and contralesional dominance in language functions. Ipsilesional SMC activation involves the recruitment of preserved perilesional tissue, and generally correlates with better clinical outcomes in UCP[133] and stroke.[134]

The diverse SMC lateralization patterns reflect the nuanced dynamics of cortical activation in UCP, a complexity further highlighted by intervention studies. The sole fNIRS study reporting SMC changes postintervention found increased contralesional SMC dominance in UCP immediately after CIMT[99] that declined at 6 months and was related to worse bimanual function.[99] A review of interventional neuroplasticity reported increased ipsilesional SMC activity as the most common change observed postintervention in UCP.[23] Conversely, a recent functional MRI study reported increased ipsilesional and decreased contralesional SMC activity after hand–arm bimanual intensive therapy including lower extremities (HABIT-ILE) intervention, with better clinical outcomes related to reduced brain activity.[135] Lateralization of SMC activity in UCP reflects adaptive developmental processes after early developmental injury (see Eyre[136] and Friel et al.[137] for detailed review) that vary by lesion size[138] and timing.[139] Large lesions may prevent ipsilesional SMC control, rendering contralesional activity the sole contributor to motor function.[79] Laterality also varies by side tested and fatigue.[140] A multimodal neuroimaging study highlighted unique neurophysiological patterns across individuals with UCP,[32] emphasizing significant individual variability and highlighting the challenge of defining clear neural structure–function relationships in this population.

Bilateral CP

While limited, fNIRS studies in BCP offer valuable insights into this group's distinct neurophysiology. Increased SMC and superior parietal lobule activity during treadmill walking in an exploratory study in children with BCP[101] mirrors the excessive motor and parietal cortex activation observed in a larger EEG gait study in UCP.[33] Similar to fNIRS reports in UCP,[104] greater SMC activation in BCP was related to lower functional abilities (higher GMFCS levels),[104] worse selective motor control, and lower PEDI-CAT mobility scores.[102] However, unlike UCP, where greater SMC activation is seen during non-dominant hand squeezing than ankle dorsiflexion, the BCP cohort demonstrated similar SMC activity across these tasks,[104] potentially indicating more severe upper extremity involvement in this group.[141] This is supported by EEG evidence of exaggerated dominant SMC activation in BCP during reaching[142,143] that was also associated with slower, less efficient movements and poor dexterity, suggesting SMC over-recruitment may reflect excessive cortical resource use during arm movements in BCP.[142]

Hemispheric lateralization of SMC activity in BCP was task-dependent, with ipsilateral SMC dominance during non-dominant ankle dorsiflexion[102] and contralateral dominance during non-dominant hip movements, cycling,[102] and hand squeezing.[104] This pattern contrasts with the bilateral activation commonly noted in UCP, where underlying brain lesions are often focal, well-defined, and distinctly impacted by the timing and location of insult, such as in perinatal stroke.[144] The more widespread bilateral brain injury in BCP results in more severe motor impairments and higher incidences of comorbidities such as intellectual and visual impairments,[145] that further complicates task performance during neuroimaging studies. Reorganization following bilateral lesions probably follows different developmental patterns than those seen after unilateral injuries, owing to the absence of a relatively intact hemisphere that can act as a scaffold to support adaptive plasticity.[145] A recent functional MRI study in mildly impaired children with BCP[146] reported contralateral SMC dominance during non-dominant ankle dorsiflexion, although a shift to greater ipsilateral dominance and lower activation volume postintervention were independently associated with motor skill gains. These observations highlight the potential for targeted interventions to influence cortical reorganization and improve motor outcomes in BCP. However, the scarcity of functional neuroimaging studies in BCP is a significant barrier to understanding the complexity and variability of neural structure–function relationships in this group. Mobile neuroimaging tools such as fNIRS, with their methodological flexibility and resilience to motion artifacts, are well-suited to addressing this research gap.

PFC activity

Greater PFC activity in UCP during a shape-matching task scaled with increased task difficulty, non-dominant arm use,[105] and concurrent postural challenge.[107] After CIMT intervention, PFC activity in CP attenuated to levels comparable to typically developing children,[106] but no link to

improved functional outcomes was reported, generating doubt on whether attenuated PFC activity reflected 'normalization' of cortical activity or was the byproduct of generalized motor skill acquisition. The PFC is a prime target for interrogation by fNIRS because of its accessible location underneath the hairless forehead region, allowing for optimal signal acquisition.[147] Although the PFC is not involved in motor execution, it mediates executive functions such as working memory, sustained attention, and action planning that support and enable motor planning and prediction.[148,149] Exaggerated PFC activity during motor tasks may represent a resources allocation strategy[150] for enhanced motor planning in UCP.[151] In contrast, children with BCP with greater motor involvement displayed more variable PFC activity patterns after robot-assisted gait training,[108] although the small, heterogenous sample and absence of a comparison group limits definitive conclusions on the functional impact of these changes.

The variability in PFC activity changes following different motor interventions highlights a need for further investigation into the neural correlates of cognitive deficits and their impact on motor outcomes in CP. Half of all children with CP are estimated to display concurrent intellectual disability,[152] with a recent meta-analysis identifying moderate–large deficits across all executive function domains in individuals with CP, regardless of gross motor or manual ability (i.e. GMFCS and MACS levels, respectively).[153] Given the intimate linkage of cognitive and motor development[154] and their combined relation to the PFC,[155] cognitive deficits in CP significantly impact their ability to navigate real-world tasks that involve dual-tasking.[156,157] A recent MEG study in adults with CP[158] reported weaker PFC oscillatory activity during the encoding phase of working memory was related to worse cognitive outcomes and lower gross motor function (higher GMFCS levels). Despite the potential for fNIRS to assess PFC activity during ecologically valid tasks in real-world settings, fNIRS studies assessing PFC activity during cognitive tasks or during physical activity are lacking.[159] Notably, the sole fNIRS study to incorporate a physically demanding task reported suppressed PFC activity in children with CP during a progressive lateral step-up test[111] which was maintained after controlling for their lower performance. However, the lack of significant associations between PFC activity and step-up performance in CP suggests factors such as lower exercise tolerance or psychological factors such as impaired attention and emotional dysregulation may contribute to the suppressed PFC activity patterns observed in this group. These novel observations emphasize the need for future fNIRS research to explore how PFC activity impacts cognitive–motor interactions in CP.

Functional connectivity and cortical networks

Early fNIRS-based functional connectivity research[99] revealed greater frequency of connections between the supplementary motor, premotor, and primary motor cortices in children with UCP, with most connections observed from the supplementary motor area, although connection strength was not quantified. Conversely, recent fNIRS studies[109,110] reported lower intra- and interhemispheric resting-state functional connectivity in the PFC and SMC of children with UCP, with attenuated connectivity maintained during assisted arm[109] and passive leg cycling,[110] and related to lower gross motor function. Reduced functional connectivity across the sensory and motor areas was also widely reported in the functional MRI literature in UCP,[51] although intrahemispheric connectivity in these regions may vary by pattern of corticospinal tract wiring.[160] Lower efficiency of both global and local cortical networks in UCP reported in a recent fNIRS study[110] mirrored observations from studies using structural MRI[161] and diffuse tensor imaging[162] reporting similar lowered global efficiency in children with BCP.

Notably, fNIRS functional connectivity research did not include studies of individuals with BCP, in whom functional MRI revealed widely varying patterns of functional connectivity across cortical regions. Significantly widened and increased connections reported with functional MRI in BCP between the somatosensory cortices,[163] SMC, and supplementary motor areas[164] contrasts against decreased connectivity in the bilateral SMC and parietal cortices.[118,165] Functional connectivity analyses have also been used to examine neural networks mediating non-motor functions, with evidence of altered networks in CP extending to domains of language,[27] visuomotor function,[166] and cognition.[26] These domains represent rich avenues for future research, with recent development of wearable, high-density fNIRS devices[167] setting the stage for fNIRS investigation of these unexplored topics in CP.

fNIRS methodologies

While fNIRS is a promising tool for real-world neuroimaging, its outcomes are susceptible to subjective decisions by researchers[168] on issues of signal quality assessment,[147,169,170] data processing pipelines,[171,172] and methods of statistical analyses.[173] Concerns about potential data misreporting have spurred a movement towards greater transparency in decision-making and reporting within the fNIRS community, with calls for preregistration of study protocols and algorithms for analyses decision-making[119] to mitigate publication bias and false positive results.[69,174] While assessing methodological rigor and modality-specific challenges of fNIRS exceeds the scope of this review (see Yücel et al.[175] for comprehensive recommendations), we provide a detailed summary and critical appraisal of fNIRS methods in Table S8 and Appendix S1, respectively. Further, as fNIRS shares neurovascular underpinnings (blood oxygen level dependent response) with functional MRI, readers are referred to the excellent review by Reid et al.[24] for a detailed examination of challenges in interpreting activation changes in functional neuroimaging.

Limitations

This review aimed to inform future research by synthesizing peer-reviewed empirical literature on the application of fNIRS in CP, and excluded grey literature and non-scientific articles. While this approach is consistent with other scoping reviews,[92,176,177] it may have resulted in the omission of additional experimental settings and observations. However, we provide readers with a list of relevant doctoral dissertations and theses obtained through a systematic search (see Table S2). The inclusion of studies with small sample sizes and methodological limitations (e.g. the pilot study by Chaudhary et al.[100] on two adults with CP) was necessitated by the nature of scoping reviews. Quality appraisal analyses were performed to address concerns about potential bias, although we acknowledge that caution is warranted when interpreting the study results. Finally, the diversity of fNIRS outcomes across studies prevented aggregation and quantification by meta-analyses, emphasizing the need for standardized experimental protocols for easier data pooling and comparisons across studies.[51] Despite these limitations, this review provides a comprehensive overview on the use of fNIRS in CP that can inform future investigations in this field.

Challenges with fNIRS use in CP

Despite its advantages as a user-friendly, motion-resistant, and cost-effective functional neuroimaging modality, fNIRS remains underutilized in CP neuroimaging research, with only 16 studies identified in this review. Alongside the aforementioned limitations such as poor imaging depth, inability to image deeper brain structures, systemic contamination, and data collection challenges with darker skin tones or thick hair, other potential barriers also require recognition. A lack of research confirming fNIRS reliability in CP undermines confidence in its ability to track intervention effects on cortical function. Recruitment and compliance issues are frequent, with early studies that used wired systems reporting high attrition rates (10–33%) and exclusion of data (20% in one study[103]) owing to cortical lesions in brain regions of interest. Practical challenges include prolonged setup times, resistance to fNIRS caps from sensory hypersensitivity, and participants' discomfort, compounded by the lower signal-to-noise ratio of fNIRS than functional MRI, necessitating longer and more frequent trials.[80] The physiological underpinnings of fNIRS also present challenges in CP. Neurovascular coupling, the basis of fNIRS measurements, may be altered in CP owing to brain injuries such as periventricular leukomalacia or perinatal stroke,[178] which impair vascular autoregulation[179] and integrity.[180] This disrupts hemodynamic signals and complicates interpretation of cortical activity.[181] Additionally, historical reliance on conventional neuroimaging modalities such as functional MRI and EEG, coupled with limited awareness of recent advances in fNIRS technology, has slowed the adoption of fNIRS in CP research.

However, rapid improvements in fNIRS hardware and software offer solutions to many of these challenges.[182] Recent innovations such as infant-friendly dual-tip optodes,[183] scalable modules for high-density whole-head imaging in infants,[184] and customizable optode attachments have significantly improved feasibility. Implementing standardized fNIRS methodologies,[185] analyses pipelines,[122,186] and reporting guidelines[175] can further enhance reliability and reproducibility. Targeted efforts to establish fNIRS reliability in CP and adapt this technology for neurodiverse populations could significantly expand its utility in understanding neurophysiology and intervention effects in CP.

Future directions

The exponential rise in fNIRS studies in neurodevelopmental disorders and neurodivergent populations[187–192] reflects the growing recognition of fNIRS as a valuable tool for investigating brain function in neurodivergent populations for whom conventional neuroimaging is challenging.[193] Rapid technical, methodological, and technological developments in fNIRS have propelled the field beyond initial feasibility assessments[194–196] towards the identification of diagnostic and prognostic biomarkers ('fNIRS signatures'[197]) of significant translational value to clinicians and researchers. Future research avenues for exploration include the integration of fNIRS with other neuroimaging modalities such as functional MRI,[198] EEG,[199] MEG,[200,201] and transcranial magnetic stimulation,[202,203] to provide real-time feedback of functional performance and progress during rehabilitation.[204] This multimodal approach may also uncover underlying pathophysiology[24,32,205] and enhance confidence in reported results by reducing bias, and minimizing signal noise.[73] Hyperscanning protocols that enable synchronous assessment of multiple interacting individuals in naturalistic settings are particularly well-suited for fNIRS, and hold promise for studying parent–child interactions.[206] This innovative approach may shed light on the neurophysiological underpinnings of impaired interpersonal social interactions in CP,[207] and promote family-centered care by facilitating parental involvement in therapy.[208] Additionally, the integration of fNIRS into brain–computer interface applications,[209] either alone or in conjunction with other modalities such as EEG,[199,210] may offer tangible benefits to individuals with CP who experience severe motor, language, or cognitive impairments.[211]

The overarching goal of translational fNIRS research is to integrate fNIRS into clinical settings for individualized assessment, prognosis, and monitoring of treatment fidelity and effectiveness in clinical populations of all ages and functional profiles. Achieving these goals in the context of CP requires: (1) continuous advances in fNIRS hardware and software; (2) transparent and comprehensive reporting of experimental methods and results; (3) collaboration between funding agencies, industry, researchers, and community partners; and most importantly, (4) sustained involvement

of individuals with lived experience and their families, who stand to benefit most from this research. This review comprehensively summarizes the current state of fNIRS research in CP and represents a critical first step towards realizing these ambitious objectives.

CONCLUSION

This review analyzed 16 studies that confirmed the feasibility and utility of fNIRS for evaluating cortical activity, functional connectivity, and neuroplasticity in individuals with CP, with exaggerated SMC activity observed across motor tasks alongside task-dependent PFC activity patterns. While fNIRS demonstrated utility in capturing neuroplastic changes postintervention, the lack of reliability data undermines confidence in its application in interventional research. While most studies demonstrated moderate–strong methodological quality, specific challenges to fNIRS use were identified, with recommendations for enhanced rigor and transparency outlined. Leveraging recent technical advancements may help address these challenges and transition fNIRS research beyond feasibility towards integration into clinical practice. By enabling individualized assessments and real-time monitoring, and facilitating family-centered care through improved neurophysiological understanding of parent–child interactions, fNIRS offers transformative potential for CP research and rehabilitation that remains largely untapped.

ACKNOWLEDGEMENTS

This study was supported by the Eunice Kennedy Shriver National Institute of Child Health and Human Development (RO1 HD090126) and the University of Georgia Athletic Association. The sponsors had no role in the collection, analysis, or interpretation of data, in the writing of the report, or in the decision to submit the article for publication.

FUNDING INFORMATION

The Eunice Kennedy Shriver National Institute of Child Health and Human Development (RO1 HD090126) and the University of Georgia Athletic Association.

CONFLICT OF INTEREST

The authors have no interests which might be perceived as posing a conflict or bias.

DATA AVAILABILITY STATEMENT

Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

ORCID

Owais A. Khan https://orcid.org/0000-0001-9133-0264
Simin Rahman https://orcid.org/0000-0002-1395-7915
Kanishka Baduni https://orcid.org/0009-0000-0542-3289
Christopher M. Modlesky https://orcid.org/0000-0003-2654-6311

REFERENCES

1. Robinson MN, Peake LJ, Ditchfield MR, Reid SM, Lanigan A, Reddihough DS. Magnetic resonance imaging findings in a population-based cohort of children with cerebral palsy. Developmental medicine and child neurology. 2009;51(1):39–45.
2. Reid SM, Dagia CD, Ditchfield MR, Carlin JB, Reddihough DS. Population-based studies of brain imaging patterns in cerebral palsy. Developmental medicine and child neurology. 2014;56(3):222–32.
3. de Vries LS, van Haastert IC, Benders MJ, Groenendaal F. Myth: cerebral palsy cannot be predicted by neonatal brain imaging. Semin Fetal Neonatal Med. 2011;16(5):279–87.
4. Ashwal S, Russman BS, Blasco PA, Miller G, Sandler A, Shevell M, et al. Practice parameter: diagnostic assessment of the child with cerebral palsy: report of the Quality Standards Subcommittee of the American Academy of Neurology and the Practice Committee of the Child Neurology Society. Neurology. 2004;62(6):851–63.
5. Feys H, Eyssen M, Jaspers E, Klingels K, Desloovere K, Molenaers G, et al. Relation between neuroradiological findings and upper limb function in hemiplegic cerebral palsy. Eur J Paediatr Neurol. 2010;14(2):169–77.
6. Laporta-Hoyos O, Pannek K, Pagnozzi AM, Whittingham K, Wotherspoon J, Benfer K, et al. Cognitive, academic, executive and psychological functioning in children with spastic motor type cerebral palsy: Influence of extent, location, and laterality of brain lesions. Eur J Paediatr Neurol. 2022;38:33–46.
7. Mailleux L, Klingels K, Fiori S, Simon-Martinez C, Demaerel P, Locus M, et al. How does the interaction of presumed timing, location and extent of the underlying brain lesion relate to upper limb function in children with unilateral cerebral palsy? Eur J Paediatr Neurol. 2017;21(5):763–72.
8. Forssberg H, Eliasson AC, Redon-Zouitenn C, Mercuri E, Dubowitz L. Impaired grip-lift synergy in children with unilateral brain lesions. Brain. 1999;122 (Pt 6):1157–68.
9. Mailleux L, Simon-Martinez C, Klingels K, Jaspers E, Desloovere K, Demaerel P, et al. Structural Brain Damage and Upper Limb Kinematics in Children with Unilateral Cerebral Palsy. Front Hum Neurosci. 2017;11:607.
10. Klingels K, Jaspers E, Staudt M, Guzzetta A, Mailleux L, Ortibus E, et al. Do mirror movements relate to hand function and timing of the brain lesion in children with unilateral cerebral palsy? Developmental medicine and child neurology. 2016;58(7):735–42.
11. Reid LB, Rose SE, Boyd RN. Rehabilitation and neuroplasticity in children with unilateral cerebral palsy. Nat Rev Neurol. 2015;11(7):390–400.
12. Kennard MA. Age and other factors in motor recovery from precentral lesions in monkeys. American Journal of Physiology. 1936;115(1):138–46.
13. Lewis SA, Ruttenberg A, Iyiyol T, Kong N, Jin SC, Kruer MC. Potential clinical applications of advanced genomic analysis in cerebral palsy. EBioMedicine. 2024;106:105229.
14. Romero B, Robinson KG, Batish M, Akins RE. An Emerging Role for Epigenetics in Cerebral Palsy. J Pers Med. 2021;11(11).
15. Damiano DL. Meaningfulness of mean group results for determining the optimal motor rehabilitation program for an individual child with cerebral palsy. Developmental medicine and child neurology. 2014;56(12):1141–6.
16. Islam M, Nordstrand L, Holmstrom L, Kits A, Forssberg H, Eliasson AC. Is outcome of constraint-induced movement therapy in unilateral cerebral palsy dependent on corticomotor projection pattern and brain lesion characteristics? Developmental medicine and child neurology. 2014;56(3):252–8.
17. Damiano DL, Pekar JJ, Mori S, Faria AV, Ye X, Stashinko E, et al. Functional and Structural Brain Connectivity in Children With Bilateral Cerebral Palsy Compared to Age-Related Controls and in Response to Intensive Rapid-Reciprocal Leg Training. Front Rehabil Sci. 2022;3:811509.
18. Gaberova K, Pacheva I, Ivanov I. Task-related fMRI in hemiplegic cerebral palsy-A systematic review. J Eval Clin Pract. 2018;24(4):839–50.

19. Azhari A, Truzzi A, Neoh MJ, Balagtas JPM, Tan HH, Goh PP, et al. A decade of infant neuroimaging research: What have we learned and where are we going? Infant Behav Dev. 2020;58:101389.
20. Brown GG, Perthen JE, Liu TT, Buxton RB. A primer on functional magnetic resonance imaging. Neuropsychol Rev. 2007;17(2):107–25.
21. Phillips JP, Sullivan KJ, Burtner PA, Caprihan A, Provost B, Bernitsky-Beddingfield A. Ankle dorsiflexion fMRI in children with cerebral palsy undergoing intensive body-weight-supported treadmill training: a pilot study. Developmental medicine and child neurology. 2007;49(1):39–44.
22. Doucet GE, Baker S, Wilson TW, Kurz MJ. Weaker Connectivity of the Cortical Networks Is Linked with the Uncharacteristic Gait in Youth with Cerebral Palsy. Brain Sci. 2021;11(8).
23. Inguaggiato E, Sgandurra G, Perazza S, Guzzetta A, Cioni G. Brain reorganization following intervention in children with congenital hemiplegia: a systematic review. Neural Plast. 2013;2013:356275.
24. Reid LB, Boyd RN, Cunnington R, Rose SE. Interpreting Intervention Induced Neuroplasticity with fMRI: The Case for Multimodal Imaging Strategies. Neural Plast. 2016;2016:2643491.
25. Manning KY, Fehlings D, Mesterman R, Gorter JW, Switzer L, Campbell C, et al. Resting State and Diffusion Neuroimaging Predictors of Clinical Improvements Following Constraint-Induced Movement Therapy in Children With Hemiplegic Cerebral Palsy. J Child Neurol. 2015;30(11):1507–14.
26. Ilves N, Ilves P, Laugesaar R, Juurmaa J, Mannamaa M, Loo S, et al. Resting-State Functional Connectivity and Cognitive Impairment in Children with Perinatal Stroke. Neural Plast. 2016;2016:2306406.
27. Carlson HL, Sugden C, Brooks BL, Kirton A. Functional connectivity of language networks after perinatal stroke. Neuroimage Clin. 2019;23:101861.
28. Woodward KE, Carlson HL, Kuczynski A, Saunders J, Hodge J, Kirton A. Sensory-motor network functional connectivity in children with unilateral cerebral palsy secondary to perinatal stroke. Neuroimage Clin. 2019;21:101670.
29. Demas J, Bourguignon M, Perivier M, De Tiege X, Dinomais M, Van Bogaert P. Mu rhythm: State of the art with special focus on cerebral palsy. Ann Phys Rehabil Med. 2020;63(5):439–46.
30. Inuggi A, Bassolino M, Tacchino C, Pippo V, Bergamaschi V, Campus C, et al. Ipsilesional functional recruitment within lower mu band in children with unilateral cerebral palsy, an event-related desynchronization study. Exp Brain Res. 2018;236(2):517–27.
31. Kukke SN, de Campos AC, Damiano D, Alter KE, Patronas N, Hallett M. Cortical activation and inter-hemispheric sensorimotor coherence in individuals with arm dystonia due to childhood stroke. Clin Neurophysiol. 2015;126(8):1589–98.
32. Weinstein M, Green D, Rudisch J, Zielinski IM, Benthem-Muniz M, Jongsma MLA, et al. Understanding the relationship between brain and upper limb function in children with unilateral motor impairments: A multimodal approach. Eur J Paediatr Neurol. 2018;22(1):143–54.
33. Short MR, Damiano DL, Kim Y, Bulea TC. Children With Unilateral Cerebral Palsy Utilize More Cortical Resources for Similar Motor Output During Treadmill Gait. Front Hum Neurosci. 2020;14:36.
34. Kurz MJ, Heinrichs-Graham E, Becker KM, Wilson TW. The magnitude of the somatosensory cortical activity is related to the mobility and strength impairments seen in children with cerebral palsy. J Neurophysiol. 2015;113(9):3143–50.
35. VerMaas JR, Lew BJ, Trevarrow MP, Wilson TW, Kurz MJ. Children with Cerebral Palsy Have Altered Occipital Cortical Oscillations during a Visuospatial Attention Task. Cereb Cortex. 2021;31(7):3353–62.
36. Hoffman RM, Embury CM, Lew BJ, Heinrichs-Graham E, Wilson TW, Kurz MJ. Cortical oscillations that underlie visual selective attention are abnormal in adolescents with cerebral palsy. Sci Rep. 2021;11(1):4661.
37. VerMaas JR, Embury CM, Hoffman RM, Trevarrow MP, Wilson TW, Kurz MJ. Beyond the eye: Cortical differences in primary visual processing in children with cerebral palsy. Neuroimage Clin. 2020;27:102318.
38. Hinton EH, Busboom MT, Embury CM, Spooner RK, Wilson TW, Kurz MJ. Adults with cerebral palsy exhibit uncharacteristic cortical oscillations during an adaptive sensorimotor control task. Sci Rep. 2024;14(1):10788.
39. Kurz MJ, Becker KM, Heinrichs-Graham E, Wilson TW. Neurophysiological abnormalities in the sensorimotor cortices during the motor planning and movement execution stages of children with cerebral palsy. Developmental medicine and child neurology. 2014;56(11):1072–7.
40. Bergwell H, Trevarrow M, Corr B, Baker S, Reelfs H, Wilson TW, et al. Power training alters somatosensory cortical activity of youth with cerebral palsy. Ann Clin Transl Neurol. 2022;9(5):659–68.
41. Busboom M, Corr B, Reelfs A, Trevarrow M, Reelfs H, Baker S, et al. Therapeutic Lower Extremity Power Training Alters the Sensorimotor Cortical Activity of Individuals With Cerebral Palsy. Arch Rehabil Res Clin Transl. 2022;4(1):100180.
42. Altman NR, Bernal B. Pediatric applications of functional magnetic resonance imaging. Pediatr Radiol. 2015;45 Suppl 3:S382–96.
43. Tajik-Parvinchi DJ, Black KR, Roudbarani F, Weiss JA, King G. Functional magnetic resonance imaging (fMRI) in typical and atypical brain development: Challenges and suggestions. In: Halpern-Felsher B, editor. Encyclopedia of Child and Adolescent Health. Oxford: Academic Press; 2023. p. 4–13.
44. Raschle NM, Lee M, Buechler R, Christodoulou JA, Chang M, Vakil M, et al. Making MR imaging child's play - pediatric neuroimaging protocol, guidelines and procedure. J Vis Exp. 2009(29).
45. Wilke M, Groeschel S, Lorenzen A, Rona S, Schuhmann MU, Ernemann U, et al. Clinical application of advanced MR methods in children: points to consider. Ann Clin Transl Neurol. 2018;5(11):1434–55.
46. Greene DJ, Koller JM, Hampton JM, Wesevich V, Van AN, Nguyen AL, et al. Behavioral interventions for reducing head motion during MRI scans in children. Neuroimage. 2018;171:234–45.
47. Parkes L, Fulcher B, Yucel M, Fornito A. An evaluation of the efficacy, reliability, and sensitivity of motion correction strategies for resting-state functional MRI. Neuroimage. 2018;171:415–36.
48. Ickx G, Hatem SM, Riquelme I, Friel KM, Henne C, Araneda R, et al. Impairments of Visuospatial Attention in Children with Unilateral Spastic Cerebral Palsy. Neural Plast. 2018;2018:1435808.
49. Stadskleiv K, Jahnsen R, Andersen GL, von Tetzchner S. Neuropsychological profiles of children with cerebral palsy. Developmental Neurorehabilitation. 2018;21(2):108–20.
50. Kotsoni E, Byrd D, Casey BJ. Special considerations for functional magnetic resonance imaging of pediatric populations. J Magn Reson Imaging. 2006;23(6):877–86.
51. Jacobs NPT, Pouwels PJW, van der Krogt MM, Meyns P, Zhu K, Nelissen L, et al. Brain structural and functional connectivity and network organization in cerebral palsy: A scoping review. Developmental medicine and child neurology. 2023;65(9):1157–73.
52. Nebel MB, Lidstone DE, Wang L, Benkeser D, Mostofsky SH, Risk BB. Accounting for motion in resting-state fMRI: What part of the spectrum are we characterizing in autism spectrum disorder? Neuroimage. 2022;257:119296.
53. Hillman EM. Coupling mechanism and significance of the BOLD signal: a status report. Annu Rev Neurosci. 2014;37(1):161–81.
54. Huneau C, Benali H, Chabriat H. Investigating Human Neurovascular Coupling Using Functional Neuroimaging: A Critical Review of Dynamic Models. Front Neurosci. 2015;9:467.
55. Kozberg M, Hillman E. Chapter 10 - Neurovascular coupling and energy metabolism in the developing brain. In: Masamoto K, Hirase H, Yamada K, editors. Progress in Brain Research. 225: Elsevier; 2016. p. 213–42.
56. Obrig H, Villringer A. Beyond the visible--imaging the human brain with light. J Cereb Blood Flow Metab. 2003;23(1):1–18.
57. Patil AV, Safaie J, Moghaddam HA, Wallois F, Grebe R. Experimental investigation of NIRS spatial sensitivity. Biomed Opt Express. 2011;2(6):1478–93.

58. Oshina I, Spigulis J. Beer-Lambert law for optical tissue diagnostics: current state of the art and the main limitations. J Biomed Opt. 2021;26(10):100901.
59. Scholkmann F, Kleiser S, Metz AJ, Zimmermann R, Mata Pavia J, Wolf U, et al. A review on continuous wave functional near-infrared spectroscopy and imaging instrumentation and methodology. Neuroimage. 2014;85 Pt 1:6–27.
60. Cutini S, Moro SB, Bisconti S. Functional near infrared optical imaging in cognitive neuroscience: an introductory review. Journal of near Infrared Spectroscopy. 2012;20(1):75–92.
61. Pinti P, Aichelburg C, Gilbert S, Hamilton A, Hirsch J, Burgess P, et al. A Review on the Use of Wearable Functional Near-Infrared Spectroscopy in Naturalistic Environments(). Jpn Psychol Res. 2018;60(4):347–73.
62. Balardin JB, Zimeo Morais GA, Furucho RA, Trambaiolli L, Vanzella P, Biazoli C, Jr., et al. Imaging Brain Function with Functional Near-Infrared Spectroscopy in Unconstrained Environments. Front Hum Neurosci. 2017;11:258.
63. Schmit JM, Riley M, Cummins-Sebree S, Schmitt L, Shockley K. Functional Task Constraints Foster Enhanced Postural Control in Children With Cerebral Palsy. Phys Ther. 2016;96(3):348–54.
64. Okamoto M, Dan H, Shimizu K, Takeo K, Amita T, Oda I, et al. Multimodal assessment of cortical activation during apple peeling by NIRS and fMRI. Neuroimage. 2004;21(4):1275–88.
65. Hoshi Y, Yamada Y. Overview of diffuse optical tomography and its clinical applications. J Biomed Opt. 2016;21(9):091312.
66. McIntyre S, Goldsmith S, Webb A, Ehlinger V, Hollung SJ, McConnell K, et al. Global prevalence of cerebral palsy: A systematic analysis. Developmental medicine and child neurology. 2022;64(12):1494–506.
67. Monbaliu E, Himmelmann K, Lin JP, Ortibus E, Bonouvrie L, Feys H, et al. Clinical presentation and management of dyskinetic cerebral palsy. Lancet Neurol. 2017;16(9):741–9.
68. Kirilina E, Jelzow A, Heine A, Niessing M, Wabnitz H, Bruhl R, et al. The physiological origin of task-evoked systemic artefacts in functional near infrared spectroscopy. Neuroimage. 2012;61(1):70–81.
69. Tachtsidis I, Scholkmann F. False positives and false negatives in functional near-infrared spectroscopy: issues, challenges, and the way forward. Neurophoton. 2016;3(3):031405.
70. Kwasa J, Peterson HM, Karrobi K, Jones L, Parker T, Nickerson N, et al. Demographic reporting and phenotypic exclusion in fNIRS. Front Neurosci. 2023;17:1086208.
71. Parker TC, Ricard JA. Structural racism in neuroimaging: perspectives and solutions. Lancet Psychiatry. 2022;9(5):e22.
72. Louis CC, Webster CT, Gloe LM, Moser JS. Hair me out: Highlighting systematic exclusion in psychophysiological methods and recommendations to increase inclusion. Front Hum Neurosci. 2022;16:1058953.
73. Doherty EJ, Spencer CA, Burnison J, Ceko M, Chin J, Eloy L, et al. Interdisciplinary views of fNIRS: Current advancements, equity challenges, and an agenda for future needs of a diverse fNIRS research community. Front Integr Neurosci. 2023;17:1059679.
74. Khan B, Wildey C, Francis R, Tian F, Delgado MR, Liu H, et al. Improving optical contact for functional near-infrared brain spectroscopy and imaging with brush optodes. Biomed Opt Express. 2012;3(5):878–98.
75. Giacometti P, Diamond SG. Compliant head probe for positioning electroencephalography electrodes and near-infrared spectroscopy optodes. J Biomed Opt. 2013;18(2):27005.
76. Lloyd-Fox S, Blasi A, McCann S, Rozhko M, Katus L, Mason L, et al. Habituation and novelty detection fNIRS brain responses in 5- and 8-month-old infants: The Gambia and UK. Dev Sci. 2019;22(5):e12817.
77. Mailleux L, Franki I, Emsell L, Peedima ML, Fehrenbach A, Feys H, et al. The relationship between neuroimaging and motor outcome in children with cerebral palsy: A systematic review-Part B diffusion imaging and tractography. Res Dev Disabil. 2020;97:103569.
78. Franki I, Mailleux L, Emsell L, Peedima ML, Fehrenbach A, Feys H, et al. The relationship between neuroimaging and motor outcome in children with cerebral palsy: A systematic review - Part A. Structural imaging. Res Dev Disabil. 2020;100:103606.
79. Craig BT, Hilderley A, Kirton A, Carlson HL. Imaging Developmental and Interventional Plasticity Following Perinatal Stroke. Can J Neurol Sci. 2021;48(2):157–71.
80. Yeung MK. An optical window into brain function in children and adolescents: A systematic review of functional near-infrared spectroscopy studies. Neuroimage. 2021;227:117672.
81. Su WC, Colacot R, Ahmed N, Nguyen T, George T, Gandjbakhche A. The use of functional near-infrared spectroscopy in tracking neurodevelopmental trajectories in infants and children with or without developmental disorders: a systematic review. Front Psychiatry. 2023;14:1210000.
82. Monden Y, Dan I, Nagashima M, Dan H, Uga M, Ikeda T, et al. Individual classification of ADHD children by right prefrontal hemodynamic responses during a go/no-go task as assessed by fNIRS. Neuroimage Clin. 2015;9:1–12.
83. Shevell M. Cerebral palsy to cerebral palsy spectrum disorder: Time for a name change? Neurology. 2019;92(5):233–5.
84. Munn Z, Peters MDJ, Stern C, Tufanaru C, McArthur A, Aromataris E. Systematic review or scoping review? Guidance for authors when choosing between a systematic or scoping review approach. BMC Med Res Methodol. 2018;18(1):143.
85. Lockwood C, Dos Santos KB, Pap R. Practical Guidance for Knowledge Synthesis: Scoping Review Methods. Asian Nurs Res (Korean Soc Nurs Sci). 2019;13(5):287–94.
86. Khalil H, Peters M, Godfrey CM, McInerney P, Soares CB, Parker D. An Evidence-Based Approach to Scoping Reviews. Worldviews Evid Based Nurs. 2016;13(2):118–23.
87. Tricco AC, Lillie E, Zarin W, O'Brien KK, Colquhoun H, Levac D, et al. PRISMA Extension for Scoping Reviews (PRISMA-ScR): Checklist and Explanation. Ann Intern Med. 2018;169(7):467–73.
88. Peters MDJ, Marnie C, Tricco AC, Pollock D, Munn Z, Alexander L, et al. Updated methodological guidance for the conduct of scoping reviews. JBI Evid Implement. 2021;19(1):3–10.
89. Penfold R. Using the Lens Database for Staff Publications. Journal of the Medical Library Association. 2020;108(2):341–4.
90. Miles M, Rodrigues A, Tajali S, Xiong Y, Orchanian-Cheff A, Reid WD, et al. Muscle and cerebral oxygenation during cycling in chronic obstructive pulmonary disease: A scoping review. Chron Respir Dis. 2021;18:1479973121993494.
91. Gentles S, Duku E, Kerns C, McVey AJ, Hunsche MC, Ng Cordell EC, et al. Trajectory research in children on the autism spectrum: a scoping review protocol. BMJ Open. 2021;11(11):e053443.
92. Le Cunff AL, Dommett E, Giampietro V. Neurophysiological measures and correlates of cognitive load in attention-deficit/hyperactivity disorder (ADHD), autism spectrum disorder (ASD) and dyslexia: A scoping review and research recommendations. Eur J Neurosci. 2024;59(2):256–82.
93. Ouzzani M, Hammady H, Fedorowicz Z, Elmagarmid A. Rayyan-a web and mobile app for systematic reviews. Syst Rev. 2016;5(1):210.
94. Parazzini C, Baldoli C, Scotti G, Triulzi F. Terminal zones of myelination: MR evaluation of children aged 20-40 months. AJNR Am J Neuroradiol. 2002;23(10):1669–73.
95. Irving DB, Cook JL, Menz HB. Factors associated with chronic plantar heel pain: a systematic review. J Sci Med Sport. 2006;9(1–2):11–22; discussion 3–4.
96. Khan B, Tian F, Behbehani K, Romero MI, Delgado MR, Clegg NJ, et al. Identification of abnormal motor cortex activation patterns in children with cerebral palsy by functional near-infrared spectroscopy. J Biomed Opt. 2010;15(3):036008.
97. Tian F, Delgado MR, Dhamne SC, Khan B, Alexandrakis G, Romero MI, et al. Quantification of functional near infrared spectroscopy to assess cortical reorganization in children with cerebral palsy. Opt Express. 2010;18(25):25973–86.

98. Hervey N, Khan B, Shagman L, Tian F, Delgado MR, Tulchin-Francis K, et al. Motion tracking and electromyography-assisted identification of mirror hand contributions to functional near-infrared spectroscopy images acquired during a finger-tapping task performed by children with cerebral palsy. Neurophoton. 2014;1(2):025009.
99. Cao J, Khan B, Hervey N, Tian F, Delgado MR, Clegg NJ, et al. Evaluation of cortical plasticity in children with cerebral palsy undergoing constraint-induced movement therapy based on functional near-infrared spectroscopy. J Biomed Opt. 2015;20(4):046009.
100. Chaudhary U, Hall M, Gonzalez J, Elbaum L, Bloyer M, Godavarty A. Motor response investigation in individuals with cerebral palsy using near infrared spectroscopy: pilot study. Appl Opt. 2014;53(3):503–10.
101. Kurz MJ, Wilson TW, Arpin DJ. An fNIRS exploratory investigation of the cortical activity during gait in children with spastic diplegic cerebral palsy. Brain and Development. 2014;36(10):870–7.
102. Sukal-Moulton T, de Campos AC, Alter KE, Huppert TJ, Damiano DL. Relationship between sensorimotor cortical activation as assessed by functional near infrared spectroscopy and lower extremity motor coordination in bilateral cerebral palsy. Neuroimage Clin. 2018;20:275–85.
103. de Campos AC, Sukal-Moulton T, Huppert T, Alter K, Damiano DL. Brain activation patterns underlying upper limb bilateral motor coordination in unilateral cerebral palsy: an fNIRS study. Developmental medicine and child neurology. 2020;62(5):625–32.
104. Sukal-Moulton T, de Campos AC, Alter KE, Damiano DL. Functional near-infrared spectroscopy to assess sensorimotor cortical activity during hand squeezing and ankle dorsiflexion in individuals with and without bilateral and unilateral cerebral palsy. Neurophoton. 2020;7(4):045001.
105. Surkar SM, Hoffman RM, Harbourne R, Kurz MJ. Neural activation within the prefrontal cortices during the goal-directed motor actions of children with hemiplegic cerebral palsy. Neurophoton. 2018;5(1):011021.
106. Surkar SM, Hoffman RM, Willett S, Flegle J, Harbourne R, Kurz MJ. Hand-Arm Bimanual Intensive Therapy Improves Prefrontal Cortex Activation in Children With Hemiplegic Cerebral Palsy. Pediatr Phys Ther. 2018;30(2):93–100.
107. Surkar SM, Hoffman RM, Harbourne R, Kurz MJ. Cognitive-Motor Interference Heightens the Prefrontal Cortical Activation and Deteriorates the Task Performance in Children With Hemiplegic Cerebral Palsy. Arch Phys Med Rehabil. 2021;102(2):225–32.
108. Perpetuini D, Russo EF, Cardone D, Palmieri R, Filippini C, Tritto M, et al. Identification of Functional Cortical Plasticity in Children with Cerebral Palsy Associated to Robotic-Assisted Gait Training: An fNIRS Study. JCM. 2022;11(22).
109. Zhang T, Xu G, Huo C, Li W, Li Z, Li W. Cortical hemodynamic response and networks in children with cerebral palsy during upper limb bilateral motor training. J Biophotonics. 2023;16(5):e202200326.
110. Xie P, Nie Z, Zhang T, Xu G, Sun A, Chen T, et al. FNIRS based study of brain network characteristics in children with cerebral palsy during bilateral lower limb movement. Med Phys. 2024;51(6):4434–46.
111. Licea J, Khan OA, Singh T, Modlesky CM. Prefrontal cortex hemodynamic activity during a test of lower extremity functional muscle strength in children with cerebral palsy: A functional near-infrared spectroscopy study. Eur J Neurosci. 2024;59(2):298–307.
112. Olusanya BO, Gladstone M, Wright SM, Hadders-Algra M, Boo NY, Nair MKC, et al. Cerebral palsy and developmental intellectual disability in children younger than 5 years: Findings from the GBD-WHO Rehabilitation Database 2019. Front Public Health. 2022;10:894546.
113. Murugasen S, Springer P, Olusanya BO, Gladstone M, Newton C, Kakooza-Mwesige A, et al. Cerebral palsy in African paediatric populations: A scoping review. Developmental medicine and child neurology. 2024;66(8):990–1012.
114. Di Lonardo Burr SM, Pirazzoli L, Dopierala AW, Bejjanki VR, Nelson CA, Emberson LL. Longitudinal assessments of functional near-infrared spectroscopy background functional connectivity in low- and middle-income infants during a social cognition task. J Exp Psychol Gen. 2024;153(3):798–813.
115. Lloyd-Fox S, McCann S, Milosavljevic B, Katus L, Blasi A, Bulgarelli C, et al. The Brain Imaging for Global Health (BRIGHT) Project: Longitudinal cohort study protocol. Gates Open Research. 2023;7(126).
116. Horber V, Andersen GL, Arnaud C, De La Cruz J, Dakovic I, Greitane A, et al. Prevalence, Clinical Features, Neuroimaging, and Genetic Findings in Children With Ataxic Cerebral Palsy in Europe. Neurology. 2023;101(24):e2509–e21.
117. Ballester-Plane J, Schmidt R, Laporta-Hoyos O, Junque C, Vazquez E, Delgado I, et al. Whole-brain structural connectivity in dyskinetic cerebral palsy and its association with motor and cognitive function. Hum Brain Mapp. 2017;38(9):4594–612.
118. Qin Y, Li Y, Sun B, He H, Peng R, Zhang T, et al. Functional Connectivity Alterations in Children with Spastic and Dyskinetic Cerebral Palsy. Neural Plast. 2018;2018:7058953.
119. Schroeder PA, Artemenko C, Kosie JE, Cockx H, Stute K, Pereira J, et al. Using preregistration as a tool for transparent fNIRS study design. Neurophoton. 2023;10(2):023515.
120. Reid LB, Pagnozzi AM, Fiori S, Boyd RN, Dowson N, Rose SE. Measuring neuroplasticity associated with cerebral palsy rehabilitation: An MRI based power analysis. Int J Dev Neurosci. 2017;58:17–25.
121. Frank MC, Bergelson E, Bergmann C, Cristia A, Floccia C, Gervain J, et al. A Collaborative Approach to Infant Research: Promoting Reproducibility, Best Practices, and Theory-Building. Infancy. 2017;22(4):421–35.
122. Pinti P, Scholkmann F, Hamilton A, Burgess P, Tachtsidis I. Current Status and Issues Regarding Pre-processing of fNIRS Neuroimaging Data: An Investigation of Diverse Signal Filtering Methods Within a General Linear Model Framework. Front Hum Neurosci. 2018;12:505.
123. Gervain J. ManyBabies3NIRS: a large-scale, multi-lab NIRS replication study assessing infants' ability to extract regularities from speech 2022 [Available from: https://manybabies.org/MB3N/.
124. Reid SM, Carlin JB, Reddihough DS. Using the Gross Motor Function Classification System to describe patterns of motor severity in cerebral palsy. Developmental medicine and child neurology. 2011;53(11):1007–12.
125. Bailes AF, Greve K, Long J, Kurowski BG, Vargus-Adams J, Aronow B, et al. Describing the Delivery of Evidence-Based Physical Therapy Intervention to Individuals With Cerebral Palsy. Pediatr Phys Ther. 2021;33(2):65–72.
126. Van de Winckel A, Klingels K, Bruyninckx F, Wenderoth N, Peeters R, Sunaert S, et al. How does brain activation differ in children with unilateral cerebral palsy compared to typically developing children, during active and passive movements, and tactile stimulation? An fMRI study. Res Dev Disabil. 2013;34(1):183–97.
127. Novak I, Morgan C, Fahey M, Finch-Edmondson M, Galea C, Hines A, et al. State of the Evidence Traffic Lights 2019: Systematic Review of Interventions for Preventing and Treating Children with Cerebral Palsy. Curr Neurol Neurosci Rep. 2020;20(2):3.
128. Vandermeeren Y, Sebire G, Grandin CB, Thonnard JL, Schlogel X, De Volder AG. Functional reorganization of brain in children affected with congenital hemiplegia: fMRI study. Neuroimage. 2003;20(1):289–301.
129. Kuo HC, Friel KM, Gordon AM. Neurophysiological mechanisms and functional impact of mirror movements in children with unilateral spastic cerebral palsy. Developmental medicine and child neurology. 2018;60(2):155–61.
130. Norton J, Sawicka K. The significance of hand movement mirroring in cerebral palsy. Developmental medicine and child neurology. 2016;58(7):655–6.

131. Simon-Martinez C, Decraene L, Zielinski I, Hoare B, Williams J, Mailleux L, et al. The impact of brain lesion characteristics and the corticospinal tract wiring on mirror movements in unilateral cerebral palsy. Sci Rep. 2022;12(1):16301.
132. Zielinski IM, Steenbergen B, Schmidt A, Klingels K, Simon Martinez C, de Water P, et al. Windmill-task as a New Quantitative and Objective Assessment for Mirror Movements in Unilateral Cerebral Palsy: A Pilot Study. Arch Phys Med Rehabil. 2018;99(8):1547–52.
133. Gaberova K, Pacheva I, Timova E, Petkova A, Velkova K, Ivanov I. An Individualized Approach to Neuroplasticity After Early Unilateral Brain Damage. Front Psychiatry. 2019;10:747.
134. Ward NS. Functional reorganization of the cerebral motor system after stroke. Curr Opin Neurol. 2004;17(6):725–30.
135. Araneda R, Dricot L, Ebner-Karestinos D, Paradis J, Gordon AM, Friel KM, et al. Brain activation changes following motor training in children with unilateral cerebral palsy: An fMRI study. Ann Phys Rehabil Med. 2021;64(3):101502.
136. Eyre JA. Corticospinal tract development and its plasticity after perinatal injury. Neuroscience & Biobehavioral Reviews. 2007;31(8):1136–49.
137. Friel KM, Chakrabarty S, Martin JH. Pathophysiological mechanisms of impaired limb use and repair strategies for motor systems after unilateral injury of the developing brain. Developmental medicine and child neurology. 2013;55 Suppl 4:27–31.
138. Staudt M, Grodd W, Gerloff C, Erb M, Stitz J, Krageloh-Mann I. Two types of ipsilateral reorganization in congenital hemiparesis: a TMS and fMRI study. Brain. 2002;125(Pt 10):2222–37.
139. Staudt M, Gerloff C, Grodd W, Holthausen H, Niemann G, Krageloh-Mann I. Reorganization in congenital hemiparesis acquired at different gestational ages. Ann Neurol. 2004;56(6):854–63.
140. Hilderley AJ, Taylor MJ, Fehlings D, Chen JL, Wright FV. Optimization of fMRI methods to determine laterality of cortical activation during ankle movements of children with unilateral cerebral palsy. Int J Dev Neurosci. 2018;66:54–62.
141. Makki D, Duodu J, Nixon M. Prevalence and pattern of upper limb involvement in cerebral palsy. J Child Orthop. 2014;8(3):215–9.
142. Hinchberger V, Kang SH, Kline J, Stanley CJ, Bulea TC, Damiano DL. Investigation of brain mechanisms underlying upper limb function in bilateral cerebral palsy using EEG. Clin Neurophysiol. 2023;151:116–27.
143. Phillips C, Kline J, Stanley CJ, Bulea TC, Damiano DL. Children With Bilateral Cerebral Palsy Exhibit Bimanual Asymmetric Motor Deficits and EEG Evidence of Dominant Sensorimotor Hemisphere Overreliance During Reaching. Neurorehabil Neural Repair. 2023;37(9):617–27.
144. Kirton A. Modeling developmental plasticity after perinatal stroke: defining central therapeutic targets in cerebral palsy. Pediatr Neurol. 2013;48(2):81–94.
145. Himmelmann K, Horber V, Sellier E, De la Cruz J, Papavasiliou A, Krageloh-Mann I, et al. Neuroimaging Patterns and Function in Cerebral Palsy-Application of an MRI Classification. Front Neurol. 2020;11:617740.
146. Hilderley AJ, Wright FV, Taylor MJ, Chen JL, Fehlings D. Functional Neuroplasticity and Motor Skill Change Following Gross Motor Interventions for Children With Diplegic Cerebral Palsy. Neurorehabil Neural Repair. 2023;37(1):16–26.
147. Orihuela-Espina F, Leff DR, James DR, Darzi AW, Yang GZ. Quality control and assurance in functional near infrared spectroscopy (fNIRS) experimentation. Phys Med Biol. 2010;55(13):3701–24.
148. Fuster JM. Prefrontal Executive Functions Predict and Preadapt. Executive Functions in Health and Disease2017. p. 3–19.
149. Fuster JM, Bressler SL. Past makes future: role of pFC in prediction. J Cogn Neurosci. 2015;27(4):639–54.
150. Alonso R, Brocas I, Carrillo JD. Resource Allocation in the Brain. The Review of Economic Studies. 2013;81(2):501–34.
151. Goodale MA. Transforming abstract plans into concrete actions. Proceedings of the National Academy of Sciences. 2020;117(47):29265–7.
152. Novak I, Hines M, Goldsmith S, Barclay R. Clinical prognostic messages from a systematic review on cerebral palsy. Pediatrics. 2012;130(5):e1285–312.
153. Zimonyi N, Koi T, Dombradi V, Imrei M, Nagy R, Pulay MA, et al. Comparison of Executive Function Skills between Patients with Cerebral Palsy and Typically Developing Populations: A Systematic Review and Meta-Analysis. JCM. 2024;13(7).
154. Oudgenoeg-Paz O, Mulder H, Jongmans MJ, van der Ham IJM, Van der Stigchel S. The link between motor and cognitive development in children born preterm and/or with low birth weight: A review of current evidence. Neuroscience & Biobehavioral Reviews. 2017;80:382–93.
155. Diamond A. Close interrelation of motor development and cognitive development and of the cerebellum and prefrontal cortex. Child Dev. 2000;71(1):44–56.
156. Piitulainen H, Kulmala JP, Maenpaa H, Rantalainen T. The gait is less stable in children with cerebral palsy in normal and dual-task gait compared to typically developed peers. J Biomech. 2021;117:110244.
157. Roostaei M, Raji P, Morone G, Razi B, Khademi-Kalantari K. The effect of dual-task conditions on gait and balance performance in children with cerebral palsy: A systematic review and meta-analysis of observational studies. J Bodyw Mov Ther. 2021;26:448–62.
158. Trevarrow MP, Reelfs A, Ott LR, Penhale SH, Lew BJ, Goeller J, et al. Altered spontaneous cortical activity predicts pain perception in individuals with cerebral palsy. Brain Commun. 2022;4(2):fcac087.
159. Herold F, Wiegel P, Scholkmann F, Muller NG. Applications of Functional Near-Infrared Spectroscopy (fNIRS) Neuroimaging in Exercise(–)Cognition Science: A Systematic, Methodology-Focused Review. JCM. 2018;7(12).
160. Simon-Martinez C, Jaspers E, Alaerts K, Ortibus E, Balsters J, Mailleux L, et al. Influence of the corticospinal tract wiring pattern on sensorimotor functional connectivity and clinical correlates of upper limb function in unilateral cerebral palsy. Sci Rep. 2019;9(1):8230.
161. Duan SF, Mu XT, Huang Q, Ma Y, Shan BC. Occult Spastic Diplegic Cerebral Palsy Recognition Using Efficient Machine Learning for Big Data and Structural Connectivity Abnormalities Analysis. Journal of Medical Imaging and Health Informatics. 2018;8(2):317–24.
162. Zhang W, Zhang S, Zhu M, Tang J, Zhao X, Wang Y, et al. Changes of Structural Brain Network Following Repetitive Transcranial Magnetic Stimulation in Children With Bilateral Spastic Cerebral Palsy: A Diffusion Tensor Imaging Study. Front Pediatr. 2020;8:617548.
163. Burton H, Dixit S, Litkowski P, Wingert JR. Functional connectivity for somatosensory and motor cortex in spastic diplegia. Somatosens Mot Res. 2009;26(4):90–104.
164. Mu X, Wang Z, Nie B, Duan S, Ma Q, Dai G, et al. Altered regional and circuit resting-state activity in patients with occult spastic diplegic cerebral palsy. Pediatr Neonatol. 2018;59(4):345–51.
165. Qin Y, Sun B, Zhang H, Li Y, Zhang T, Luo C, et al. Aberrant Interhemispheric Functional Organization in Children with Dyskinetic Cerebral Palsy. Biomed Res Int. 2019;2019:4362539.
166. Bauer CM, Papadelis C. Alterations in the Structural and Functional Connectivity of the Visuomotor Network of Children With Periventricular Leukomalacia. Semin Pediatr Neurol. 2019;31:48–56.
167. Vidal-Rosas EE, von Luhmann A, Pinti P, Cooper RJ. Wearable, high-density fNIRS and diffuse optical tomography technologies: a perspective. Neurophoton. 2023;10(2):023513.
168. Hocke LM, Oni IK, Duszynski CC, Corrigan AV, Frederick BD, Dunn JF. Automated Processing of fNIRS Data-A Visual Guide to the Pitfalls and Consequences. Algorithms. 2018;11(5).
169. Hernandez SM, Pollonini L, editors. NIRSplot: A Tool for Quality Assessment of fNIRS Scans. Biophotonics Congress: Biomedical Optics 2020 (Translational, Microscopy, OCT, OTS, BRAIN); 2020 2020/04/20; Washington, DC: Optical Society of America.

170. Sappia MS, Hakimi N, Colier W, Horschig JM. Signal quality index: an algorithm for quantitative assessment of functional near infrared spectroscopy signal quality. Biomed Opt Express. 2020;11(11):6732–54.
171. Klein F, Kranczioch C. Signal Processing in fNIRS: A Case for the Removal of Systemic Activity for Single Trial Data. Front Hum Neurosci. 2019;13:331.
172. Klein F, Lührs M, Benitez-Andonegui A, Roehn P, Kranczioch C. Performance comparison of systemic activity correction in functional near-infrared spectroscopy for methods with and without short distance channels. Neurophoton. 2022;10(1):013503.
173. Tak S, Ye JC. Statistical analysis of fNIRS data: a comprehensive review. Neuroimage. 2014;85 Pt 1:72–91.
174. Santosa H, Aarabi A, Perlman SB, Huppert TJ. Characterization and correction of the false-discovery rates in resting state connectivity using functional near-infrared spectroscopy. J Biomed Opt. 2017;22(5):55002.
175. Yücel MA, Lühmann Av, Scholkmann F, Gervain J, Dan I, Ayaz H, et al. Best practices for fNIRS publications. Neurophoton. 2021;8(1):012101.
176. McCall JV, Ludovice MC, Elliott C, Kamper DG. Hand function development of children with hemiplegic cerebral palsy: A scoping review. J Pediatr Rehabil Med. 2022;15(1):211–28.
177. De Campos AC, Hidalgo-Robles A, Longo E, Shrader C, Paleg G. F-words and early intervention ingredients for non-ambulant children with cerebral palsy: A scoping review. Developmental medicine and child neurology. 2024;66(1):41–51.
178. Bell AH, Miller SL, Castillo-Melendez M, Malhotra A. The Neurovascular Unit: Effects of Brain Insults During the Perinatal Period. Front Neurosci. 2019;13:1452.
179. Brew N, Walker D, Wong FY. Cerebral vascular regulation and brain injury in preterm infants. Am J Physiol Regul Integr Comp Physiol. 2014;306(11):R773–86.
180. Kratzer I, Chip S, Vexler ZS. Barrier mechanisms in neonatal stroke. Front Neurosci. 2014;8:359.
181. Hoshi Y. Hemodynamic signals in fNIRS. In: Masamoto K, Hirase H, Yamada K, editors. Progress in Brain Research. 225: Elsevier; 2016. p. 153–79.
182. Pinti P, Tachtsidis I, Hamilton A, Hirsch J, Aichelburg C, Gilbert S, et al. The present and future use of functional near-infrared spectroscopy (fNIRS) for cognitive neuroscience. Ann N Y Acad Sci. 2020;1464(1):5–29.
183. Paranawithana I, Mao D, Wong YT, McKay CM. Reducing false discoveries in resting-state functional connectivity using short channel correction: an fNIRS study. Neurophoton. 2022;9(1):015001.
184. Zhao H, Frijia EM, Vidal Rosas E, Collins-Jones L, Smith G, Nixon-Hill R, et al. Design and validation of a mechanically flexible and ultra-lightweight high-density diffuse optical tomography system for functional neuroimaging of newborns. Neurophoton. 2021;8(1):015011.
185. Sukal-Moulton T, de Campos AC, Stanley CJ, Damiano DL. Functional near infrared spectroscopy of the sensory and motor brain regions with simultaneous kinematic and EMG monitoring during motor tasks. J Vis Exp. 2014(94).
186. Pfeifer MD, Scholkmann F, Labruyere R. Signal Processing in Functional Near-Infrared Spectroscopy (fNIRS): Methodological Differences Lead to Different Statistical Results. Front Hum Neurosci. 2017;11:641.
187. Sato JR, Junior CEB, de Araujo ELM, de Souza Rodrigues J, Andrade SM. A guide for the use of fNIRS in microcephaly associated to congenital Zika virus infection. Sci Rep. 2021;11(1):19270.
188. Da C, Jj L, Metting Z, Se R, Jm S, Jwj E, et al. The feasibility of fNIRS as a diagnostic tool for pediatric TBI: A pilot study. Eur J Paediatr Neurol. 2021;30:22–4.
189. Mihara M, Miyai I. Review of functional near-infrared spectroscopy in neurorehabilitation. Neurophoton. 2016;3(3):031414.
190. Xu SY, Lu FM, Wang MY, Hu ZS, Zhang J, Chen ZY, et al. Altered Functional Connectivity in the Motor and Prefrontal Cortex for Children With Down's Syndrome: An fNIRS Study. Front Hum Neurosci. 2020;14(6):6.
191. Gosse LK, Bell SW, Hosseini SMH. Functional near-infrared spectroscopy in developmental psychiatry: a review of attention deficit hyperactivity disorder. Eur Arch Psychiatry Clin Neurosci. 2022;272(2):273–90.
192. Zhang F, Roeyers H. Exploring brain functions in autism spectrum disorder: A systematic review on functional near-infrared spectroscopy (fNIRS) studies. Int J Psychophysiol. 2019;137:41–53.
193. Gallagher A, Wallois F, Obrig H. Functional near-infrared spectroscopy in pediatric clinical research: Different pathophysiologies and promising clinical applications. Neurophoton. 2023;10(2):023517.
194. Nishiyori R. fNIRS: An Emergent Method to Document Functional Cortical Activity during Infant Movements. Front Psychol. 2016;7:533.
195. Cacola P, Getchell N, Srinivasan D, Alexandrakis G, Liu H. Cortical activity in fine-motor tasks in children with Developmental Coordination Disorder: A preliminary fNIRS study. Int J Dev Neurosci. 2018;65:83–90.
196. Biallas M, Trajkovic I, Hagmann C, Scholkmann F, Jenny C, Holper L, et al. Multimodal recording of brain activity in term newborns during photic stimulation by near-infrared spectroscopy and electroencephalography. J Biomed Opt. 2012;17(8):086011–1.
197. Conti E, Scaffei E, Bosetti C, Marchi V, Costanzo V, Dell'Oste V, et al. Looking for 'fNIRS Signature' in Autism Spectrum: A Systematic Review Starting From Preschoolers. Front Neurosci. 2022;16:785993.
198. Scarapicchia V, Brown C, Mayo C, Gawryluk JR. Functional Magnetic Resonance Imaging and Functional Near-Infrared Spectroscopy: Insights from Combined Recording Studies. Front Hum Neurosci. 2017;11:419.
199. Li R, Yang D, Fang F, Hong KS, Reiss AL, Zhang Y. Concurrent fNIRS and EEG for Brain Function Investigation: A Systematic, Methodology-Focused Review. Sensors (Basel). 2022;22(15).
200. Ru X, He K, Lyu B, Li D, Xu W, Gu W, et al. Multimodal neuroimaging with optically pumped magnetometers: A simultaneous MEG-EEG-fNIRS acquisition system. Neuroimage. 2022;259:119420.
201. Grassler B, Herold F, Dordevic M, Gujar TA, Darius S, Bockelmann I, et al. Multimodal measurement approach to identify individuals with mild cognitive impairment: study protocol for a cross-sectional trial. BMJ Open. 2021;11(5):e046879.
202. Chen S, Zhang X, Chen X, Zhou Z, Cong W, Chong K, et al. The assessment of interhemispheric imbalance using functional near-infrared spectroscopic and transcranial magnetic stimulation for predicting motor outcome after stroke. Front Neurosci. 2023;17:1231693.
203. Curtin A, Tong S, Sun J, Wang J, Onaral B, Ayaz H. A Systematic Review of Integrated Functional Near-Infrared Spectroscopy (fNIRS) and Transcranial Magnetic Stimulation (TMS) Studies. Front Neurosci. 2019;13:84.
204. Berger A, Horst F, Muller S, Steinberg F, Doppelmayr M. Current State and Future Prospects of EEG and fNIRS in Robot-Assisted Gait Rehabilitation: A Brief Review. Front Hum Neurosci. 2019;13:172.
205. Vallinoja J, Nurmi T, Jaatela J, Wens V, Bourguignon M, Maenpaa H, et al. Functional connectivity of sensorimotor network is enhanced in spastic diplegic cerebral palsy: A multimodal study using fMRI and MEG. Clin Neurophysiol. 2024;157:4–14.
206. Scholkmann F, Holper L, Wolf U, Wolf M. A new methodical approach in neuroscience: assessing inter-personal brain coupling using functional near-infrared imaging (fNIRI) hyperscanning. Front Hum Neurosci. 2013;7:813.
207. Tan SS, van Gorp M, Voorman JM, Geytenbeek JJ, Reinders-Messelink HA, Ketelaar M, et al. Development curves of communication and social interaction in individuals with cerebral palsy. Developmental medicine and child neurology. 2020;62(1):132–9.
208. Harniess PA, Gibbs D, Bezemer J, Purna Basu A. Parental engagement in early intervention for infants with cerebral palsy-A realist synthesis. Child Care Health Dev. 2022;48(3):359–77.

209. Paulmurugan K, Vijayaragavan V, Ghosh S, Padmanabhan P, Gulyás B. Brain–Computer Interfacing Using Functional Near-Infrared Spectroscopy (fNIRS). Biosensors [Internet]. 2021; 11(10).
210. Jadavji Z, Kirton A, Metzler MJ, Zewdie E. BCI-activated electrical stimulation in children with perinatal stroke and hemiparesis: A pilot study. Front Hum Neurosci. 2023;17:1006242.
211. Orlandi S, House SC, Karlsson P, Saab R, Chau T. Brain-Computer Interfaces for Children With Complex Communication Needs and Limited Mobility: A Systematic Review. Front Hum Neurosci. 2021;15:643294.
212. Lee-Park JJ, Deshpande H, Lisinski J, LaConte S, Ramey S, DeLuca S. Neuroimaging Strategies Addressing Challenges in Using fMRI for the Children with Cerebral Palsy. Journal of Behavioral and Brain Science. 2018;08(05):306–18.

SUPPORTING INFORMATION

The following additional material may be found online:
Appendix S1: fNIRS methodology.
Figure S1: PRISMA-ScR flow diagram.
Table S1: Systematic search strategy used for the PubMed database.
Table S2: Relevant grey literature from ProQuest database search and hand-searching.
Table S3: Modified Downs and Black checklist for methodological quality assessment.
Table S4: Methodological quality scores based on the modified Downs and Black checklist.
Table S5: Study background and sample characteristics.
Table S6: Experimental procedures.
Table S7: Research questions, sample characteristics, and primary findings
Table S8: Technical specification for fNIRS data collection and processing.

How to cite this article: Khan OA, Rahman S, Baduni K, Modlesky CM. Assessment of cortical activity, functional connectivity, and neuroplasticity in cerebral palsy using functional near-infrared spectroscopy: A scoping review. Dev Med Child Neurol. 2025;67:875–891. https://doi.org/10.1111/dmcn.16238