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Motor Cortex Activation Patterns in Both Hemispheres Induced by Motor Imagery in Patients With Right- and Left-Sided Cerebral Infarction: An fNIRS Study

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ABSTRACT

This study aimed to explore the neuroimaging basis of motor imagery (MI) in stroke rehabilitation, particularly focusing on the brain activation patterns during MI tasks. Additionally, this study may provide insights into clinical rehabilitation strategies. A total of 40 right-handed stroke patients from Zhejiang Rehabilitation Medical Center were assigned to either the right-sided or left-sided cerebral infarction group. They were right-handed and recruited from Zhejiang Rehabilitation Medical Center. A portable near-infrared brain function imaging system was used to detect changes in oxyhemoglobin concentration in the bilateral sensorimotor cortex, premotor cortex, and supplementary motor area during the MI task. Activated channels and intensity changes in brain regions under the MI state were observed and analyzed. In patients with right-sided cerebral infarction, brain activation was left-lateralized during both left- and right-limb MI. Patients with left-sided cerebral infarction exhibited left lateralization during right-limb MI and right lateralization during left-limb MI. Functional near-infrared spectroscopy was utilized to investigate the activation of motor-related brain regions during MI after stroke. These regions of interest were associated with hand motor tasks and were successfully activated during the MI task. Following infarction, the activation of the MI cortex was asymmetric. When imagining movements on the dominant-hand side, MI becomes more vivid and activates bilateral motor cortex areas.

1 | Introduction

Stroke is characterized by high morbidity, disability, and mortality (Zhang and Han 2018) and remains the leading cause of permanent neurogenic disability in adults (Johnson et al. 2016). Approximately 30%–66% of stroke patients experience upper-limb dysfunction of varying degrees, significantly affecting their quality of life and imposing an economic

Abbreviations: AO, action observation; Dex-O_2Hb, deoxyhemoglobin; fMRI, functional magnetic resonance imaging; fNIRS, functional near-infrared spectroscopy; LI, laterality index; LPMC, left PMC; LSMA, left SMA; LSMC, left SMC; M1, primary motor cortex; MI, motor imagery; O_2Hb, oxyhemoglobin; PMC, premotor cortex; ROIs, regions of interests; RPMC, right PMC; RSMA, right SMA; RSMC, right SMC; S1, primary somatosensory cortex; SMA, supplementary motor area; SMC, sensorimotor cortex.

burden on their families (Youfei et al. 2017). Motor function rehabilitation has become a critical area of medical research, with motor imagery (MI) therapy increasingly employed in the clinical rehabilitation of stroke patients. MI has been demonstrated to improve rehabilitation outcomes and enhance the performance of MI-related tasks in poststroke patients (Kim et al. 2017); Guerra et al. 2017; Cantillo-Negrete et al. 2018). Additionally, MI offers several advantages, including the absence of required motor input, independence from the patient's residual motor function, and applicability at any stage of the stroke process (Sharma et al. 2006). Even patients with severe motor impairments can engage in rehabilitation actively and achieve more favorable outcomes (Kim et al. 2018). According to several brain imaging studies, MI activates regions similar to those involved in motor execution (Guillot et al. 2012; Garrison et al. 2010). The mirror neuron theory serves as a fundamental basis for MI (Catmur 2015). Mirror neurons, a special type of neuron, are activated both during the observation and execution of purposeful actions (Page et al. 2005; Rizzolatti et al. 2009). Located in various brain regions, these neurons collectively form the mirror neuron system, which plays a key role in essential neural activities, such as observation, imitation, imagination, and learning of movement (Keysers et al. 2018). Thus, MI may replace motor execution as a novel approach to activating motor networks in patients with cerebral infarction (Macuga and Frey 2012; Chiew et al. 2012; Szameitat, McNamara, et al. 2012).

Functional near-infrared spectroscopy (fNIRS) is a new, noninvasive technique for assessing brain function. It can indirectly reflect neural activity of the brain by detecting the levels of oxyhemoglobin (O_2Hb) and deoxyhemoglobin (Dex-O_2Hb) in the cerebral cortex. Additionally, fNIRS can be used to evaluate functional recovery and therapeutic efficacy after stroke (Yi 2020). A recent systematic review has comprehensively examined the role of fNIRS in poststroke rehabilitation, particularly in monitoring brain function, predicting outcomes, and assessing intervention efficacy in upper-limb hemiplegia (Gong et al. 2024). This highlights the increasing clinical significance of fNIRS as a neuroimaging tool in stroke recovery. Therefore, fNIRS enables real-time dynamical monitoring during MI, providing a comprehensive assessment of brain activation patterns in patients with stroke and reflecting neural remodelling of patients (Zhang et al. 2021; Yanxiang et al. 2016).

Attention must be paid to issues related to lesion sides when using MI for early upper-limb rehabilitation after stroke (Kemlin et al. 2016). Therefore, fNIRS was employed in this study to detect the activation degree in relevant functional areas of the cerebral cortex and to evaluate changes in O_2Hb concentration during MI. To investigate central neural activity, a comparison was made of brain activation differences between the left and right sides of hemiplegic patients during MI. Such a process provided a theoretical basis for the clinical application of MI therapy in rehabilitation. This study focused on identifying predictive factors for MI therapy outcomes in patients with stroke, rather than evaluating prognostic factors related to rehabilitation.

2 | Methods

2.1 | Participants

This prospective study enrolled 40 consecutive patients with cerebral infarction who underwent rehabilitation at Zhejiang Rehabilitation Medical Center from January to December 2022. All patients were identified as right-handed according to the Edinburgh Handedness Inventory (Oldfield 1971). The right-sided cerebral infarction group consisted of 20 patients with infarctions on the right side of the brain, including 15 males and 5 females. Similarly, the left-sided cerebral infarction group included 20 patients with infarctions on the left side of the brain, comprising 16 males and 4 females.

The inclusion criteria for this study were displayed as follows: (1) aged between 21 and 80 years; (2) first-onset stroke with unilateral lesions; (3) diagnosis consistent with the criteria outlined in the Chinese Guidelines for Diagnosis and Treatment of Acute Ischemic Stroke 2018 (Chinese Society of Neurology CSS 2018), as revised by the Neurology Branch of Chinese Medical Association and Cerebrovascular Disease Group of Neurology Branch of Chinese Medical Association, and confirmed by cranial computed tomography or magnetic resonance imaging; (4) affected hand classified as Brunnstrom stages I–III; (5) no cognitive impairment, with a Mini-Mental State Examination score of ≥ 25; and (6) intact skull, with no history of craniotomy or cranial repair.

The exclusion criteria included (1) seizure period; (2) severe cognitive and communication disorders; and (3) visual or auditory impairments, or lateralized neglect.

This study was approved and reviewed by the Ethics Committee of Zhejiang Rehabilitation Medical Center (Zhejiang, China, No. ZKLL21121501) and was registered with the Chinese Clinical Trial Registry (ChiCTR2400081810). Informed consent was obtained from all participants.

2.2 | Procedures

A 14-in. computer monitor was positioned in front of the participants in a quiet environment. Participants sat comfortably in a chair, with their body midline aligned with the midline of the screen. Then, their affected hand was placed on the knee, their upper arm and torso remained relaxed, and head movements were avoided. Prior to the MI task, the movements were explained and analyzed by the therapist. Participants were instructed to carefully observe the demonstrated movements to grasp the movement patterns and MI sensations. The MI tasks were conducted using kinesthetic MI, focusing on the feeling of movement rather than visual representation. However, the MI questionnaires were not used to assess the vividness or proficiency of MI.

The MI tasks included finger flexion and extension (Roland et al. 1980). Participants were instructed to keep their hands open, bring their palms together for 4 s, and then open them again for 4s (Avanzino et al. 2015). They were asked to carefully watch the video from a first-person perspective and imagine that they were performing the movements shown. Such a process was recorded using surface electromyography to ensure that no voluntary activity was generated during MI (Avanzino et al. 2015; Amemiya et al. 2010). The video depicted first-person perspective images of healthy adults performing finger flexion and extension with both the left and right hands (Figure 1). These images were applied to explain the MI task to participants and to administer the MI test.

2.3 | Measurements

2.3.1 | fNIRS

The patient's brain activity was observed using a portable near-infrared brain function imaging system, LIGHTNIRS, manufactured by Shimadzu Corporation (Kyoto, Japan). This system consists of eight light source probes and eight detection probes, forming 22 effective channels in the experimental design. The distance between channels was set at 3cm, with a sampling frequency of 13.33Hz. The wavelengths used by the light source probes were 780, 805, and 830nm. These wavelengths enable the detection of O_2Hb and Dex-O_2Hb concentrations in cortical regions under MI conditions. Given that O_2Hb is a stronger indicator of activation than Dex-O_2Hb (Hoshi et al. 2001; Murphy and Corbett 2009), and more reliable for detecting task-related cortical activation in real-time assessment (Mihara et al. 2012), changes in O_2Hb during the MI task were used as indicators of regional cerebral hemodynamics.

Currently, numerous functional magnetic resonance imaging studies have investigated brain activity in healthy individuals during various movement patterns (Szameitat, Shen, et al. 2012; Cai et al. 2011). These studies have demonstrated that brain regions, such as the sensorimotor cortex (SMC), premotor cortex (PMC), supplementary motor area (SMA), and cerebellum, are primarily activated during active upper-limb movements. These regions of interest (ROIs) are associated with hand movement tasks (Leff et al. 2011). The test was performed at positions of Cz, C3, C4, F3, and F4 according to the electroencephalogram International 10–20 system to ensure probe coverage of six ROIs (Teo et al. 2018), including bilateral SMC, PMC, and SMA. A three-dimensional positioning pen was used to mark the exact location of each probe on a standardized brain model (Tsuzuki and Dan 2014). These coordinates were then converted into 22 channel locations at the Montreal Neurological Institute using the NIRS-SPM software package in the MATLAB toolbox, creating a three-dimensional channel distribution map (Delorme et al. 2019) (Figure 2). Based on the Montreal Neurological Institute coordinates and Brodmann partitioning correspondence, the division of the 22 channels covering the six ROIs is presented in Table 1.

As shown in Figure 3, a block design was employed for fNIRS data collection. Baseline data were collected for 40s, followed by the generation of four MI blocks. Each block consisted of a 40-s imagining period and a 20-s rest period. During the rest period, participants were instructed to focus on white dots displayed on a black background on the monitor and to remain still. After a 5-min rest, participants completed the same task using the other hand.

2.3.2 | Lateralization Between the Left or Right Hemispheres of the Brain

The mean values of the 40-s task intervals from the block design were used to analyze the eigenvalues and calculate the changes in blood oxygen concentration within individual channels during this time window. The laterality index (LI) was calculated using

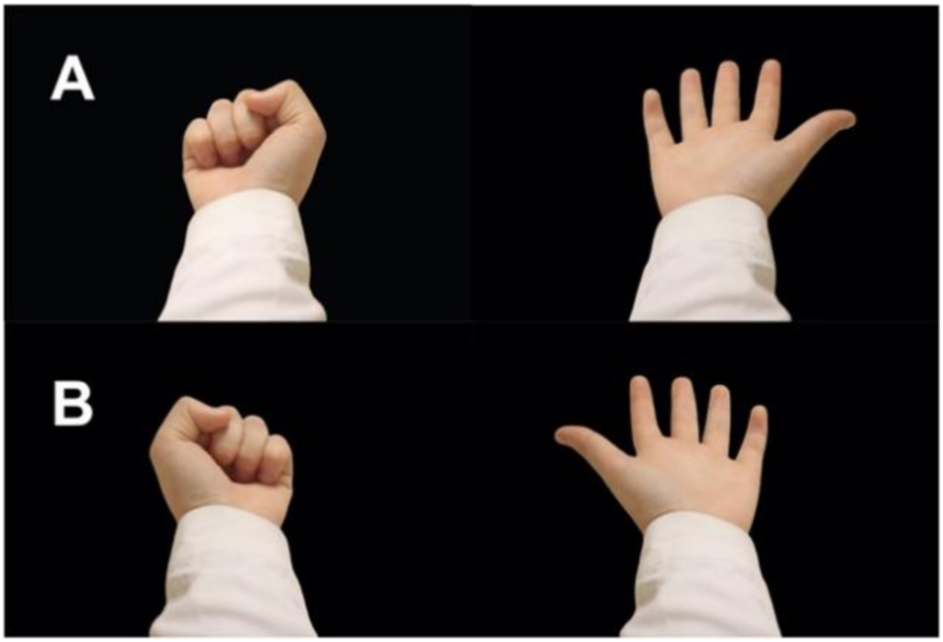

FIGURE 1 | First-person perspective video of finger flexion and extension movements of the left and right hands in healthy adults. This experiment involved right-limb MI (Task A) and left-limb MI (Task B).

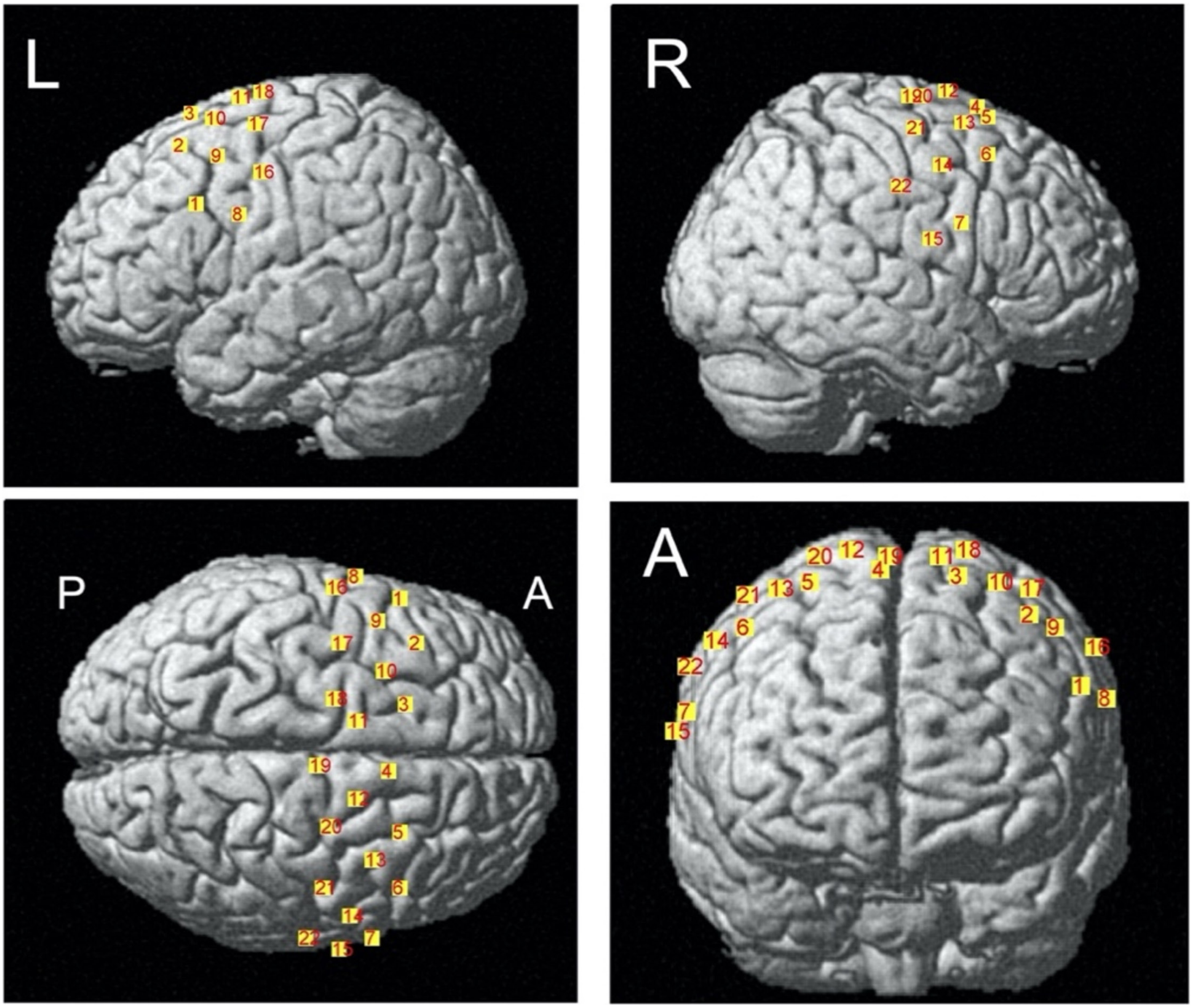

FIGURE 2 | Localization model of the near-infrared brain function imaging system in the brain. Notes: A, anterior (front) view of the brain; L, left view of the brain; P, posterior (back) view of the brain; R, right view of the brain.

TABLE 1 | Channel division based on ROIs (excluding Channels 4 and 19 on the midline of the brain).

Brain region	Number of channels	Corresponding channel
LSMC	3	16/17/18
RSMC	3	20/21/22
LPMC	4	1/2/8/9
RPMC	4	6/7/14/15
LSMA	3	3/10/11
RSMA	3	5/12/13

Abbreviations: LPMC, left premotor cortex; LSMA, left supplementary motor area; LSMC, left sensorimotor cortex; RPMC, right premotor cortex; RSMA, right supplementary motor area; RSMC, right sensorimotor cortex.

the following formula: $LI=(N_L-N_R)/(N_L+N_R)$, where N_L and N_R referred to the change in blood oxygen concentration in the left and right hemispheres, respectively (Ohyanagi et al. 2018). Lateralization was defined based on the LI values: $LI \geq 0.1$ indicated left lateralization, while $LI \leq -0.1$ represented right lateralization (Vernooij et al. 2007).

2.4 | Statistical Analysis

To assess the impact of various characteristics on outcomes, both univariate and multivariate logistic regression models were employed. Characteristics were compared between groups using a Fisher's exact test.

For the statistical analysis of fNIRS data, MATLAB software (R2012b, MathWorks Inc., Natick, MA) was adopted. Motion artifacts were automatically detected and corrected on a channel-by-channel basis using the Homer2 automated processing flow. A bandpass filter ranging from 0.01 to 0.1 Hz was applied to eliminate interference caused by heartbeat (1.0–2.0 Hz), respiration (0.4 Hz), and blood pressure (0.1 Hz or lower) (Franceschini et al. 2006; Julien 2006). NIRS-SPM

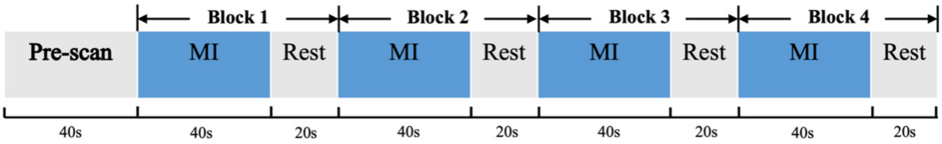

FIGURE 3 | Schematic diagram of the fNIRS motor imagery task paradigm. fNIRS, functional near-infrared spectroscopy.

TABLE 2 | Baseline characteristics of subjects in the right-sided cerebral infarction group and the left-sided cerebral infarction group.

General information on stroke patients			
Items	**Right-sided cerebral infarction group ($n = 20$)**	**Left-sided cerebral infarction group ($n = 20$)**	***p***
Sex (m/f, person)	15/5	16/4	0.705
Age (x ± s, years)	57.85 ± 8.04	55.05 ± 8.17	0.281
Years of education (x ± s, years)	8.35 ± 4.27	9.85 ± 3.50	0.232
Disease duration (x ± s, months)	4.40 ± 1.67	4.20 ± 2.04	0.736
MMSE (x ± s, points)	27.65 ± 1.53	27.85 ± 1.23	0.651
Fugl-Meyer upper extremity (x ± s, points)	21.50 ± 8.94	24.95 ± 8.48	0.218

Abbreviations: MMSE, Mini-Mental State Examination; x ± s, mean ± standard deviation.

and SPM8 software packages were utilized in this study to perform linear detrending, fit a general linear regression model, and calculate the regression coefficients (β-values) for various task conditions. The β-values were employed as quantitative indicators of activation intensity in brain regions (Hou et al. 2021).

SPSS 25.0 statistical software was used to analyze the data. The baseline characteristics of the two groups were statistically analyzed. Categorical data were evaluated using a chi-squared test, while measurement data were expressed as mean ± standard deviation. For measurement data, a paired *t*-test was used for those that conformed to a normal distribution, whereas the rank-sum test was utilized for nonnormally distributed data. $p > 0.05$ indicated no significant difference in the baseline characteristics between the two groups. For each group, one-sample *t*-tests were performed to analyze the β-values of each channel during the left and right-sided MI tasks. To correct for multiple comparisons across channels, the false discovery rate method was applied, with $p < 0.05$ considered statistically significant.

3 | Results

No significant differences were observed between the right- and left-sided cerebral infarction groups regarding gender, age, years of education, disease duration, Mini-Mental State Examination score, and Fugl-Meyer upper extremity score ($p > 0.05$, Table 2). In the right-sided infarction group, there were three patients with corona radiata injury, eight with basal ganglia and corona radiata infarction, six with basal ganglia injury, one with brain stem injury, and two with thalamus injury. Similarly, the left-sided infarction group included two patients with corona radiata injury, 11 with basal ganglia and corona radiata infarction, and seven with basal ganglia injury. The majority of stroke lesions involved subcortical regions, including basal ganglia, corona radiata, thalamus, and internal capsule. These subcortical lesions disrupted the anatomical connections between these regions and sensorimotor areas.

3.1 | Cortical Activation of the Brain

In patients with right-sided cerebral infarction, 13 channels were activated during the right-sided limb MI task. Among these, nine channels were located on the left side, involving three brain regions: the left PMC (LPMC) (Channels 1, 2, 8, and 9), the left SMA (LSMA) (Channels 3, 10, and 11), and the left SMC (LSMC) (Channels 16 and 17). The remaining four channels were located on the right side, involving three brain regions: the right PMC (RPMC) (Channel 6), the right SMA (RSMA) (Channels 5 and 12), and the right SMC (RSMC) (Channel 21). Similarly, four channels were significantly activated during the left-sided limb MI task. Of these, three channels were on the left side, involving two brain regions: the LPMC (Channels 2 and 8) and the LSMC (Channel 16). One channel was located on the right side, involving one brain region: the RSMC (Channel 22). Detailed information is presented in Table 3.

In patients with left-sided cerebral infarction, 17 channels were markedly activated during the right-sided limb MI task. Among them, nine channels were located on the left side, involving three brain regions: the LPMC (Channels 1, 2, and 9), the LSMA (Channels 3, 10, and 11), and the LSMC (Channels 16, 17, and 18). The remaining eight channels were located on the right side, involving three brain regions: the RPMC (Channels 6 and 14), the RSMA (Channels 5, 12, and 13), and

TABLE 3 | Activated channels during limb MI in patients with right-sided cerebral infarction.

Brain region	Channel	Right-sided cerebral infarction patients while performing right-sided limb MI			Right-sided cerebral infarction patients while performing left-sided limb MI		
		β	t	p	β	t	p
LPMC	1	0.0028	6.59	< 0.001*	0.0054	2.60	0.065
	2	0.0028	4.42	< 0.001*	0.0026	3.25	0.031*
	8	0.0028	2.91	0.016*	0.0045	2.93	0.047*
	9	0.0031	8.19	< 0.001*	0.0031	1.95	0.111
LSMA	3	0.0025	3.16	0.011*	0.0012	2.22	0.095
	10	0.0022	4.79	< 0.001*	0.0015	2.32	0.093
	11	0.0019	3.30	0.010*	0.0014	2.01	0.107
LSMC	16	0.0032	6.88	< 0.001*	0.0048	3.90	0.019*
	17	0.0042	7.82	< 0.001*	0.0031	2.62	0.065
	18	0.0008	1.31	0.216	0.0010	1.05	0.323
RPMC	6	0.0012	2.60	0.028*	0.0006	1.11	0.309
	7	0.0017	2.08	0.070	0.0038	1.62	0.159
	14	0.0012	1.50	0.166	0.0019	1.31	0.253
	15	0.0025	1.75	0.118	0.0051	1.71	0.151
RSMA	5	0.0016	3.29	0.010*	0.0012	2.29	0.093
	12	0.0020	4.45	< 0.001*	0.0021	2.09	0.107
	13	0.0011	1.90	0.094	0.0005	0.75	0.464
RSMC	20	0.0010	1.56	0.157	0.0013	1.64	0.159
	21	0.0021	3.01	0.014*	0.0008	1.13	0.309
	22	0.0008	0.72	0.481	0.0041	3.64	0.019*

Abbreviations: LPMC, left premotor cortex; LSMA, left supplementary motor area; LSMC, left sensorimotor cortex; MI, motor imagery; RPMC, right premotor cortex; RSMA, right supplementary motor area; RSMC, right sensorimotor cortex.
*$p \leq 0.05$.

the RSMC (Channels 20, 21, and 22). During the left-sided limb MI task, two channels were remarkably activated, both on the left side. The left side included two brain regions: the RPMC (Channel 14) and the RSMC (Channel 21). Detailed information is listed in Table 4.

Compared to the baseline, the t-map of the changes in O_2Hb depicted the activation patterns related to each experimental condition (Figure 4).

3.2 | Cortical Functional Lateralization During the Task

The lateralization of motor cortical areas analysis during the MI task revealed that patients with right-sided cerebral infarction showed left lateralization, regardless of whether they underwent left- or right-limb MI. In contrast, patients with left-sided cerebral infarction exhibited left lateralization during right-limb MI and right lateralization during left-limb MI. The results are shown in Table 5.

4 | Discussion

The MI training is known for its high safety and operability (Nicholson et al. 2018; Mahmoud et al. 2018). MI is a form of psychological intervention that simulates the activity within the brain and mirrors the movement perceived by the brain (Jeannerod 1994). MI can be applied in cases of physical restrictions or limited movement space, as it does not require actual physical movement. Additionally, MI shares the same neurophysiological characteristics as actual movement. Jacobson argued that the peripheral physiological effects experienced during MI are similar to those observed during actual movements, such as action potentials and heart rates (Jacobson 1930). According to Jeannerod's motor simulation theory (Jeannerod 1994), MI is functionally equivalent to actual movement in terms of neural

TABLE 4 | Activated channels during limb MI in patients with left-sided cerebral infarction.

Brain region	Channel	Left-sided cerebral infarction patients while performing right-sided limb MI			Left-sided cerebral infarction patients while performing left-sided limb MI		
		β	t	p	β	t	p
LPMC	1	0.0043	4.31	0.002*	0.0007	1.53	0.408
	2	0.0025	2.61	0.021*	0.0001	0.25	0.841
	8	0.0010	0.93	0.363	0.0001	0.05	0.959
	9	0.0053	3.00	0.010*	0.0008	1.29	0.408
LSMA	3	0.0019	3.85	0.003*	−0.0006	−1.20	0.417
	10	0.0023	4.07	0.002*	0.0003	0.70	0.634
	11	0.0024	3.30	0.007*	−0.0020	−1.27	0.408
LSMC	16	0.0018	3.24	0.007*	0.0013	1.40	0.408
	17	0.0034	5.49	<0.001*	0.0007	1.55	0.408
	18	0.0030	4.47	0.001*	−0.0003	−0.53	0.724
RPMC	6	0.0017	4.69	0.001*	0.0004	1.26	0.408
	7	0.0011	2.09	0.056	0.0012	2.90	0.067
	14	0.0039	3.11	0.009*	0.0024	3.78	0.014*
	15	0.0028	1.88	0.080	0.0016	2.33	0.137
RSMA	5	0.0016	2.85	0.013*	−0.0002	−0.50	0.724
	12	0.0023	3.64	0.004*	0.0004	0.85	0.559
	13	0.0025	3.65	0.004*	0.0008	1.38	0.408
RSMC	20	0.0024	3.44	0.006*	0.0005	0.90	0.559
	21	0.0029	3.25	0.007*	0.0018	3.89	0.014*
	22	0.0016	2.58	0.021*	0.0012	2.45	0.134

Abbreviations: LPMC, left premotor cortex; LSMA, left supplementary motor area; LSMC, left sensorimotor cortex; MI, motor imagery; RPMC, right premotor cortex; RSMA, right supplementary motor area; RSMC, right sensorimotor cortex.
*$p \leq 0.05$.

circuit planning and engagement (Moran and O'Shea 2020). Therefore, MI has been used in rehabilitation research to leverage brain plasticity and enhance the recovery of motor function following brain injury (Faralli et al. 2013; Yang et al. 2012).

Malouin et al. (2012) discovered that patients with right-sided cerebral infarcts required more MI due to impairment in the frontoparietal network involved in visuospatial processing. Additionally, an fMRI study on patients with cerebral infarction reveals that compared to patients with right-hemisphere lesions, patients with left-hemisphere lesions exhibit higher activation levels in visual processing (including the fovea, lingual gyrus, and dorsal premotor areas) and experience more vivid imagery (Dettmers et al. 2015). However, a study on patients with cerebral infarction has shown that the left hemisphere is the dominant hemisphere for MI, making it more difficult for patients with concomitant left hemisphere damage to perform the MI task (Sabate et al. 2004). Previous studies have reported varying results, raising questions about the feasibility of combining MI in patients with cerebral infarction on both the right and left sides. This study aimed to compare the cortical activity in patients with right- and left-sided cerebral infarction during MI tasks and to identify differences between the two groups.

The experiment covered the bilateral SMC through Channels 16, 17, 18, 20, 21, and 22, which primarily include the primary somatosensory cortex (S1) and the primary motor cortex (M1). These regions are involved in motor learning (Gomez et al. 2021) and motor execution (Leff et al. 2011) through sensory and motor inputs. Additionally, Channels 1, 2, 3, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, and 15 contribute to motor planning (Li et al. 2015) of the bilateral PMC and SMA. As reported by Vogt et al., performing action observation (AO) while watching task-related videos increases the vividness of MI (Vogt et al. 2013). Compared to AO and MI alone, the intervention, which combines AO and MI, has been shown to further increase activity in motor-related areas, such as the SMA and PMC (Taube et al. 2015). This study confirmed that MI had an effect on neural activation in the motor

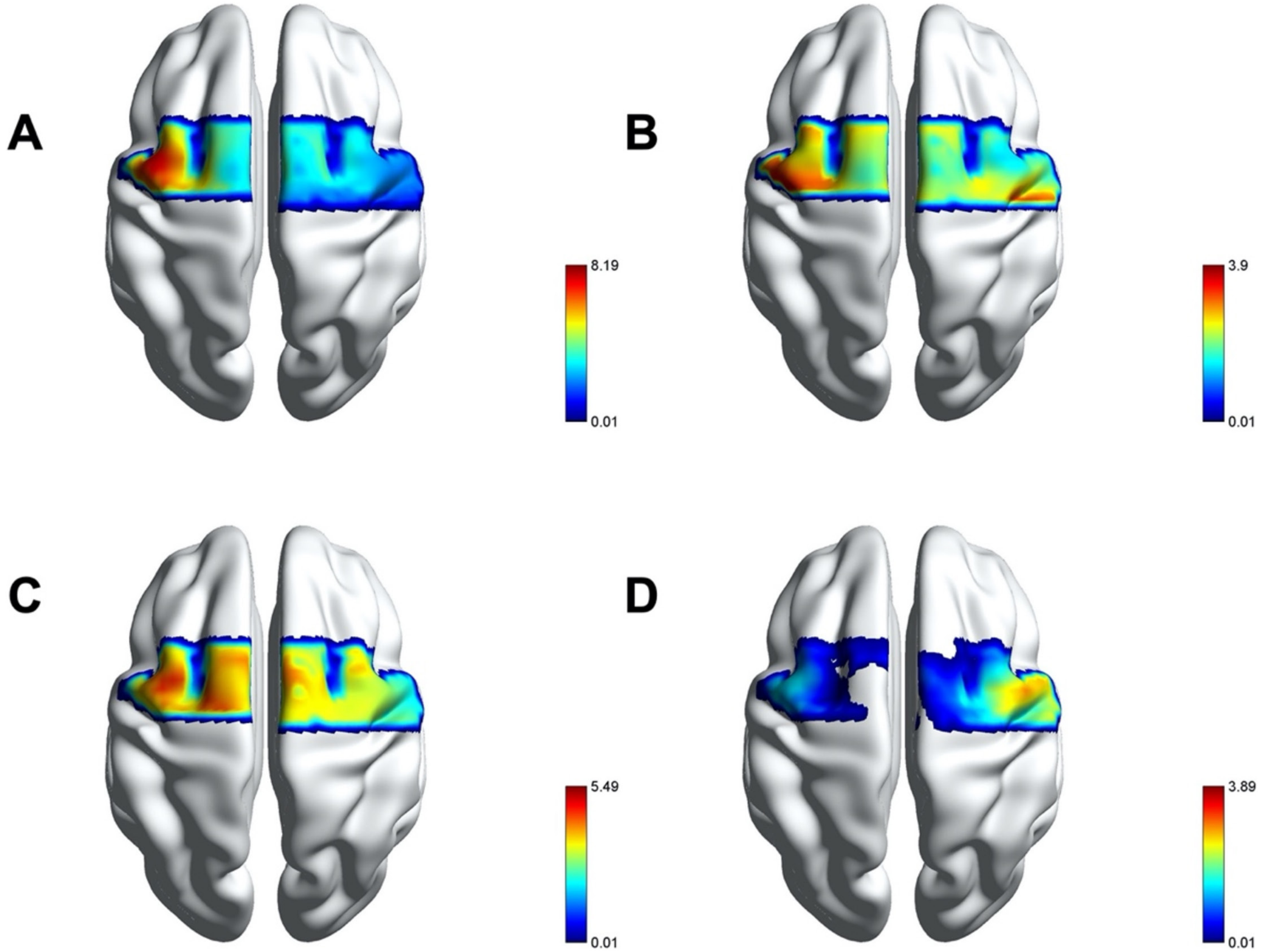

FIGURE 4 | Brain activation in patients with cerebral infarction while performing MI task. (A–B) Right-sided cerebral infarction patients while performing right-sided (A) and left-sided (B) limb MI. (C–D) Left-sided cerebral infarction patients while performing right-sided (C) and left-sided (D) limb MI.

TABLE 5 | Cortical functional laterality index and lateralization in different tasks.

Task	LI	Lateralization
Patients with cerebral infarction on the right-sided experience MI in the right limb	0.2675	Left lateralization
Patients with cerebral infarction on the right-sided experience MI in the left limb	0.1440	Left lateralization
Patients with cerebral infarction on the left-sided experience MI in the right limb	0.1006	Left lateralization
Patients with cerebral infarction on the left-sided experience MI in the left limb	−0.8036	Right lateralization

Abbreviation: LI, laterality index.

areas of the brain, similar to actual movement execution, and played a role in motor learning. These findings align with the conclusions of recent systematic reviews, which emphasize the utility of fNIRS in stroke rehabilitation for tracking neuroplastic changes and evaluating the efficacy of interventions (Mihara and Miyai 2016). This reinforces the growing recognition of fNIRS as a valuable tool in poststroke recovery.

During the dominant hand MI task, bilateral activation was observed in the SMC, SMA, and PMC regions of the brain in both patients with left- and right-sided cerebral infarction. The O_2Hb analysis revealed that 13 channels were activated by patients with right-sided cerebral infarction in LPMC, LSMA, LSMC, RPMC, RSMA, and RSMC, while patients with left-sided cerebral infarction activated 17 channels in the same regions. In the nondominant hand MI task, the number of activated channels was significantly lower.

De Vries et al. (2011) demonstrated that MI ability is more relevant than actual motor function in the early postinfarction period. The M1 and S1 of the contralateral cerebral hemisphere control human movement and sensation. These brain regions are linked by a large number of corpus callosum, and there is also a dynamic functional connectivity and mutual inhibition between the M1 and S1 of both hemispheres in a state of normal checks and balances (Ocklenburg et al. 2015). When brain injury on the affected side is too severe, functional recovery may depend more on functional compensation in the contralateral hemisphere. This compensation may occur between bilaterally equivalent brain regions or between brain regions that are normally structurally and functionally connected. Furthermore, this process may result in the formation of new structural and functional connectivity between the hemispheres (Auriat et al. 2015). This study suggested that the brain might compensate for the function of the injured affected side by establishing new functional connections during MI. However, cortical activation alone cannot fully account for this phenomenon, and further investigation was needed to explore the network connectivity or reconstruction inherent in the brain during the activity.

Another new finding is that MI ability after cerebral infarction is asymmetrical. As displayed in Table 4, the cortical function LI and lateralization vary across tasks. Casasanto (2009) found that the activation of cortical areas involved in the planning and execution of movements during hand MI is left-lateralized in right-handed individuals, consistent with the results of this study. When comparing dominant-hand MI with nondominant-hand MI, patients with cerebral infarction exhibited greater channel activation when imagining the dominant hand. This suggests that they perceived imagined movement more vividly on that side. An experiment has demonstrated that the dominant hand influences the mental representation of movement, which is evident in both behavioral outcomes (Ni Choisdealbha et al. 2011) and differences in brain activity patterns (Carino-Escobar et al. 2020; Zapala et al. 2020). Crotti et al. (2022) conducted an fMRI study comparing the neural correlates of imagining a simple task (squeezing a ball) with the dominant hand, nondominant hand, and both hands. The results exhibited that the nondominant precentral gyrus was active regardless of whether the MI task involved the dominant or nondominant hand. In contrast, activation in the dominant lateral precentral gyrus occurred only during MI of the dominant hand. Perruchoud et al. (2018) further identified that the activation of the precentral gyrus played a causal role in MI. This study supported this proposal, suggesting that precentral gyrus activation occurred during MI, particularly in right-handed dominant hands.

Johnson et al. (2002) discovered that after cerebral infarction, the perceptual recalibration of MI favored the unaffected side, while the accuracy of MI benefited the affected side. They interpreted this “hemiplegic advantage” as a broad rehabilitation, which focused on planning and imagining movements that are currently impossible to perform. However, this interpretation is not entirely consistent with our findings. The results remain speculative and require further confirmation.

Neurofeedback has also shown promise as a tool for enhancing MI in stroke rehabilitation. Additionally, combining MI with neurofeedback has been demonstrated to improve the activation of motor cortical areas, leading to more effective rehabilitation outcomes. For example, a study demonstrated the efficacy of real-time neurofeedback in improving MI-related cortical activation in stroke patients (Berman et al. 2012). This approach can offer an exciting avenue for future research and clinical applications, as fNIRS enables noninvasive, real-time monitoring of cortical activation patterns associated with MI. Given its ability to provide neurofeedback on hemodynamic responses, fNIRS holds promise for enhancing MI training and facilitating neuroplasticity in stroke rehabilitation (Klein et al. 1915).

Furthermore, a reduction in M1 activity was observed during kinesthetic MI. This result aligns with previous studies, which have demonstrated that MI, particularly kinesthetic imagery, leads to reduced activation of motor execution regions, such as M1. This deactivation may reflect a dissociation between motor execution and mental movement simulation, indicating that kinesthetic MI primarily activates cognitive systems related to the representation of movement rather than the motor system responsible for execution (Mehler et al. 2020).

This study revealed that MI training activated the affected motor areas in patients with cerebral infarction. However, the findings also indicated differences in motor cortex activation during MI of left- and right-sided limb activities in patients with right- and left-sided cerebral infarction. When selecting an MI paradigm for patients with right-sided infarction, it is essential to consider strategies to improve the activation of the right motor areas by enhancing the vividness of the left upper-limb imagery.

5 | Limitations

This study has several limitations that should be addressed in future research. One methodological limitation is the absence of short-distance channels, which may not only lead to potential contamination of the data but also affect the accuracy of brain activation measurement. To address this limitation, future studies should apply data cleaning techniques, such as common average referencing, to mitigate the impact of noise, as suggested by previous research (Nguyen et al. 2014).

Secondly, the small sample size and intersubject variability may lead to imprecise effect estimates, possibly overestimating the true effect (Algermissen and Mehler 2018).no formal power analysis was conducted to determine the required sample size, which may affect the reliability of the results. Future studies should include power calculations to ensure robust statistical analysis.

Third, this study was not preregistered, which may impact the transparency and reproducibility of the findings. Preregistration helps enhance methodological rigor by specifying the study design, hypotheses, and analysis plans in advance (Schroeder et al. 2023). Future studies should consider preregistration to improve study transparency.

Another limitation of this study is the traditional publication format, which, unlike Registered Reports (RRs), does not undergo peer review before data collection. RRs have been recognized as a means to reduce publication bias by promoting transparency and methodological rigor (Allen and Mehler 2019;

Scheel et al. 2021). Future studies in this field should consider submitting RRs to ensure a more structured and unbiased research process.

Finally, this study only included right-handed patients. Future research should also examine left-handed individuals.

6 | Conclusion

In summary, this study utilized fNIRS to analyze cortical activation and lateralization in patients with cerebral infarction during MI tasks. The results demonstrated that the SMC, PMC, and SMA-ROIs related to the hand motor task were activated during the MI task and may be associated with the dominant hand and hemisphere. Investigating the cortical activation and lateralization patterns of MI-related tasks may provide insights into the clinical application of MI therapy, improving limb dysfunction after brain injury.

Author Contributions

Jialing Wang: conceptualization, formal analysis, funding acquisition, methodology, project administration, writing – original draft, writing – review and editing. **Xinyu Jia:** conceptualization, investigation. **Jianfei Song:** conceptualization, investigation. **Zhengyuan Qin:** writing – review and editing. **Manting Cao:** funding acquisition, methodology, writing – review and editing. **Jianer Chen:** conceptualization, methodology, supervision, writing – review and editing.

Ethics Statement

This study was approved and reviewed by the Ethics Committee of Zhejiang Rehabilitation Medical Center (No. ZKLL21121501) and was registered with the Chinese Clinical Trial Registry (ChiCTR2400081810). Informed consent was obtained from all participants.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Data will be made available upon request.

Peer Review

The peer review history for this article is available at https://www.webofscience.com/api/gateway/wos/peer-review/10.1111/ejn.70079.

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