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Neural mechanisms underlying the improvement of gait disturbances in stroke patients through robot-assisted gait training based on QEEG and fNIRS: a randomized controlled study

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Abstract

Background Robot-assisted gait training is more effective in improving lower limb function and walking ability in stroke patients compared to conventional rehabilitation, but the neural mechanisms remain unclear. This study aims to explore the effects of robot-assisted gait training on lower limb motor dysfunction in stroke patients and its impact on neural activity in the motor cortex, providing objective evidence for clinical application.

Methods Forty-two stroke patients meeting the inclusion criteria were randomly assigned to either the experimental group receiving robot-assisted gait training or the control group receiving conventional overground walking training. Assessments were conducted at baseline and after four weeks of treatment. Primary outcome measures included cortical activation measured by functional near-infrared spectroscopy (fNIRS), power ratio index (PRI), and delta/alpha power ratio (DAR) measured by quantitative electroencephalography (QEEG), and their correlation with the Fugl-Meyer Assessment (FMA) for lower limb motor function. Secondary outcome measures included FMA and Functional Ambulation Category (FAC).

Results Data from 36 patients (18 in each group) after four weeks of treatment were analyzed. The fNIRS results indicated better activation in the premotor and supplementary motor cortices in the robot-assisted gait training group compared to the control group. QEEG analysis showed reduced PRI and DAR in the premotor, supplementary motor, and primary motor cortices in the robot-assisted gait training group, suggesting improved motor function recovery in stroke patients. Clinical scale analysis revealed superior motor function recovery in the robot-assisted gait training group compared to the control group.

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Conclusions Robot-assisted gait training significantly enhances activation in the primary motor cortex and supplementary motor area, potentially aiding stroke patients in recovering their ability to plan. PRI and DAR, particularly PRI, are valuable clinical indicators for assessing motor function recovery in stroke patients.

Trial registration Chinese Clinical Trial Registry (ChiCTR2200060668). Registered on June 6, 2022; https://www.chictr.org.cn/showproj.html?proj=171610.

Keywords Rehabilitation robot, Stroke, Lower limb motor dysfunction, Functional near-infrared spectroscopy, Quantitative electroencephalography

Background

Stroke is a global health issue and one of the leading causes of long-term disability. Approximately one-third of stroke patients experience permanent motor deficits, severely affecting their daily activities [1]. Lower limb motor dysfunction is a common problem among stroke patients, leading to difficulties in mobility, posture maintenance, balance, and walking. Therefore, providing rehabilitation to improve walking ability in stroke patients is necessary [2, 3].

In recent years, rehabilitation robots have become increasingly important in clinical rehabilitation [4]. Their application can relieve therapists from strenuous training tasks. By analyzing data from rehabilitation robot training, the patient's recovery status can be assessed [5]. Due to their precision and reliability, rehabilitation robots are an effective method for improving stroke rehabilitation [6].

Currently, the neurophysiological mechanisms by which rehabilitation robots enhance functional walking ability remain unclear [7, 8]. Some scholars believe that the effectiveness of rehabilitation robots in improving functional walking ability depends on the high repetition frequency and intensity of task-oriented movements [9]. Studies have shown that conventional exercise therapy can enhance patients' neuroplasticity [10, 11]. Compared to traditional therapy, robot-assisted gait training may more effectively promote neuroplasticity mechanisms related to motor learning and functional recovery, such as sensorimotor plasticity, effective connectivity of the frontal-parietal cortex, and interhemispheric inhibition [12].

The rise of multimodal neuroimaging technologies has significantly impacted modern neuroscience. These methods contribute independently to understanding cognitive processing [13, 14] and improving clinical diagnosis [15]. Functional near-infrared spectroscopy (fNIRS) combined with quantitative electroencephalography (QEEG) is currently favored due to its non-invasiveness, low cost, and system flexibility [16]. fNIRS is suitable for monitoring cortical activation during dynamic movement, making it possible to visualize cortical activation during dynamic movement [17]. Based on this, this research will use fNIRS to detect patients before and after robot-assisted gait training, indirectly assessing cortical neural activation by observing changes in beta values across different brain regions.

QEEG can record synchronous postsynaptic potentials of cortical neurons from the scalp [18]. The raw electroencephalography (EEG) signal is amplified, digitized, mapped, and filtered to isolate narrow frequency bands (in Hz) reflecting specific brain sources and functions, typically divided into delta (0.3–3.5 Hz), theta (4–7.5 Hz), alpha (8–13 Hz), and beta (14–30 Hz) bands. This study will use the delta/alpha ratio (DAR) and the power ratio index (PRI), which is (delta + theta)/(alpha + beta), to assess the degree of motor dysfunction and motor gain in stroke patients.

Robot-assisted gait training has been shown to effectively improve walking ability, correct abnormal gait, and promote motor function recovery and balance in hemiplegic stroke patients, but its neural mechanisms remain unclear. In this study, hemiplegic stroke patients will undergo fNIRS and QEEG assessments over a four-week period both before and after receiving robot-assisted gait training and conventional gait training, with subsequent analysis of the correlations between EEG indices and clinical outcome measures. For the first time, this research combine fNIRS and QEEG to evaluate the dynamic effects of lower limb robotic rehabilitation on the motor cortex, providing multidimensional evidence to elucidate the neuroplastic mechanisms underlying lower limb robotic therapy in stroke patients and laying a theoretical foundation for the design of personalized rehabilitation protocols.

Methods

Trial design

This trial was designed as an assessor-blinded, randomized controlled trial based on the CONSORT statement. The study was approved by the Ethics Committee of the Third Affiliated Hospital of Zhejiang Chinese Medical University (No. ZSLL-ZN-2022-011-1). The study is registered with the Chinese Clinical Trial Registry (No. ChiCTR2200060668). All subjects signed a written informed consent form before initiating the trial.

Study setting and participants.

It includes 42 patients receiving rehabilitation treatment at the Third Affiliated Hospital of Zhejiang Chinese Medical University. A computer-generated random sequence assigned patients equally to either the robot-assisted or control group (1:1 ratio). An independent statistician, uninvolved in the study, conducted the randomization while maintaining allocation concealment until final assignment. All assessments were conducted by therapists blinded to the group assignments. The inclusion criteria were: (1) Meets stroke diagnostic criteria; (2) Aged over 18 years, first onset stroke duration of 1–6 months; (3) Lower limb modified Ashworth scale ≤ 2, Brunnstrom stage ≥ III; (4) Standing balance level II; (5) Able to walk independently for at least 15 m with assistive devices; (6) Able to understand and follow instructions; (7) No skull defects, significant brain edema, or significant brain atrophy; (8) Stable condition; (9) All patients provided informed consent signed by the patient or their legal guardian. The exclusion criteria were: (1) Severe cognitive impairment or speech disorders that prevent cooperation with training; (2) Hemianopia or visual impairments; (3) Vestibular dysfunction such as vertigo or tinnitus; (4) Severe bone and joint diseases, severe cardiopulmonary diseases preventing training; (5) Condition deteriorating, unable to continue treatment.

Sample size

This study is a randomized controlled trial using the Fugl-Meyer lower extremity motor function score as the outcome measure. According to the literature [19], it is anticipated that the intergroup difference in the Fugl-Meyer lower extremity motor function score at the end of the intervention will be 0.8 points, with a standard deviation of 0.7. A two-sided test with an α of 0.05 and a power (test efficiency) of 90% was used. Calculations determined that 16 subjects are required in each group. Considering a 10% dropout rate, a minimum of 18 subjects per group is needed, totaling at least 36 subjects for the study.

Intervention

Experimental Group: Patients undergo robot-assisted gait training using a treadmill-based rehabilitation robot (model: GR-A1). During training, patients wear a safety harness connected to the robot system for body weight support, with leg devices simulating a complete physiological gait cycle on the treadmill. Parameters such as hip and knee joint angles, leg length, and walking speed (0.5–3.0 m/s) can be adjusted. Initial training parameters are personalized and adjusted based on patient response. Training sessions last 30 min, five times a week, for a total of 20 sessions.

Control Group: Patients receive conventional overground walking training, walking back and forth in a flat indoor corridor until reaching a Borg perceived exertion level of 4. After resting, patients resume training following the same procedure until the session ends. Each session lasts 30 min, five times a week, for a total of 20 sessions.

fNIRS data processing and analysis

All selected patients were evaluated in an awake and quiet state by personnel who were professionally and uniformly trained according to standard operating procedures. Evaluations were conducted one day before treatment and four weeks after treatment for both the experimental and control groups to ensure consistency in assessment time points, allowing for accurate comparison of pre- and post-treatment effects.

fNIRS: Using a portable functional near-infrared spectroscopy (fNIRS) brain imaging device from Japan (LIGHTNIRS), which has 22 channels, including 8 transmitters and 8 receivers, the detection is performed. The data collection environment should be quiet, with subdued lighting, and free from electromagnetic interference. The electrodes are attached to the corresponding scalp positions, and the patient walks in a straight line for 20 s, then rests for 20 s, repeating this measurement five times while maintaining an upright posture during walking. The primary areas of data collection include the primary motor cortex, premotor cortex, and supplementary motor cortex, observing hemodynamic changes in the cortex until stable signals of oxygenated hemoglobin concentration changes are obtained. Thus, the change in oxygenated hemoglobin for each channel is determined. The coordinate information for each channel is confirmed using a 3D positioning system on a standard head model to activate the cortical areas of the corresponding channels. According to the modified Beer-Lambert law, the change in hemoglobin level can be quantified by the β value of fNIRS, which indirectly reflects neural activation in various cortical areas.

The target localization was performed using the FASTRAK digital three-dimensional digitizer (Polhemus USA) to ensure sufficient precision for measuring the activity of the primary motor cortex, premotor cortex, and supplementary motor area (Fig. 2).

This study used the NIRS_KIT software based on Matlab 2021a (MathWorks Inc., Natick, MA, USA) to remove artifacts and preprocess the raw intensity data of fNIRS [20]. To reduce errors, this research excluded the data from the first and last task periods and selected data from the middle three task periods for analysis to obtain beta values reflecting the corresponding cortical activation levels. This research used the beta values before treatment as baseline (beta1), subtracted beta1 from the beta values after treatment (beta2), and obtained the beta change values (Δbeta = beta2 - beta1) after treatment.

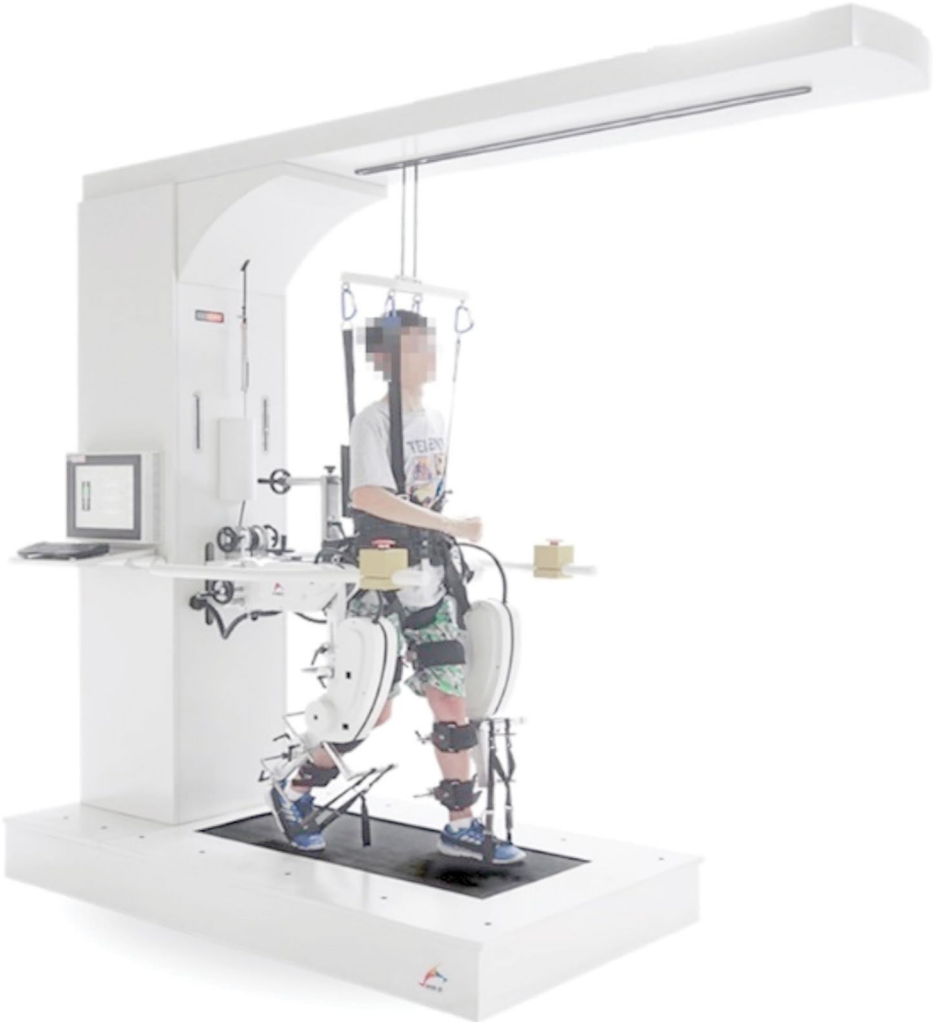

Fig. 1 Robotic-assisted gait training setup

Subsequently, this research used statistical methods such as two-sample t-tests, rank sum tests, etc., to analyze the cortical activation of each channel in the experimental and control groups. This research generated heat maps and placed them on 3D brain models to visually demonstrate changes in cortical activation before and after treatment [21].

QEEG data processing and analysis

QEEG: One day before and four weeks after treatment, researcher conducted QEEG examinations on the patients. The QEEG data collection environment was kept quiet and free from electromagnetic interference. The German QEEG device (actiCHamp) was used, and after confirming the connection between the EEG software and the relevant acquisition devices, electrodes were placed on the corresponding scalp positions according to the international 10–20 system. Medical conductive gel was applied to achieve appropriate impedance levels. Patients were comfortably seated with eyes closed to maintain an awake state and avoid movement during the assessment. The main areas of data collection included the primary motor cortex (Cz, C3, C4), premotor cortex (FC1, FC2), and supplementary motor area (FCz), with each data collection session lasting three minutes to obtain stable signals of EEG parameters (absolute power in δ, θ, α, and β frequency bands) [22].

After data collection, the QEEG data were processed and analyzed for artifact removal and preprocessing using the original QEEG analyzer software. To minimize errors, EEG data from the first minute and the last minute were excluded, and data from the middle minute were selected for analysis to extract the absolute power values of each frequency band. Subsequently, the DAR (Delta Absolute Ratio) and PRI (Peak Ratio Index) were calculated for each patient, with the data before treatment as baseline (DAR1 and PRI1). The values after treatment (DAR2 and PRI2) were subtracted from the baseline

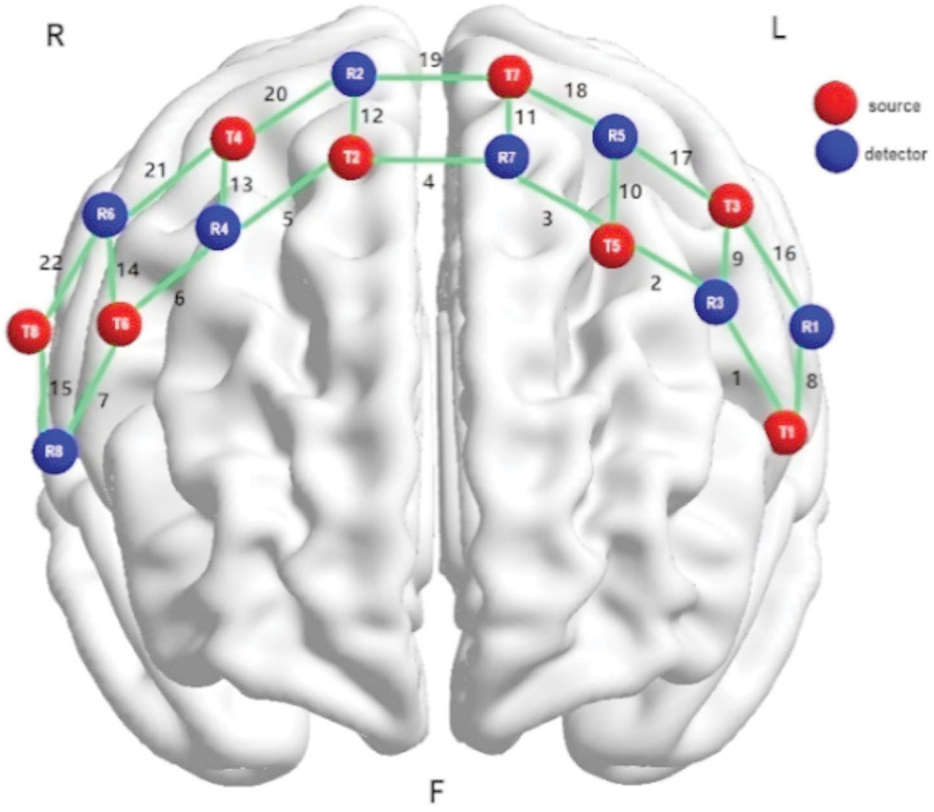

Fig. 2 fNIRS channel positions overlaid on a 3D brain model

values to obtain the changes in DAR and PRI after treatment (ΔDAR = DAR2 - DAR1, ΔPRI = PRI2 - PRI1). Finally, statistical methods such as two-sample t-tests, non-parametric tests, etc., were used to analyze the data. Using R (version 3.5.3), correlations between the ΔDAR and ΔPRI values of the premotor cortex, supplementary motor area, and primary motor cortex of each patient and the changes in the Fugl-Meyer Lower Extremity Assessment (FMA) scores were explored to investigate the relationship between treatment effects and neurophysiological indicators.

Clinical assessment scales

Functional Ambulation Classification (FAC): A scale consisting of six grades designed to classify the level of physical support required for safe walking by subjects, ranging from Level 0 (unable to walk without the help of two people) to Level 5 (independent walking on uneven surfaces and stairs) [23].

Fugl-Meyer Lower Extremity Assessment (FMA): Consists of 17 items, each scored out of two points. Evaluates the patient's lower limb motor function, including exaggerated reflexes, synergistic movement of extensor and flexor muscles, movements without synergistic coordination, coordination speed, and ability, among others [24].

Table 1 Baseline characteristics of study participants

Characteristic	Experimental Group	Control Group	*P*
Age(years)	57.83 ± 13.85	63.22 ± 13.53	0.246
Male/ female	13/5	14/4	0.700
Months post stroke	2.50 ± 1.79	2.11 ± 1.08	0.791
Disease site (left/ right)	11/7	10/8	0.735
Stroke type (hemorrhage/infarction)	4/14	4/14	1.000
FMA	21.61 ± 4.41	20.06 ± 3.17	0.304
FAC	2.78 ± 0.73	2.78 ± 0.65	0.944

Values denote means ± SD unless specified otherwise

Outcome measures

At the beginning stage of the study, researcher collected medical and demographic information as shown in Table 1. The study included fNIRS and QEEG examinations of participants before treatment and after four weeks of rehabilitation therapy, along with clinical scale assessments.

Primary outcomes: Changes in cerebral cortical oxygenated hemoglobin measured by fNIRS (Δbeta); changes in DAR and PRI measured by QEEG after treatment; correlation between changes in DAR and PRI after treatment and the Fugl-Meyer Lower Extremity Assessment (FMA).

Secondary outcomes: Functional Ambulation Classification (FAC); FMA scores.

There were no statistically significant differences between the two groups of patients in terms of gender, age, duration of illness, affected side (left/right), nature of onset (hemorrhage/infarction), and pre-treatment FMA and FAC scores ($P > 0.05$).

Statistical analysis

Statistical analysis was performed using SPSS 25.0 software. All data passed normality tests. Continuous variables are presented as mean ± standard deviation (X ± s). Group comparisons were conducted using two-sample t-tests and non-parametric rank-sum tests, while paired t-tests were used for within-group comparisons before and after treatment. A significance level of $P < 0.05$ was considered statistically significant. For correlation analysis, "R" (version 3.5.3) was used to conduct linear correlation analysis, with correlation coefficients represented by r and $P < 0.05$ considered statistically significant.

Results

The study included 42 patients from June 2022 to March 2023. During the study, five patients withdrew from assessment due to transfer to another hospital or discharge home, and one patient withdrew due to unwillingness to continue treatment. In the experimental group, three patients deviated from the protocol: two were transferred to another hospital or discharge home and one declined to continue treatment. In the control group, all three patients were transferred to another facility. Ultimately, 36 patients completed the entire study, with 18 patients in the experimental group and 18 patients in the control group (Fig. 3).

In the experimental group, the Δbeta values of channels 1, 8, 9, 11, 12, 18, 19, 20, and 21 showed a significant increase compared to the control group with statistical significance ($P < 0.05$) (Figs. 4 and 5). According to the three-dimensional digitizer, channels with statistically significant differences were mainly distributed in the premotor cortex and supplementary motor area (channels 1, 8, 9, 11, 12, 18, 19, 20) with only one channel located in the primary motor cortex (channel 21) (Table 2).

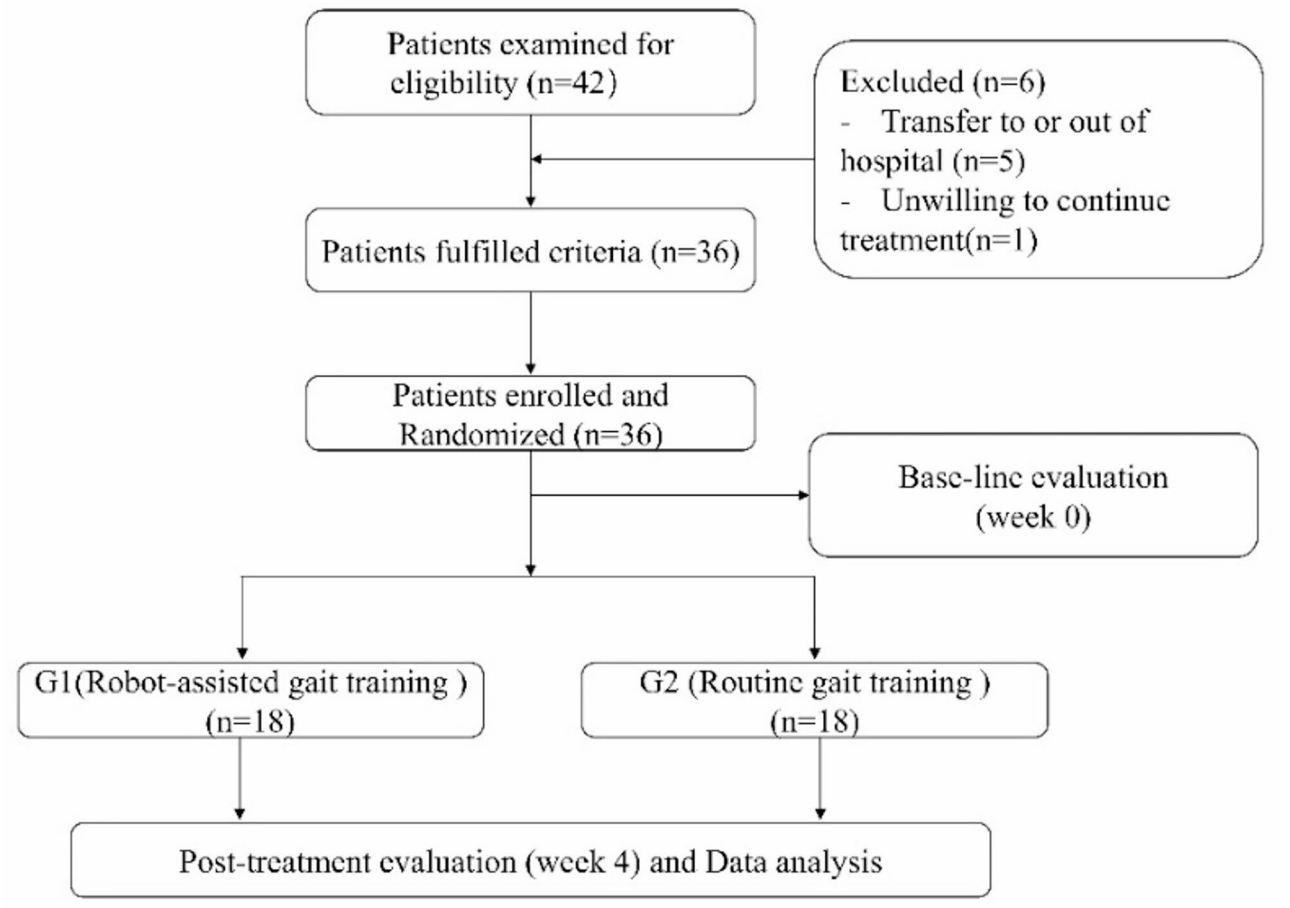

Fig. 3 Flow diagram of the study

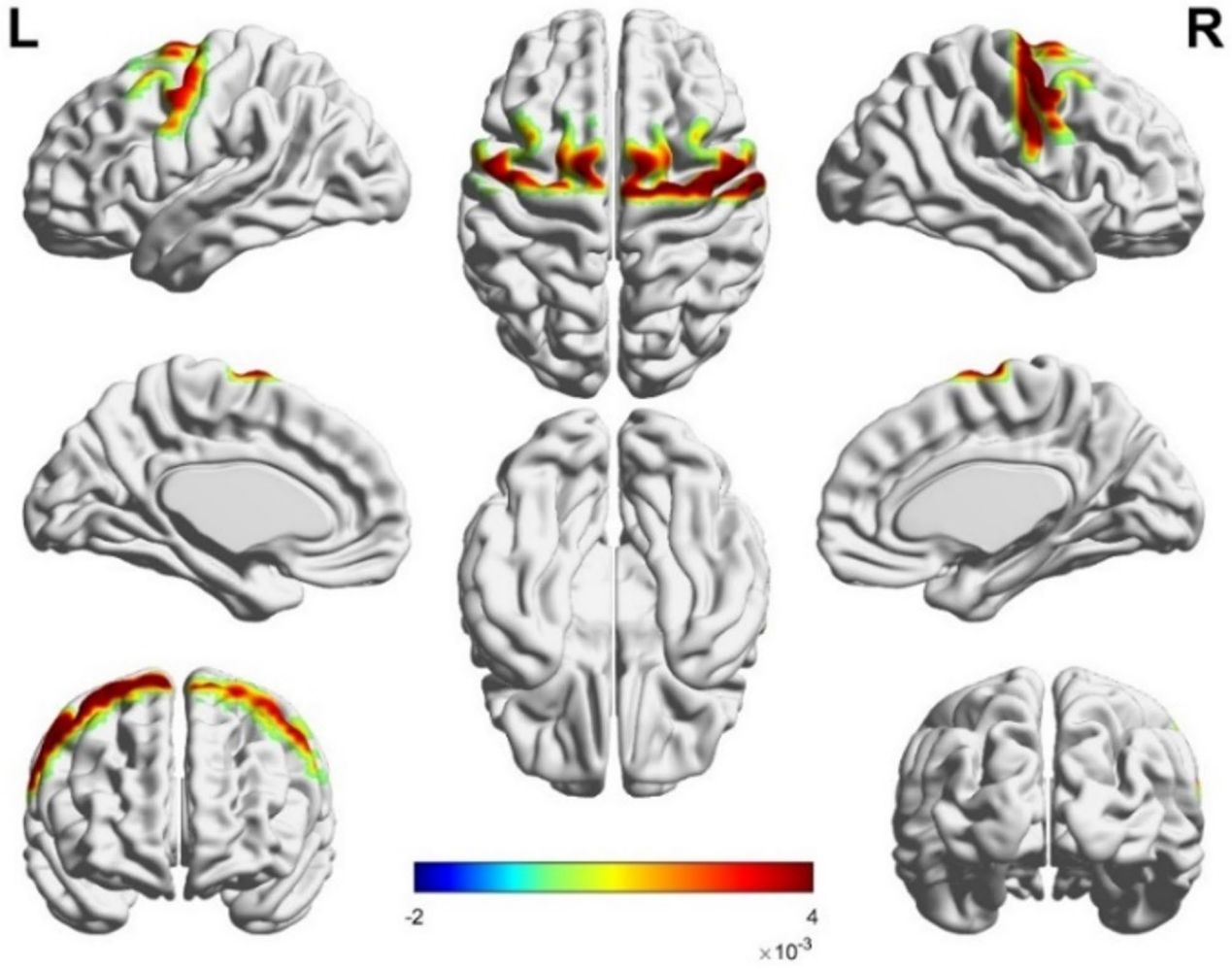

Fig. 4 Cortical activation patterns in the experimental group

Due to the time-intensive nature of QEEG assessments and limited equipment availability, this research randomly selected nine patients from both the experimental and control groups, resulting in a total of 18 participants, who underwent QEEG evaluations before and after the intervention. The analysis results showed that ΔPRI in the primary motor cortex (M1), premotor cortex (PMC), and supplementary motor area (SMA) were significantly reduced in the experimental group compared to the control group with statistical significance (Table 3). ΔDAR in the primary motor cortex and premotor cortex was significantly reduced in the experimental group compared to the control group with statistical significance (Table 4).

This research conducted a correlation analysis between ΔPRI in the primary motor cortex, premotor cortex, supplementary motor area, and changes in Fugl-Meyer Assessment (ΔFMA) scores. The results showed that ΔPRI before and after treatment in these areas were correlated with ΔFMA scores with statistical significance (Fig. 6).

This research conducted a correlation analysis between ΔDAR in the primary motor cortex, premotor cortex, supplementary motor area, and changes in Fugl-Meyer Assessment (ΔFMA). This research found that ΔDAR before and after treatment in the primary motor cortex and supplementary motor area were correlated with ΔFMA scores with statistical significance (Fig. 7).

Through clinical scale assessments, it was found that after treatment, patients in the experimental group showed significant improvement in Fugl-Meyer Assessment (FMA) scores and Functional Ambulation Classification (FAC) scores. The FAC scores of patients in the control group also showed significant improvement. Compared to the control group, the improvement in FMA and FAC scores was more significant in the experimental group, and these differences were statistically significant (Table 5).

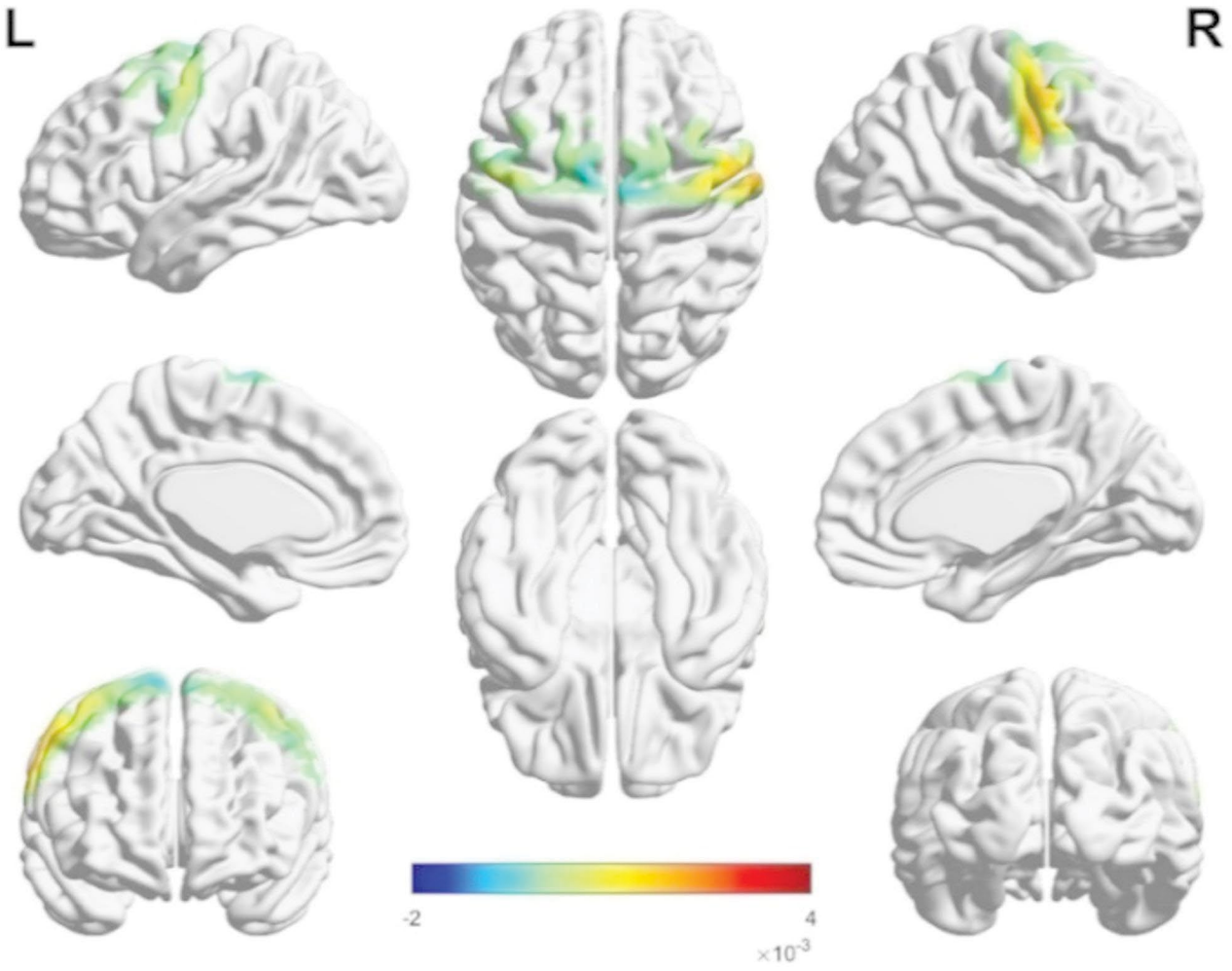

Fig. 5 Cortical activation patterns in the control group

Discussion

In recent years, rehabilitation robotics have shown tremendous potential in promoting lower limb motor function recovery in stroke patients, although their neural mechanisms remain unclear. This study employed a combined approach of neurophysiological and clinical assessments to delve deeper into the therapeutic effects of rehabilitation robotics and their underlying neural mechanisms.

This research utilized the FMA and FAC scales to evaluate the effects of robotic-assisted gait training on improving walking function in stroke patients. This research applied fNIRS and QEEG analyses to investigate the effects of robotic-assisted gait training on motor cortical neural activity in stroke patients. Compared to the control group receiving conventional gait training, patients undergoing robotic-assisted gait training showed significantly greater improvements in lower limb motor function and walking ability. fNIRS indicated significant activation in the premotor cortex and supplementary motor area in the experimental group compared to the control group. QEEG revealed significantly decreased Delta Absolute Ratio (DAR) and Peak Ratio Index (PRI) in the motor cortex of the experimental group compared to the control group. Moreover, PRI showed a higher correlation with FMA scores than DAR, suggesting that PRI may be more suitable for predicting motor function recovery outcomes.

The FMA scale is widely used to evaluate motor impairments following stroke and is globally recognized as a critical assessment tool in clinical practice and research [25, 26]. This research used the FMA and FAC scales to evaluate patients undergoing rehabilitation robotic-assisted gait training compared to those receiving conventional gait training. The results showed that patients undergoing rehabilitation robotic-assisted gait training had significantly better recovery outcomes compared to the control group, suggesting that robotic-assisted gait training is crucial in promoting lower limb motor function recovery in stroke patients. These findings are

Table 2 Changes in cortical activation (Δbeta) measured by fNIRS across different channels

Channel	Experimental Group	Control Group	*P*
1	0.0027 ± 0.0044	-0.0006 ± 0.0031	0.012*
2	0.0028 ± 0.0048	0.0017 ± 0.0030	0.448
3	0.0026 ± 0.0075	0.0022 ± 0.0055	0.874
4	0.0028 ± 0.0081	0.0002 ± 0.0062	0.184
5	0.0018 ± 0.0074	-0.0001 ± 0.0049	0.506
6	0.0024 ± 0.0040	0.0011 ± 0.0022	0.216
7	0.0016 ± 0.0036	0.0025 ± 0.0048	0.899
8	0.0024 ± 0.0032	0.0002 ± 0.0027	0.031*
9	0.0049 ± 0.0060	-0.0008 ± 0.0027	0.002*
10	0.0012 ± 0.0063	0.0019 ± 0.0032	0.975
11	0.0087 ± 0.0132	-0.0046 ± 0.0128	0.008*
12	0.0048 ± 0.0070	-0.0024 ± 0.0066	0.002*
13	0.0040 ± 0.0044	0.0012 ± 0.0038	0.114
14	0.0022 ± 0.0036	0.0011 ± 0.0028	0.305
15	0.0056 ± 0.0082	0.0023 ± 0.0086	0.174
16	0.0021 ± 0.0035	0.0008 ± 0.0032	0.243
17	0.0037 ± 0.0049	0.0014 ± 0.0027	0.174
18	0.0024 ± 0.0043	-0.0005 ± 0.0034	0.034*
19	0.0056 ± 0.0110	-0.0009 ± 0.0084	0.040*
20	0.0029 ± 0.0033	-0.00003 ± 0.0031	0.029*
21	0.0039 ± 0.0071	0.0015 ± 0.0030	0.023*
22	0.0018 ± 0.0032	0.0004 ± 0.0039	0.253

*Indicates statistical significance ($P < 0.05$)

Table 3 Inter-group comparison of ΔPRI in various regions of the motor cortex before and after treatment

Motor cortex	Experimental Group	Control Group	*P*
M1	-4.361 ± 8.266	-4.199 ± 0.798	0.038*
PMC	-10.426 ± 17.574	-0.526 ± 0.723	0.007*
SMA	-9.703 ± 13.590	-0.700 ± 1.172	0.015*

Table 4 Inter-group comparison of ΔDAR in various regions of the motor cortex before and after treatment

Motor cortex	Experimental Group	Control Group	*P*
M1	-6.482 ± 12.542	-0.511 ± 0.721	0.038*
PMC	-15.781 ± 27.464	-0.628 ± 0.666	0.047*
SMA	-14.415 ± 21.656	0.877 ± 1.834	0.102

consistent with previous literature [27, 28]. Prior studies [29] have demonstrated that robot-assisted training more effectively activates the motor cortex and promotes neural remodeling, thereby enhancing motor coordination and gait stability. The clinical data from our study further substantiate this observation.

Stroke-induced motor impairments are primarily associated with the pathophysiology affecting different regions of the motor cortex [30, 31]. The motor cortex is a critical area in the cerebral cortex involved in the planning, control, and execution of voluntary movements [32]. It consists primarily of the primary motor cortex, the premotor cortex, and the supplementary motor area [33]. The primary motor cortex is the main region responsible for generating neural impulses that are transmitted to the spinal cord to control body movements [34]. The premotor cortex is involved in movement preparation, sensory integration, and spatial navigation, particularly in the direct control of proximal and trunk muscles [35]. The supplementary motor area is closely associated with motor planning and is primarily involved in the generation and control of voluntary movements [36]. Analysis using fNIRS has shown significant enhancement in neural activation in the premotor cortex and supplementary motor area during walking after rehabilitation robotic-assisted gait training. This indicates that rehabilitation robotic training is crucial for restoring motor planning and control abilities in stroke patients.

In recent years, QEEG has been widely used to assess brain function and identify biomarkers associated with brain injury and recovery. In stroke patients, QEEG power is significantly affected, characterized by increased δ band power and decreased α and β band powers, resulting in a diffuse slow-wave QEEG pattern [37]. The increase in slow waves and decrease in fast waves are directly related to neuronal metabolism and reflect ischemic injury [38]. Analysis using QEEG can provide valuable information about the recovery of motor function in stroke patients, aiding in the personalized development of rehabilitation plans [39].

Our study utilized QEEG as a non-invasive assessment method with high temporal resolution, facilitating rapid evaluation of brain function [40]. Power changes in specific frequency bands are closely related to brain functional status, allowing QEEG to sensitively detect typical QEEG abnormalities in stroke patients [41]. DAR and PRI, commonly used QEEG parameters, are considered potential indicators for predicting the severity of post-stroke functional impairments. In studies by VAN et al. [42], PRI was found to be closely associated with upper limb motor recovery post-stroke, suggesting that PRI may be more sensitive in assessing rehabilitation outcomes. Another study [43] found that DAR and PRI were negatively correlated with motor recovery in stroke patients before and after rehabilitation. Our research observed that stroke patients undergoing rehabilitation robot-assisted walking training showed significant reductions in PRI in the primary motor cortex, premotor cortex, and supplementary motor area compared to the control group. Furthermore, the changes in these PRI values were significantly negatively correlated with ΔFMA. In contrast, ΔDAR showed significant negative correlations only with ΔFMA in the supplementary motor cortex and primary motor cortex. These findings suggest that PRI may be a more sensitive indicator for assessing gains in post-stroke rehabilitation of walking function, consistent with the findings of Trujillo [44].

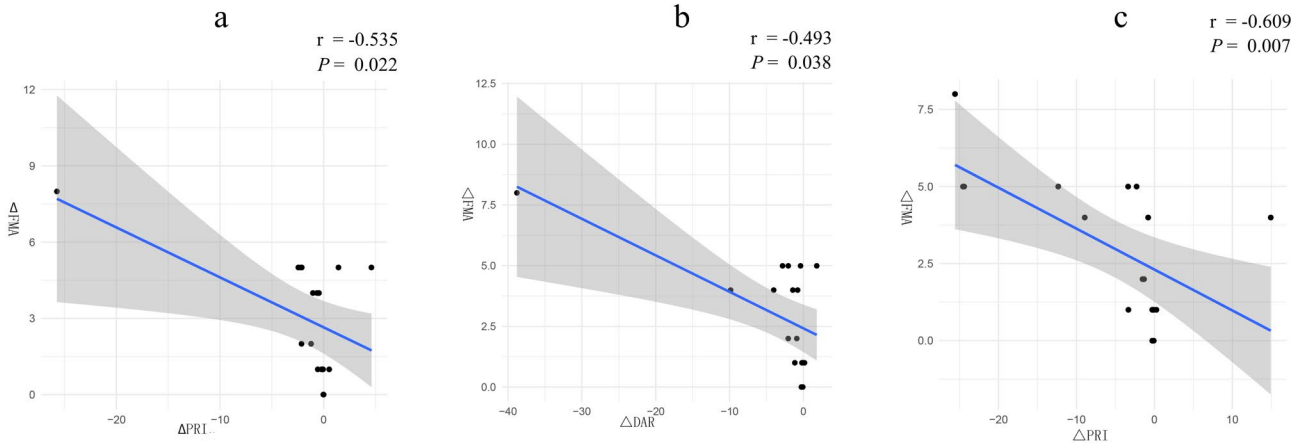

Fig. 6 Correlation between ΔPRI and changes in FMA scores. (**a**) Correlation between ΔPRI and ΔFMA of M1; (**b**) Correlation between ΔPRI and ΔFMA of PMC; (**c**) Correlation between ΔPRI and ΔFMA of SMA

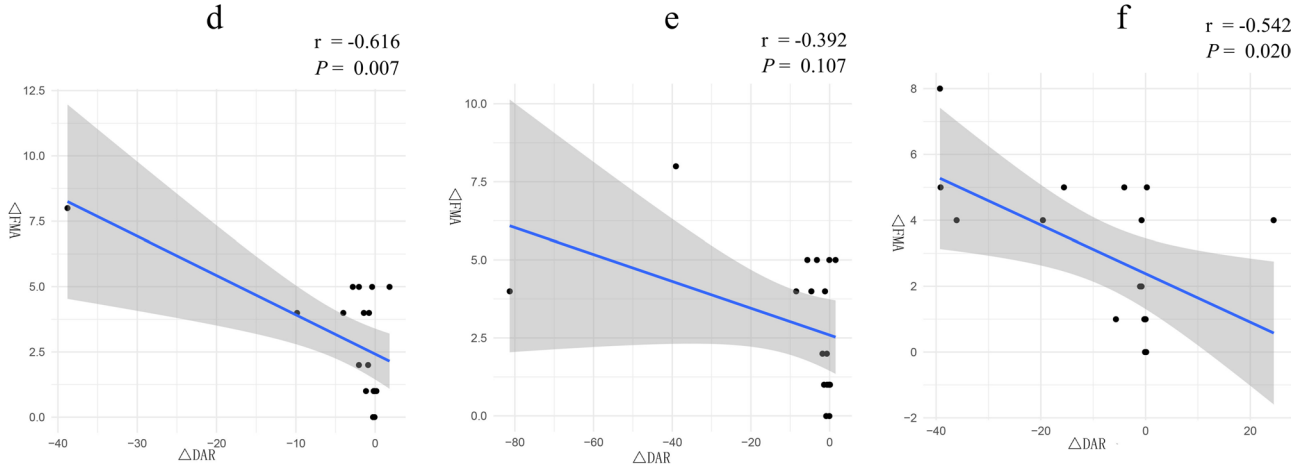

Fig. 7 Correlation between ΔDAR and changes in FMA scores. (**a**) Correlation between ΔDAR and ΔFMA of M1; (**b**) Correlation between ΔDAR and ΔFMA of PMC; (**c**) Correlation between ΔDAR and ΔFMA of SMA

Table 5 Comparison of FMA scores and FAC scores before and after treatment in both groups

	Experimental Group		Control Group		*P* -value		
					Intragroup difference		Interaction effect
	Week0	Week4	Week0	Week4	Experimental Group	Control Group	
FMA	21.61 ± 4.41	26.06 ± 3.72	20.06 ± 3.17	21.33 ± 3.13	0.001*	0.105	<0.001*
FAC	2.78 ± 0.73	4.11 ± 0.68	2.78 ± 0.65	3.28 ± 0.75	<0.001*	0.040*	0.002*

Using combined fNIRS and QEEG monitoring, this study revealed that robot-assisted gait training significantly enhances neural activation in the premotor cortex and supplementary motor area, while electrophysiological indices such as PRI and DAR show a marked reduction. These findings suggest that robotic training facilitates neuroplasticity, thereby accelerating motor function recovery. Compared with conventional rehabilitation approaches, this mechanism highlights the unique role of robotic-assisted training in modulating neural activity, providing new experimental evidence for post-stroke neural remodeling. Moreover, our results offer robust theoretical support for clinical translation. Objective monitoring of electrophysiological changes not only enables a more precise assessment of rehabilitation progress but also provides quantifiable metrics for designing personalized rehabilitation strategies. In the future, an evaluation system integrating fNIRS and QEEG data may allow real-time tracking of neural recovery in clinical settings, guiding the dynamic adjustment of rehabilitation protocols. This approach holds promise

for achieving precision, personalization, and enhanced therapeutic outcomes in stroke rehabilitation.

Limitations

This study has two main limitations: (1) It is a small-sample study without follow-up, so conclusions drawn need caution. Further research could consider larger sample sizes and multi-center clinical trials with longer treatment and follow-up periods. (2) The study did not classify subjects based on the type and location of stroke, leading to potential heterogeneity among patients. Future studies could involve stratified classification to provide more personalized research outcomes and treatment strategies.

Conclusion

Robotic-assisted gait training effectively promotes lower limb motor recovery in stroke patients compared to conventional overground walking training. fNIRS analysis revealed increased activation in the premotor cortex and supplementary motor area, suggesting enhanced motor planning and execution. QEEG findings demonstrated significant reductions in PRI and DAR, which were negatively correlated with FMA scores, indicating their potential as biomarkers for motor function recovery. These results provide neurophysiological evidence supporting the role of robotic-assisted rehabilitation in facilitating neuroplasticity. Future studies should explore long-term outcomes and optimize rehabilitation protocols to enhance clinical efficacy.

Author contributions

XL, HHZ and JEC were involved in the development and design of the study concept; WYZ, JNW and LD were responsible for intervention and assessment; XL, WYZ and LD were in charge of data acquisition and analysis; XL, NSL, TFJ and LG contributed to the initial manuscript writing. All authors revised and agreed to the final version of this article. XL, HHZ and WYZ contributed equally to this work.

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Data availability

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

Declarations

Ethical approval

The study was approved by the Ethics Committee of the Third Affiliated Hospital of Zhejiang Chinese Medical University (No. ZSLL-ZN-2022-011-1). The study is registered with the Chinese Clinical Trial Registry (No. ChiCTR2200060668). All subjects signed a written informed consent form before initiating the trial.

Competing interests

The authors declare no competing interests.

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