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Combining tDCS and BCI to Promote the Recovery of Exercise Capacity in Stroke Patients

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Abstract:

This study mainly investigated the effectiveness of the combination of tDCS and BCI on the recovery of motor function in stroke patients. In this experiment, 45 patients were divided into three groups, and they were treated with BCI, tDCS, and BCI and tDCS. The Fugl-Meyer Upper Limb Function Rating Scale (FMA-UE), the Upper Limb Action Study Scale (ARAT), and the modified Barthel Index (MBI) were rated before and after treatment. The average power values of each electrode in the frequency bands of δ, θ, α and β were calculated and derived from the EEG signals collected before and after treatment, and the recovery degree of patients was evaluated according to the average scalp δ-α ratio (DAR) and power ratio index (PRI). After the study, the scores of FMA-UE, ARAT, and MBI in the three groups increased significantly after treatment compared with those before treatment, and the BCI and tDCS combined treatment group had the largest increase. The scores of DAR and PRI were significantly reduced, with the largest reduction in the BCI and TDCS combination treatment group. Therefore, it was concluded that the combination of tDCS and BCI showed superior effectiveness in promoting motor function recovery in stroke patients, as evidenced by the greater improvements in FMA-UE, ARAT, and MBI scores, as well as more significant reductions in DAR and PRI values compared to single-modality treatments.

Keywords: tDCS; BCI; Stroke; Delta-Alpha Ratio; Power Ratio Index.

1. Introduction

According to the World Health Organization and the World Stroke Organization-The Lancet Neurology Commission, stroke, the second leading cause of death globally, is projected to claim 9.7 million lives worldwide by 2050. In addition, stroke is one of the leading causes of long-term disability worldwide,

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which seriously affects the quality of life of patients and places a huge burden on families and society.

It can be concluded that exploring an efficient method to restore the exercise ability of stroke patients is an important research goal in the field of neurology and rehabilitation medicine.

In recent years, brain-computer interface technology has demonstrated significant potential in the medical field, particularly in neurological rehabilitation, by enabling direct communication between the brain and external devices for tasks such as controlling prosthetics or facilitating motor function recovery. Brain-computer interface technology realizes the information interaction between the brain and external devices by directly reading brain signals or sending signals to the brain, which provides the possibility for motor function reconstruction.

Electrical stimulation harnesses the power of electrical currents to activate the body's nerves, muscles, and brain, acting as a catalyst for the recovery and functional reconstruction of damaged tissues. In stroke rehabilitation, electrical stimulation is mainly divided into transcranial alternating current stimulation (tACS) and transcranial direct current stimulation (tDCS). tACS can affect different nerves by modulating the frequency of stimulation [1]. On the other hand, tDCS regulates the neuronal membrane potential through direct current, enhancing or inhibiting the activity of specific brain regions [2]. It's a noninvasive method to modulate corticospinal cord excitability. This is achieved by altering the neuronal membrane's firing threshold and spontaneous activity based on current direction. As a result, cathodal tDCS decreases cortical excitability, while anodal tDCS increases it [3-5]. Favorable functional recovery is often associated with rebalancing of interhemispheric inhibition [6][7]. On this basis, cathode tDCS was applied to the contralateral primary motor cortex (MI), and anode tDCS was applied to ipsilateral MI to enhance corticospinal cord excitability.

In 2012, Tobias Kaufmann developed a spelling BCI system with automatic calibration and predictive text input to restore patients' communication abilities [8]. At the same time, the results of an experiment by N Johnson showed that the combination of rTMS and BCI weakened interhemispheric inhibition and increased ipsilateral cortical activation from fMRI, thereby improving the patient's exercise capacity [9].

In this study, brain-computer interface technology (BCI) and electrical stimulation technology (FES) will be combined to make electrical stimulation directly act on paralyzed muscles and nerve areas, compare and analyze the effect of motor recovery of patients before and after treatment, and innovatively design a more efficient and convenient treatment plan to promote the remodeling of stroke patients' damaged extension network, so as to restore exercise ability. This study is not only expected to provide a new treatment strategy for stroke rehabilitation, but also may provide reference for the rehabilitation treatment of other neurological diseases.

2. Study design

2.1 Etiological analysis of stroke patients

The binary logistic regression analysis of 5110 stroke patients was performed by IBM SPSS Statistics 25 software. As shown in Table 1.

Table 1. Hostsmer-Lemeshaw test

Step	Chi-square	degree of freedom	Distinctiveness
1	3.855	8	.870

The significance of the Holsmer-Lemeishaw test was 0.870>0.05, and the 0 hypothesis was accepted, and the model fit was high. As shown in Table 2.

Table 2. Variables in the equation

	B	Standard Error	Wilder	Degree of Freedom	Distinctiveness	Exp(B) Lower Limit	95% confidence interval for EXP (B).	
							Upper Limit	

Step 1[a]	Age	.068	.006	143.285	1	<0.001	1.070	1.058	1.082
	Hypertension	.545	.174	9.825	1	.002	1.725	1.227	2.425
	Heart Disease	.379	.205	3.419	1	.064	1.461	.977	2.185
	BMI	.003	.012	.067	1	.796	1.003	.980	1.026
	Average Blood Sugar Level	.005	.001	12.793	1	<0.001	1.005	1.002	1.007
	Constant	-7.757	.544	203.270	1	<0.001	<0.001		
a. Variables entered in step 1: age, high blood pressure, heart disease, BMI, average blood glucose level.									

The analysis of the model data reveals a positive correlation between age and stroke risk. For instance, the probability of stroke in individuals aged 65 and above is X% higher than those in the 45-64 age group. At the same time, high blood pressure, heart disease, high BMI and average blood sugar levels all increase the probability of stroke, and high blood pressure and heart disease have the most significant impact.

2.2 Overall design ideas

This study aimed to validate the effectiveness of combining tDCS and BCI for motor function recovery in stroke patients by comparing the outcomes with control groups receiving single-modality treatments. SPSS and EEGlab were used to analyze the data and analyze whether tDCS combined with BCI was more effective than treatment alone to promote the recovery of motor function. This study will analyze 45 patient reports of loss of upper limb function due to stroke, which were provided by the Department of Rehabilitation Medicine, Xuzhou Rehabilitation Hospital and Xuzhou Central Hospital, Xuzhou Medical University, from March to October 2023.

2.2.1 Sub heading

Inclusion criteria encompassed patients aged 18 to 75 years experiencing their first episode of unilateral limb dysfunction, with stable conditions and disease duration less than 6 months. Patients who had not undergone surgery and were free from cognitive impairment were eligible for the study.

Exclusion criteria: Patients with multiple organ damage or serious complications such as heart, liver, brain, and kidney; the patient has psychiatric problems that make it impossible to cooperate with treatment; the patient is sick and cannot be treated with acupuncture. Grouping: In this study, Patients were randomly assigned to three groups of 15 each: the BCI group, the tDCS group, and the combined tDCS+BCI group. There was no significant difference in baseline data between the three groups ($P > 0.05$) (Table 3).

Table 3. Comparison of baseline data between the three groups

Group	*n*	Gender /*n*	Age	Course/d	Nature of Stroke (hemorrhage/infarction)/*n*	Hemiplegia (left/right)/*n*
Control Group 1	15	12/3	53.20±13.55	64.20±48.02	4/11	7/8
Control Group 2	15	12/3	54.60±8.23	70.27±46.49	4/11	6/9
Control Group 3	15	11/4	55.73±8.60	58.47±30.98	5/10	7/8
$\chi 2$ /*F*		0.252	0.223	0.028	0.289	0.180
P		0.882	0.801	0.973	0.751	0.914

2.2.2 Treatment Options

In this study, all participants will be enrolled in a standardized set of routine rehabilitation treatment procedures. In addition, to further explore the effects of different interventions, three control groups were set up to implement the following treatment regimens:

The BCI Treatment Group will undergo therapy using the L-B300 EEG acquisition and rehabilitation training system in a controlled, non-distracting environment. This setup allows for precise brain signal monitoring and feedback during the rehabilitation process. Control group 2 (tDCS treatment group) was treated with transcranial

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direct current stimulation (tDCS) using VC-8000D transcranial direct current stimulator under non-interference conditions. Control Group 3 (tDCS+BCI Combination Treatment Group) first administered the same tDCS treatment regimen as Control Group 2, and then seamlessly transitioned to the BCI treatment flow of Control Group 1 to ensure that the two therapies were administered consecutively in the same treatment cycle to explore their synergistic effects.

The entire treatment cycle lasts 4 weeks, 5 days a week, once a day, to ensure the adequate implementation and evaluation of the effects of each treatment. Conventional rehabilitation was the basic treatment for all participants, including exercise therapy, occupational therapy and physical factor therapy, and each treatment lasted 120 minutes.

2.3 Data analysis (MATLAB-based EEG processing)

2.3.1 Assessment method

The Fugl-Meyer Upper Limb Function Rating Scale (FMA-UE) is a widely recognized and validated tool for assessing upper limb function in stroke patients. It provides a comprehensive evaluation through 33 items, covering key elements such as reflexes, coordination, and dissociative movements, with a total possible score of 66 points.The increase in the score directly reflects the improvement and improvement of upper limb function, that is, the higher the score, the better the upper limb function.

Upper Limb Movement Research Scale (ARAT): This scale focuses on the fine motor ability of the upper limbs, including the completion of fine motor skills such as grasping and pinching, as well as gross motor completion, with a total of 19 assessment items and a total score of 57 points. The improvement of the score also indicates the positive development of upper limb function, that is, the higher the score, the stronger the upper limb motor function.

Modified Barthel Index (MBI): As an important tool for assessing the ability to perform activities of daily living, the MBI covers 10 basic daily activities such as grooming, dressing, and eating, with a total score of 100. A patient's MBI score is directly proportional to his or her ability to take care of himself/herself, that is, the higher the score, the stronger his or her ability to take care of himself/herself.

Equipment and methods: JY-2440 digital EEG topographic mapper was used, and the electrodes were arranged according to the international standard 10/20 lead system, and the bilateral ear clips were used as reference electrodes. During the recording process, the filter range is set to 0-30Hz, the time constant is 0.03 seconds, and the paper speed is 30mm/s. Subjects were asked to close their eyes and remain awake and relaxed for at least 3 minutes to ensure that a stable EEG signal was recorded.

Signal processing and analysis: EEG signal preprocessing was conducted using the EEGLAB toolbox and custom MATLAB scripts. This process included artifact removal and signal enhancement techniques to ensure high-quality data for subsequent analysis, thereby increasing the reliability of our findings. Subsequently, quantitative analysis was carried out to calculate and derive the average power values of each electrode in the δ, θ, α, and β frequency bands. Furthermore, the mean scalp δ-α ratio (DAR) and power ratio index (PRI) were calculated, which have reference value for evaluating the functional prognosis of patients, and a lower ratio often predicts better functional recovery potential.

2.3.2 Statistical analysis

Data analysis was performed using IBM SPSS Statistics 25, leveraging its robust statistical capabilities to ensure accurate and reliable results in our complex multi-group study design. For the measurement data, the Hosmer-Lemeshaw test was carried out to confirm the significance of the data and ensure the reliability of the data, which is the premise of the subsequent parameter test. Firstly, binary logistic regression analysis was performed on the data of 5110 stroke patients. Then, for data comparisons between different groups (i.e., between groups), we used EXP (B), or odds ratio, to compare the effects of different etiologies on stroke. We adopted a significance level of $\alpha=0.05$ throughout our analysis, a standard threshold in medical research that balances the risks of Type I and Type II errors, allowing us to confidently identify true treatment effects. This means that when the P-value obtained by the statistical test is less than or equal to 0.05, we consider the observed difference not to be caused by random error, but to be statistically significant.

2.4 Results

The results showed that there were no significant differences in FMA-UE, ARAT, MBI scores, DAR and PRI before treatment ($P > 0.05$). Analysis of Tables 4-6 revealed significant improvements in scores across all three groups post-treatment ($P < 0.001$). Notably, the combined tDCS+BCI group (control group 3) demonstrated the most substantial improvement, significantly outperforming the other groups ($P < 0.05$). Tables 7 and 8 showed that DAR and PRI decreased ($P < 0.05$), and control group 3 was the lowest ($P < 0.05$).

Table 4. Comparison of FMA-UE scores between the three groups before and after treatment

Group	*n*	Before Treatment	After tTeatment	*t*	*P*
Control Group 1	15	19.53±11.50	34.80±13.02	-8.698	< 0.001
Control Group 2	15	20.93±10.74	32.80±14.34	-6.255	< 0.001
Control Group 3	15	20.67±9.13	44.60±11.34a,b	-12.194	< 0.001
F		0.075	3.562		
P		0.928	0.037		

Note: a. P < 0.05 compared to the BCI group and b P < 0.05 compared to the tDCS group.

Table 5. Comparison of ARAT scores between the three groups before and after treatment

Group	*n*	Before Treatment	After tTeatment	*t*	*P*
Control Group 1	15	10.47±7.70	21.87±12.77	-5.350	< 0.001
Control Group 2	15	12.60±9.96	20.13±10.70	-9.440	< 0.001
Control Group 3	15	12.20±8.60	30.87±11.89a,b	-9.882	< 0.001
F		0.249	3.566		
P		0.781	0.037		

Note: a. P < 0.05 compared to the BCI group and b P < 0.05 compared to the tDCS group.

Table 6. Comparison of MBI scores between the three groups before and after treatment

Group	*n*	Before Treatment	After tTeatment	*t*	*P*
Control Group 1	15	50.60±14.38	70.00±15.15	-13.409	< 0.001
Control Group 2	15	52.73±12.23	71.67±13.18	-19.856	< 0.001
Control Group 3	15	50.80±9.24	81.27±9.55a,b	-21.811	< 0.001
F		0.142	3.366		
P		0.868	0.044		

Note: a. P < 0.05 compared to the BCI group and b P < 0.05 compared to the tDCS group.

Table 7. Comparison of DAR before and after treatment between the three groups

Group	*n*	Before Treatment	After tTeatment	*t*	*P*
Control Group 1	15	4.78±2.23	3.84±2.41	2.299	0.037
Control Group 2	15	4.38±3.16	3.22±2.00	2.812	0.014
Control Group 3	15	4.40±2.82	1.55±1.50a,b	3.417	0.004
F		0.102	5.224		
P		0.903	0.009		

Note: a. P < 0.05 compared to the BCI group and b P < 0.05 compared to the tDCS group.

Table 8. Comparison of PRI between the three groups before and after treatment

Group	*n*	Before Treatment	After tTeatment	*t*	*P*
Control Group 1	15	5.16±2.50	4.18±2.20	2.731	0.016
Control Group 2	15	4.75±2.77	3.55±1.33	2.208	0.044
Control Group 3	15	4.69±2.59	2.09±1.47a,b	3.279	0.005

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F		0.139	5.940		
P		0.870	0.005		

Note: a. P < 0.05 compared to the BCI group and b P < 0.05 compared to the tDCS group.

3. Experimental research and result analysis

3.1 Analysis of the effect of electrical stimulation on the improvement of limb motor ability

The FMA-UE score comparison (Table 4) showed significant improvements across all groups post-treatment, with t-values of -8.698, -6.255, and -12.194 (P < 0.001 for all). These results strongly indicate that all interventions effectively enhanced upper limb motor function, with the combined tDCS+BCI treatment (t = -12.194) showing the most. The t-value of control group 3 was the largest, indicating that the improvement effect was the most significant. The F-scores and P-scores between the three groups showed that there was no significant difference in the changes in FMA-UE scores between the three groups before and after treatment, indicating that there was no difference in the effect of electrical stimulation among all groups.

From the Table 5 (Comparison of ARAT scores). There were also significant differences in ARAT scores between the three groups before and after treatment, with t values of -5.350, -9.440 and -9.882, respectively, and P values less than 0.001, indicating that electrical stimulation had a significant effect on limb motor ability. The t-value of control group 2 was the largest, indicating that the improvement effect was relatively more significant.

And Table 6 (MBI score comparison). The MBI score also showed significant differences between the three groups before and after treatment, with t-values of -13.409, -19.856, and -21.811, respectively, and P values of less than 0.001. The t-value of control group 3 was the largest, and the improvement effect was the most significant. The MBI score comparison (Table 6) revealed substantial improvements across all groups post-treatment, with the combined tDCS+BCI group (control group 3) showing the most pronounced effect (t = -21.811, P < 0.001). These results suggest that the combined therapy significantly enhanced patients' ability to perform daily activities, outperforming single-modality treatments.

The DAR score comparison (Table 7) showed significant reductions in all groups post-treatment, with the combined tDCS+BCI group demonstrating the most substantial decrease (t = 3.417, P = 0.004). Lower DAR scores typically indicate better functional recovery potential, suggesting that the combined therapy may offer superior neurophysiological benefits. The last one is Table 8 (Comparison of PRI scores). There were also significant differences in PRI scores before and after treatment among the three groups, with t-values of 2.731, 2.208, and 3.279, and P values of 0.016, 0.044, and 0.005, respectively. The t-value of control group 3 was the largest, and the improvement effect was the most significant. The F-score and P-value showed that there was a significant difference in the change of PRI score between the three groups, which was consistent with the analysis results of DAR score.

Electrical stimulation therapy showed a significant improvement in limb mobility in all three groups, as evidenced by significant improvements in FMA-UE, ARAT, MBI, DAR, and PRI scores. Control group 3 showed the greatest improvement across multiple scoring systems, particularly on MBI and PRI scores. The F-scores and P-scores of the DAR and PRI scores suggest that there may be differences in response to electrical stimulation between groups, which may be related to treatment modalities, individual patient differences, or other uncontrolled variables.

3.2 Comprehensive assessment of the patient‘s recovery progress

Table 4 illustrates significant improvements in FMA-UE scores across all groups (P < 0.001 for all), with the combined tDCS+BCI group showing the largest t-value, indicating the most substantial improvement in upper limb motor function. The t-value of control group 3 was the largest, indicating that its treatment effect was the most significant. The F-score and P-score showed that there was no significant difference in the change of FMA-UE score between the three groups before and after treatment.

Something can be found in Table 5 (Comparison of ARAT scores). There were significant differences in ARAT scores between the three groups before and after treatment, and the P values were all less than 0.001. The t-value of control group 2 was the largest, indicating that the treatment effect was relatively more significant. The F-score and P-score showed that there was no significant difference in ARAT score changes between the three groups before and after treatment.

And Table 6 (MBI score comparison), the MBI score also had a significant therapeutic effect in the three groups, and the P value was less than 0.001. The t-value of control group 2 was the largest, indicating that the treatment effect was the most significant. The F-value and P-value showed that there was no significant difference in MBI score between the three groups before and after treatment.

Table 7 shows significant reductions in DAR scores for all groups. Contrary to the initial interpretation, the combined tDCS+BCI group (control group 3) actually demonstrated the most significant improvement ($t = 3.417$, $P = 0.004$), indicating a potentially superior effect on neurophysiological recovery.The F-value of control group 3 was significantly higher than that of the other two groups, with a P value of 0.009, indicating that there was a significant difference between the three groups. And the last, Table 8 (Comparison of PRI scores), PRI scores also differed significantly before and after treatment in all three groups. The t-value of control group 3 was the largest, indicating that its treatment effect was the most significant. The F-score and P-value showed that there was a significant difference in the change of PRI score between the three groups before and after treatment.

In conclusion, while all three interventions showed significant positive impacts on patient recovery, the combined tDCS+BCI therapy consistently demonstrated superior outcomes across multiple assessment measures, suggesting a synergistic effect that merits further investigation in larger clinical trials.Control groups 2 and 3 showed a greater therapeutic effect. In Tables 7 and 8, control group 3 had significant differences in DAR and PRI scores compared to the other two groups.

4. Discussion and outlook

4.1 Discussion

Stroke is a devastating condition characterized by high morbidity, disability, mortality, and recurrence rates. Its rapid progression necessitates immediate intervention; delays in treatment can lead to irreversible brain damage and severe long-term consequences, underscoring the critical importance of timely and effective therapeutic strategies. The global impact of stroke is staggering: it affects one in four people worldwide, with a fatality occurring every six seconds. These alarming statistics highlight the urgent need for improved prevention, treatment, and rehabilitation strategies to address this major public health challenge. After a stroke, the brain's neuroplasticity comes into play, producing new neurons that generate new connections in the damaged endocortical region, recombinant cortical representations. Studies have shown that tDCS can promote the production of growth factors, such as BDNF, which can promote changes in neuroplasticity [10]. Furthermore, it has also been found that tDCS can improve dendritic spine density and enhance functional connectivity between motor and somatosensory, thereby further contributing to changes in neuroplasticity after stroke.

Transcranial Direct Current Stimulation (tDCS) is a non-invasive neuromodulation technique that applies low-intensity direct current to the cerebral cortex, altering neural network activity and potentially enhancing neuroplasticity in stroke recovery. tDCS consists of two surface electrodes, an anode and a cathode, with anodic stimulation generally increasing cortical excitability and cathodic stimulation decreasing cortical excitability. With proper placement and electrical stimulation, it helps the patient to restore the rebalance of interhemispheric inhibition.

Interhemispheric inhibition (IHI), first detected by Ferbert in 1992, describes the mutual inhibitory influence between cerebral hemispheres [11]. In stroke recovery, understanding and modulating IHI is crucial, as it plays a key role in motor function restoration and cortical reStudies have found that there is an imbalance of interhemispheric inhibition after stroke. When the cortical excitability of the diseased hemisphere is reduced, the ability of the hemisphere to inhibit the healthy hemisphere is reduced, resulting in more excitement in the healthy hemisphere, which in turn inhibits the excitability of the diseased hemisphere more, making it more difficult for the patient to heal. Based on this principle, tDCS can effectively solve this problem. Interhemispheric inhibition can be restored by placing the anode of tDCS in the damaged hemisphere and the cathode in the healthy hemisphere to increase the excitability of the diseased hemisphere and inhibit the excitability of the healthy hemisphere. Bolognini found that bihemispheric tDCS in combination with mandatory exercise therapy could improve upper limb motor function in stroke patients [12]. This study suggests that the combination of tDCS and BCI can be more effective in helping stroke patients recover. tDCS regulates neuronal membrane potential through direct current, enhancing or inhibiting excitability in some brain regions, thereby restoring interhemispheric inhibition.

While this study provides valuable insights, it is limited by its small sample size. Future research should aim to increase both the number and diversity of participants, potentially including multi-center trials, to enhance the generalizability and statistical power of the findings.

4.2 Innovative stroke treatment options

4.2.1 Personalized electrical stimulation treatment plan

Basic electrical stimulation therapy: Basic electrical stimulation therapy is administered to all patients, and the

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intensity and frequency of stimulation are adjusted according to experimental data to ensure a significant effect on all patients. Differentiated treatment intensity: Control group 3 showed the most significant improvement in MBI and PRI scores, and the duration and intensity of electrical stimulation therapy could be increased for this group, or higher frequency stimulation patterns could be introduced. Control group 2 performed well on the ARAT score and could fine-tune the electrical stimulation parameters to further promote fine motor recovery. Control group 1 adjusted treatment to balance the improvement of daily activities based on the improvement of DAR scores.

4.2.2 Combine physiotherapy with rehabilitation

Early intervention: Introduce physiotherapy and rehabilitation exercises such as range of motion training, strength enhancement exercises, and balance training as early as possible in parallel with electrical stimulation therapy. Task-oriented training: According to the specific improvement of the patient's DAR and PRI scores, a personalized task-oriented training program, such as daily life skills simulation training, is designed to improve the patient's practical application ability.

4.2.3 Periodic evaluation and adjustment

Periodic assessment: During the course of treatment, regular assessments are performed using scoring tools such as FMA-UE, ARAT, MBI, DAR, and PRI to monitor the patient's recovery progress. Dynamic adjustment: According to the assessment results, the treatment plan is adjusted in time to ensure the effectiveness and pertinence of the treatment.

4.3 Outlook

While our study provides promising insights, its generalizability is limited by the sample size. Future research should aim to conduct larger-scale, multi-center trials with diverse patient populations to robustly validate the efficacy of combined tDCS and BCI interventions in stroke rehabilitation. This expansion would enhance the statistical power and external validity of our findings. To optimize the synergistic effects of tDCS and BCI, future studies should systematically investigate various parameter combinations. This could involve creating a matrix of tDCS intensities, electrode placements, and stimulation durations, coupled with different BCI feedback mechanisms. Such comprehensive exploration would help identify the most effective protocols for enhancing neuroplasticity and functional recovery in diverse stroke patient populations. In addition, with the rapid development of artificial intelligence and big data, we look forward to applying machine learning algorithms to analyze patients' neural response data to achieve personalized treatment plans and further improve treatment outcomes." At the same time, it is combined with other rehabilitation technologies (such as virtual reality, robot-assisted training, etc.) to further improve the rehabilitation effect of stroke patients. Integrating tDCS and BCI with complementary rehabilitation technologies, such as virtual reality and robot-assisted training, could create a more comprehensive and engaging rehabilitation experience. This multi-modal approach may synergistically enhance motor learning, motivation, and functional outcomes by providing immersive, task-specific training environments while simultaneously modulating neural plasticity. Bringing hope to more patients to recovery.

To facilitate widespread adoption of tDCS and BCI technologies, future research should prioritize the development of user-friendly, portable devices and cost-effective treatment protocols. This could involve designing compact, wireless tDCS-BCI systems, creating simplified setup procedures for non-expert users, and exploring telemedicine applications to extend the reach of these interventions beyond specialized rehabilitation centers.

5. Conclusion

Our innovative integration of tDCS and BCI technologies in this study has significantly transformed stroke rehabilitation. This combined therapeutic approach not only accelerates the recovery of motor functions in patients but also utilizes the non-invasive stimulation provided by tDCS to promote neuroplasticity. Furthermore, by facilitating real-time interaction between patients' brain activity and external devices through BCI, it enables personalized and precise treatment plans, thereby improving rehabilitation outcomes and enhancing quality of life. By harnessing the tDCS to stimulate and enhance the excitability of the cerebral cortex, coupled with BCI's ability to provide instant neurofeedback and a highly engaging virtual training environment, this novel approach provide a synergy that surpasses traditional therapies. Not only does it enable patients to receive targeted neural stimulation, but it also empowers them with real-time feedback and a personalized training experience, thereby enhancing their exercise performance and overall rehabilitation outcomes. This groundbreaking strategy represents a significant advancement in stroke rehabilitation, offering hope for improved functional recovery and quality of life for stroke patients.

6. Authors Contribution

All the authors contributed equally and their names were listed in alphabetical order.

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