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ARTICLE

Analysis of electroencephalography characteristics during walking in stroke patients under different conditions: a cross-sectional study

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Abstract

Aims/Background Backward walking is gaining traction in rehabilitation therapy, showing promise as an intervention for stroke patients with walking difficulties. However, the brain activity patterns (neurophysiological mechanisms) underlying backward walking in these patients remain unclear. This study investigated the neurophysiological mechanism in stroke patients within 1 year of their stroke.

Methods Twenty-four subjects walked forward and backward for 5 min on an 8-m track while their electroencephalographic signals were collected. The power values of each frequency band were compared during forward and backward walking, and the delta to alpha power ratio (DAR) was calculated.

Results The results showed a significant increase in α-band activity within the frontal cortex during backward walking ($p < 0.05$). This increase correlated positively with scores on the Fugl-Meyer lower extremity motor function assessment scale. Similarly, α-band activity showed significant enhancement within the right parietal cortex during backward walking ($p < 0.05$). There were no significant differences between forward and backward walking states in δ, θ, and β wavebands across the entire brain region ($p > 0.05$). Additionally, the DAR was significantly lower during backward walking than during forward walking ($p < 0.05$).

Conclusion This study suggests that backward walking may more effectively activate neural activity in the prefrontal and right posterior parietal cortices. This finding supports the potential of backward walking to enhance motor execution and walking function in stroke patients, thereby supporting its application as a rehabilitation method.

Key words: Backward walking; Electroencephalogram; Power spectral density; Stroke

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Introduction

Walking ability is essential for maintaining a good quality of life after a stroke. However, stroke patients often experience walking difficulties due to various neurological impairments which include reduced muscle strength in the affected limbs, diminished balance, impaired proprioception, and abnormal gait patterns, leading to walking dysfunction (Hyun et al, 2021). In one study, researchers conducted a 1-month programme of backward walking and balance training for patients with acute stroke. Their results showed that patients who participated in backward walking training experienced improvements in both forward and backward walking speed, as well as better balance, suggesting that backward walking training could be valuable to stroke rehabilitation programmes (Rose et al, 2018). Another study by Chang et al (2021) observed significant improvements in walking speed, balance, and cardiopulmonary function in patients with chronic stroke after a 4-week programme of backward walking. Their findings further support the potential clinical benefits of backward walking for stroke patients, particularly in improving walking ability and standing balance. However, despite the promising results of these studies, we still need an understanding of the neurophysiological mechanisms underlying how backward walking benefits stroke patients.

Previous research indicates that forward and backward walking share some of the same neural circuits, particularly central pattern generators (CPGs) in the spinal cord, which can also connect with higher brain centres to control movement (Hoogkamer et al, 2014). The

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extent to which these neural circuits are shared depends on how similar the muscle activity patterns and limb movements are between the two walking directions (Choi and Bastian, 2007). Grasso et al (1998) found that, even though forward and backward walking involves different timing and coordination of lower-limb muscle activity, the overall movement patterns of the lower limbs are quite similar. This suggests that the brain can reorganise the activity of synergistic muscles to achieve a reversed gait pattern of backward walking while still maintaining similar overall movement. This could be because both walking directions involve a central network system for motor control.

Electroencephalography (EEG) is a widely used tool for monitoring brain activity due to its ease of use, affordability, and non-invasive nature. It measures electrical signals with the high temporal resolution, providing insights into underlying neuronal processes, and is commonly used in predicting, diagnosing, and evaluating rehabilitation progress for various neurological disorders (Qin et al, 2020; Saes et al, 2021). The α-band, a specific frequency range, is closely related to brain activity. Changes in the α-band can reflect the brain's response and performance when engaged in different tasks. In this study, an increase in α-band activity was interpreted as enhanced neuronal activity (Liu et al, 2023). Finnigan et al (2016) compared various EEG indicators between healthy individuals and stroke patients and found that the delta to alpha power ratio (DAR) was the most accurate indicator for distinguishing stroke patients from healthy individuals. This suggests that the DAR is a key index for assessing the effectiveness of treatment in stroke and other neurological disorders. Therefore, monitoring brain activity through EEG is a valuable method to explore the neurophysiological mechanisms underlying the benefits of backward walking in stroke patients. To provide a theoretical basis for using backward walking as a rehabilitation method for stroke patients, this study investigated the differences in brain activity (cortical neuronal activity) between forward and backward walking in stroke patients.

Methods

Participants

Twenty-four patients with stroke (15 males and 9 females) aged between 40 and 70 years were included, of which 18 patients had cerebral infarction and 6 had cerebral haemorrhage. Patients with a definitive diagnosis of stroke with residual motor dysfunction and disease onset within 1 year of stabilisation were enrolled. Patients had no cognitive impairment and could communicate normally with investigators. Patients scoring at least 3 on the Holden Walking Function Classification and walking independently under supervision were eligible. Patients with a history of other diseases, such as brain tumour and brain trauma, were excluded. Patients who underwent craniotomy decompression surgery for haemorrhagic stroke; patients with severe bone, joint, and muscle diseases; patients with life-threatening diseases and mental illnesses; patients currently participating in other clinical trials; patients with missing data; and patients unwilling to cooperate were also excluded. Written informed consent was obtained from all patients. The study was approved by the Ethics Committee of Shanghai Zhongye Hospital [(2023) LS0054], and was conducted in strict accordance with the ethical principles outlined in the Declaration of Helsinki.

Electroencephalography signal collection

The EEG activity was recorded using an EEG-1200C electroencephalograph (Nihon Kohden, Tokyo, Japan) and a 64-channel EEG cap (Brain Link, Wuhan, China). The international 10–20 system for electrode placement was used to collect EEG signals from patients walking forward and backward. The horizontal electrooculogram (EOG), vertical EOG, and reference electrodes were removed, as shown in Figure 1. Patients walked forward at a natural pace for 5 min on an 8-m walkway, which included turning around, followed by a 2-min rest, and then walked backward under the same conditions for 5 min, which also included turning around. During EEG signal collection, markers were placed when the patients reached 1 and 7 m to indicate the turning times, as shown in Figure 2. These markers allowed us to exclude data from the turning times during the data trimming. Next, each patient’s data were preprocessed Matrix Laboratory 2023a (MathWorks, Natick,

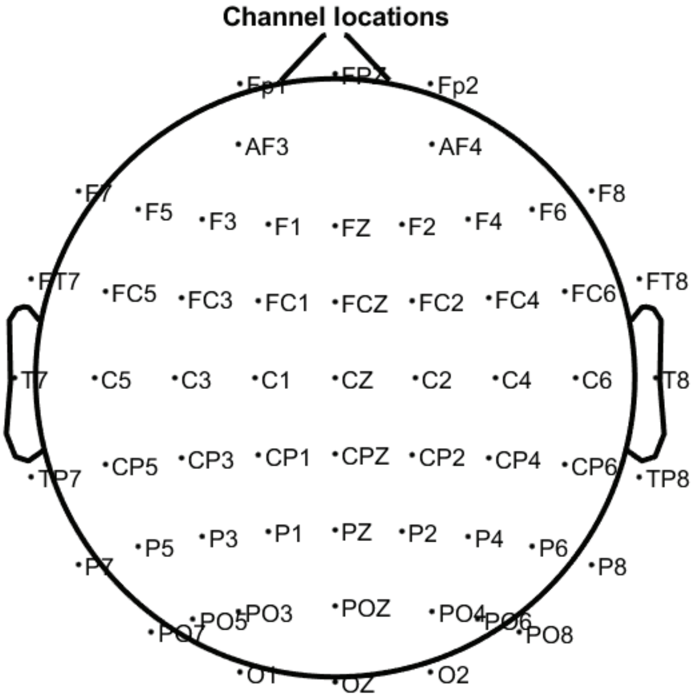

Figure 1. Layout of 60 electrodes.

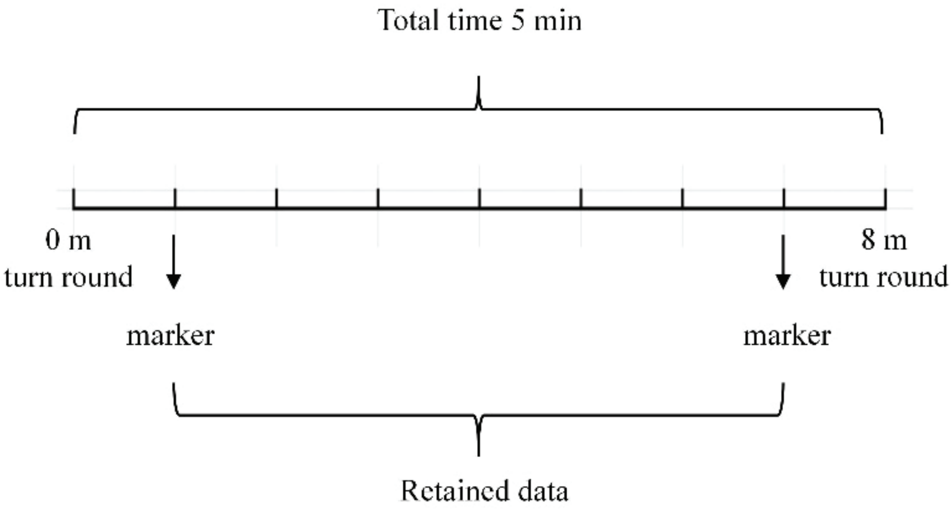

Figure 2. Walking patterns and signal acquisition.

MA, USA) using the EEGlab toolbox (University of California, San Diego, CA, USA). The power spectral density was calculated using the study module and compared between forward and backward walking after false discovery rate (FDR) correction. During the preprocessing stage, the EEG signals were subjected to bandpass filtering between 1 and 40 Hz. Additionally, an average reference was applied across the entire brain, utilising a sampling rate of 250 Hz. The power values in the α-band (8–12 Hz) were calculated for each electrode, and those in the δ-band (1–3 Hz) were extracted to compute the DAR. Concurrently, the alpha power values from the electrodes FC1, FC2, FC3, FC4, C1, C2, C3, C4, CP1, CP2, CP3, and CP4, corresponding to the motor-sensory cortex, were extracted for comparative analysis.

Delta to alpha power ratio assessment

In stroke rehabilitation, the DAR is important for evaluating a patient's progress. Lower DAR values indicate better outcomes after a stroke (Saes et al, 2020). The DAR is calculated for each electrode channel (labelled ‘c’) and represents the ratio between the average activity in the δ-band and the average activity in the α-band of the EEG signal. This is defined by the equation below:

$$\text{DARc} = \frac{< P_c(f) > \delta}{< P_c(f) > \alpha}$$

(1) Calculation formula for the delta to alpha power ratio channel (DARc).

In this context, $< \text{Pc}(\text{f}) > \delta$ denotes the average power in the δ-band, whereas $< \text{Pc}(\text{f}) > \alpha$ represents the average power in the α-band for channel c. The global DAR for the relevant electrodes is defined by the equation below, where N denotes the total number of global electrodes involved in the study.

$$\text{DAR} = \frac{1}{N}\sum_{c=1}^{N} DAR_c$$

(2) Calculation formula for the delta to alpha power ratio (DAR).

Fugl-Meyer assessment of lower extremity motor function

Motor function is measured via the Fugl-Meyer assessment (FMA), which assesses the lower limbs through seven categories: reflex activity, flexor synergy, extensor synergy, activities with synergy, activities without synergy, coordination, and speed. Each movement receives a score from 0 to 2 based on the degree of completion, with a maximum total score of 34. Higher scores indicate better lower-limb function.

Statistical analysis

To compare brain activity between forward and backward walking, we used EEGlab (University of California, San Diego, CA, USA) to conduct paired *t*-tests in the patients’ EEG signals. Statistical results were adjusted using FDR correction. Electroencephalography power ratios were analysed using SPSS 25.0 (IBM SPSS Statistics, Chicago, IL, USA) software. The EEG data for both walking conditions followed a normal distribution. Pearson’s correlation coefficient was used to assess whether the EEG signals correlated with the FMA scores for the lower limbs. The p values less than 0.05 were considered statistically significant.

Sample size calculation

By calculating the power value of the frontal lobe Fz channel in the α-band, the mean power difference in different conditions was 1.22, with a standard deviation of 2.0. Using the paired comparison sample size estimation formula, the sample size was calculated as follows:

$$\text{N} = \frac{(Z_\alpha + Z_\beta)^2 \times \sigma^2}{\delta^2}$$

(3) Estimation formula for sample size.

The test study assumed $\sigma = 2.0$, $\delta = 1.22$, $\alpha = 0.05$ (two-sided), $1–\beta = 0.8$, and a power of 80%. Calculating the sample size for this test, we should have had at least 22 cases.

Results

Power spectrum analysis results

As shown in Figure 3, FC1, FC2, FC3, FC4, C1, C2, C3, C4, CP1, CP2, CP3, and CP4 channels were categorised into either the affected or the unaffected hemisphere. We compared the α-band values in the motor-sensory cortex and found a significant increase in the α-band value in the affected hemisphere during backward walking ($t = –2.718$, $p = 0.012$), while there was no significant difference in the α-band value in the unaffected hemisphere between forward walking and backward walking ($t = 0.03$, $p = 0.977$). As shown in Figure 4, after FDR correction of the δ-band, there were no significant differences in the electrode channels of the whole brain cortex between stroke patients walking forward and backward ($p > 0.05$). In the α-band, activation of the frontal cortex in stroke patients during

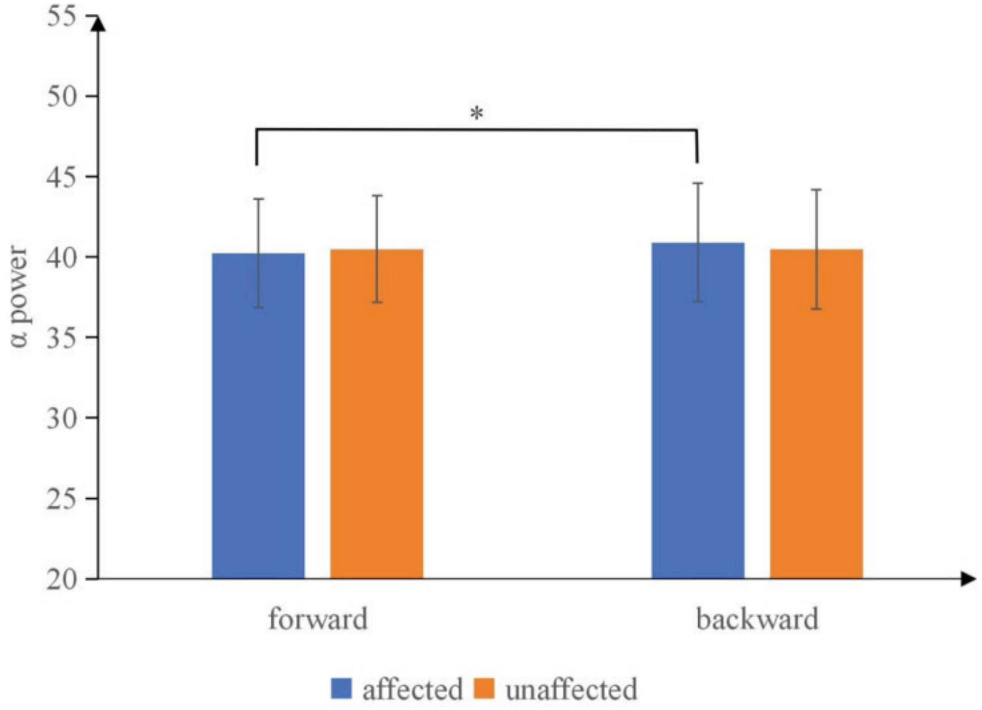

Figure 3. Comparison of cortical electroencephalography activity between the affected hemisphere and the unaffected hemisphere while walking forward and backward. * $p < 0.05$.

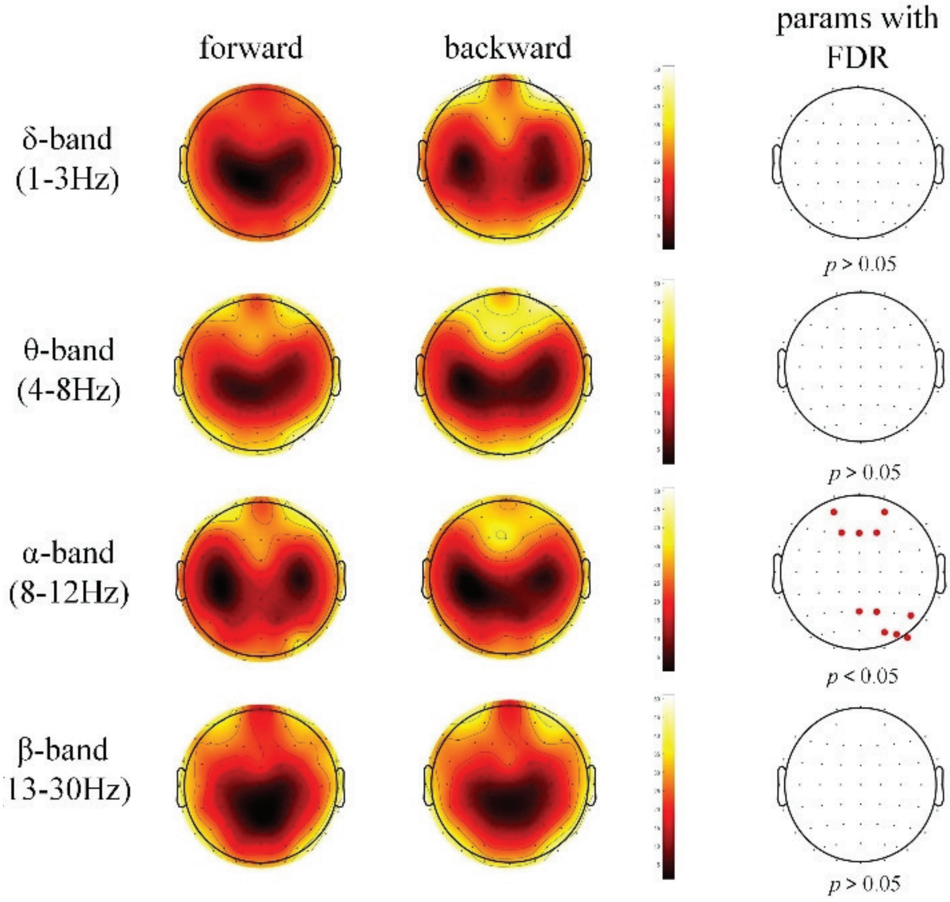

Figure 4. Whole-brain power spectrum analysis. FDR, false discovery rate.

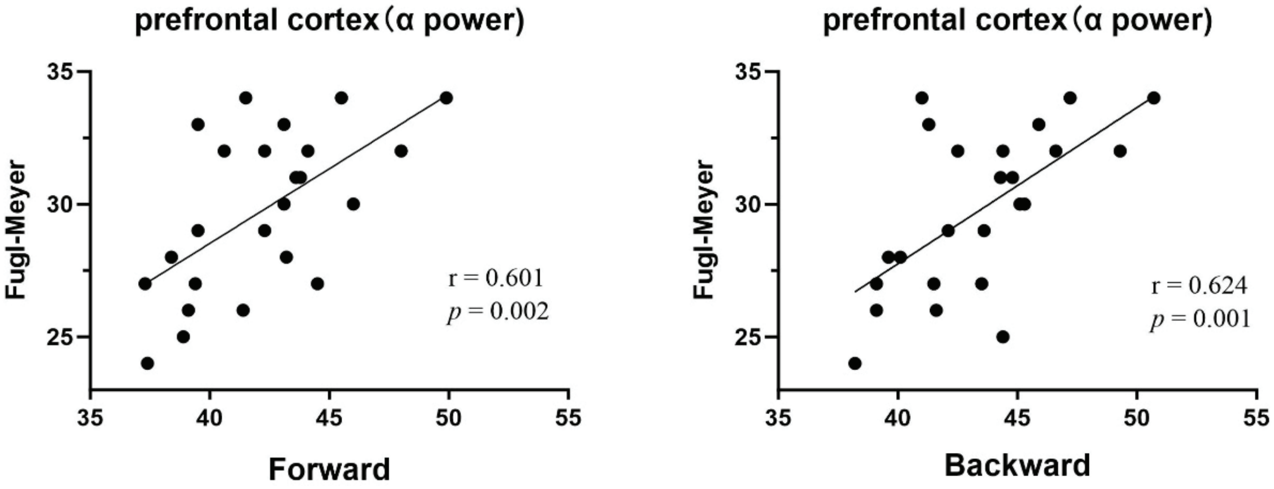

Figure 5. Correlation between prefrontal cortex and Fugl-Meyer assessment.

backward walking was more significant than that during forward walking ($p < 0.05$), and activation of the right parietal lobe during backward walking was more pronounced than that during forward walking ($p < 0.05$). In the θ-band, there were no significant differences in the electrode channels of the whole brain cortex between stroke patients walking forward and backward ($p > 0.05$). In the β-band, there were no significant differences in the electrode channels of the whole brain cortex between stroke patients walking forward and backward ($p > 0.05$).

Correlation between prefrontal cortex electroencephalography signals and Fugl-Meyer assessment

As shown in Figure 5, there was a positive correlation between the alpha power value and the FMA of the prefrontal cortex during forward walking. Similarly, there was a positive correlation between the alpha power value and the FMA of the prefrontal cortex during backward walking.

Delta to alpha power ratio analysis results

The DAR was calculated, as shown in Figure 6. During backward walking, there was a statistically significant decrease in the DAR in the frontal cortex ($t = 2.831$, r = 0.009; 95% confidence interval (CI): 0.001, 0.042). Similarly, a significant decrease in the DAR was observed in the parietal cortex in stroke patients ($t = 2.15$, r = 0.042; 95% CI: 0.009, 0.056). This suggests that backward walking can be a valuable tool for stroke rehabilitation, as it appears to activate specific brain regions associated with physical movement and spatial awareness.

Discussion

α-waves, a type of brain wave associated with calmness and wakefulness, are recognised as fundamental for the brain's sensory and cognitive processes (Başar, 2012). Lin et al (2020) compared the α-band characteristics of healthy adults before and after forward and backward walking and found that α-wave activity decreases during walking and that walking backward can induce motor-sensory cortex activity. In this study, no significant differences in sensorimotor cortex activation were found in stroke patients during forward and backward walking. However, after adjusting the electrode channels of the motor-sensory cortex of the patient's affected and unaffected hemispheres, it was found that the excitability of the motor-sensory cortex of the affected hemisphere increased significantly when walking backward, while the excitability of the unaffected hemisphere was not significantly suppressed. Some studies (Rose et al, 2018; Moon and Bae, 2022; Bansal et al,

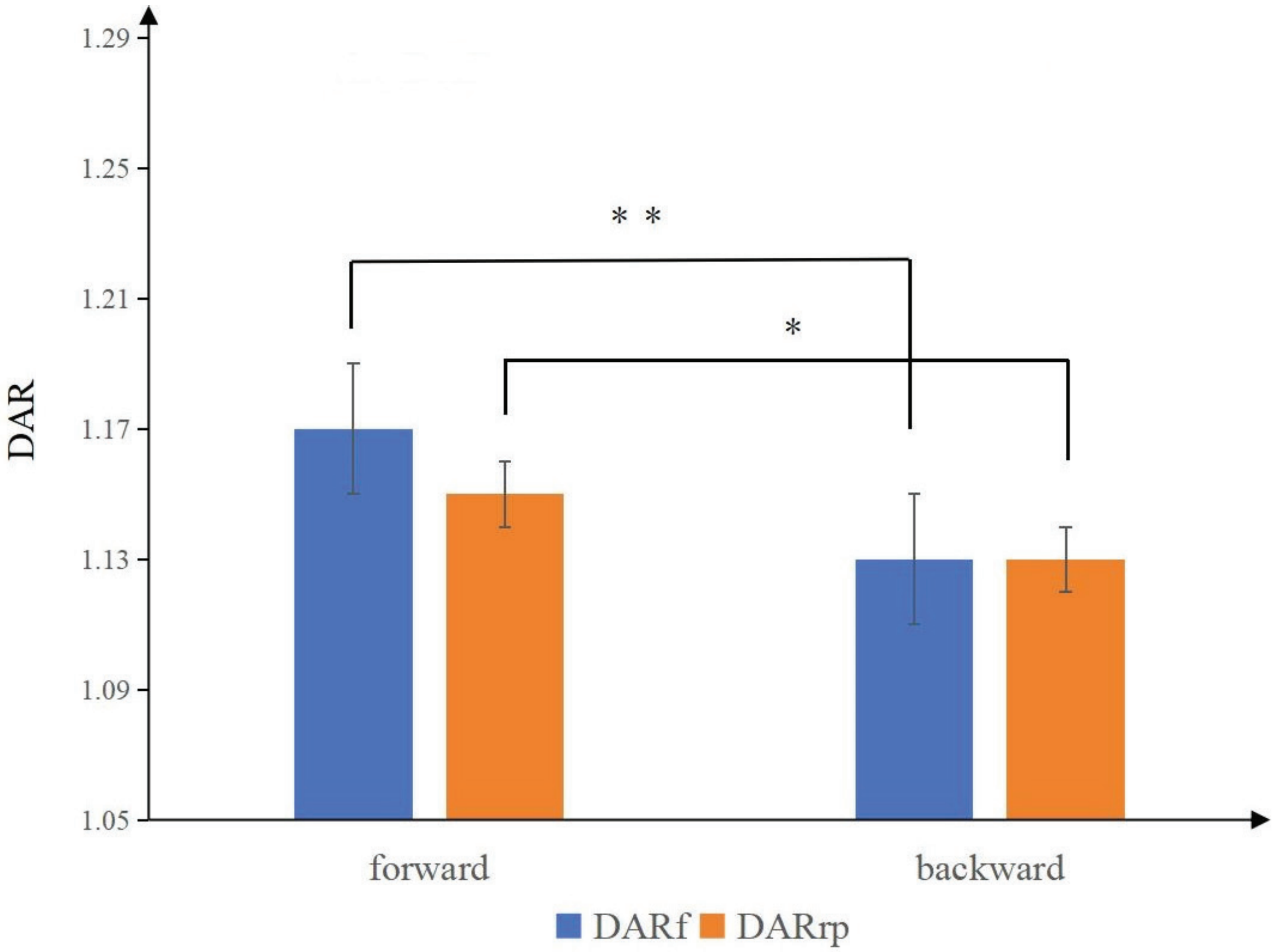

Figure 6. The DAR values of the patient walking forward and backward. DARf: delta to alpha power ratio of the prefrontal cortex; DARrp: delta to alpha power ratio of the right posterior parietal cortex. *$p < 0.05$; **$p < 0.01$.

2023) indicate that after backward walking training, walking speed and standing balance improve significantly in stroke patients, but this is related to the increased force generated by the healthy lower limb. They also showed that there was no significant difference in functional outcomes between forward and backward walking training, suggesting backward walking training may increase the compensatory role of the healthy limb in stroke patients, leading to improved walking ability and balance.

The exact mechanism by which backward walking affects stroke patients is still unclear. We propose that it may be related to deficits in brain function after a stroke. When the brain network of stroke patients is damaged, neural conduction is disrupted, which may prevent stroke patients from relying on the spinal cord's CPG for walking. The increased excitability in the affected hemisphere may be due to a higher compensatory effect by the affected limb. Furthermore, stroke patients may require more cortical involvement for walking due to brain function impairment, and this could lead to a greater demand on the frontal lobe, which is responsible for motor cognition and executive ability. These events may score higher than the direct instructions from the motor-sensory cortex. Additionally, activation of the right posterior parietal cortex, which plays a role in spatial awareness, may be crucial for stroke patients to maintain postural stability when walking.

Gait control is a complex brain function. It integrates cognitive (including motor, perceptual, memory, and attention functions) and executive functions. Good executive function helps older adults maintain dynamic balance while walking. Brain regions mainly responsible for executive functions are primarily situated in the frontal cortex, where they are closely associated with the dorsolateral prefrontal cortex (Radel et al, 2017). In stroke patients, executive function is impaired, leading to difficulties in walking and speaking.

Gait function is closely linked to complex cognitive function and is no longer considered a simple automatic movement independent of cognitive function (Hausdorff et al, 2005; Scherder et al, 2007). Nosaka et al (2022) observed increased oxygenated haemoglobin levels in the frontal cortex of individuals older than 70 years during dual-task walking, indicating more active neuronal activity in this region. Backward walking also activates the frontal cortex, implying it can be a cognitively demanding exercise for stroke patients.

The dorsolateral prefrontal cortex is important for the regulation of cognitive and motor executive abilities. A near-infrared study of postural control tasks found that dorsolateral prefrontal cortex (DLPFC) activation significantly increased in healthy individuals around the age of 70, while it did not during cognitive tasks (Marusic et al, 2019). This may explain why dorsolateral prefrontal cortex activation during backward walking was more pronounced than during forward walking in stroke patients. Backward walking, an unconventional movement, requires higher postural stability and cognitive demands. The authors believe that the increase in prefrontal cortex activation may be a compensatory mechanism during walking in stroke patients, as the prefrontal cortex is crucial for selectively allocating attention and integrating visual and proprioceptive information to maintain or restore postural stability. Our study found a positive correlation between the α-band power values of the dorsolateral prefrontal cortex and the Fugl-Meyer motor function scores of the lower limbs, regardless of whether patients walked forward or backward. These results suggest that backward walking may be a beneficial exercise for stroke patients, as it activates the dorsolateral prefrontal cortex, thus improving the motor executive abilities of stroke patients.

Wang (2021) posited that long-term motor domain training can induce changes in resting-state functional connectivity of brain regions associated with cognitive control, including the prefrontal-parietal and motor networks, which means that the impact of sports training on connectivity depends on the proficiency of motor skills. The increase in brain activation may reflect the integration of new motor skills during the learning phase. The human parietal cortex, referred to as an ‘association’ area, combines inputs from multiple brain regions, including the somatosensory, auditory, visual, motor, cingulate, and frontal cortices, as well as proprioceptive and vestibular signals from subcortical areas (Whitlock, 2017). Duan and Zheng (2023) conducted sensory integration tests in stroke patients to assess the relative contributions and utilisation rates of proprioception, vestibular sense, and vision in maintaining standing balance. The results showed that vestibular contribution was the most significant factor in postural control, while proprioception was the most utilised, suggesting the reduced contributions and utilisation rates of the sensory system are key factors in postural control disorders in stroke patients. During backward walking, diminished visual support potentially stimulates the activation of the proprioceptive and vestibular systems, thereby enhancing spatial positioning sensation and improving postural stability. Bönstrup et al (2018) showed that the function of the frontal-parietal motor integration system, which is related to visual-guided movement, is upregulated after stroke, and this is of great significance for the recovery of motor function after stroke. It was also pointed out that motor neglect often occurred in lesions on the non-dominant side. Koch et al (2013) demonstrated functional asymmetry of the parietal cortex in guiding visual-spatial attention, with the right hemisphere being dominant, and suggested a competitive theory between the parietal cortices of the left and right hemispheres.

In summary, the results of this study align with previous investigations, suggesting that backward walking can enhance neuronal activity in the right parietal lobe, thereby improving the visual-spatial attention capabilities of stroke patients and the feedback of proprioceptive and vestibular systems. Stroke patients exhibit interhemispheric energy asymmetry, characterised by enhanced low-frequency signals and suppressed high-frequency signals (Saes et al, 2019). However, in this study, no significant differences in low-frequency delta power values were found between walking forward and backward. However, during backward walking, the DAR in the parietal and frontal cortices was significantly lower than that during forward walking. A higher DAR was indicative of a suppressive state of the brain cortex and a lower DAR was suggestive of an excited state. Therefore, backward walking can stimulate the dorsolateral prefrontal cortex and parietal cortex regions of the brain, which is beneficial for the recovery of walking ability and promotion of brain function reorganisation in stroke patients.

Conclusion

This study compared brain activity (measured by EEG) in stroke patients during forward and backward walking. These findings showed that backward walking increased neuronal activity in the frontal and right parietal cortices, suggesting backward walking could be a valuable tool for rehabilitation aimed at improving walking ability in stroke patients. However, the study did not find significant differences in activity within the motor-sensory cortex between forward and backward walking in stroke patients. This may be due to the sample size, and further research with more participants is needed for more conclusive results. Stroke can disrupt connections within the brain, leading to neurological problems. Therefore, this underscores the importance of analysing brain connectivity at rest in stroke patients performing backward walking.

Key points

- This article explores the differences in electroencephalogram (EEG) characteristics during walking under different conditions in stroke patients, particularly focusing on the brain activity patterns of forward and backward walking.
- The study found that during backward walking, there was a significant increase in α-band activity in the frontal and right parietal cortices, which positively correlated with lower extremity motor function scores.
- Additionally, the delta to alpha power ratio (DAR) was significantly lower during backward walking than during forward walking, indicating that backward walking can more effectively activate these brain regions.
- The results support the use of backward walking as an effective rehabilitation method to enhance motor execution and walking function in stroke patients.
- The study emphasizes the importance of EEG in monitoring and evaluating the rehabilitation progress of stroke patients.

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Availability of data and materials

All data included in this study are available upon request by contact with the corresponding author.

Author contributions

TL was responsible for data analysis and the writing of the paper. YTJ and WYF collected the data and processing. KZ was responsible for visualisation. KLL and ZKH provided help and advice on the EEG experiment. JH and SJM carried out the experimental design. All authors contributed to the important editorial changes in the manuscript. All authors read and approved the final manuscript. All authors have participated sufficiently in the work and agreed to be accountable for all aspects of the work.

Ethics approval and consent to participate

This study has been approved by the Ethics Committee of Shanghai Zhongye Hospital [(2023) LS0054]. Written informed consent was obtained from all patients.

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Conflict of interest

The authors declare no conflicts of interest.

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