Research on Blood Oxygen Activity in Cerebral Cortical Motor Function Areas With Adjustment Intention During Gait

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Research

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Abstract

BACKGROUND: The study of the neural mechanism of human gait control can provide a theoretical basis for the treatment of walking disorders or the improvement of rehabilitation strategies, and further promote the functional rehabilitation of patients with movement disorders. However, the performance and changes of cerebral cortex activity corresponding to gait adjustment intentions arestill not clear.

OBJECTIVE: The purpose of this study was to detect the blood oxygen activation characterization of the cerebral cortex motor function area when people have intention to adjust gait during walking.

METHODS: 30 young volunteers (21 ± 1 years old) perform normal walking (NW), speed increase (DI), speed reduction (DR), step increase (PI) and step reduction (PR), during which continuous monitoring of oxygenated hemoglobin (HbO), deoxygenated hemoglobin (HbR) and total oxyhemoglobin (HbT) information in the prefrontal cortex (PFC), premotor cortex (PMC), supplementary motor area (SMA) using near infrared brain functional imaging.

RESULTS: (1) With the intention to adjust gait, the HbO concentration in the SMA increased significantly (p=0.0029), while the HbT concentration in the Medial-PFC decreased significantly (p=0.0088). (2) In the HbO concentration, step reduction is more activated than the step increase in the Left-PMC (p=0.0130); step adjustment is more activated thanspeed adjustment in the Right-PMC (p=0.0067).In the HbR concentration, speed reduction is more activated than the speed increase in the Left-PFC(p=0.0103). In the HbT concentration, an increase in gait parameters is more activated than the decrease in gait parameters in the Left-PFC(p=0.0042).

CONCLUSIONS: (1) When the intention of gait adjustment occurs, the increase of HbO concentration in the SMA indicates the initial stage of gait adjustment will increase the motion cognitive needs of the brain.(2) The right brain area, especially the Right-PMC, is responsible for step adjustment. While the left brain area, especially the Left-PFC, meets the additional nerve needs of speed adjustment. The increase in gait parameters promotes more blood oxygen metabolism in the Left-PFC to meet the needs of enhanced nerve activity. The preliminary findings of this study can lay an important theoretical foundation for the realization of gait control based on fNIRS-BCI technology.

1. Introduction

Patients with stroke have severe motor dysfunction, especially a severe decline in walking ability of the lower limbs[1]. Moreover, the instability of gait puts them in a dangerous state that is easy to fall[2].The restoration of the walking ability of the elderly or patients with dysfunction plays an important role in the quality of life and reduces the socioeconomic burden.

There have been many studies on gait control and activation of brain regions. Different pace controls on a treadmill affect blood oxygen response in specific brain regions of a subject[3, 4].Previous studies have shown that the brainstem and cerebellum compensate for the neuromotor control system of stroke patients during walking[5], and the reduction in stride and increase in walking speed can improve the gait stability of the elderly while walking and reduce the risk of falls. Thisshows that daily walking training is beneficial to improve the walking ability of patients with dysfunction[6]. But detection of motion intention faces two problems, one is recognition accuracy, and the other is time latency. In the existing research, Niazi et al.[7]based onthe EEG to identify the lower limb movement intention of ankle dorsiflexion, and finally theaccuracy was 82.5% ± 7.8% based on motion-related cortical potential (MRCP) characteristics and optimized spatial filtering. Zhang et al.[8] extracted the sample entropy features in the EMG signal, effectively reducing the probability of error in detecting muscle activity, and significantly reducing the time latency in detecting motion intention by increasing the signal-to-noise ratio. Khan et al.[9]based onfNIRS to detect walking intentions and compared the recognition results of 6 different classifiers. Finally, the classification model established by SVM had the highest recognition accuracy of 86.7%. In practical applications, improving the accuracy of the system's recognition of motion intent as much as possible is essential. Therefore, we hope to observe the characteristics of the activation and representation of motor functional regions of the brain when walking to find features that are conducive to detecting motor intentions.

In previous studies, multiple motion patterns of people can be identified through devices such as acceleration sensors [10-12]. However, participants in such studies are required to be healthy and have independent exercise ability. However, for patients with motor dysfunction, the use of such devices cannot effectively obtain motion data, which is not conducive to detecting the change of gait movement intention of patients. In this article, the near-infrared device will be used to observe the activation of the relevant cerebral cortex when the subject's gait adjustment intention occurs, which is more conducive to identifying the movement state of patients with motor dysfunction in advance.Based on the advantages of fNIRS equipment's portability and low sensitivity to the environment[13], the real-time imaging technology of the brain during walking activities has been rapidly developed. Miyai et al.[14] detected medial primary sensorimotor cortices and supplementary motor areas (SMA) in young brain regions that were activated when walking on a treadmill at 1km/h. In addition, SMA and prefrontal cortices (PFC) are involved in the motor preparation and execution stages[15, 16], and control the pace during walking[17, 18].While premotor cortex(PMC)for healthy subjects and stroke patients plays an important role in bipedal walking[19], and can reflect upcoming changes in motion speed[20]. Suzuki et al.[21] have investigated the degree of activation of bilateral PFC and PMC related to the walking speed on a treadmill. The greater the velocity intensity, the more significant the activation of the brain region[4].Some studies have shown that the oxygenated hemoglobin content in the PFC brain region is significantly related to the step size[22, 23]. Therefore, we assume that gait adjustment during continuous walking is related to neuromodulation activities in brain regions such as PFC, PMC, and SMA. To verify the hypothesis, we used fNIRS equipment to detect changes in oxygenated hemoglobin(HbO), oxygenated

hemoglobin(HbR), and total hemoglobin(HbT) information in the brain regions of PFC, SMA, and PMC from normal walking tasks to gait adjustment tasks.

2. Materials And Methods

2.1. Subjects

Thirty young volunteers (21 ± 1 years old, male: female = 8: 7) from Soochow University participated in this walking experiment. All volunteers were right-handed, in good health, and had no history of mental illness or cerebrovascular disease. All of them participated in this walking experiment for the first time, and all volunteers signed informed consent before the experiment.

2.2. Experiment Procedure

The experiment mainly includes two types of gait adjustments, the first type is the step adjustment, and the other type is the speed adjustment. In order to avoid the influence of the sequence of experiments, 30 young volunteers were randomly divided into two groups. The first group performed the step adjustment experiment before performing the speed adjustment experiment. In the second group, the speed is adjusted first and then the step is adjusted. Among them, step adjustment includes two states: step increase and step reduction; speed adjustment includes two states: speed increase and speedreduction. That is, there are four gait adjustment modes. The walking experiment was performed in the corridor of a laboratory. The experimental environment is shown in Figure 1.a. The experimental walking distance was 21m. Each participant walked 10.5m in a natural state (step speed range: 0.8-1.2m / s, step size range: 50-65cm), adjusted the gait at 10.5m, and the remaining 10.5m finished in the adjusted state. This requires that the subject's adjustment range when the speed or step size changes are significantly different from the normal walking. The range of gait parameter changes is about half of the speed or step size in the natural state. All subjects performed 2-3 times of pre-walking experiments before the experiment. A marking line is set at 10.5m. When the participants start the walking task, walk to the middle marking line and end the walking task, the operator should use fNIRS software to mark a Mark respectively. Participants went from one end to the other to complete a state adjustment, which was defined as a task. After completing one walking task, participants were required to take a break and turn to prepare for the next walking task. The rest time after each turn was not less than 45s. The specific length of the rest period was controlled by the subjects themselves. Each participant has to perform four types of gait adjustment tasks: speed increase, speed reduction, step increase, and stepreduction. The experimental process is shown in Figure 1.c. When subjects adjusted the walking speed, the step size remained the same. Similarly, when the participants adjust the step size, the walking speed is unchanged, and each gait adjustment task is performed twice.

Different from previous experiments on treadmills, in order to achieve walking tasks in the natural environment, this experiment did not deliberately require specific walking speed and step size. The

experiment operator does not issue any instructions except the two commands "experiment start" and "experiment end" at the beginning and end of the experiment. The start, end, and rest time of the experiment are completely controlled by the subjects. All participants will perform pre-walking experiments 2-3 times before the actual experiment begins to grasp the corresponding start-stop and rest periods. In addition, we pay more attention to the changes in blood oxygen activation of the subjects before and after adjusting the gait. Therefore, the subjects are required to maintain their most natural walking state in the first stage of walking and must have a clear gait adjustment in the second stage.

2.3. NIRS imaging

The near-infrared brain imaging device used in this paper is a portable near-infrared brain imaging device (LIGHTNIRS)[24] of Shimadzu Corporation, Japan, as shown in Figure 1.b. The test wavelength is 780nm, 805nm, and 830nm, and the sampling frequency is 13.33Hz. During the experiment, the participants only need to walk naturally with the equipment on their backs.

LightNIRS has 8 detectors and 8 emitters. Two 2 × 4 areas are measured before and after the experiment. The first area is used to measure the PFC, and the second area is used to measure the SMA and PMC. Each brain area requires 4 detectors and 4 emitters, and a complete head holder is used to hold the detector and transmitter. The experiment is based on the 10-20 system[25] to locate the brain area. The specific hood layout is shown in Figure 2. Cz in the figure represents the vertical intersection of the anterior-posterior sagittal line and the left-right sagittal line of the human brain. Among them, the anterior-posterior sagittal line is the line connecting the nasal root and the posterior occipital bone, while the left-right sagittal line is the line connecting the left earlobe to the right earlobe. Channels 1-10 in the first area measure the blood oxygen content of the PFC, channels 11, 14, and 18 in the second area measure the left PMC, channels 13, 17, and 20 measure the right PMC, and 12, 15, 16, and 19 channels measure SMA. According to the Brodman brain area distribution, the distance between Cz and 19 channels is 30mm, and the distance between adjacent emitters and receivers is also 30mm. During the actual wearing of the headgear, due to the difference in the size of the skull of each subject, the area of each functional area of the brain differed. Therefore, it is necessary to use corresponding mathematical methods to reduce this difference in the subsequent data processing.

2.4. Data analysis

Walking tasks often cause motion artifacts and physical noise to be included in brain signals. At the same time, the continuous data monitoring process may cause zero drift [25]. In order to reduce these effects, combined filtering is used in this paper to remove related noise. According to the literature[26], different physiological information contained in oxyhemoglobin is distributed in different frequency bands, such as heart rate effect (0.6 ~ 2.0Hz), respiration effect (0.145 ~ 0.6Hz), and myogenic effect (0.052 ~ 0.145Hz), neurological effect (0.021 ~ 0.052Hz), endothelial cell metabolism activity (0.0095 ~ 0.021Hz) and endothelial cell activity (0.005 ~ 0.0095Hz). The neural activity of the human brain

dominates gait adjustment intention during walking,so it is hoped that the corresponding frequency band range that reflects nerve activity in the hemoglobin information of the brain is extracted, that is, the frequency band less than 0.145Hz[27, 28].AChebyshev low-pass filter[29] with a second-order and a maximum ripple gain of 1dB in the passband is used to filter out noise caused by breathing and heartbeat, and the cutoff frequency is set to 0.145Hz. Then, a mathematical morphological filter (MMF) is used to eliminate baseline drift while maintaining the main morphology of blood oxygen signals. MMF can be expressed by the following formula:

$$y = x - (filter_{oc}(x) + filter_{co}(x))/2 \quad (1)$$

$filter_{oc}$ and $filter_{co}$ represent morphological open filtering and morphological closed filtering, which are composed of corrosion and expansion[30].

In order to reduce the impact of different individuals' skull differences, the regions of interest (ROI) divided in this study are shown in Table 1. In order to reduce the impact of noise such as body motion, and to find the highest commonality in walking tasks for the brain region, using the weight method to calculate the overall blood oxygen signal of the ROI brain region. The calculation formula is as follows:

$$y = \sum_j X_{ij}\,\omega_j \ (i = 1,2,\ldots,N, j = 1,2,\ldots,M) \quad (2)$$

X represents the matrix of the original channel blood oxygen signal composed of M channels and N sampling points, and ω_j represents the weight of each channel calculated from the blood oxygen concentration information entropy of each channel[31].

Table 1
The divide of the ROI brain

The number of ROI	The name of ROI	Channel number included
1	L-PFC	1, 4, 8
2	M-PFC	2, 5, 6, 9
3	R-PFC	3, 7, 10
4	L-PMC	11, 14, 18
5	SMA	12, 15, 16, 19
6	R-PMC	13, 17, 20
The letters L, M, and R represent Left, Medial, and Right respectively. For example, L-PFC indicates the left part of the PFC.		

First, four different gait adjustment tasks are uniformly defined as gait adjustment tasks. In order to analyze the differences in the activation of brain areas when subjects perform gait adjustment tasks, it is necessary to predict in advance which specific gait adjustment intention. Previous studies have shown that[7, 32], lower limb motor intention can usually be detected 0.5-2s in advance.The blood oxygen data within 2 seconds before and after the Mark position marked during the experiment is selected for analysis. The sliding-window method is used to calculate the time-domain characteristics of the blood oxygen signal to find the difference in the distribution of blood oxygen activation of the ROI in the two states. Among them, the window length is set to 40 sampling points, and the step size is set to 1 sampling point.

After finding the turning point of gait adjustment, in order to further distinguish the four states of speedincrease, speed reduction,step increase, and step reduction, we calculated the original signal of blood oxygen concentration and the rate of change of blood oxygen concentration in the ROI. The concentration change rate is calculated as $dx_i = x_{i+1}-x_i$, where x_i represents the blood oxygen data at the i sampling point in the time window. Similarly, x_{i+1} represents the blood oxygen data at the i+1 sampling point in the time window. Then calculate the Pearson correlation coefficient as the feature score for each of the ROI of the original signal and the blood oxygen difference signal. A feature score corresponds to two brain regions, and it is added to the corresponding ROI. All feature scores follow this operation to get the cumulative feature score of each ROI. After normalization, observing the spatial distribution of the correlation characteristics of the brain area under the different state adjustment states.

All analyses and calculations in this article are run under Windows 10 system (I5-8250 CPU and 8G memory). The analysis software is Anaconda3-4.3.1 with python 3.6. In order to statistically compare the validity of the results of blood oxygen activation in the ROIbetween the normal walking task and the gait adjustment task, this paper uses the function 'ttest_ind' of the 'stats.scipy' in the python package to calculate the significance level pvalues.Each t-test contains 30 sample data. If p values less than 0.05 indicate rejection of the null hypothesis.

3. Results

Among the walking blood oxygen concentration data of 30 people in this experiment, one person's channel blood oxygen data showed a significantly larger abnormal value, and this person's experimental data has been excluded. The comparison curve of the blood oxygen signal of one of the channels without filtering, filtering, and mathematical morphological filtering is shown in Figure 3. It can be seen from the figure that the signal processed by combining low-pass filtering and mathematical morphology filtering can eliminate the influence of baseline drift while maintaining the main shape of the original signal.

During normal walking and gait adjustment, two types of blood oxygen concentration activation in the ROI are shown in Figure 4. Compared with the normal walking, the concentration of HbO of the SMA increased significantly during gait adjustment ($t = 3.1158$, $p = 0.0029$).Meanwhile, the concentration of HbT of the medial-PFC decreased significantly ($t = 2.7164$, $p = 0.0088$).

This paper analyzes the spatial distribution of brain activation in four gait adjustment states from the HbO and HbR information levels based on the correlation coefficient characteristics between brain regions. The sliding window method calculation found that the 15th sample after the marked mark point the difference in activation of the brain area is the most significant at the point of time. The results are shown in Figure 5 and Figure 6.

Table 2
Differences in activation of ROI between four adjusted states

cerebral blood oxygen	walking state 1	walking state 2	Brain regions	correlation coefficient	significant difference
HbO	step increase	step reduction	L-PMC	0.7471,0.8730	p = 0.0130
HbO	step increase	speed increase	R-PMC	0.7937,0.5893	p = 0.0314
HbO	speed reduction	step reduction	L-PMC	0.7538,0.8730	p = 0.0279
HbO	speed reduction	step reduction	R-PMC	0.7639,0.8898	p = 0.0056
HbR	speed increase	speed reduction	L-PFC	0.5923,0.7533	p = 0.0103
HbR	speed increase	step increase	L-PFC	0.5923,0.7787	p = 0.0460
The letters L and R represent Left and Right respectively. For example, L-PFC indicates the left part of the PFC.					

At the level of HbO information, there is no significant difference in the activation of the brain area between speed increase and speed reduction.Compared with the step increase, the activation of Left-PMC is significant when the step reduction (t=-2.5670, p = 0.0130, the average values are: 0.7471 and 0.8730 respectively). Compared with the speed increase, the activation of the Right-PMC is significant when the step increase (t=-2.2074, p = 0.0314,the average values are: 0.5893 and 0.7937 respectively). Compared with speed reduction, Left-PMC and Right-PMC are significantly activated when the step reduction (Left-PMC: t = -2.2572, p = 0.0279, the average values are:0.7538 and 0.8730 respectively; Right-PMC: t = -2.8797, p = 0.0056, the average values are: 0.7639 and 0.8898 respectively). In the HbR information level, compared with the speed increase, the Left-PFC is significantly activated when the speed reduction (t = -2.6106, p = 0.0103, the average values are: 0.5923 and 0.7533 respectively). There was no significant difference in activation of brain regions between step increase and step reduction.Compared with the speed increase, the activation of Left-PFC was significant when the stepincrease (t = -2.0411, p = 0.0460, the average values are: 0.5923 and 0.7787 respectively).There was no significant difference in the activation of brain regions between speedreduction and step reduction. The areas with significant differences in brain area activation are shown in Table 2.

In addition, this paper also analyzes the spatial distribution of walking speed parameter and step size parameter changes and the spatial distribution of gait parameter adjustment from the HbO and HbT information level with the correlation characteristics of brain regions, as shown in Figure 7.At the level of HbO information, compared with the adjustment of walking speed, the activation of Right-PMC was significant during the adjustment of step size($t = -2.8282$, $p = 0.0067$, the average values are: 0.7719 and 0.8567 respectively). At the level of HbT information, compared with the reduction in gait parameters, the activation of Left-PFC was significant when the gait parameters were increased ($t = 2.9848$, $p = 0.0042$, the average values are: 0.4322 and 0.6141respectively).

4. Discussion

The research results show that the normal walking task and gait adjustment task show different blood oxygen activation patterns corresponding to the cerebral cortex.At the same time, there were significant differences in the activation modes of the brain regions among the four gait adjustment states.

At the level of HbO concentration, compared with normal walking, the SMA is activated significantly when gait adjustment intent occurs. Previous studies have also shown that SMA has significant activation during gait adjustment[3, 33]. We know that SMA plays an important role in exercise planning[34, 35], and it may be that the subject planned the exercise in advance when the gait adjustment intention occurred. This process promoted the activation of the SMA. At the level of HbT concentration, compared with normal walking, the total oxygenated hemoglobin in the medial-PFC decreased significantly during gait adjustment. This means that the brain region needs to consume more stored energy when gait adjustment intention occurs. This result is consistent with previous studies[36] suggesting that the PFC plays an important role in preparing for the motor.

In the current study, the identification of upper and lower extremity movement adjustment intentions was mostly performed in discrete states[37-39]. In this paper the intention of lower limb movement adjustment in the continuous state, and analyze the differences of the four gait adjustment states from the perspective of brain region correlation.Experimental results show that the Left-PFC was activated significantly at speed reduction compared to a speed increase. The PFC plays a role in cognitive needs[40], Taeko[4] pointed out that when walking on a treadmill, the left-PFC is at 70% walking intensity, compared with 30% and 50% walking HbO there is a large increase in content. The reason for the difference in the activation results of the two brain regions may be that the experiment was performed in a natural environment and the precise walking speed control on the treadmill could not be achieved. Participants needed extra attention to deliberately maintain a slow speed. In addition, the left-PMC was significantly activated when the step reduction compared with the step increase. From normal walking to step reduction is a gait task that needs to be maintained deliberately, which will cause the subject to perform spontaneous fine motion control. From the perspective of physiological needs, intentional motion control requirements mean that more brain resources need to be called, thereby promoting significant activation of PMC. Compared with the decrease of gait parameters, the activation of Left-PFC was significant when the gait parameters were increased. It can be seen that the increase in walking

speed has a significant effect on the activation of the brain region, indicating that an increase in gait parameters requires more blood oxygen metabolism in the brain to meet motor cognitive needs.

This article also compares the differences in activation of the brain regions with changes in walking speed and step size. At present, there are many types of research on the brain mechanism related to changes in walking speed[41, 42], and they observed that the PFC is significantly activated when the speed increases, indicating that the PFC plays an important role in controlling the speed of movement. This study found that the Right-PMC was significantly activated when the step increase compared with speed increase.The Left-PMC and Right-PMC were significantly activated when the step reduction compared to the speed reduction.Indicating that the PMC plays a promoting role in completing the step adjustment task. However, there are few studies on the mechanism of changes in step size and changes in blood oxygen in the brain[23], and most of the research goals are usually the effects on gait parameters during dual-task walking[43, 44]. From a theoretical perspective, walking speed adjustment and step size adjustment belong to two different gait adjustment modes. The walking frequency determines the size of the walking speed, and the step size changes depend on the distance of the thigh. This difference in walking posture control has led to different areas of brain activation to some extent.

There are some shortcomings in this study. In the experiment, we only required the subjects to complete a gait adjustment of one intensity level. In future research, we can focus on distinguishing gait adjustment modes of more intensity levels to achieve more detailed gait mechanism research. In addition, the Mark point marking at the turning point of the gait adjustment task in this experiment was manually marked by the experimenter. The timing of the gait adjustment intent of different subjects was also advanced or delayed to a certain extent. More research in the future can be achieved by designing and using more sensitive sensors to achieve amore accurate recording of the starting point of walking tasks.

5. Conclusion

This study observed the spatial distribution of cortical activity and brain region correlation characteristics indifferentgait tasks and gait adjustment states. During walking, an increase in HbO concentration in the SMA when gait adjustment intention occurs indicates that additional blood oxygen activity is required to meet brain motor cognitive needs. There are also significant differences in the degree of blood oxygen activation in functional areas of the brain under different gait adjustment modes:blood oxygen activation in the Left-PFC is enhanced when the speed reduction; blood oxygen activation is increased in the Left-PMC when the step reduction; blood oxygen activation is increased in the Left-PFC when the gait parameters are increased.In addition, compared with the walking speed adjustment, the step size adjustment requires more blood oxygen metabolism in the PMC to meet the needs of enhanced nerve activity. The preliminary findings of this study can provide an important theoretical basis for implementing gait control based on fNIRS-BCI technology.

Abbreviations

NW: Normal walking; DI: speed increase; DR: Speed reduction; PI: Step increase; PR: Step reduction;

HbO: Oxygenated hemoglobin; HbR:Deoxygenated hemoglobin;HbT:Total oxyhemoglobin;

PFC: Prefrontal cortex; PMC: Premotor cortex; SMA: Supplementary motor area;MMF:Mathematical morphological filter; ROI: Regions of interest; BCI: Brain computer interface

Declarations

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Authors' contributions

Chunguang Li and Yufei Zhu designed the study. Wei Qu and Lining Sun organize volunteers to participate in the walking experiment. Yufei Zhu designed the head layout and the division of ROI.Chunguang Li writed this article.All authors revised and approved the final manuscript.

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Availability of data and materials

Data are essentially medical data that are not publically available.

Ethics approval and consent to participate

All subjects participated in this walking experiment for the first time, and they participated only once. Each of them knew and signed the walking experimentinformed consent before the experiment. The data of the walking experiment is only used to analyze the functional connection of the brain.

Consent for publication

All data are anonymized, informed consent includes the right to useanonymized data for scientific publication.

Competing interests

The authors declare that they have no conflicts of interest.

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Figures

(a) (b)

(c)

Fig 1. (a) Laboratory corridor environment; (b) Experimental equipment; (c) Experimental process, S for Start, E for End, R for Rest, NW for Normal Walk, DI for Speed Increase, DR for Speed reduction, PI stands for Step Increase, PR stands for Step Reduction, and TA stands for Turn. Around.

Figure 1

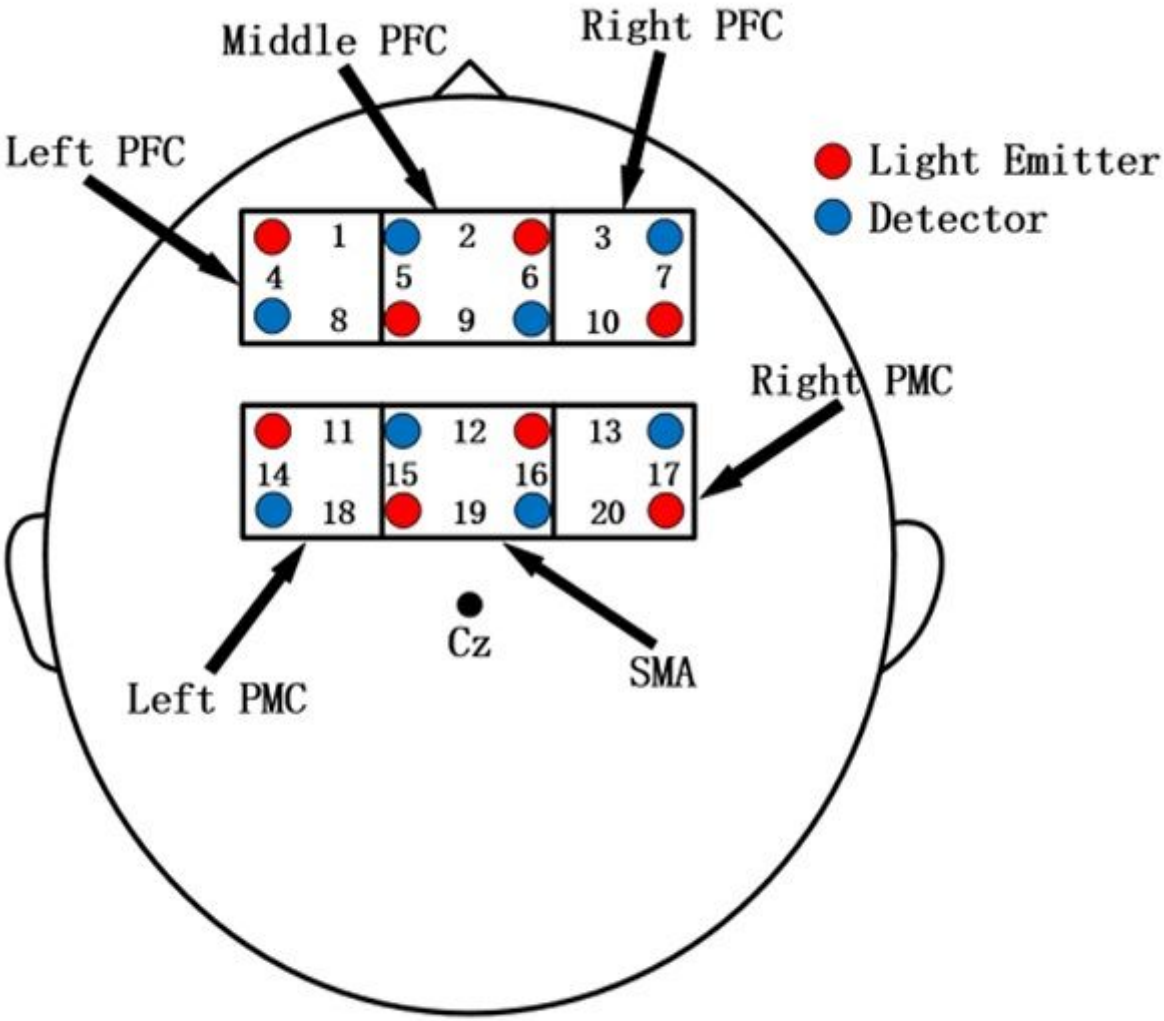

Fig 2. Measurement distribution of probe and brain area. Cz represents the vertical intersection of the anterior and posterior sagittal lines of the human brain with the left and right sagittal lines.

Figure 2

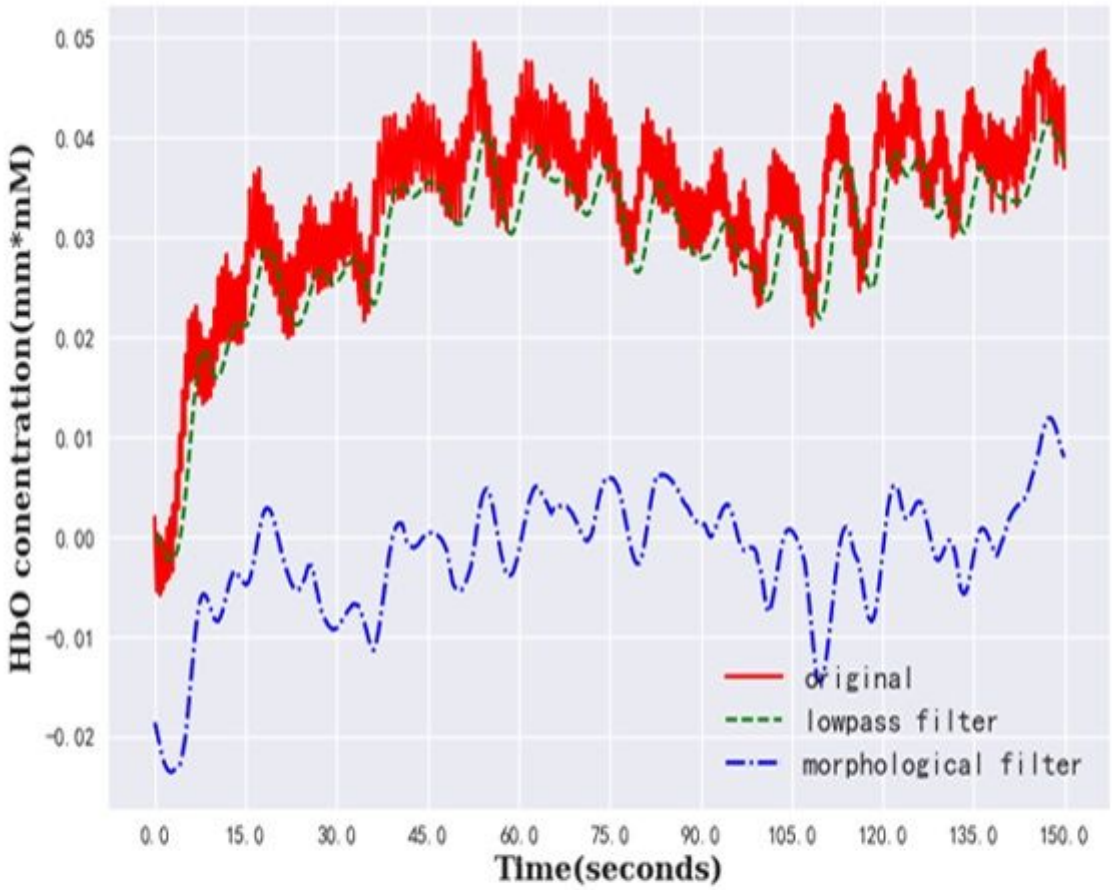

Fig 3. Comparison of unfiltered and filtered morphological distribution of a channel's blood oxygen signal. The red line represents the original channel signal, the green line represents the channel signal after chebyshev low-pass filtering, and the blue line represents the channel signal after chebyshev low-pass filtering and mathematical morphology filtering.

Figure 3

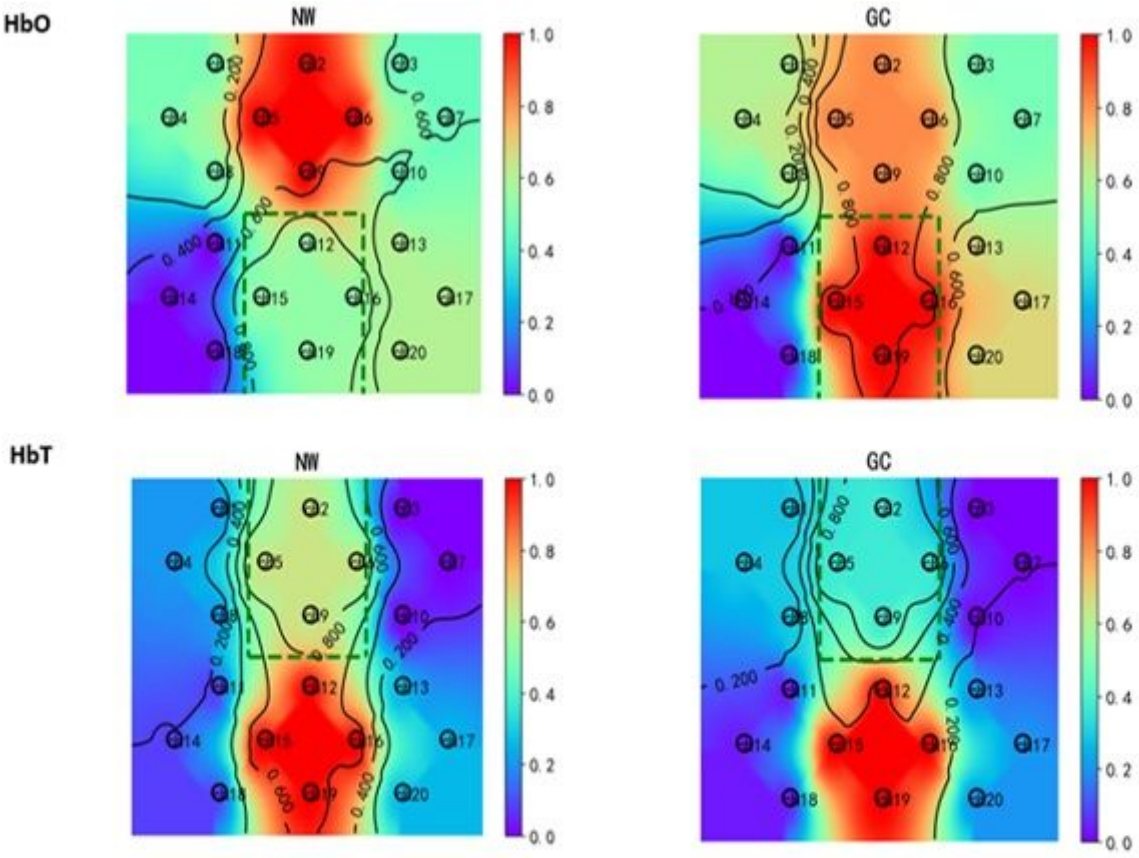

Fig 4. The spatial distribution of blood oxygen activation in the ROI before and after gait adjustment. The red color area indicates that the brain area is obviously activated. NW indicates normal walking, and GC indicates gait adjustment. ch1 represents channel 1 of blood oxygen, and so on.

Figure 4

HbO

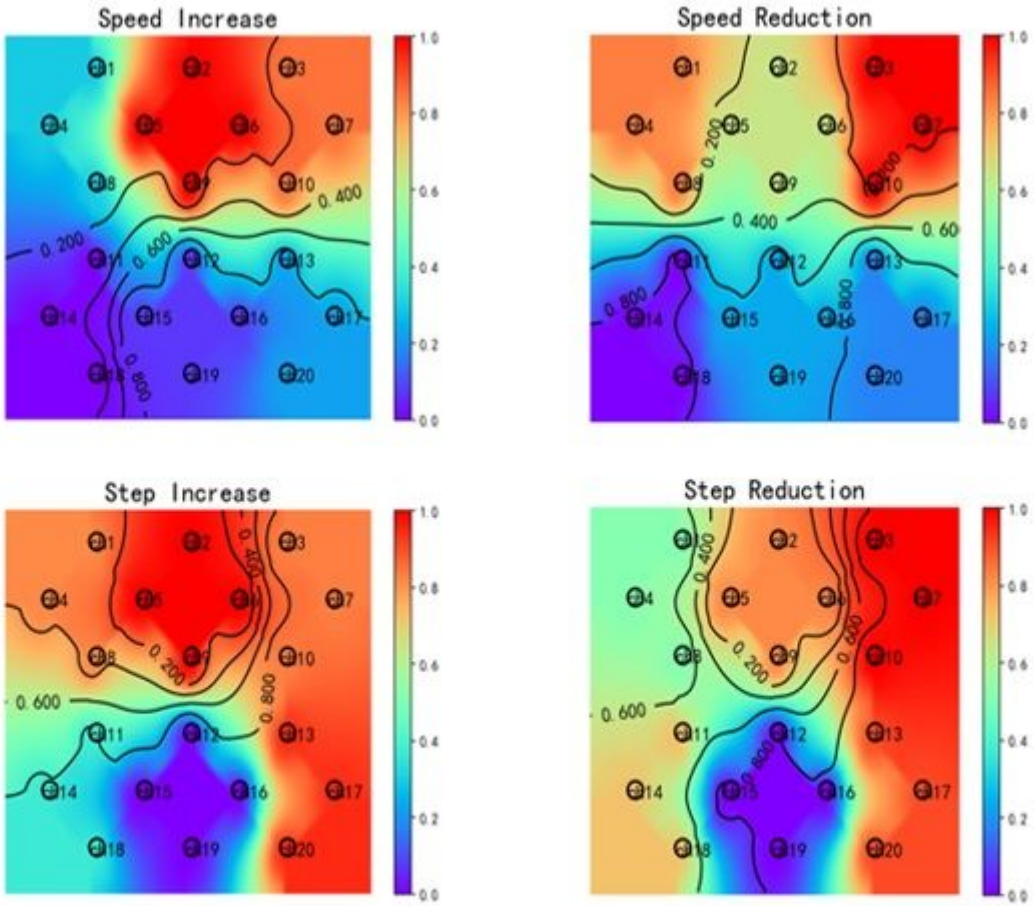

Fig 5. The spatial distribution of the correlation characteristics of the brain area during the four gait adjustment states under the HbO signals. The red color area indicates that the brain area is obviously activated. ch1 represents channel 1 of blood oxygen, and so on.

Figure 5

HbR

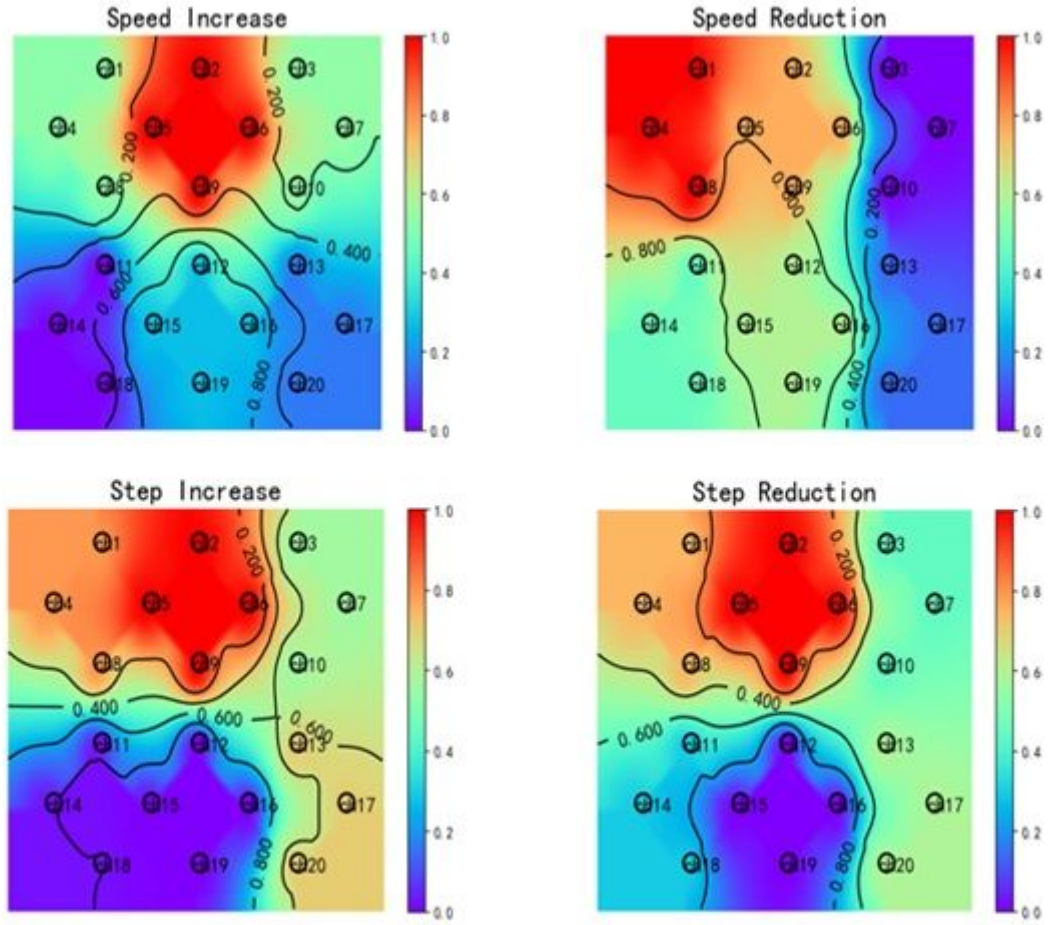

Fig 6. The spatial distribution of the correlation characteristics of the brain area during the four gait adjustment states under the HbR signals. The red color area indicates that the brain area is obviously activated. ch1 represents channel 1 of blood oxygen, and so on.

Figure 6

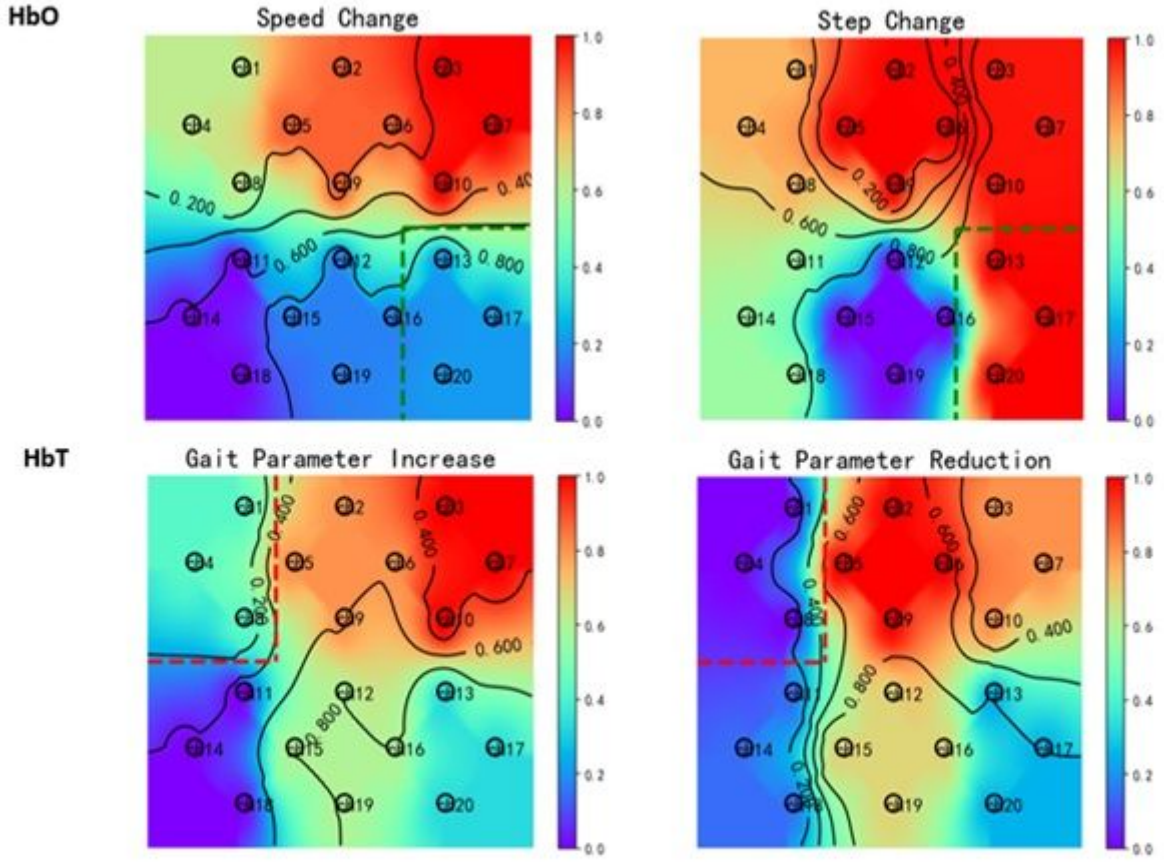

Fig 7. Spatial distribution of brain area correlation characteristics under changes in walking speed and step size and gait parameter adjustment under HbO and HbT signals. The red color area indicates that the brain area is obviously activated. ch1 represents channel 1 of blood oxygen, and so on.

Figure 7