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Original Article

Changes in cerebral blood flow during forward and backward walking with speed misperception generated by virtual reality

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Abstract. [Purpose] The purpose of this study was to investigate the effect of speed misperception on brain activity, created by a speed difference between actual walking and virtual reality walking videos. [Participants and Methods] The participants were 20 healthy young people. The walking speed in the video was set to 3 km/h to induce an error, while the actual walking speed was 1 km/h. Cerebral blood flow was measured using an optical imaging brain function measurement device. Left and right prefrontal cortices were analyzed using two channels and oxyhemoglobin level change from rest was used as a cerebral blood flow index. A t-test compared the cerebral blood flow dynamics before, during, and after the virtual reality video viewing under forward and backward walking conditions. [Results] Regarding changes in oxyhemoglobin levels during walking after watching the virtual reality video, cerebral blood flow increased especially in the backward walking state, where the difference was large in the right prefrontal cortex. [Conclusion] The backward walking that caused misperception by virtual reality is an extraordinary movement compared to forward walking. Thus, it is necessary to voluntarily adjust the movement by the cerebral cortex, and it is thought that activation of the prefrontal cortex occurs.
Key words: Virtual reality, Cerebral blood flow, Walking

INTRODUCTION

The application of virtual reality (VR) for rehabilitation using visual stimuli has become increasingly common in the medical field because of its familiarity and the ability to create illusions for viewers. In a systematic review and meta-analysis on the effectiveness of VR-based treatment for stroke patients, de Rooij et al[1]. reported improvements in gait and balance function. Other studies have also reported an improvement in upper limb function[2–5]. Additionally, backward walking exercise is said to have some efficacy compared with normal walking exercise for rehabilitation for stroke patients. We examined acute stroke patients within 5 weeks of stroke onset who underwent backward gait training using a partially unloaded treadmill and found that the training was effective in improving their gait ability[6]. However, there are no studies on improvement of physical performance through rehabilitation training in combination with a VR gait video of backward walking. Although a number of studies have reported the effect of backward walking training on stroke patients, there are no reports that discuss the basis of the intervention effect, such as increased brain activity or brain activation, and the intervention has not led to an overall improvement in physical performance.

Therefore, the purpose of this study was to investigate the effect of speed misperception on brain activity by intentionally creating a speed difference between the actual walking speed and the speed of the walking video by presenting a VR video before the participants walked forward and backward on a treadmill, thereby creating an illusion of the perceived speed.

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PARTICIPANTS AND METHODS

The participants were 18 healthy young people (12 males and 6 females, age 24.3 ± 1.7 years, height 167.5 ± 5.2 cm, 14 right-handed and 4 left-handed) who understood the purpose of this study and gave their consent in writing. Patients with orthopedic diseases and those with psychiatric diseases were excluded.

We conducted a basic survey on age, gender, and handedness. Smart glasses (EPSON MOVERIO BT-300, weight 69 g, Tokyo, Japan) were used to present the video to the participants. The walking video was filmed using a camera built into smart glasses and a walker, and the walking speed was adjusted to 3.0 km/h. The height of the walker was adjusted during the shooting, such that the average height of the participants' eyes was 150 cm. The video provided an experience of walking around a walking path with a width of approximately 3 m and a circumference of 35 m.

Brain activity was measured using fNIRS (Spectratech OEG-16, sampling frequency: 0.76 Hz, distance between the transmitter and receiver probes: 3 cm) with a total of 16 channels with the probe attached to the midline of the front forehead of the participant, following the method of Nakata et al[7]. The recording was started when the cerebral hemodynamics in all channels of the region of analysis became stable at the beginning of the experiment. For the fNIRS signal, oxyhemoglobin (oxy-Hb) with unit of mM/mm was used as an index of prefrontal hemodynamics, because it has the highest correlation with changes in regional cerebral blood flow, and oxy-Hb changes best reflect the brain activity.

A treadmill (SAKAI, BDX-T400, Tokyo, Japan) was used for the actual walking speed, which was set to 1 km/h. This was to take into account the backward walking conditions and to standardize the speed at which stroke patients can safely walk. It was measured using the method shown in Fig. 1. (1) In the independent walking condition, the patient walked forward or backward after resting. (2) In the VR viewing condition, the patient watched the VR after resting and then walked forward or backward, while cerebral blood flow was measured. To prevent noise caused by head movements, the participants were asked to gaze at a fixed point set in front of them and hold a handrail for safety.

Among 16 channels of NIRS that reflected the brain activity in the prefrontal cortex, we analyzed data from Ch7 (right prefrontal cortex) and Ch10 (left prefrontal cortex), where we obtained stable data with little noise[7], and used oxy-Hb as an index of brain activity. A period of quiet standing was set before each task as the habituation time, and the average of oxy-Hb values for the last 30 sec was used as baseline. It took 1 to 4 sec from the start of neuronal activity for the fNIRS signal to reach its half maximal value[8]. In this study, participants took about 5 sec from the start of the treadmill operation to reach a constant speed. Therefore, to analyze the cerebral nerve activity after the speed became constant, we referred to the method of Harada et al.[9] and defined Δoxy-Hb as the amount of change from baseline to the average of last 30 sec of each task. Furthermore, if an abnormal value such as an artifact is confirmed on the graph output, it is excluded.

Regarding the statistical analysis, the baseline before execution of each task was first identified within Ch7 and Ch10 and we found that there was no difference in the baseline and therefore no need for correction to compare Δoxy-Hb. We then compared forward and backward walking before viewing VR with respect to Δoxy-Hb values. After confirming normality of Δoxy-Hb values during VR viewing and Δoxy-Hb values during walking after VR viewing, a t-test of two independent groups was conducted for forward and backward walking. R-3.6.3 software was used for analysis, and the significance level was set at 5%.

This study was approved by the Ethics Committee of the Reimeikyou Hirosaki Stroke and Rehabilitation Center (Approval No. 19A008). This study was approved by the Ethics Committee of the Graduate School of Health Sciences, Hirosaki University (Approval No. 2019-035).
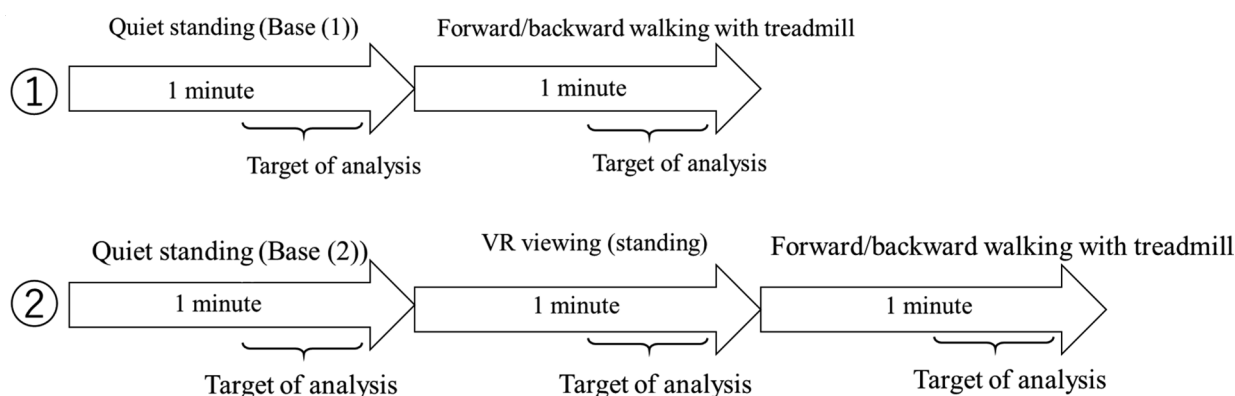

Fig. 1. Experimental procedures.

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RESULTS

A comparison of brain activity during walking before and after VR viewing is shown (Table 1). The mean values of Δoxy-Hb during "independent walking" before viewing VR were calculated and compared between the forward and backward walking conditions. The Δoxy-Hb in Ch7 was −0.043 (± 0.27) mM/mm in the forward walking condition and −0.12 (± 0.21) mM/mm in the backward walking condition. There were no significant differences between the two conditions (p=0.13). Δoxy-Hb in Ch10 was −0.053 (± 0.25) mM/mm in the forward walking condition and −0.10 (± 0.23) mM/mm in the backward walking condition. There were no significant differences between the two conditions (p=0.42).

A comparison of brain activity during walking before and after VR viewing is shown (Table 2).

The mean values of Δoxy-Hb during VR viewing were calculated and compared between forward and backward walking conditions. Δoxy-Hb in Ch7 was −0.065 (± 0.50) mM/mm in the forward walking condition and −0.064 (± 0.37) mM/mm in the backward walking condition. There were no significant differences between the two conditions (p=0.99). Δoxy-Hb in Ch10 was −0.025 (± 0.38) mM/mm in the forward walking condition and −0.084 (± 0.31) mM/mm in the backward walking condition. There was no significant difference between the groups (p=0.32).

A comparison of brain activity during walking before and after VR viewing is shown (Table 3).

The mean values of Δoxy-Hb during walking after viewing VR were calculated and compared between the forward and backward walking conditions. Δoxy-Hb in Ch7 was −0.10 (± 0.34) mM/mm in the forward walking condition and 0.035 (± 0.31) mM/mm in the backward walking condition. There was a significant difference between the two conditions, with an increase in cerebral blood flow in the backward walking condition (p=0.04). Δoxy-Hb in Ch10 was −0.048 (± 0.26) mM/mm in the forward walking condition and 0.034 (± 0.28) mM/mm in the backward walking condition. Although the difference was not significant, there was an increase in cerebral blood flow in the backward walking condition (p=0.07). Furthermore, only backward walking after watching VR, the cerebral blood flow turned positive, which was one of the features (Tables 1–3).

DISCUSSION

There was no significant difference in the brain activity between forward and backward walking conditions in both the left and right prefrontal cortices, before and during VR viewing. However, in the backward walking condition after VR viewing, the cerebral blood flow in the right prefrontal cortex significantly increased compared to the forward walking condition, and the brain activity tended to increase in the left prefrontal cortex, although the difference was not significant.

The function of the optic flow is essential for visual motion illusion. The ventral interparietal sulcus area is among the many

Table 1. Comparison of brain activity during forward and backward walking before viewing VR

	Forward walking	Backward walking
Ch7 (mM/mm)	−0.043 (± 0.27)	−0.12 (± 0.21)
Ch10 (mM/mm)	−0.053 (± 0.25)	−0.10 (± 0.23)

Mean (± SD) t-test (already translated).

Table 2. Comparison of brain activity between forward and backward walking conditions during VR viewing

	Forward walking	Backward walking
Ch7 (mM/mm)	−0.065 (± 0.50)	−0.064 (± 0.37)
Ch10 (mM/mm)	−0.025 (± 0.38)	−0.084 (± 0.31)

Mean (± SD) t-test (already translated).

Table 3. Comparison of brain activity during forward and backward walking after viewing VR

	Forward walking	Backward walking
Ch7 (mM/mm)	−0.10 (± 0.34)	0.035 (± 0.31)*
Ch10 (mM/mm)	−0.048 (± 0.26)	0.034 (± 0.28)

Mean (± SD) t-test (already translated), *p<0.05.

areas reported to be responsible for this. It has been observed that this area is part of the dorsal visual pathways, particularly the dorso-dorsal visual pathway, in the visual network[10]. The dorso-dorsal visual pathway is believed to be responsible for the "how" system, which processes information about the position, motion, and shape of objects in a less conscious manner to induce appropriate actions. The dorso-dorsal visual pathway projects from the visual cortex, through the superior parietal lobule, and finally to the dorsolateral prefrontal cortex, therefore, its connectivity to the prefrontal cortex cannot be ignored.

While there are many reports on brain activity during forward walking, there are few studies on brain activity during backward walking. Kurz et al. reported higher activation in the supplementary motor area, central gyrus, superior parietal lobule, and central posterior gyrus during backward walking than forward walking[11]. Similarly, Naito et al. reported that the supplementary motor cortex, right prefrontal cortex, and right premotor cortex showed characteristic activation during backward walking[12]. In the present study, no significant change was observed in activity of the prefrontal cortex during simple backward walking before viewing the VR, which is inconsistent with the results of the study by Naito et al. This may be attributed to the difference in the backward treadmill walking speed. The treadmill backward walking speed in the study by Naito et al. was as high as 4 km/h, while the set backward walking speed in the present study was low at 1 km/h. In terms of differences in the brain activity during backward walking due to differences in speed, Teranishi et al. reported that the activity of motor-related areas increased due to an increase in lower limb muscle activity during high-speed backward walking[13]. In the present study, it is suspected that since the backward walking speed was low at 1 km/h, the activity of the prefrontal cortex did not change during independent backward walking.

In the present study, the brain activity of the prefrontal cortex increased only when the participants walked backward after watching the VR, compared to walking forward. This is probably due to the effect of speed misperception formed by VR viewing. When a participant with a misperception of speed actually walks after watching a video of walking at a speed of 3 km/h, it may be necessary to adapt the walking speed and correct the movement. Forward walking is a highly automated movement, and it is difficult to imagine that the cerebral cortex is actively mobilized. In contrast, backward walking is considered to be a non-automated movement because it lacks visual information about the direction of movement, is prone to loss of balance, and has unusual gait patterns requiring hip extension movements to swing the lower limbs. It can therefore be inferred that the movement correction was made not automatically, but rather by the strong voluntary control of the cerebral cortex, especially the prefrontal cortex and premotor cortex. In particular, the increase in activity in the prefrontal cortex during the last 30 sec of 1-min walking task was considered to be in the steady phase of the task, when control by the cerebral cortex is supposed to be unnecessary, suggesting that the prefrontal cortex was voluntarily regulating the movement.

The comparison between forward and backward walking revealed that the activity of the bilateral prefrontal cortex, especially the right prefrontal cortex, increased during backward walking after viewing VR. Since backward walking is considered to be a non-routine, non-automated movement, it requires a higher level of postural control, visuospatial ability, and spatial attention than forward walking, and therefore aright prefrontal cortex activity involved in these functions significantly increased[14].

A limitation of the study was that the prefrontal cortex was the only area in which brain activity was measured. Although we were able to find that the intervention using VR and backward walking together increased the activity of the prefrontal cortex, the activity of other brain areas remains unknown. Many previous studies examining the cerebral hemodynamics during walking measured activity in the prefrontal cortex, supplementary motor cortex, and parietal lobe regions. Our study limitation was that we were not able to measure the activity of brain regions known to be associated with the prefrontal cortex, and thus failed to examine their relationship.

Conflict of interest

None.

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