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Investigation of optimal gait speed for motor learning of walking using the vibro-tactile biofeedback system

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***Abstract*—In stroke patients, sensory loss often reduces the sensation of ground contact, which impairs motor learning during rehabilitation. In our previous study, we proposed a vibro-tactile biofeedback system (which we called the perception–empathy biofeedback system) for gait rehabilitation. The results of our 9-week pilot clinical test suggested that patients who had reached the autonomous phase in gait learning had difficulty noticing the external vibratory feedback provided by the biofeedback system, leading to ineffective intervention. We considered the possibility that slower walking speed might return the patient to the association phase and allow patients to improve their gait according to the sensory feedback provided. Thus, in this research, a method based on reducing walking speed to guide patients' attention was derived. A pilot clinical trial shows that there is a statistically significant increase of ankle dorsiflexion in the initial contact phase and increase of ankle plantarflexion in the push-off phase after vibro-tactile biofeedback system intervention with speed reduction, compared to intervention without speed reduction. The results suggest that, by reducing their walking speed during intervention, patients return to the association phase and recognize external vibratory feedback, which may result in better intervention effects.**

***Clinical Relevance*—This study provides knowledge about the optimal walking speed when using vibro-tactile biofeedback for motor learning in stroke patients.**

I. INTRODUCTION

It is reported that about 250,000 people suffer from stroke every year. This results in a large population of survivors needing a rehabilitation plan [1]. A common symptom is impaired plantar foot sensation on the paralyzed side of the body [2]. Therefore, it is difficult for patients to correct their ankle movements based on foot pressure during walking, and this inhibits motor learning during rehabilitation. Current research on gait rehabilitation shows that results using tactile biofeedback (BF) devices are better than traditional therapies alone [3][4].

Based on previous research, we have devised a vibro-tactile BF system called "perception–empathy BF system" [5] to assist hemiplegic patients with sensory problems in gait rehabilitation. Based on foot-pressure detection, corresponding haptic BF is provided to the back by vibrating motors worn in a vest. Using this device, patients can correct their ankle movement according to the position of the foot. A clinical pilot test of six patients showed that after using the BF system for 3 weeks, patients might be expected to improve both dorsiflexion in the swing phase, and push-off motion [6]. Subsequently, in a 9-week clinical trial [7], a patient received gait measurement during the whole period. In the first six weeks, the patient underwent traditional rehabilitation training, during which neither dorsiflexion in the swing phase nor push-off motion improved. After that, BF system intervention was carried out for 2 weeks, also with no improvement.

We believed that this lack of result might be because the patients in the trial had entered the autonomous phase of gait learning [8]. In this phase, movement is controlled through latent memory and knowledge of results (KR) [9], which causes the patient to be unable to integrate the external feedback (vibration information) of a BF system. On the other hand, in the cognitive and association phases, patients can integrate awareness of vibrational feedback.

In previous dual-task research [10], it was found that the more attention the participants paid to external feedback, the slower their walking speed. In this study, we propose a method of attention guidance that allows patients to pay attention to external vibration feedback by reducing walking speed, thereby returning patients from the autonomous phase to the association phase. Thus, the purpose of this study was to find the optimal walking speed and to conduct a validation test in stroke patients.

II. SYSTEM OVERVIEW

A. Vibro-Tactile BF system

The proposed vibro-tactile BF system is shown in Fig. 1. It consists of a pair of insole sensor units and a BF unit that comprises a set of vibration motors installed on a vest.

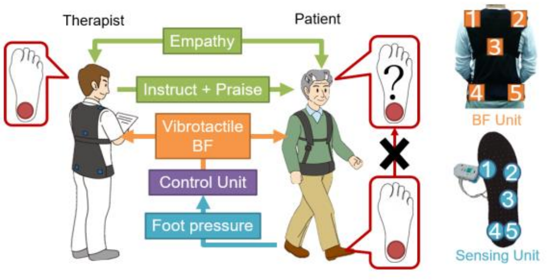

Figure 1. The vibro-tactile BF system

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Five pressure-sensing channels are deployed, from the forefoot to the heel. The corresponding back vibration BF can be used to perceive a change in foot pressure during the stance phase of the gait, and this vibration can also be felt empathetically by the therapist. In this way, although the plantar sensation of hemiplegic patients is usually impaired, they can perceive the landing status of their feet through vibration stimulation on their backs.

B. Vibration Belt system

During the process of walking speed reduction, another vibration belt system [11], was also used. As shown in Fig. 2, this is a cueing system for patients to follow the designated cadence of walking. Previous work has shown this method to increase patients' walking cadence and speed according to an increasing tempo of rhythmic vibration, without worsening the gait pattern. In this study, we use the same concept to decrease patients' speeds by lowering the pace of cueing vibration rhythms.

Figure 2. The vibration belt system

III. RESEARCH HYPOTHESIS

For the BF intervention, the goal was to improve walking speed and ankle joint agility (dorsiflexion in the swing phase and plantarflexion in the push-off motion). However, our previous clinical trial of a nine-week gait intervention on a patient with hemiplegia showed disappointing results [6]. In the first six weeks, the patient received traditional rehabilitation training, and the BF system intervention trial was carried out from the 7th to the 9th week. In the first 6 weeks, the walking speed of this case increased significantly, but ankle joint agility had not improved. After that, the patient underwent BF system intervention for an additional 2 weeks. The result shows that although the walking speed increased more, there was still no significant difference in ankle joint movement.

A. Motor learning analysis

We analyzed the intervention from the perspective of motor learning. We considered the three phases of cognitive, association, and autonomous learning proposed by Paul Fitts [8]. Fig. 3 shows the level of attention to external feedback during the three gait-learning phases of patients with hemiplegia. In the cognitive phase, much attention is spent on external feedback regarding gait. Due to conscious control of gait, the movement speed is slow, and the gait is very chaotic. Once basic walking ability is acquired, the association phase begins. This phase is the phase of fine-tuning the gait. The gait becomes more stable, and the walking speed also begins to increase. Finally comes the autonomous phase. The gait at this phase is orderly. Walking is performed automatically by relying on latent memory rather than external feedback.

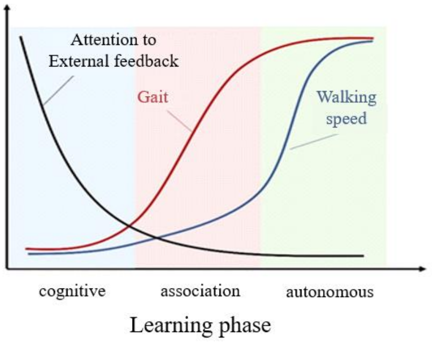

Figure 3. Motor learning phases and attention to feedback

We speculated that the patient described above had reached the autonomous phase and formed his personal stable gait, although his gait still had abnormalities. Having entered the autonomous phase means that the patient will only pay a small amount of attention to external feedback (in this case, vibrational BF). This explains why the BF system was ineffective at yielding gait improvement.

B. Relationship between attention and walking speed

In previous dual-task studies, it was found that the more participants paid attention to external feedback, the slower they walked [10]. Consistent with the above analysis of motor learning, we speculated that the patient can apply more attention capacity to external feedback by reducing walking speed, in other words, going back from the autonomous phase to the association phase. In order to verify this hypothesis, we proposed a dual-task experiment for healthy people. Participants were asked to walk at different speeds under the guidance of a vibrating cadence belt. While walking, the participants were also asked to subtract 13 from a four-digit number consecutively, and we used the arithmetic accuracy rate as an index of attention capacity for external feedback [9].

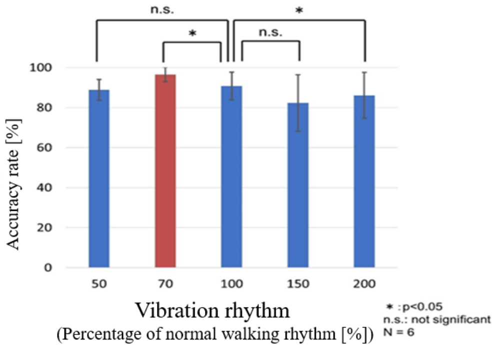

Figure 4. Accuracy rate of subtraction.

We conducted a test on six healthy adults and asked them to walk 10 meters under five conditions, of 50%, 70%, 100%, 150%, and 200% normal walking cadence. Each condition was repeated twice. The result is shown in Fig. 4. At 70% of the walking cadence, the accuracy rate increased compared with the normal walking cadence. In the case of 50% cadence, the accuracy rate was unchanged from baseline, and in the case of 150% and 200% cadence, it was reduced. The results show that reducing the speed to 70% can allow the participants to gain attention capacity for external feedback. This, in turn, suggests that participants are likely going back from the autonomous phase to the association phase.

In summary, we have confirmed that reducing walking speed to the proper degree (70% in this study) can increase the patient's attention capacity for external feedback. So we hypothesized that reducing the speed to 70% of normal walking could increase patients' attention capacity and improve the intervention effectiveness of the vibro-tactile BF system.

IV. EXPERIMENT

A. Participants

The participants included four patients with stroke, as shown in Table 1: three males and one female with a mean age of 56.3 ± 7.3 years. Inclusion criteria consisted of the following: a) BRS IV or above [12]; b) judgment by the therapist that the patient had entered the autonomous phase; c) the ability to effectively communicate and sufficiently understand instructions provided by the researcher; and d) absence of any other disease that might interfere with walking performance.

B. Ethical approval

All procedures were approved by the Waseda University Ethics Committee for Human Research. After a complete description of the procedures and purpose of the study, written informed consent was obtained from all participants (Approval Number: 2020-045).

C. Experimental design

In order to verify our hypothesis, we designed a three-condition experimental process as shown in Fig. 5: (a) normal walking before intervention; (b) BF system intervention without speed reduction; (c) BF system intervention with speed reduction. Normal and non-reduced-speed BF system intervention conditions were 10 m of walking and each was conducted twice. Speed reduced walking was 10 m and was conducted five times, BF system intervention with speed reduction was also 10 m and was conducted twice. Taking into consideration the "Forgetting Curve" [13], a phenomenon in which people forget the fastest in a short period of time after learning, specifically, it is difficult for people to remember and maintain the walking cadence, they will walk faster again after walking at reduced speed. We tested six healthy individuals by setting the rhythm of the vibration belt during speed reduction to 50%, 60%, and 70% of normal walking, and observed the subjects' walking speed after speed reduction walking. We conclude that set the rhythm of the vibration belt during speed reduction to 60% of normal walking can meet the requirement of maintaining 70% walking cadence during the BF system intervention.

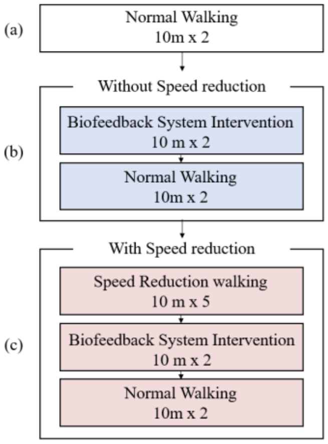

Figure 5. Experimental flow.

C. Dependent variables

The angle of the ankle joint on the paralyzed side during the initial contact and push-off was recorded to describe the patient's walking ability. The angle was measured by an inertial sensor [14] (Rehagait, Hasomed Gmbh, Germany). The angle average was calculated at the initial contact and push-off and analyzed as a dependent measure.

V. RESULTS AND DISCUSSIONS

Statistical analysis was performed on each index using the Friedman's test. If a significant difference was observed, multiple comparison tests were performed with Wilcoxon's signed rank test. The significance levels were set as <5%, and marginal levels were set as <10%. Box and whisker plots are used to present the analyzed data, showing median, first and third quartiles, and the maximum and minimum values. we took two series of measurements on one patient, so the number of measurements in the data set is 8 (N = 8).

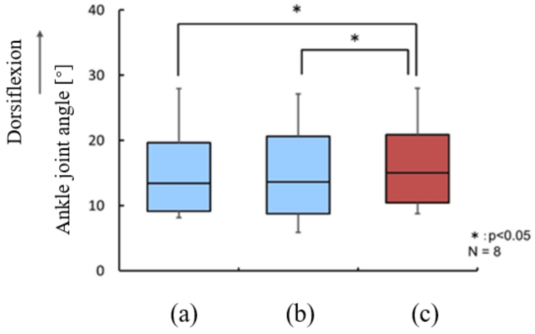

Figure 6. Ankle-joint angle of the paralyzed side at initial contact.

TABLE I. CHARACTERISTICS OF PATIENTS

No	Sex	Age	Time since stroke	Affected side	Brs.	Hypoesthesia	MMSE score
1	F	66	3 months	Right	IV	Mild	29
2	M	54	Unavailable	Left	V	Mild	29
3	M	59	6 months	Left	IV	Mild	29
4	M	46	6 months	Left	V	Moderate	24

MMSE, Mini-Mental State Examination

Fig. 6 shows the ankle joint angle of the paralyzed side at initial contact. For the Friedman test, the ankle joint angle shows a significant change ($p = 0.010$). Compared with normal walking before intervention (a) and after intervention in condition (b), the ankle joint angle after intervention in condition (c) was significantly increased. ($p = 0.025$, $p = 0.012$). The results show that dorsiflexion movement is improved, during swing phase, during BF system intervention with speed reduction.

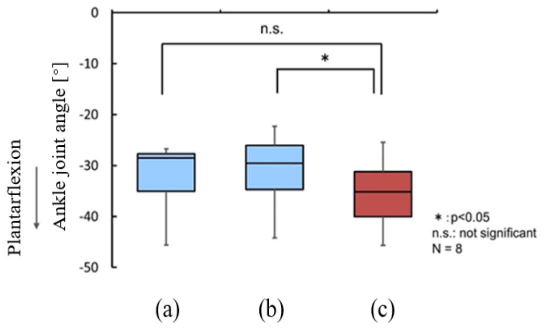

Figure 7. Ankle joint angle of the paralyzed side at push-off.

Fig. 7 shows the ankle joint angle of the paralyzed side at push-off. For the Friedman test, the ankle joint angle has marginally changes ($p = 0.072$). Compared with after intervention in condition (b), the ankle joint angle after intervention in condition (c) has significantly increased ($p = 0.012$). However, no significant differences ($p = 0.327$) exist between normal walking before intervention (a) and after intervention in condition (c). In this regard, our analysis from an individual perspective revealed that one participant was unable to maintain 70% speed after speed reduction. The results of this participant showed that the ankle angle did not improve in the initial contact and push-off stages after intervention (c) with speed reduction compared to before intervention (a). We believe this was due to the lack of speed reduction and the failure to return to the association phase. In light of this finding, the artificial speed reduction method may not be suitable for some patients; it is necessary to study the training method further.

In addition, we also considered the possibility that speed reduction can improve the effectiveness of BF system intervention. In the training of motor learning, from feedback to the beginning of the next trial, there must be time to process the information (post-KR delay). By walking at a reduced speed, patients have more time to deal with external feedback, that is, to find abnormal gait and correct gait through external feedback.

Due to the insufficient number of patients, we chose to have each patient repeat the experiment twice, while conditions (b) and (c) were not randomized in the design of the experiment. These limitations may reduce the reliability of the data. We therefore plan to conduct future experiments with larger numbers and a more scientific experiment flow.

VI. CONCLUSION

In this paper, an intervention with a vibro-tactile BF system under low-speed walking was conducted to examine expansion of users' available attention capacity and transition to an earlier stage of motor learning. The results suggest that there is a statistically significant increase in ankle dorsiflexion in the initial contact phase and plantar flexion in the push-off phase after vibro-tactile BF system intervention with speed reduction. The results of this study suggest that some stroke patients may benefit from adjusting their gait speed when using a vibro-tactile BF system in gait rehabilitation. As this is a preliminary study, further validation with a larger number of patients is needed.

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