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Development of Virtual Reality-based Gait Training System Simulating Personal Home Environment *

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Abstract— **We developed a virtual reality (VR)-based gait training system, which could be used by inpatients to train their gait function in a simulated home environment, to reduce the risk of falling after discharge. The proposed system simulates the home environment on a head-mounted display, in which a user can walk around freely. The system provides visual feedback in the event of a collision with an indoor object such as a wall or furniture, prompting the user to modify his or her gait pattern. We first applied the system to healthy young adults and confirmed the usefulness of visual feedback in reducing the walking time and the number of collisions in the simulated room environment. Further, we applied the system to an inpatient with stroke and lower limb paralysis. The patient performed gait training based on a scenario of daily activity using the VR environment that mimicked his house. Five days of training significantly improved the gait and balance functions of the patient. These results suggest that the proposed system foster attention to the surrounding environment and improve gait function in both healthy participants and patients with stroke.**

Clinical Relevance— **This study establishes the importance of visual feedback for VR-based gait training. Additionally, it provides a novel application of VR for gait and balance training in patients with stroke and lower limb paralysis.**

I. INTRODUCTION

Since patients with stroke typically endure physical impairments such as paralysis of their limbs, they experience a decrease in quality of life that may be problematic. Recent advancements in virtual reality (VR) technology have tackled this issue to provide an efficient rehabilitation program for patients with impaired physical function. Clinical studies have shown the superiority of VR-based training over conventional training in upper limb rehabilitation [1, 2] and gait training [3, 4] for patients with stroke, and the elderly [5].

Falling at home is a clinical problem encountered in discharged patients with stroke, which may occur even after their gait function had been sufficiently restored by in-hospital rehabilitation before discharge [6]. The visually condensed environment of the house comprising narrower corridors and a larger number of objects and furniture is potentially causing the inappropriate allocation of visual attention and increasing the risk of falling [7]. Since falls worsen the physical ability and the quality of life of the patient [8], an efficient training strategy is required with which the patient could confirm the locations of high risks in the home and start training even before discharge. We propose a VR-based gait training system that utilizes a head-mounted display (HMD) to allow users to walk around a simulated home environment. Training for daily activities that may involve risks can be safely performed in the VR room without the need for real objects. The proposed system also provides visual feedback upon collision with an object or wall that can help patients regain visual attention while walking and develop a strategy to walk safely at home.

This study had two purposes. First, we aimed to determine the effect of visual feedback in the proposed system on improving gait performance (Experiment 1). We recruited healthy young adults and investigated how the walking speed, number of collisions with objects, and number of steps changed depending on the presence or absence of visual feedback in the proposed VR system for gait training. Second, we applied the proposed system to a patient with stroke and lower limb paralysis to investigate its clinical efficacy (Experiment 2). The patient underwent gait training in VR rooms that simulated his home environment for consecutive 5 days. The immediate and post-training outcomes on gait and balance functions were evaluated.

II. METHOD

A. Participant

Forty healthy young adults (aged 20.3 ± 1.67 years; 30 men) without perceived problems in gait function participated in Experiment 1. They were randomly divided into two groups (n = 20 each; visual feedback and no feedback groups), depending on the presence or absence of visual feedback upon collision with objects in the VR environment during the experiment.

A 78-year-old, male inpatient who survived from a cerebral hemorrhage at the right thalamus-putamen participated in Experiment 2. His lower limb was diagnosed as motor paralysis of Broomstrom recovery stage IV [9] with moderate sensory impairment. The time from onset to intervention was 123 days. The participant was selected by the physical/occupational therapists (D.I. and R.O.) who were in charge of his rehabilitation.

Participants in both experiments were informed beforehand about the purpose of the experiment and informed consent was obtained. All experiments were conducted with approval of the Ethics Committee on Experimental Research on Humans, School of Science and Technology, Meiji University, and Suisyoukai Murata Hospital.

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B. *VR-based gait training system*

We developed gait training software using Unity. It was installed on a stand-alone type of HMD (Lenovo Mirage Solo with Daydream). The advantages of the stand-alone type of HMD include the provision of a VR experience with minimum physical constraints and ease of operation.

Typical rooms consisting of a studio apartment (Fig. 1) and a bedroom with a corridor connected to a bathroom (Fig. 2) were simulated in Experiments 1 and 2, respectively. The participants were instructed to walk around those rooms according to the training scenario which is described in the following sections. In the training sessions with feedback, collision with an object alerted the participant by turning the surface color of the object red. A cylinder with a diameter of 27 cm and the same height as the HMD was located under the HMD, and the collision was detected when the cylinder collided with a wall or furniture. The immediate, trial-to-trial basis of the feedback encouraged participants to develop the appropriate balance and speed required to walk around in the simulated environment. We did not use other modalities of feedback, such as sound and vibration, since patients might require verbal instructions and physical assistance by therapists during the training.

In Experiment 2, the VR home platform was used to simulate the patient's renovated house, in which he underwent training for daily walking activities. The rooms selected included those that would be the main living space for the patient after discharge. The sizes of the virtual rooms and furniture were determined based on their actual sizes measured using a Laser Rangefinder (Elikliv JQ40). Photographs of the actual room and furniture were pasted onto the surface of the three-dimensional (3D) room and furniture to precisely simulate the patient's home environment. We additionally installed a desk, a chair, an L-shaped bed fence in the bedroom, and handrails on the corridor wall next to the bathroom door, upon request from the patient and his therapists.

C. *Experiment 1*

Participants in both groups performed four consecutive walking trials in the VR room (Fig. 3). The objects in the room were intentionally arranged with minimal distances to pass through. They were instructed to walk around the room on a fixed route (Fig. 1) as fast as possible while avoiding collision with objects. The participants assigned to the visual feedback group received immediate visual feedback upon collision with objects in their second and third trials. Nonetheless, the number of collisions was communicated to all participants after each trial, regardless of the allocated group.

We investigated changes in the time taken to complete the route (walking time), the number of collisions with walls and furniture, and the number of steps. We used the Wilcoxon signed-rank test to compare the gait parameters between the first and the last trials in each group, where participants performed the same walking task without visual feedback (Fig. 3). The Wilcoxon rank-sum test of the gait parameters in the first trial was also conducted to confirm whether walking ability between the two groups was comparable. The data of both sex were combined since there was no statistically significant difference in the gait parameters between men and women. We considered $p < 0.05$ as statistically significant.

Figure 1. VR home environment used in Experiment 1. Left: overview of the room. Right: walking route for gait training.

Figure 2. VR home environment used in Experiment 2. Left: overview of the room. Right: walking route for gait training.

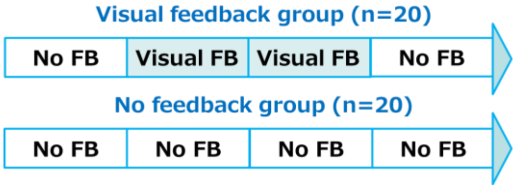

Figure 3. Experimental protocol in healthy participants.

D. *Experiment 2*

Figure 4 illustrates the protocol of the clinical experiment. The patient first underwent three types of pre-training evaluation for balance function, mobility function, and fear of falling on the first day of training. Balance function was evaluated using the Berg balance scale (BBS) [10]. Mobility function was evaluated using the timed up and go (TUG) test [11] in real-space. The TUG test is a typical method used in the assessment of mobility and balance functions in rehabilitation; it measures the time and the number of steps taken by a patient to rise from a chair, walk 3 m ahead, turn around, walk back to the chair, and sit down. Fear of falling was evaluated using the modified falls efficacy scale (MFES) [12]. The patient performed five sessions of gait training in the VR home environment every day for five consecutive days (Fig. 5). Mobility function of the participant was evaluated using the VR version of the TUG test (VR-TUG, Fig. 6), before and after daily training to determine the immediate effect of the intervention. In the VR-TUG test, the patient performed the TUG test from a sitting position with an actual chair provided. After 5 days of intervention, the BBS, TUG, and the MFES were evaluated again to determine the post-training effect. The safety of the patient was ensured by the use of a four-point cane and the supervision of a therapist for the whole duration of the interventions and evaluations.

The training scenario for the patient involved walking from the bed and entering the bathroom in the VR home environment (Fig. 2). The patient was instructed to walk to the bathroom door using a four-point cane and to simulate opening the door by holding the handrail. He was advised to keep as close as possible to the right when reaching for the bathroom

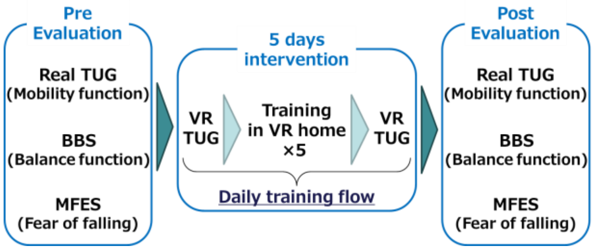

Figure 4. Training and evaluation protocol in Experiment 2.

Figure 5. VR training being performed by the patient.

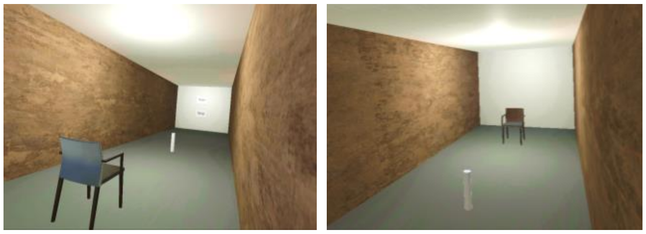

Figure 6. VR-simulated TUG test environment (VR-TUG).

door in order to prevent his affected left side from hitting the wall and furniture. The patient was notified of a collision via visual feedback through the HMD worn by the patient in both sessions of the VR home training and the VR-TUG.

III. RESULT

A. Healthy participants

The number of collisions, walking time, and number of steps were comparable between both groups in the first trial. Two training sessions with visual feedback significantly reduced the walking time ($p = 0.04$) and the number of collisions ($p = 0.02$). These parameters did not improve in participants without visual feedback (Table I). There was no change in the number of steps, regardless of the group.

B Stroke patient

Figures 7 and 8 show the transition in walking time and the number of steps in the VR-TUG test, before and after the daily intervention. Both the walking time and the number of steps decreased after training on the first day. Although there was day-to-day variation, both parameters showed an overall decrease over the study period. Table II shows the changes in walking time and the number of steps in the TUG test in real-space throughout the 5-day intervention. The intervention improved walking time and the number of steps in the TUG tests both in VR and in real-space. The therapist confirmed that the turning radius around the pole decreased, and the swinging movement of the affected (left) leg improved in the TUG test. Although the MFES scores were unchanged, the BBS scores showed improvement after the intervention (Table III).

TABLE I. RESULTS OF EXPERIMENT 1
VALUES ARE EXPRESSED AS MEDIAN (INTERQUARTILE RANGE). ASTERISKS INDICATE SIGNIFICANT CHANGES RELATIVE TO THE 1ST TRIAL.

		1st trial	4th trial
Visual feedback group	Walking time [s]	9.94 (4.41)	8.69 (2.40)*
	Number of steps	13 (4.00)	13 (1.50)
	Number of collisions	2 (1.00)	1 (1.25)*
No feedback group	Walking time [s]	9.53 (3.88)	8.29 (3.33)
	Number of steps	13 (3.00)	12.5 (3.50)
	Number of collisions	1 (2.00)	1 (2.00)

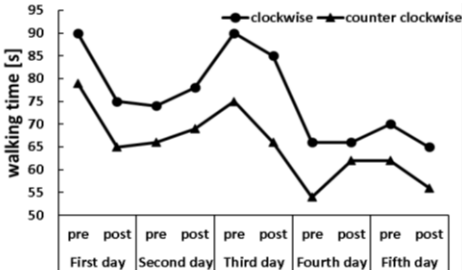

Figure 7. Daily transitions in walking time in the VR-TUG before and after intervention.

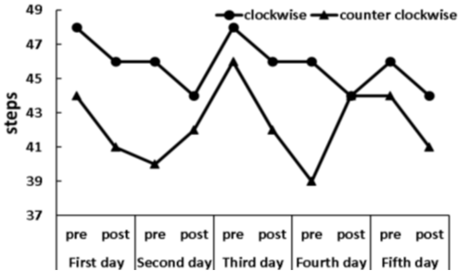

Figure 8. Daily transitions in the number of steps in the VR-TUG before and after intervention.

TABLE II. CHANGES IN WALKING TIME AND THE NUMBER OF STEPS IN REAL-SPACE TUG BEFORE AND AFTER VR TRAINING INTERVENTION.

		Pre	Post
Walking time [s]	clockwise	77	47
	counterclockwise	56	44
Number of steps	clockwise	44	37
	counterclockwise	37	33

TABLE III. CHANGES IN BBS AND MFES SCORES BEFORE AND AFTER VR TRAINING INTERVENTION.

	Pre	Post
BBS (Maximum possible score: 56)	34	40
MFES (Maximum possible score: 80)	69	69

IV. DISCUSSION

The proposed VR gait training system significantly improved the walking time and the number of collisions in healthy participants who received visual feedback as opposed to those who did not receive any feedback. These results suggest the importance of visual feedback as an indicator of objects that necessitate the participant's attention while walking. The immediate feedback successfully contributed to the development of participants' sense of distance from themselves to an object, and to the adjustment of their gait pattern in the VR space. The positive results of Experiment 1 further motivated us to employ the proposed system for gait rehabilitation for the patient with paralysis as a result of stroke.

The results of Experiment 2 demonstrated that the gait function of the patients could also be improved with the proposed VR training system. Importantly, the improved gait function in a home environment scenario was replicated in other scenarios as evaluated by the TUG test in real and VR spaces. The current training scenario in the VR home environment required adequate movement of the center of gravity to the paralyzed side in order to achieve precise rotation of the body in a confined space. Such goal-directed training might have contributed to the smaller turns recorded in the TUG tests. Although this is a single case report, these findings suggest the potential of gait training using a VR home environment to improve the mobility and balance functions of patients with stroke with lower limb paralysis.

The reduced walking time found in the current study also supports the previous findings of improved walking speed by VR-based rehabilitation [3, 4], although the walking time and the number of steps in VR-TUG showed a day-to-day variation. The increase in the time and number of steps after the training on the second day suggests that the patient began to take more time to carefully turn around without hitting the pole. The decrease of walking time after the third day indicates that the patient found an appropriate walking strategy. The MFES score of the patient was relatively high at the beginning of the intervention, suggesting that the patient originally had little fear of falling. The unchanged MFES score may be attributed to the ceiling effect.

The patient expressed the opinion that the VR used in this training was highly immersive and enjoyable. This suggests that VR training could be utilized as a rehabilitation tool that maintains the motivation of patients. Motivation is a predictor of outcomes, including health-related quality of life. In the early stages of intervention, motivation has been shown to have an important influence on the outcomes of rehabilitation [13]. VR-based gait training could contribute toward rehabilitation effectiveness. However, both the patient and therapists requested greater variation in the training scenarios and situations (i.e., other rooms of the house). We plan to increase the number of rooms and apply gamification functions in our program to maintain the motivation of patients over the long term. Therapists also commented that they could identify activities that were difficult to perform alongside patients when the latter actually performed the intended movements. Additionally, they were able to identify locations in the patient's house where the risk of falling was high. The standard training provided at the hospital did not allow such individualized therapy. The proposed VR platform could be useful to simulate walking at home as well as to confirm the renovation plan before the patient is discharged.

In conclusion, the results suggest that gait training in a VR-simulated home environment with visual feedback could improve mobility and balance functions in patients with lower limb paralysis due to stroke. The benefit of using a VR home environment is that patients can simulate walking in a customized home environment before discharge without the risk of collisions and falls. Since the duration of the training was limited to five days due to the scheduled discharge date of the patient, further study is required to determine whether long-term and repetitive VR-based training would be necessary to maintain improved gait function. Further studies should also increase the number of patients, compare the outcome with control patients who underwent conventional in-hospital gait training, and include a follow-up investigation of falls in discharged patients.

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