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Abstract

Background: Rehabilitation therapy using virtual reality (VR) system for stroke patients has gained attention. However, only few studies have investigated fully immersive VR using a head-mount display (HMD) for upper extremity rehabilitation in stroke patients.

Objective: To investigate the feasibility, preliminary efficacy, and usability of a fully immersive VR rehabilitation program using a commercially available HMD for upper-limb rehabilitation in stroke patients.

Design: A feasibility study

Setting: Two rehabilitation centers

Participants: Twelve stroke patients with upper extremity weakness

Interventions: Five upper extremity rehabilitation tasks were implemented in a virtual environment, and the participants wore an HMD (HTC Vive) and trained with appropriate tasks. Participants received a total of 10 sessions two to three times a week, consisting of 30 minutes per session.

Main Outcome Measures: Both patients' participation and adverse effects of VR training and were monitored. Primary efficacy was assessed using functional outcomes (action arm reach test, box and block test, and modified Barthel index), before and after the intervention. Usability was assessed using a self-reported questionnaire.

Results: Three patients discontinued VR training, and nine patients completed the entire training sessions and there were no adverse effects due to motion sickness. The patients who received all sessions showed significant functional improvement in all outcome measures

after training ($P < .05$ for all measures). The overall satisfaction was 6.3 ± 0.8 on a 7-point Likert scale in all participants.

Conclusions: A fully immersive VR rehabilitation program using an HMD for rehabilitation of the upper extremities following stroke is feasible and, in this small study, no serious adverse effects were identified.

Level of evidence: Level IV

Keywords : Upper extremity rehabilitation, Virtual reality, Head-mount display

Introduction

The term virtual reality (VR) is as a device-driven definition coined by Jaron Lanier in 1989 [1]. Currently, the term VR refers to an interactive computer-generated experience with multimodal sensory feedback provided through a variety of hardware. VR has been used in medicine as a tool for rehabilitation therapy in various diseases such as stroke, cerebral palsy, and severe burns [2–4], as well as in medical education using three-dimensional computer graphics [5]. In particular, rehabilitation therapy using VR for patients with brain injury has gained attention because it can provide a more enriched environment and goal-oriented tasks with repetition, and stimulate the neuroplasticity of the injured brain in terms of interest and motivation [6,7]. VR technologies can be categorized as non-immersive, semi-immersive, and fully immersive according to the degree of immersion [8]. Immersion means the perception of being physically present in a virtual environment. This may prove to be an important feature of VR rehabilitation.

The Cochrane group performed a systematic review and meta-analysis of rehabilitation in patients with stroke using VR. A total of 37 studies involving 1019 subjects reported that VR rehabilitation was somewhat effective in improving upper extremity function and daily life function, but the level of evidence in each study was low [9]. However, since most of the studies were based on simple non-immersive VR systems, such as commercial game devices (e.g., Nintendo Wii), they did not fully reflect recent technological developments. A recent multicenter, randomized controlled trial using non-immersive VR has also not demonstrated the superiority of VR rehabilitation in stroke patients [10].

With the recent introduction of commercially available head-mounted display (HMD)

technology, such as the Oculus Rift and HTC Vive, the accessibility of fully immersive VR technology has dramatically improved. In addition to the advantages of existing VR rehabilitation therapy, fully immersive VR using an HMD might have further benefits which can enhance brain plasticity by similar mechanism of mirror therapy or action observation through self-awareness of the body in the virtual space [11,12]. Therefore, we developed VR rehabilitation software by incorporating tasks targeting upper extremity rehabilitation using fully immersive HMD. The purpose of this study was to investigate whether fully immersive VR rehabilitation using HMD is feasible in stroke patients with upper extremity weakness.

Methods

Participants

The study included 12 consecutive participants with upper extremity weakness caused by stroke in two rehabilitation centers. The inclusion criteria were as follows: (1) age > 18 years; (2) upper extremity weakness due to stroke (3) a score of at least 3 points on the Medical Research Council scale for shoulder flexion/extension and elbow flexion/extension; (4) presence of stable sitting balance; and (5) voluntary agreement to participate in the study. The exclusion criteria were as follows: (1) cognitive impairment resulting in cooperation difficulties (a score of ≤18 in the mini-mental state examination); (2) peripheral nerve injury, joint disease, and other diseases of the upper extremity dysfunction other than brain disorders; (3) predisposing vestibular disorders or any history of seizure; and (4) any medical problem that could impede participation. The study was approved by the appropriate ethics review board and registered at ClinicalTrials.gov (NCT03196739). All participants provided written informed consent that included a detailed description of the potential adverse effects of VR rehabilitation, in particular, symptoms of motion sickness.

Intervention

HTC Vive (HTC Corporation, Xindian City, Taipei) was used as an HMD, and the positions of the HMD and the controllers were calibrated before the training. The participant was sitting on a chair, holding a controller in the affected upper extremity, and supervised by an experienced occupational therapist during the entire training process. The therapist trained participants to use the VR device and informed them about the possible adverse effects of

HMD. He also set up the VR tasks and helped to manipulate the software for the duration of the training session. Physical assistance was provided for certain patients who had weak hand power and therefore could not manipulate the controller. In a virtual training space, the controller is designed to look like a patient's own hand. Our VR upper extremity rehabilitation program consisted of five types of tasks: hammering, ball catch, cup pour, bubble touch, and playing a xylophone (Figure 1). Participants experienced all the tasks before the VR intervention. The participants then trained with appropriate tasks according to their function and preference. To perform each task, the participants gripped the controller and manipulated the controller using their index finger to implement the grip motion of the virtual hand. For those participants who could not operate the controller with their index fingers, it was automatically operated by applying the program's easy-mode. The easy-mode works by automatically grasping when a hand in virtual space approaches a target object such as a ball, cup, or bubble. The training had a total of 10 sessions two to three times a week, consisting of 30 minutes per session. Each task was performed for at least 10 minutes and a maximum of three tasks could be performed in one session. Rehabilitation therapies prior to study enrollment were allowed during the training period.

Outcome Measures

The baseline characteristics including age, sex, handedness, time since stroke onset, stroke type, and affected body side were assessed. Before starting the training session, participants were given information about VR devices and the content of the intervention. We fully informed participants about the risk of motion sickness symptoms such as dizziness, nausea, and headache, which can occur when using HMD, and the participants were required to

report any adverse events or discomfort, including motion sickness, experienced at any point during training. All reported adverse events that occurred during the training session were recorded. The Action Research Arm Test (ARAT) and box and block test (BBT), which are highly reliable upper extremity functional assessments in brain disorders, were performed before and after an intervention [13]. Modified Barthel index (MBI) was also used to measure performance in activities of daily living. Participants' training completion was recorded, and the usability of VR rehabilitation program was assessed using a self-report questionnaire with a 7-point Likert scale on 8 items (symptom improvement, interest, motivation, difficulty, discomfort, anxiety, intent to continue training, overall satisfaction, and expectations for VR rehabilitation) after the training.

Statistical analysis

The differences in ARAT, BBT, and MBI before and after VR rehabilitation training were compared using Wilcoxon signed-rank test. P values $< .05$ were considered statistically significant. Statistical analyses were performed with SPSS 21.0 (IBM Corp, Armonk, NY, USA).

Results

The mean age of the twelve patients (male 7) was 40.2 ± 17.8 years, and the mean duration of the disease was 36.0 ± 61.9 months. Only three patients had ischemic stroke, and the others had hemorrhagic stroke (Table 1). Patient 6 discontinued training after six sessions due to the adverse effects of training on preexisting shoulder pain symptoms. However, no adverse effects related to motion sickness, such as nausea and dizziness, were reported during the training session in all patients. Three patients, including patient 6, discontinued VR training. Patient 2 discontinued after two sessions due to severe depression. Patient 12 dropped out after three sessions due to personal reasons as she no longer wished to participate in the study. Of the nine patients who completed the training, five showed improvement both in ARAT and BBT. ARAT (pre-training 22.3 ± 20.1, post-training 31.1 ± 19.6; P = .028), BBT (pre-training 11.2 ± 16.3, post-training 19.6 ± 29.3; P =.012), and MBI (pre-training 90.4 ± 8.5, post-training 93.0 ± 5.0; P = .042) significantly improved after the training (Figure 2). The 95% confidence intervals of improvement were 1.0-16.5 and -0.8-17.5 in the ARAT and BBT tests, respectively. Of note, patients 1 and 6 showed an improvement of 35 in the ARAT score and 44 in the BBT score, respectively. The self-report questionnaire was obtained from all twelve patients, including the three patients who dropped out, and the result showed a score of 5 or higher on all items. Overall satisfaction was 6.3 ± 0.8. Interest (6.4 ± 0.9) and intent to continue training (6.4 ± 0.8) items had the highest scores, whereas discomfort (4.9 ± 1.8) had the lowest score (Figure 3).

Discussion

The results of our study showed that a fully immersive VR rehabilitation program using HMD was feasible and might improve upper extremity function and activities of daily living in stroke patients. This VR rehabilitation program did not show any serious adverse events during the training period, and the overall satisfaction was very high. Only a few studies have used a fully immersive VR using HMD for upper extremity rehabilitation in stroke patients. Crosbie et al. [14] developed the HMD hardware and rehabilitation program and applied it to the upper extremity rehabilitation in stroke patients. However, no data on functional improvement was reported and high incidence of side effects was noted (transient symptoms of headache, dizziness, discomfort, and nausea)[14]. Levin et al. [15] applied HMD and haptic device to the upper extremities of stroke patients, but they focused on the effects of haptic feedback on subject's motion in virtual environment and physical environment. This clinical study is the first to evaluate the feasibility and preliminary efficacy of a fully immersive VR using a commercially available HMD in upper extremity rehabilitation of stroke patients.

Anyone over 18 years of age was able to participate in this study; however, it seems that relatively young patients showed more interest in VR rehabilitation during the recruitment process. The average age of the participants was 40.2 ± 17.8 years, which may reflect this preference. The generation gap may be considered as another issue confronting VR rehabilitation and further investigation is required.

In this study, nine subjects who completed whole VR training sessions showed significantly improved upper extremity function in the ARAT and BBT tests. Although this study is not a

randomized controlled trial, a remarkable change was found considering that all patients were in a chronic state (onset > 5 months). One of the possible mechanisms of a fully immersive VR rehabilitation is motor imagery, which is proposed as the underlying mechanism of mirror therapy in stroke [16]. VR can provide visual feedback to the patient like a mirror. Giraux and Sirigu have proven that VR increases the activity of the corresponding M1 cortex in patients with brachial plexus injury [17,18]. Reversing the "learned nonuse" of the affected limb can also be another mechanism of VR upper extremity rehabilitation. Constraint-induced movement therapy is known to be an effective treatment for chronic stroke patients, and overcoming learned nonuse of the paretic arm through intensive training is regarded as an important mechanism [19,20]. Fully immersive VR rehabilitation programs may enhance immersion and facilitate task performance using the affected upper limb in a similar manner to constraint-induced movement therapy. Further investigations on the effect of immersion and the mechanism of VR rehabilitation are required.

Although one patient dropped out due to the adverse effects of aggravation of preexisting shoulder pain, this was not considered to be a direct effect of VR and therefore could not have been prevented by the therapist who provided the VR training. Motion sickness is a common serious adverse effect of the VR system, particularly when using HMD [21]. This has been pointed out as a limitation in applying HMD to patients, and a previous study showed such results [14]. There is a possibility that symptoms of motion sickness could have gone unreported as no structured questionnaire was used to assess adverse effects; however, the patients in our study did not explicitly report these adverse effects. One of the possible causes is the improved image resolution and time lag between the motion and display output in the current HMD device compared with previous devices. Various factors, such as standing

postures and head movements, are known to aggravate motion sickness in the HMD [22,23]. Therefore, the patient sat in a chair and requested to reduce any movement other than the upper extremities, including head movements, during our VR rehabilitation training. The virtual environment was also configured to be as simple and familiar as possible.

According to the results for the usability of the system, participants' satisfaction was very high and levels of discomfort were modest. Anxiety was reported to be low during the VR training. Although wearing an HMD was an inconvenience, this appeared to be tolerable to most of the study participants. Although it is not apparent from this small study, demographic factors such as sex and age may determine a preference for virtual environment and VR equipment. These influences could be reflected in the changes to the VR rehabilitation program in the future.

Our study has a number of limitations. First, it is not sufficient to demonstrate the clinical usefulness of VR rehabilitation using HMD in stroke patients because this is a feasibility study with a small number of heterogeneous patients. Both ischemic and hemorrhagic stroke were included, and we enrolled both cortical and subcortical lesions including brain stem involvement. All patients had chronic stroke (onset > 5 months); however, the range in months after stroke varies from 5 to 227. Second, the problem on adverse effects has not been completely resolved. Further investigations, such as large-scale randomized controlled trial incorporating a more systematic approach to monitor adverse effects, are needed.

This fully immersive VR rehabilitation program also requires further improvements. First, our VR program does not include various tasks with hand motion except the second finger movement to manipulate the controller. This is a major limitation of upper extremity rehabilitation in stroke patients and should be overcome by applying various VR-related

devices about hand motion and haptics. Second, patients with severe hemiplegia or hand weakness after stroke cannot participate in our VR rehabilitation. This limitation can be improved by combining robotics with VR. Finally, the virtual environment needs to be further improved. In the current program, only the patient's hand appears in the virtual space, not the whole upper extremity, which can interfere with the patient's embodiment [24]. This may affect the actual therapeutic effect in terms of motor imagery.

Conclusion

Our preliminary study suggests that a fully immersive VR rehabilitation program using an HMD can be used for upper extremity rehabilitation in patients with chronic stroke without serious adverse effects. This VR rehabilitation system requires further investigations, such as a large-scale clinical trial with a structured questionnaire to monitor potential adverse effects in the future.

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Figure legends

Figure 1. Five upper extremity rehabilitation tasks (hammering, catch ball, cup pouring, bubble touching, and xylophone playing) in the virtual environment. The left column shows the captured virtual space that appears on the computer screen and the patient experiences the 3-dimensional virtual space in the head-mount display (HMD). The right column shows the patient wearing the HMD and performing the actual tasks. Participants experience all the tasks before the virtual reality (VR) intervention and then select two most favorite tasks. The participant performs the VR task while holding the controller by hand and manipulating (gripping subjects such as hammer or ball) it with the index finger. For those participants who cannot use their index fingers, it is automatically operated by easy-mode provided by the program. (A) Affected limb holds the hammer and hits the nail in the virtual space. The hand holding the nail is automatically created in virtual space. (B) Affected limb catches the ball from the front of the virtual space and throws it again. (C) Affected hand in virtual space pours the strawberry in the cup to the bowl. (D) Touching and blooming the floating bubble in the virtual space with the affected limb. (E) Affected limb plays a xylophone in virtual space.

Figure 2. Results of upper extremity function and activity of daily living evaluation before and after virtual reality rehabilitation using head-mount display in nine chronic stroke patients. (A) Action arm reach test, (B) box and block test, and (C) modified Barthel index. *$P < .05$.

Figure 3. Usability assessment results of virtual reality rehabilitation program using head-mount display by a self-report questionnaire using a 7-point Likert scale on 8 items.

Table 1. Clinical characteristics and functional outcome measures before and after VR training using HMD in all subjects

No	Age	Sex	Stroke type	Brain lesion	Affected side	Duration (Mos)	ARAT		BBT		MBI	
							pre	post	pre	post	pre	post
1	30	F	H	Lt. BG	Rt	5	13	48	5	9	70	83
2	29	M	H	Rt. BG	Lt.	7	11	-	16	-	67	-
3	24	F	H	Lt. frontal	Rt.	22	5	5	0	1	96	97
4	19	M	H	Lt. thalamus	Rt.	19	8	13	1	4	92	92
5	23	F	H	Lt. thalamus	Rt.	20	56	57	19	21	96	98
6	49	M	H	Lt. BG	Rt.	6	38	-	22	-	93	-
7	23	F	I	Lt. MCA territory	Rt.	57	20	31	1	2	95	95
8	55	M	I	Rt. Medullar	Lt.	5	57	57	51	95	94	95
9	61	M	H	Lt. thalamus	Rt.	22	22	29	8	22	87	93
10	40	M	H	Rt. BG	Lt.	11	10	10	6	12	87	87
11	59	M	H	Lt. BG	Rt.	31	10	30	10	10	97	97
12	70	F	I	Rt. IC	Lt.	227	37	-	31	-	65	-

VR= virtual reality; HMD = head-mount display; No = number; F = female; M = male; H = hemorrhagic: I = ischemic; Rt = right; Lt = left; BG = basal ganglia; MCA = middle cerebral artery; IC = internal capsule; Mo = month; ARAT = action arm reach test; BBT = box and block test; MBI = modified Barthel index