Task-specific virtual reality training on hemiparetic upper extremity in patients with stroke

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Abstract

Task-specific training has been proven to be effective in promoting recovery of the hemiparetic upper extremities after a stroke. This study was to develop a task-specific VR (TS-VR) program using a leap motion controller device and the Unity3D game - engine to promote recovery of the hemiparetic upper extremity in patients with stroke based on a hierarchy of seven functional tasks in the ~~Functional Test~~ functional test for the ~~Hemiplegic Upper Extremity~~ hemiplegic upper extremity (FTHUE). The final version of the TS-VR was tested on 20 patients suffering from chronic stroke with upper-extremity hemiparesis over 2 weeks, 5 sessions per week, 30 min per session. Outcomes were assessed using the Fugl-Meyer ~~Assessment~~assessment ~~Upper Extremity~~ upper extremity score (FMA-UE), the Wolf ~~Motor Function Test~~ motor function test (WMFT), and the ~~Motor Activity Log~~ motor activity log (MAL) at the first (week 0), last (week 2), and follow-up sessions (week 5). Patients' arm impairments were stratified into lower (levels 1–4) and higher (levels 5–7) functioning groups according to the FTHUE. Significant improvements were found after TS-VR training in FMA-UE total score and its subscores, and WFMT score among the three time occasions (p = 0.000), but no significant effect on grip strength was found. The higher-functioning group benefited more from the TS-VR, as indicated in outcome measures as well as amount of use score in MAL, but this was not the case for those in the lower-functioning group. Our findings show the TS-VR training was useful for upper-extremity recovery in patients with chronic stroke. It has potential to be applied in clinical settings in future.

Keywords: Rehabilitation, Training stroke, Virtual reality, Evaluation, Upper limb, Task-specific training, Leap motion controller

Abbreviations

AR	Augmented reality
FMA-UE Total score	Fugl-Meyer assessment-upper-extremity total score
FMA-Hand	Fugl-Meyer assessment-upper limb subscore
FMA-Hand	Fugl-Meyer assessment hand subscore
FTHUE	Functional test for the hemiplegic upper extremity
Group 1	Higher-functioning group
Group 2	Lower-functioning group
LMC	Leap motion controller
MAL-AOU	Motor activity log-amount of use scale (AOU)
MAL-QOM	Motor activity log-quality of movement scale (QOM)
TS-VR	Task-specific virtual reality program

WMFT	Wolf motor function test
VR	Virtual reality

Introduction

Upper-extremity hemiparesis is one of the major concerns for patients who have suffered a stroke following their discharge from the hospital. Up to 70% of chronic stroke patients have motor dysfunction in their upper extremities to perform meaningful activities after stroke (Borschmann and Hayward **2020**), and only 5% of them demonstrating complete functional recovery (Dobkin **2005**). Among them, only 5–20% of acute stroke patients regained full function, while 33–60% continued to have a limited function after 6 months (Kwakkei and Kollen **2013**).

According to the current international clinical guidelines for stroke management, intensive and frequent practice of task-specific training in the activities of daily living (ADL) has been proven to be effective in promoting recovery of the upper extremities following a stroke (Cunningham et al. **2016**). Many research findings have indicated that the best way to relearn a given functional task in ADL is to train specifically for that task through repetitive and consistent practice (Cauraugh and Kim **2003**). Task-specific training has the benefits of promoting cortical reorganization and associated functional improvements~~,~~; hence, the rehabilitation outcomes are more successful when the tasks are meaningful to the person (Bayona et al. **2005**). Previous studies have found that task-specific upper limb training can lead to significant improvements in motor function and daily use of the hemiparetic limb among stroke patients (Galea et al. **2001**; Page **2003**). There is also an increasing trend for task-specific training to move away from traditional approaches that use objects in ADL ~~towards~~ toward the use of novel technology so as to meet the evolving needs of stroke patient care (Timmermans et al. **2009**).

Virtual reality is nowadays widely used as part of rehabilitation (Ghassemi et al. **2019**) because of its ability to bridge the gap between laboratory training and the real-life tasks involved in daily living. Virtual reality (VR) is a technology that allows people to view, navigate, and interact with a simulated three-dimensional world in real - time. VR comes with different kinds of interactivity according to different immersion levels. Two of its advantages are that it poses no threat to or physical limitations upon patients in the simulated environment, and it can easily be modified to change levels of difficulty, which may not be possible in the real world (Tang et al. **2020a**, ~~**2020b**~~ **b**). It also has advantages over normal computer-based rehabilitation programs. It can address real-time aspects of information processing, enhance dynamic interaction with the virtual environment, and promote patients' intention and willingness to do training (De Mauro **2011**). Moreover, a VR environment allows real-time data to be collected and analyzed, so that therapists can adjust and monitor patients' progress in order to increase the efficiency and effectiveness of rehabilitation (Fong et al. **2010**). There is mounting evidence showing that VR technology provides therapeutic benefits in the ~~improving~~ improvement of the motor function of the upper extremities during stroke rehabilitation (Saposnik et al. **2011**). VR using ~~3~~three-dimensional motion tracking system with adapted complexity of motor tasks in an augmented environment and a high-resolution screen displaying the virtual scenarios had been found to be useful to improve motor function of the upper limb after stroke in recent randomized controlled studies (Kiper et al. **2018**; Turolla et al. **2013**). However, most existing VR-based rehabilitation ~~focus~~ focuses on training of the proximal upper extremity, and there is limited research on its effectiveness on the distal upper extremity (Shin et al. **2016**). For this reason, it would be useful to develop a task-specific VR training program for a hemiplegic hand and examine its effects on patients following a stroke.

The VR system comprises five classical elements. These are the VR engine; input and output devices; the software and database; the user; and the task. Unity3D is a cross-platform game engine used to develop 3D games and applications for computers, consoles, websites, and mobile devices. The input and output devices include traditional ~~Head~~head-~~Mounted Display~~ mounted display (HMD), VR gloves, etc. Recently, Microsoft HoloLens was developed, providing holographic experiences for the user and allowing interaction with digital content dynamically in real - time (Tang et al. **2018**, **2020b**). These devices are used not only for training but also in musculoskeletal rehabilitation (Condino et al. **2019**) and post-stroke rehabilitation (Hossain et al. **2016**). However, these devices have some limitations including usability, potential risks to the users and discomfort after prolonged usage (Renganayagalu et al. **2021**; Syberfeldt et al. **2015**). On the other hand, a lot of VR training focuses on collecting patients' cognitive performance data rather than their physical performance and motion data. The leap motion controller (LMC), shown in Fig. **1**a, is a modern, low-cost,

contact-free, and portable input device used for real-time gesture and position tracking of hands (Okazaki et al. 2017). The accuracy of fingertip position tracking is very precise (approximately 0.01 mm) (Weichert et al. 2013; Lee et al. 2018). Given these benefits, it was judged that the LMC could best serve as a cost-effective input device for motor recovery training focused on the distal upper extremity.

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Fig. 1 The experimental setup. **a** The leap motion controller used to capture the motion of the wrist and each finger joint. **b** Setup of the experiment. The LMC was installed in front of the monitor. The patients were seated in front of the computer and the LMC is located at the waist level of the patients. This provided enough space for them to move the upper extremity in order to complete the TS-VR tasks

A recent systematic review and meta-analysis shows that the use of LMC in combination with conventional therapy improved upper-extremity mobility and mobility-oriented on both gross and fine motor dexterity in stroke (Cortés-Pérez et al., 2021). Recently, Fernández-González et al. (2019) designed a video game-based therapy that used the LMC to provide upper limb rehabilitation for patients with Parkinson's disease. The LMC was used to capture the movement of the patient's forearms and hands. Wang et al. (2017) explored the effects of a leap motion-based virtual reality system on subacute stroke. The trainings were designed based on the pinching, grasping, and individuating motor skills of fingers. Home-based training is particularly important for patients after hospital discharge, allowing them to practice within a familiar environment, as well as better enabling them to recall their memories during daily practices. In this study, we sought to substantiate an interactive treatment that involves promoting the use of the hemiparetic upper extremity in chronic stroke patients by developing a VR task-specific training program with three stages. In stage 1, we aimed to design a task-specific VR program (TS-VR) using Unity3D and LMC as input devices. The program consists of seven general hand function tasks involved in ADL. In stage 2, we examined the content validity of the TS-VR according to the views of an expert panel and through field testing on patients with stroke. In stage 3, we aimed to recruit patients with stroke to participate in our 2-week TS-VR training program. Our purpose was to investigate its clinical utility. In particular, we wanted to determine whether the lower-functioning or the higher-functioning group of clients with paretic upper-extremity functional impairment would benefit more from the TS-VR program. The findings of this study could further contribute to the effective care of those with stroke by helping to extend the application of TS-VR to home-based training, as well as to rehabilitation in hospitals and community settings.

Methods

In this paper, the design of a task-specific VR program (TS-VR) using Unity3D and LMC is illustrated in Sect. 2.1. We examined the content validity of the TS-VR based on the views of the expert panel and field testing on stroke patients in Sect. 2.2. The experimental setup and study procedure are also illustrated in this section. In Sect. 2.3, patients with stroke were recruited to participate in the 2-week TS-VR training program. The outcome measures and statistical analysis are illustrated in Sects. 2.4 and 2.5, respectively.

Task-specific virtual reality training program (TS-VR)

In stage 1, we developed the TS-VR using Unity3D (version 2017.3.1f1) and the LMC (version 3.2.1) as input devices for capturing real-time 3D positioning of the hand. The computer programming language C# was used in the development of the training programming. The TS-VR consists of seven general hand function tasks involved in ADL. These are designed according to the severity of the specific upper limb impairment of stroke patients, with reference to the levels 1–7 in the ~~Functional Test~~ functional test for the ~~Hemiplegic Upper Extremity~~ hemiplegic upper extremity (FTHUE) (Fong et al. 2004; Wilson et al. 1984). This hierarchy of task-specific movements on a graded level of difficulty was based on patients' levels of upper-extremity functioning in the FTHUE and chosen with reference to their functional levels that had been reported to be useful in our previous studies (Wei et al. 2019; Fong et al. 2011). The standardized tasks in the program for each level of impairment were carried out by the performing of discrete movements used in functional activities. These included bilateral and unilateral use of both hands, range of motion tasks, pronation and supination, and grasp and release (e.g., pouring water from a bottle) with the affected upper limb. The training tasks used in the TS-VR program and the corresponding levels (1–7) in the FTHUE are: Level 1—Pushing a door with both hands (non-affected hand holding affected forearm); Level 2—Picking up a cup from the affected side of the table and moving to non-affected side; Level 3—Holding a pouch in a

static position for 15 s; Level 4—Picking up a cup from the non-affected side of the table and moving to affected side; Level 5—Picking up a water bottle and pouring water into a cup; Level 6—Picking up a book and placing it on a bookshelf; and Level 7—Pressing the password pad. Figure 2 shows a screenshot of selected training tasks used in the training program, such as pushing open a door, pouring water, and pressing a button.

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Fig. 2 Samples of the TS-VR training task. **a** Task 1—pushing door; **b** Task 5—pour water from the bottle; **c** Task 3—hold pouch for 15 s; **d** Task 7—Pressing password pad

Unity3D is a cross-platform game engine that has been widely adopted by various industries for the development of VR programs, augmented reality (AR) games, computer simulations, and other experiences. Figure 3 illustrates the workflow of the development process for the TS-VR program with the pseudo-code. The 3D virtual environment and models are first created using SolidWorks. The models are then exported to FBX format and imported to the gaming engine. The imported models are usually gray in color, and the Unity engine supports and provides a physically based rendering material system to create realistic textures and color in various virtual scenes. Custom textures like wood and bricks can be added to the 3D models. The engine also provides a user-friendly interface for the adjusting of material values and parameters, such as "Metallic" and ~~"Smoothness"~~"Smoothness." This enables the creation of a natural virtual environment under different lighting in real-time.

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Fig. 3 Example of pseudo-code of the pressing password task. Pseudo-code of the pressing password task in Fig. 2d—The program starts by generating a ~~4~~four-digit random password. All game objects in the virtual scenes will be searched. If the game object is a password pad and the collider is triggered, then the corresponding digits of the input number will be saved. Finally, the input number will be checked to see if it matches with the random password. The task will end if the password is matched; otherwise, the task will restart

In this study, we made use of the LMC to capture the 3D position of the hand, including the position of the wrist and fingers by interpret the 3D data and infer the positions of the hand (Colgan **2017**). The feature points in the wrist and fingers are extracted to interpolate the motion of the hand. The capturing space of the LMC is a 1-m hemispherical view area with a 150° field of view. The designed TS-VR program track users' finger movements at a rate of over 300 frames per second, such that the screen display changes continually along with the user's every movement. The setup of the experiment is illustrated in Fig. 1b.

In the TS-VR program, the Cartesian coordinate system in millimeters (mm) is used for calculation. In the beginning, the origin is located at the middle of the device. These coordinates are converted to screen coordinates depending on the screen size or window size of the application, calculated by Eq. 1 (Krastev and Andreeva **2015**):

$$\left({V_{x} ,V_{y} } \right) = \left({\frac{{\left({O_{x} \times U_{x} \times 2} \right)}}{{U_{x} }} + \frac{{U_{x} }}{2},U_{y} - { }O_{y} } \right), \quad (1)$$

where V_x and V_y are the x- and y-coordinates with respect to (w.r.t.) the screen coordinates; U_x and U_y are the width and height of the window; and O_x and O_y are the x- and y-coordinates w.r.t. the LMC coordinates.

To train the ~~Hemiplegic Upper Extremity~~ hemiplegic upper extremity functions of the patients, interactions between different virtual models in the TS-VR training program are required. For instance, when patients push a door or press the password pad, the door will open and the password will display on the screen. In this case, a collider defined by common primitives in the space of the virtual objects is used to determine the interaction with the patients. A collider is a bounding box surrounding the virtual models. An interaction is triggered when the distance between the models and the finger is smaller than the distance threshold. The pseudo-code in Fig. 3 illustrates the pressing password pad task. In this task, the password is randomly generated. When the virtual hand model triggers the collider, the corresponding password number will be recorded and compared with the generated password. The task ends when the password is correct; otherwise, this task will restart. Similarly, other tasks, such as holding a pouch or placing an object, also need to trigger the collider, and then a check is done to determine whether the task has been completed.

Rehabilitation and assessment

In stage 2, we sought qualitative comments for the TS-VR from an expert panel, composed of 10 occupational therapists, each with at least 3 years of experience in stroke rehabilitation. The panel interviewed 10 clients with stroke of various impairment levels recruited by convenience sampling in the community. After the interview, the object component, program structure, and demonstration videos of the program were modified according to the comments of the panel, but the VR tasks remained similar in terms of content and difficulty.

In stage 3, we investigated whether a 2-week program using TS-VR training would promote recovery of the paretic hand in patients with chronic stroke, using a single group longitudinal design study. Twenty patients were invited to participate in the TS-VR at the university laboratory. There was a total of 10 sessions, every 30 min in length, held 5 days per week over two consecutive weeks.

The equipment was set up as shown in Fig. **1**b. The LMC was installed on the table located in front of the monitor. The patients were seated in front of the computer at a distance of an arm's length in order to provide enough space for them to move the upper extremity for completing the TS-VR tasks. The tasks were displayed on the computer monitor in front of the patients at a standard table height about the level of the elbow. The study was carried out under the one-to-one supervision of an occupational therapy student who was one of the investigators and had undergone training in using the TS-VR. Patients were instructed to sit on the chair, or else on their wheelchair. The LMC was placed on a table so that it is located at the waist level of the patients. The height of the chair was adjusted to fit the waist level height of the LMC, and in front of the participant at a distance of half of the arm length to ensure the best sensitivity. In the first session, demonstrations were given by the investigator for each level of the TS-VR training tasks to ensure that patients understood how to perform the task correctly. In the following training sessions, the training regimens were tailored to the needs of the patients by adjusting the modes of training (i.e., the progressive and repetitive modes, respectively). For progressive mode, patients were instructed to perform the TS-VR tasks from level 1 to the highest level they could attain. For repetitive mode, patients were instructed to perform a specific task level repetitively for 5–10 min. Both progressive mode and repetitive mode were used in each 30 min training session, depending on patients' needs, performance, and fatigue level. Patients with lower functioning (FTHUE of 1–4) were allowed to perform the TS-VR training task level 1 or 2 with the assistance of the non-affected hand.

In the beginning, during, and after each training session, patients were allowed to take a rest and do stretching exercises to relieve any tightness, tiredness, or discomfort of their paretic upper extremity. During the training, verbal and tactile cues were given by the investigator to correct patients' abnormal posture and associated movement when they were performing the TS-VR tasks. Visual and audio cues which were built-in to the TS-VR also provided sensory feedback to the patients. The time and error records after each completion were also recorded in order to provide immediate feedback to the patients.

Participants

Twenty patients with stroke were recruited from within a community self-help group for stroke, using convenience sampling. The inclusion criteria were: (1) stroke with unilateral hemispherical involvement; (2) aged 18 or above; (3) stroke onset of 6 months or more before the study; (4) able to understand verbal instructions and follow one-step commands; (5) no excessive spasticity, defined as a score of 2 or higher on the Modified Ashworth Scale (Bohannon and Smith **1987**); (6) no complaints of excessive pain or swelling over the paretic upper extremity; (7) no prior participation in any experimental or drug studies, or conventional rehabilitation therapy within 1 month; and (8) able to understand the meaning of the study and give informed consent to participate. The choice of a post-stroke period of 6 months or above as an inclusion criterion for patients with chronic stroke reflected the probability that any spontaneous recovery would have slowed down by the time of the study, thus enabling more brain reorganization in response to the therapeutic intervention under study. Before the commencement of the study, written and informed consent was obtained from all patients. The study was carried out in accordance with the principles of the Declaration of Helsinki. Ethical approval was sought and obtained from the Human Ethics Committee of the Hong Kong Polytechnic University (Ref. no.: HSEARS20180503002).

In order to investigate which level of severity of upper-extremity impairment would benefit more from the TS-VR training, we recruited patients of different arm impairment levels. Then, patients were further

stratified into two groups according to whether their hemiparetic upper-extremity functional impairment was severe to moderate or mild: Group 1, the lower-functioning group, included eight patients with severe to moderate impairments to a hemiparetic upper extremity (i.e., FTHUE level 1–4) who were able to move with bilateral arms, to demonstrate a mass flexion pattern in the shoulder/elbow, then an active extension control of the shoulder/elbow; Group 2, the higher-functioning group, included 12 patients with moderate to mild hemiparetic upper-extremity impairments (i.e., FTHUE level ≧ 5) who were able to demonstrate the beginnings of an ability to combine components of strong mass flexion and strong mass extension patterns, and who were able to perform some release of the hand, as well as isolated control of forearm and hand with fair strength.

Outcome measurements

Outcome measurements were ~~conducted~~ taken at baseline (pre-treatment, first session, week 0), post-treatment (last session, week 2), and follow-up (week 5) at the university laboratory. The primary outcomes were two laboratory-based assessments for arm functions, including the Fugl-Meyer ~~Assessment~~assessment-~~Upper Extremity~~ upper extremity score (FMA-UE) (Duncan et al. **1983**; Fugl-Meyer and Jaasko **1980**) and the Wolf ~~Motor Function Test~~ motor function test (WMFT) (Wolf et al. **2005**). The FMA-UE (Fugl-Meyer et al. **1975**) is a well-known impairment test which evaluates patients with stroke through selective movements. The upper limb subscore consists of 32 items, each of which represents movement components, scored on a three-point scale (0, 1, and 2). A higher score denotes a better recovery. The WMFT was chosen because the score range of this test is relatively greater and therefore more suitable for capturing both higher and lower levels of arm functioning in stroke patients (Ng et al. **2008**). The secondary outcome was a self-reported questionnaire, the ~~Motor Activity Log~~ motor activity log (MAL) (including the ~~Amount~~ amount of ~~Use~~ use scale (AOU), and the ~~Quality~~ quality of ~~Movement~~ movement scale (QOM)), indicating how often and how well patients used their affected arm in ADL (Uswatte et al. **2006**). It was administered for the actual arm use of the affected hand in daily life. It was carried out by asking patients about the use of their hemiparetic upper limb in 30 daily living activities over 1 week. Both subscales in the MAL—the AOU and the QOM—were shown to the patients while going through each item over the course of a semi-structured interview.

Statistical analysis

Data analysis was performed using SPSS. Baselines, including demographic data and pre-treatment scores for the outcome measures, were calculated according to descriptive statistics. Nonparametric tests were used because the data collected ~~was~~ were either categorical or because the sample size was small. The Friedman ~~Test~~ test was used to evaluate any significant difference in the hand functions and arm use of patients before and immediately after the training and at within-group follow-up sessions. The Wilcoxon ~~Signed~~signed-~~Rank Test~~ rank test was used for post hoc analysis, in which the measurements were taken for each variable on the three occasions (i.e., before and immediately after the training, and at follow-up) were compared to determine where any significant differences lay. The level of significance was set at $p \leqq 0.05$ for the Friedman ~~Test~~ test after Bonferroni adjustment ($0.05/n$; n = number of tests). The Friedman ~~Test~~ test and the Wilcoxon ~~Signed~~signed-~~Rank Test~~ rank test were later used for separate analyses when the patients were stratified into lower-functioning and higher-functioning groups according to the severity of their hemiparetic arm functional impairment.

Results

Patients' demographic characteristics are listed in Table **1**. Table **2** ~~show~~ shows the results of primary and secondary outcome measures at the baseline, ~~post-test~~posttest, and 3-week follow-up evaluations for the whole sample and the higher- or lower-function groups.

Table 1 Baseline demographics of study participants

Characteristics	All (n = 20)	Group 1 higher functioning (n = 12)	Group 2 lower functioning (n = 8)
Gender, n (%)			
Male	15 (75.0)	10 (83.3)	5 (62.5)
Female	5 (25.0)	2 (16.7)	3 (37.5)

Age, ± SD	62.0 ± 5.1	60.9 ± 5.1	63.6 ± 5.0
Onset to treatment (months), mean ± SD	37.4 ± 31.1	33.3 ± 33.2	43.6 ± 28.7
Education, *n* (%)			
Primary	2 (10.0)	2 (16.7)	0 (0)
Lower secondary	13 (65.0)	8 (66.6)	5 (62.5)
Higher secondary	5 (25.0)	2 (16.7)	3 (37.5)
Tertiary	0 (0)	0 (0)	0 (0)
Type of stroke, *n* (%)			
Ischemia	14 (70.0)	11 (91.7)	3 (37.5)
Hemorrhage	6 (30.0)	1 (8.3)	5 (62.5)
Right hand dominance, *n* (%)	20 (100.0)	12 (100)	8 (100)
Hemiparetic side, *n* (%)			
Left	9 (45.0)	4 (33.3)	5 (62.5)
Right	11 (55.0)	8 (66.7)	3 (37.5)
Levels of FTHUE, *n* (%)			
1	1 (5.0)	0 (0)	1 (12.5)
2	2 (10.0)	0 (0)	2 (25.0)
3	1 (5.0)	0 (0)	1 (12.5)
4	4 (20.0)	0 (0)	4 (50.0)
5	0 (0)	0 (0)	0 (0)
6	4 (20.0)	4 (33.3)	0 (0)
7	8 (40.0)	8 (66.7)	0 (0)

FTHUE functional test for the hemiplegic upper extremity

Table 2 Differences in primary and secondary outcome measures at pretest, posttest, and follow-up in the sample of 20 patients

Outcome measures	Groups	Pretest (1)	Posttest (2)	Follow-up (3)	χ^2	*p*	Multiple comparisons		
FMA-UL	All	23.7 ± 7.2	28.1 ± 8.1	28.4 ± 8.3	31.20	0.000**	1, 2	1, 3	
	Group 1	26.6 ± 5.2	32.2 ± 4.2	33.1 ± 3.7	21.33	0.000**	1, 2	1, 3	
	Group 2	19.4 ± 7.9	22.0 ± 8.9	21.3 ± 8.4	10.57	0.005**	1, 2	1, 3	
FMA-Hand	All	17.1 ± 8.2	20.0 ± 8.4	20.7 ± 8.5	22.58	0.000**	1, 2	1, 3	
	Group 1	22.1 ± 3.3	24.7 ± 3.2	25.6 ± 2.4	15.80	0.000**	1, 2	1, 3	
	Group 2	9.5 ± 7.5	13.0 ± 9.1	13.4 ± 9.3	6.91	0.032*	1, 2	1, 3	
FMA-UE Total	All	41.2 ± 14.5	48.2 ± 15.9	48.8 ± 16.2	34.22	0.000**	1, 2	1, 3	
	Group 1	49.4 ± 6.6	57.0 ± 6.7	58.2 ± 5.9	21.38	0.000**	1, 2	1, 3	
	Group 2	28.9 ± 14.5	35.0 ± 17.0	34.6 ± 16.8	13.71	0.001**	1, 2	1, 3	
WMFT	All	44.1 ± 17.9	52.4 ± 19.2	53.1 ± 20.7	27.80	0.000**	1, 2	1, 3	
	Group 1	54.3 ± 9.5	64.0 ± 7.1	65.4 ± 8.8	16.87	0.000**	1, 2	1, 3	
	Group 2	28.8 ± 16.7	35.1 ± 18.7	34.5 ± 19.7	13.00	0.002**	1, 2	1, 3	

Grip strength	All	13.0 ± 7.8	14.2 ± 8.4	14.1 ± 9.3	0.97	0.615			
	Group 1	16.5 ± 6.7	18.0 ± 7.3	19.2 ± 1.9	4.17	0.124			
	Group 2	7.7 ± 6.6	8.5 ± 6.7	6.4 ± 4.9	5.85	0.054			
MAL-AOU	All	2.0 ± 1.5	2.6 ± 1.7	2.8 ± 1.7	24.62	0.000**	1, 2	1, 3	
	Group 1	2.8 ± 1.3	2.6 ± 1.1	3.6 ± 1.2	16.67	0.000**	1, 2	1, 3	2, 3
	Group 2	0.7 ± 0.6	0.6 ± 0.6	1.1 ± 1.0	12.33	0.002**		1, 3	2, 3
MAL-QOM	All	1.8 ± 1.4	2.3 ± 1.4	2.5 ± 1.5	26.64	0.000**	1, 2	1, 3	
	Group 1	3.2 ± 1.0	3.9 ± 0.9	3.5 ± 0.6	13.61	0.001**	1, 2		2, 3
	Group 2	1.1 ± 1.0	1.1 ± 1.0	1.0 ± 1.0	3.90	0.142			

Group ~~1 = Higher~~ *1* Higher-functioning group; *Group* ~~2 = lower~~ *2* lower-functioning group; *FMA-UE total* ~~score = Fugl~~*score* Fugl-Meyer assessment-upper-extremity total score; *FMA* ~~Hand = Fugl~~*Hand* Fugl-Meyer assessment-upper limb subscore; *FMA* ~~Hand = Fugl~~*Hand* Fugl-Meyer assessment hand subscore; ~~WMFT = Wolf~~ *WMFT* Wolf motor function test; *MAL* ~~AOU = motor~~ *AOU* motor activity log-amount of use scale (AOU); *MAL* ~~QOM = motor~~ *QOM* motor activity log-quality of movement scale (QOM)
*$p < 0.05$; **$p < 0.01$

Effects on hand functions

Twenty patients with stroke were recruited. There were significant differences among the three times of ~~evaluation—pre-test~~ evaluation—pretest (1), ~~post-test~~ posttest (2), and 3-week follow-up (3)—in FMA-UE Total score (Chi-square = 34.219, $p = 0.000$), FMA-UL subscore (Chi-square = 31.200, $p = 0.000$), FMA-Hand subscore (Chi-square = 22.581, $p = 0.000$), and WMFT (Chi-square = 27.795, $p = 0.000$). However, there was no significant difference in grip strength among the three evaluations, as shown in Table **2**. The TS-VR training did significantly improve affected arm functions. However, it had no significant effect on the grip strength of individuals with stroke.

Post ~~-~~ hoc analysis using ~~Multiple~~ multiple Wilcoxon signed ~~ranks~~ -rank tests with Bonferroni correction ($p \leqq 0.05/3$) revealed that there were significant differences ($p = 0.000$) in (1, 2) of FMA-UE Total score, FMA-UL subscore, FMA-Hand subscore, and WFMT, respectively. There were also significant differences ($p = 0.000$) in (1, 3) of FMA-Total, FMA-UL, FMA-Hand, and WFMT. However, there were no significant differences in (2, 3) of FMA-UE Total score ($p = 0.231$), FMA-UL subscore ($p = 0.536$), FMA-Hand subscore ($p = 0.076$), or WFMT ($p = 0.405$).

Effect on actual arm use

Actual arm use of the sample of 20 patients was measured using AOU and QOM in the MAL. Significant increases in AOU (Chi-square = 24.618, $p = 0.000$) and QOM (Chi-square = 26.638, $p = 0.000$) in MAL among the three times evaluations were found using the Friedman test. This finding suggests that TS-AR training encourages more actual arm use of the affected hand in daily life for individuals with chronic stroke, as well as improving their quality of upper-extremity movement.

Further post ~~-~~ hoc analysis using ~~Multiple~~ multiple Wilcoxon signed ~~ranks~~ -rank tests with Bonferroni correction showed that there were significant differences ($p = 0.000$) in (1, 2) and (1, 3) of AOU and QOM, respectively. By comparison, there were no significant differences in AOU scores in (2, 3) and QOM scores in (2, 3) ($p = 0.147$ and $p = 0.338$, respectively).

Higher-functioning group and lower-functioning group

To determine which level of severity of upper-extremity impairment would benefit more from this treatment, a Friedman ~~Test~~ test was used to compare the outcome measures at three times of evaluation in the samples of the higher-functioning group and lower-functioning group patients, respectively. Both groups showed significant increases in scores at (1), (2), and (3) evaluations among all outcome measures respectively, except for grip strength. In contrast to the lower-functioning group, the higher-functioning group

experienced more significant improvements with a smaller p value ($p = 0.000$) in comparisons of outcome measures of FMA-UL, FMA-Hand, FMA-UE Total, and WMFT, respectively. Regardless of the significant increases in all upper-extremity outcome measures (except grip strength), the lower-functioning group showed no significant change in multiple comparisons in most of those outcome measures, as reviewed from the post-hoc analysis results using ~~Multiple~~ multiple Wilcoxon signed~~-ranks~~-rank tests with Bonferroni correction. Moreover, there were significant increases in AOU score ($p = 0.000$) and QOM ($p = 0.001$) score in MAL in the higher-functioning group, whereas patients in the lower-functioning group only had a significant increase in their AOU score ($p = 0.002$) among the evaluations.

Discussion

We developed a TS-VR training program for the hemiparetic hand after stroke. The main finding of this study was the demonstration of statistically significant improvements in upper-extremity functional movements of patients with hemiparetic stroke after a 2-week TS-VR training program. This study showed that our newly designed TS-VR training system was useful and led to significant improvements in the upper-extremity functions of patients with chronic hemiparetic stroke after a 10-session training program. There was a statistically significant enhancement in both quality and quantity of the performance of the affected hand during the daily functions of patients. The results of FMA-UE Total, FMA-UL, FMA-Hand, WFMT, MAL-AOU, and MAL-QOM showed significant improvement within groups across the outcome measures among the three measurement occasions. The results imply that TS-VR promotes improvements in affected hand functional performance of individuals with stroke after 10 sessions of treatment. There was still a sustaining positive impact on the functioning of individuals' affected hands after the 3-week follow-up when compared to their baseline performance, and patients also maintained their performance post-training across time. The TS-VR was proved to be useful for training patients' hand function after stroke.

In order to investigate the content validity of the TS-VR, we recruited a heterogeneous sample of participants with different hemiparetic arm impairment levels. They were further stratified into two groups—higher- or lower-functioning groups, according to the levels of functional impairments. Our study found that the higher-functioning group benefited more from the TS-VR, as indicated in outcome measures of FMA-UL, FMA-Hand, FMA-UE Total, and WMFT, respectively, as well as AOU score in MAL. Compared with the higher-functioning group, patients in the lower-functioning group only participated in certain lower levels with limited use of distal joints and muscles with lower speed, whereas patients in the higher-functioning group could perform a greater variety of movements, with the involvement of greater use of different joints and muscles in upper extremity from proximal to distal, especially hand and isolated finger movement. Moreover, the nature of our TS-VR training is duration-fixed (30 min) but not repetitive or interval-fixed. Patients in the higher-functioning group were able to perform higher repetitions because of their faster rate of performance. This result highlights the significance of the design and nature of TS-VR training in achieving differential benefits to stroke patients with various levels of arm severity. Further research on training duration, repetition, and frequency of the TS-VR program would bring out significant differences in the benefits for higher- and lower-functioning groups.

The significant increase in MAL-QOM score after TS-VR training in the higher-functioning group but not in the lower-functioning group could possibly be explained by their different functional levels. Following completion of the TS-VR program, the overall upper-extremity function increased in both groups. However, in the lower-functioning group, the improvement might only be seen in the proximal joint movement (i.e., increased shoulder flexion, external rotation, and elbow extension). The improvements were insufficient for hand functions in the MAL questionnaire, like holding a cup, opening a drawer, or eating with a spoon. ~~,~~ Hence, the overall quality of movement in these tasks remained similar after the TS-VR program. The grip strength of both groups showed no significant improvement after the course of TS-VR training. This is understandable as the TS-VR training did not include any strengthening element in any of its levels but only movement control and range of motion.

One of the reasons for the significant improvements after TS-VR training might be attributed to training with high frequency and appropriate intensity. Our treatment program consisted of a total of 10 sessions, each lasting 30 min, held 5 days per week over two consecutive weeks. Previous research has revealed that the intensity of task-specific training need not necessarily be high in order to achieve optimal effects. Training sessions that are as short as 15 min have resulted in lasting changes in cortical representation (Bayona et al.

2005). Our findings are consistent with those from numerous previous studies (Bayona et al. 2005; Galea et al. 2001; Page 2003), which have suggested that less intense (i.e., 30–45 min) task-specific training regimens can lead to significant improvements in the use and functions of the affected limb.

We conducted our training on a one-to-one basis with supervised therapy. During each supervised session, the facilitator selected activities that were suitable to the functional level of the patients and determined the repetitions of activities to be performed. Moreover, the facilitator provided specific and ongoing verbal and tactile cues on participants' performance. This extrinsic and instant feedback on movement quality can effectively correct patients' unwanted or compensatory movement patterns, which is also a key principle in skill acquisition (Magill and Anderson 2007). In addition, the 3D and graphically ~~'enriched'~~ "enriched" environments with multimodal feedback (visual, auditory, tactile) in VR settings also provided sensory input to the patients, which made them more motivated to attend the training than they would have been to attend conventional training, which is less playful and interactive.

It might also be possible to explain improvements in MAL as resulting from one of the unique features of our VR training program, that is, its adoption of task-specificity in a progressive manner. In order to be ~~'task specific'~~ "task specific," each action in the training tasks must specify an object to reach for. The tasks are simulating conditions in real life in order to enhance carry-over into daily life activities (Cunningham et al. 2016). Our TS-VR program is composed of seven functional tasks according to seven ordered levels of increasing complexity. The complexity of the tasks is related to the Brunnstrom theory of the development of the hemiparetic upper limb in recovery, with reference to the respective key actions corresponding to levels 1–7 in the FTHUE (Fong et al. 2004; Wilson et al. 1984; Uswatte et al. 2006; Magill and Anderson 2007). Our study, to our knowledge, is the first one incorporating task-specificity with increasing levels of complexity into VR training for the hemiparetic upper extremity. The results may be useful as supporting evidence for integrating task-specificity and virtual reality into programs for the treatment of upper limb motor impairments during stroke rehabilitation.

In our study, we attempted to explore the effectiveness of TS-VR rehabilitation that focused on the distal upper extremity up to the forearm, using the LMC as an input device. The advantage of the LMC is that it is cheap and easily set up, requiring only a desktop computer or laptop, the LMC, and our TS-VR training program~~,~~; however, apart from visual simulation, the absence of haptic feedback for the virtual functional tasks in the LMC might not be useful to stroke patients with severe sensory impairments over their hemiparetic upper extremities. There are also existing studies focused more on proximal upper limb rehabilitation (Shin et al. 2016). Kinect, which is a widely commercially available motion sensing device, recognizes the body's joint positions, especially for proximal joints like the shoulder and elbow. However, VR systems like Kinect do not benefit the distal joints, which are important in hand function training such as grasp and release. To address this limitation, we used the LMC in our TS-VR program, as this motion sensor is able to capture the motion of the wrist and of each of the finger joints, enabling it to accurately measure fine motor movements (Okazaki et al. 2017). To further develop our TS-VR program in the future, we suggest combining the use of Kinect and the LMC, as there are currently no VR systems involving both proximal and distal upper-extremity movements at the same time (Seo et al. 2016). Lastly, this was a preliminary study, further research to explore the effectiveness of the combined use of devices that can measure both gross motor and fine motor abilities in terms of randomized controlled trials would be useful and is recommended as a direction for future investigations.

Limitations and future work

Despite the use of various scores and measurements to assess the outcomes of the hemiparetic arm impairments and functioning, the leap motion controller device was used to capture motions of the wrist and each finger joint. The assessment tools and the captured data can be further integrated into combination with the devices to measure both gross motor and fine motor abilities in order to further evaluate and analyze the TS-VR for patients with different arm functioning in the future. Despite the content validity was performed to examine the TS-VR with different hemiparetic arm impairment levels, the usability test for the patients has not been conducted. In the future, a survey using usability questionnaire can be conducted in the future to collect qualitative feedback and quantitative data to understand the feedbacks from the patients on the new TS-VR training tool. In addition, a control group has not involved in the current study. In the future, the control group can also be included to investigate the effectiveness of the TS-VR in order to understand

whether the TS-VR is superior to conventional therapy and rehabilitation exercise.

Conclusions

In this paper, we have developed a TS-VR program using a ~~Leap Motion Controller~~ leap motion controller device to determine the hand and figures positions. The VR program was developed using the Unity3D game engine. The TS-VR is a user-friendly training program that aims to simulate daily hand function tasks, with levels of difficulty customized for different patients, thus motivating them to perform similar tasks in real life. The training program was developed to promote recovery of the hemiparetic upper extremity in patients with stroke based on a hierarchy of seven functional tasks in the FTHUE. Studies have been conducted to verify the content validity of the TS-VR and determined the difference on whether the lower-functioning or the higher-functioning group of patients with paretic upper-extremity functional impairment would benefit more from the developed TS-VR program. ~~Results~~ The results have revealed that the higher-functioning group has a significant increase in MAL-QOM score after participated in the TS-VR training rather than the lower-functioning group. By undertaking high frequency and at the appropriate intensity of the TS-VR training, it is believed that this low-cost and interactive training program will provide significant benefits to people with stroke in the future. The findings of this study impact not only the design of the TS-VR training for the stroke patients, but also contribute to the effective care of stroke survivors by extending the research deliverables to home-based training, rehabilitation hospitals, and institutions.

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Declarations

Conflict of interest

The authors declare that they have no competing interests with respect to the research, authorship, and/or publication of this article.

Ethics approval

The study was carried out in accordance with the principles of the Declaration of Helsinki. Ethical approval was sought and obtained from the Human Ethics Committee of the Hong Kong Polytechnic University (HSEARS20180503002).

Consent to participate

Written and informed consent was obtained from all patients before the study commenced.

Consent for publication

Use of data and materials for purposes of reporting was included in the informed consent procedures and all

patients gave their written consent for this publication.

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