Development of a Compensation-aware Virtual Rehabilitation System for Upper Extremity Rehabilitation in Community-Dwelling Older Adults with Stroke

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Abstract

Background: Compensatory movements are commonly observed in older adults with stroke when they take motor practice for rehabilitation, which could limit their motor recovery.

Aim: This study aims to develop one virtual rehabilitation system (VRS) that can detect and reduce compensatory movements to improve the quality of upper extremity (UE) movements and hence the outcome of rehabilitation in community-dwelling older adults with stroke.

Method: To design and validate the algorithm of compensation detection equipped in VRS, a study was first conducted to recruit 17 healthy and 6 stroke participants to identify and quantify compensatory movements when they played rehabilitation games provided by the VRS. Then a pilot study was conducted to test the feasibility and efficacy of the VRS deployed in community, where 18 stroke participants were assigned to either virtual reality (VR) group or conventional treatment (CT) group, and each participant underwent 10 sessions of an additional 6 minutes of VR games or CT respectively, on top of their usual rehabilitation programme. Participants were assessed before and after interventions using Fugl-Meyer Assessment-Upper Extremity (FMA-UE), Wolf Motor Function Test (WMFT), Stroke Rehabilitation Motivation Scale (SRMS), Range of Motion (ROM) measurements and the number of compensatory movements.

Results: VR group demonstrated a trend in reduction of trunk and upper-extremity compensations, increased intrinsic motivation scores, and statistically significant improvements in FMA-UE ($p=0.045$) and WMFT ($p=0.009$, $p=0.0355$) scores. There was, however, no significant difference in all outcome measures between two groups.

Conclusion: The compensation-aware VRS demonstrates a trend towards reduced compensation and higher motivation level, which could be an effective adjunct to the conventional therapy with less supervision from a therapist as well as be potentially deployed in a community center or at an elder adult's home.

Background

Stroke has been a global healthcare challenge since it is the leading cause of death and disability. Most individuals (especially older adults) with stroke are left with perpetual and long-lasting impairments [1]. More than 80% of them reportedly present with the upper extremity (UE) motor impairment [2, 3], which continues to persist in 50% of them even after six months post stroke [4]. The continual rehabilitation at community, such as at the elderly-care center or even at home, could support older adults with stroke to re-establish UE functions as well as save their troubles on traveling [5]. The short supply of manpower resources at community, however, limits the therapist-patient interaction time [6] to monitor and motivate them to take motor intervention. The virtual rehabilitation systems (VRS) including those video game commercial gaming systems such as Wii and Kinect are increasing in popularity in community given its benefits for community rehabilitation [7], for example, delivering the individualized, embodied and immersive training with the required levels of frequency and intensity, as well as increasing older adults' engagement and adherence to motor rehabilitation. Especially in the current Covid-19 pandemic, the VRS deployed in community or at home could support older adults with stroke to take rehabilitation regimen safely and conveniently.

The deployment of VRS in community is still at its early stage as it faces a few practical challenges and barriers. One challenge with most existing VRS is missing the function to monitor older adults' compensatory movements in real time to ensure the quality of movement in UE motor practice. Older adults with stroke gradually adopt various compensatory movements in performing UE functional tasks [8, 9, 10]. The compensatory movement is the new movement pattern as it changes to accommodate altered constraints to accomplish UE motor tasks. The adoption of compensatory movement could be caused by UE impairments [11, 12] and the muscle weakness [13], which could ultimately limit the motor recovery [10, 14] and result in the secondary impairments such as the joint pain and the reduced range of motion [15]. For example, Cirstea and Levin [10] found a significant correlation between the increased trunk involvement with a reduction in active ranges of elbow extension and shoulder flexion when stroke individuals were asked to perform the reaching task. The monitoring of stroke survivor's compensation during motor practice is especially important at the context of community where the close supervision of therapist is usually missed.

Recent studies start addressing the compensation in the design of VR-based rehabilitation through applying various motion tracking technology [16, 17, 18] as well as the pressure sensors [19, 20] to detect compensatory movements when stroke survivors perform the UE reaching tasks. For example, Foreman and Engsberg [17] utilized one commercial Kinect device in their VRShape system to measure and shape the trunk compensatory movement during repetitive upper limb practices of a reaching task. Besides the trunk compensation, the affected limb could play a role in compensation, for example, the affected upper arm would compensate the lower arm motion in elevating the upper limb [21]. Cai's studies [19, 20] could further detect the shoulder elevation besides trunk compensations using the pressure mattress sit under the stroke survivors. Thus, to reduce the compensation in the UE motor practice, it is necessary to measure both the trunk and upper limb compensations.

The objective of this study is to develop one compensation-aware VRS that can reliably detect the trunk and UE compensations observed in shoulder flexion and horizontal abduction exercises and provide the audio-visual feedback to reduce the detected compensations in the community-dwelling older adults with stroke. Different from the previous study focusing on the UE reaching task, this study focuses on two planar motor exercises of UE, shoulder flexion and shoulder horizontal abduction, since the previous studies suggest that therapeutic games should not target at practicing activities of daily life (ADLs) but rather practicing the missing component and specific task [22, 23].

In the rest of this paper, we describe (1) the hardware and software of VRS, (2) the study 1 to identify and quantify compensatory movements in two shoulder planar motion exercises, (3) the design of the compensation detector to detect the identified compensatory movements, (4) the design of in-game feedback for compensation and gaming performance, and (5) last the study 2 to preliminary test the feasibility and efficacy of VRS in an local community rehabilitation center.

Virtual Rehabilitation System

Fig. 1 displays the hardware of virtual rehabilitation system comprising a Phantom Omni® haptic device (simply called the haptic device hereafter), a Kinect sensor (version 1), a display, an audio box and a personal computer. The haptic device provided a range of haptic outputs and offered six degrees of freedom allowing the user to manipulate the game objects via operating on the stylus. The Kinect sensor is low-cost, widely available, and with the release of the official software development kit (SDK), easily programmed. Evidence exists that it can accurately assess lateral trunk lean angles during postural control tests [24] as well as trunk compensatory motion [17] during the reaching task.

The software of VR system mainly comprised one compensation detector, two rehabilitation games including Shoulder Flexion Game (Game 1, shown in Fig. 2) and Shoulder Horizontal Abduction Game (Game 2, shown in Fig. 2), user profile module, and results visualization module. When playing the Shoulder Flexion Game, the player controlled a plane in the game to collect the flying coins by performing shoulder flexion and extension. When playing the Shoulder Horizontal Abduction Game, the player controlled an avatar in the game to collect the falling down coins by performing shoulder horizontal abduction.

The core of software is the compensation detector which could detect compensatory movements and trigger audio-visual feedback to support older adults with stroke to reduce the compensation. As the older participants in this study would take two planner motion exercises in VRS, to our best knowledge, there is no prior study to reveal the compensatory movements in these two planner motion exercises. Thus, we need to quantitatively determine the compensation of both trunk and upper extremity observed in these two planner motion exercises, which can guide and validate the compensation detector of VRS.

Study 1: Determine Compensation Of Trunk And Upper Extremity

The objectives of formative study 1 are twofold: 1) quantitatively determine the compensatory movements when older adults with stroke played the two rehabilitation games via the haptic device; 2) collect the kinematic data from Kinect to design the compensation detector. The two studies reported here were approved by the Ethics Committee of Nanyang Polytechnic, Singapore.

Participants

Total 6 hemiparetic stroke participants (3 males, 3 females; age range 67.5 ± 10.4 years) were recruited from a community rehabilitation center and 17 healthy older adults (7 males, 10 females; age range 58.8 ± 6.33 years) were recruited in community. The inclusion criteria for stroke participants include 1) at least 3 months stroke with hemiparesis secondary to ischemic or hemorrhagic stroke, 2) able to sit independently without trunk support, 3) able to follow verbal instructions, 4) able to provide informed consent, and 5) able to voluntarily flex shoulder to 100 degrees, extend elbow to maximum, horizontal abduct and adduct shoulder to 20-25 degrees. Musculoskeletal or neurological conditions that would affect arm function were exclusion criteria for all participants.

Experimental setup

The experiment was conducted at one research lab in the local university, where the VRS and one commercial video motion capture (VMC) system, Siliconcoach Pro, were installed in this lab. To setup the VMC system, two cameras (Panasonic 2DR – S71) with zoom lens adjusted to provide a full view of the participant were set up in both the frontal and sagittal planes. Camera One (Frontal View) was placed in line with sagittal plane, and Camera Two (Sagittal View) was placed perpendicular to the acromion process. A chair was placed on the intersection of the two horizontal scaling objects. Participants were positioned sitting on the chair with backrest with their hips and knees flexed to 90 degrees without the use of trunk restraint. Two vertical scaling objects were placed beside the subject in the frontal plane and behind the

subject in the sagittal plane. Participants were dressed a dark cloth and markers were attached on the cloth to identify the location of the joint as well as track motion in the video [25]. The placement of markers was consistent with the requirements by the International Society of Biomechanics (ISB) Recommendation to achieve high intra-ratter and inter-ratter reliability [26].

The developed VRS was placed in front of participant. Specifically, the haptic device was placed on a table next to the participants. The table's position was determined at the 45 degrees of shoulder flexion when a subject was able to hold on the haptic device's stylus while maintaining maximum elbow extension. The distance between the display and the participants was 2 meters to ensure that participant could clearly watch the scene. The Kinect was placed immediately in front of display and its height to the ground was 1 meter.

Experiment procedure

All participants firstly signed an informed consent form to learn the aim and procedure of this study as well as agree to attend the study. Secondly, participants completed a self-declaration form and a brief physical assessment to gauge the suitability of their participation in the current study. Then each participant had a one-minute trial on playing game along with the specific guidance and instruction from experimenters. Video recording of the participants would be commenced when participants started the formal gameplay. The duration of each game was five minutes. After playing the first game, each participant had a rest for ten minutes and then start playing the second game.

Data collection & analysis

The same kinematic data of participants were collected by Kinect and two cameras of the VMC system, respectively. The data stored in the designed VRS and the commercial VMC system were labeled with time stamps for the synchronization purpose. Moreover, the kinematic data collected by Kinect were used to design the compensation detector, which will be discussed at the next section. This section focuses on the analysis of kinematic data collected by the two cameras of the VMC system, which were processed in a 2D video motion analysis software, Siliconcoach Pro 7.022 application [27] accompanied by the VMC system. The 2D video motion analysis via the Siliconcoach Pro has been proved to be a valid and reliable outcome measure [28]. Siliconcoach Pro 7.022 analyzed the recorded videos by determining the compensation through quantifying its angle and distance with the use of markers recommended by ISB. For example, the angle of compensations was measured by drawing a continuous line across any three markers within the Siliconcoach application; the distance of compensations was measured by drawing a horizontal or vertical line across any two markers and then the distance in video would be calculated in the same software.

The distance and angle data of trunk, shoulder, elbow, and wrist were further analyzed in IBM SPSS Statistics version 21. The maximum, minimum, mean, median, and standard deviations (SD) of each joint's distance and angle were calculated. Shapiro-Wilk Test of normality revealed a non-normal distribution and Levene's test of homogeneity of variances of the data showed that the variances were heterogeneous, and thus a non-parametric test, the Mann-Whitney U test, was used to analyse data.

Furthermore, the above kinematic data of healthy and stroke participants were compared in two ways. First, the maximum compensations in stroke participants were compared to the maximum deviations in healthy control to find the compensation strategies adopted by the stroke participants. Second, the minimum compensations of stroke participants were compared to the maximum deviations in healthy control to determine the thresholds to quantitatively determine compensation movements.

Results

The results showed that stroke participants had more distal compensatory movement patterns (CMPs) during the first three minutes of gameplay followed by the proximal CMPs in the current five-minute VR game session, which was not observed in healthy participants. The following sections firstly introduce the differences between the maximum compensations in stroke and the maximum deviations in healthy controls, and then the difference between the minimum compensation in stroke participants and the maximum deviations in healthy controls. Lastly, it summarizes the identified compensatory movements and the thresholds to determine these compensatory movements.

(1) Differences between maximum compensation movements in stroke participants and maximum deviations in healthy participants

Table 1

Summary of maximum deviation of healthy controls and the maximum compensation of stroke participants in Shoulder Flexion and Horizontal Abduction

Movements	Shoulder Flexion					Shoulder Horizontal Abduction				
	Maximum deviation in healthy participants	Maximum compensation in stroke participants	Mann-Whitney U Test	Z value	P value	Maximum deviation in healthy participants	Maximum compensation in stroke participants	Mann-Whitney U Test	Z value	p value
Ipsilateral Shoulder Hiking	3.4cm ± 1.40 (3.00cm)	6.70cm ± 4.00 (5.00cm)	32.0	-2.27	.025*	2.30cm ± 1.20 (2.00cm)	4.80cm ± 3.20 (4.00cm)	28.5	-2.45	.014*
Contralateral Shoulder Hiking	0.80cm ± 0.90 (1.00cm)	1.70cm ± 1.40 (2.00cm)	49.0	-1.49	.173	1.40cm ± 1.10 (1.00cm)	2.30cm ± 1.90 (2.00cm)	55.5	-1.12	.285
Ipsilateral Shoulder Depression	1.40cm ± 1.20 (2.00cm)	4.70cm ± .027 (4.50cm)	20.5	-2.89	.003*	1.50cm ± 1.50 (1.00cm)	3.20cm ± 1.50 (2.50cm)	31.0	-2.32	.022*
Contralateral Shoulder Depression	0.20cm ± 0.50 (0.00cm)	2.50cm ± 2.30 (1.50cm)	9.5	-3.93	.000*	0.80cm ± 1.20 (0.00cm)	2.70cm ± 1.60 (2.50cm)	23.5	-2.79	.006*
Ipsilateral Trunk Lateral Flexion	1.00° ± 1.41 (.000°)	1.33° ± 2.16 (.000°)	78.0	0.00	1.00	.923° ± 1.41 (.000°)	2.00° ± 3.10 (1.00°)	65.0	-0.71	.556
Contralateral Trunk Lateral Flexion	.962° ± 1.56 (.000°)	4.50° ± 3.02 (4.50°)	25.5	-2.80	.008*	3.04° ± 2.44 (3.00°)	6.67° ± 4.63 (6.50°)	37.5	-1.78	.078
Forward Trunk Flexion	2.885° ± 4.24 (2.50°)	5.17° ± 2.16 (.000°)	75.0	-0.16	.906	6.69° ± 2.91 (6.00°)	5.67° ± 7.66 (2.50°)	56.0	-1.07	.308
Trunk Extension	1.58° ± 1.96 (.500°)	3.17° ± 8.73 (2.00°)	53.0	-1.27	.244	.154° ± .784 (.000°)	4.00° ± 3.52 (4.50°)	28.0	-3.82	.014*
Ipsilateral Elbow Flexion	10.42° ± 12.48 (5.50°)	27.83° ± 18.39 (27.50°)	32.5	-2.21	.025*	12.19° ± 10.78 (8.50°)	11.67° ± 20.54 (4.50°)	52.5	-1.24	.225
Note. Values are mean ± SD (median), *p < 0.05										

Table 1 lists the distance and angle differences between the maximum compensations in stroke and the maximum deviations in healthy controls. When playing the shoulder flexion game, the stroke participant's maximum compensation movements were significantly larger than the healthy control's maximum deviation in ipsilateral shoulder hiking (Z = -2.27, p = .025), ipsilateral shoulder depression (Z = -2.89, p = .003), contralateral shoulder depression (Z = -3.93, p = .000), contralateral trunk lateral flexion (Z = -2.80, p = .008), and ipsilateral elbow flexion (Z = -2.21, p = .025). Especially, the contralateral shoulder depression (Healthy = .000m, Stroke = .015m) and the contralateral trunk lateral flexion (Healthy = .000°, Stroke = 4.50°) were the most significant as these two movements were only observed in stroke participants but not in healthy controls.

When playing the shoulder horizontal abduction game, the stroke participant's maximum compensation movements were significantly larger than the healthy control's maximum deviation in ipsilateral shoulder hiking (Z = -2.45, p = .014), ipsilateral shoulder depression (Z = -2.32, p = .022), contralateral shoulder depression (Z = 2.79, p = .006), and trunk extension (Z = -3.82, p = .014). Especially, the contralateral shoulder depression (Healthy = .000m, Stroke = .015m) and trunk extension (Healthy = .000°, Stroke = 4.50°) were the most significant as these two movements were only observed in stroke participants but not in healthy controls.

(2) Differences between maximum deviations in healthy participants and the minimum compensation in stroke participants

Table 2 lists the distance and angle differences between the minimum compensations in stroke and the maximum deviations in healthy controls. When playing the shoulder flexion game, the minimum compensation movements of stroke participants were significantly larger than the maximum deviation of healthy controls in the contralateral shoulder depression (Z = -3.49, p = .002), ipsilateral shoulder abduction (Z = -2.55, p = .012), and contralateral trunk lateral flexion (Z = -1.31, p = .044). There were no significant differences found in other movements.

When playing the shoulder horizontal abduction game, the minimum compensation movements of stroke participants were significantly larger than the maximum deviation of healthy controls in the contralateral shoulder depression ($Z = -1.66$, $p = .031$), forward trunk flexion ($Z = -2.48$, $p = .012$), trunk extension ($Z = -3.67$, $p = .019$) and ipsilateral elbow flexion ($Z = -2.54$, $p = .008$). There are no significant differences found in other movements.

Table 2

Summary of maximum deviation of healthy controls and the minimum compensation of stroke participants in Shoulder Flexion and Horizontal Abduction

Movements	Shoulder Flexion					Shoulder Horizontal Abduction				
	Maximum deviation in healthy participants	Minimum compensation in stroke participants	Mann-Whitney U Test	Z value	P value	Maximum deviation in healthy participants	Minimum compensation in stroke participants	Mann-Whitney U Test	Z value	p value
Ipsilateral Shoulder Hiking	3.4cm $\pm$ 1.40 (3.00cm)	2.70cm $\pm$ 2.70 (1.50cm)	42.5	-1.76	.087	2.30cm $\pm$ 1.20 (2.00cm)	1.50cm $\pm$ 0.80 (1.00cm)	46.0	-1.60	.131
Contralateral Shoulder Hiking	0.80cm $\pm$ 0.90 (1.00cm)	1.00cm $\pm$ 0.90 (1.00cm)	66.0	-0.62	.588	1.40cm $\pm$ 1.10 (1.00cm)	1.00cm $\pm$ 0.60 (1.00cm)	61.0	-0.86	.436
Ipsilateral Shoulder Depression	1.40cm $\pm$ 1.20 (2.00cm)	1.20cm $\pm$ 0.40 (1.00cm)	69.5	-0.43	.689	1.50cm $\pm$ 1.50 (1.00cm)	1.50cm $\pm$ 0.80 (1.00cm)	68.0	-0.50	.655
Contralateral Shoulder Depression	0.20cm $\pm$ 0.50 (0.00cm)	1.00cm $\pm$ 0.00 (1.00cm)	18.0	-3.49	.002*	0.80cm $\pm$ 1.20 (0.00cm)	1.20cm $\pm$ 0.40 (1.00cm)	46.0	-1.66	.031*
Ipsilateral Trunk Lateral Flexion	1.00° $\pm$ 1.41 (.000°)	.667° $\pm$ 1.21 (.000°)	69.0	-0.49	.689	.923° $\pm$ 1.41 (.000°)	.667° $\pm$ 1.03 (.000°)	73.0	-0.280	.832
Contralateral Trunk Lateral Flexion	.962° $\pm$ 1.56 (.000°)	1.17° $\pm$.753 (1.00°)	53.5	-1.31	.044*	3.04° $\pm$ 2.44 (3.00°)	2.17° $\pm$ 1.47 (1.50°)	64.0	-0.67	.524
Forward Trunk Flexion	2.885° $\pm$ 4.24 (2.50°)	2.67° $\pm$ 4.32 (.000°)	75.5	-0.34	.760	6.69° $\pm$ 2.91 (6.00°)	3.33° $\pm$ 6.74 (.500°)	27.0	-2.48	.012*
Trunk Extension	1.58° $\pm$ 1.96 (.500°)	2.17° $\pm$ 1.72 (2.00°)	56.0	-1.12	.308	.154° $\pm$.784 (.000°)	2.00° $\pm$ 2.68 (1.00°)	30.0	-3.67	.019*
Ipsilateral Elbow Flexion	10.42° $\pm$ 12.48 (5.50°)	5.83° $\pm$ 5.56 (5.00°)	69.5	-0.41	.689	12.19° $\pm$ 10.78 (8.50°)	3.00° $\pm$ 4.98 (1.50°)	25.5	-2.54	.008*
Note. Values are mean $\pm$ SD (median), *p < 0.05										

(3) Compensatory movements

Table 3 summarizes compensatory movements and thresholds found in both shoulder flexion and should horizontal abduction. The three shoulder movements including the ipsilateral shoulder hiking, the ipsilateral shoulder depression and the contralateral shoulder depression were observed in two planar motor exercises of UE. Moreover, the contralateral shoulder depression was significantly different by comparing the maximum deviation of the healthy controls to both the maximum and minimum compensations of stroke participants. The trunk compensatory movements were different in two planar motor exercises of UE, the contralateral trunk lateral flexion observed in the shoulder flexion whilst the trunk extension observed in the shoulder horizontal abduction.

To quantify the thresholds of compensatory movements, the analysis was first to identify any significant differences between the maximum deviation of healthy controls and the minimum compensation of stroke participants. If there were significant significances, the median of the

minimum compensation of stroke participants were selected to be the threshold to determine the compensation. Otherwise, the median of the maximum deviation of healthy controls would be the recommended threshold to determine the compensatory movement of stroke participants.

Table 3

Summary of significant compensatory movements adopted by stroke participants

Shoulder Flexion			Shoulder Horizontal Abduction	
	Compensatory Movements	Threshold	Compensatory Movements	Threshold
Trunk	Contralateral trunk lateral flexion*	1.00°	Trunk extension*	1.00°
Shoulder	Ipsilateral shoulder hiking	3.00cm	Ipsilateral shoulder hiking	2.00cm
	Ipsilateral shoulder depression	2.00cm	Ipsilateral shoulder depression	1.00cm
	Contralateral shoulder depression*	1.00cm	Contralateral shoulder depression*	1.00cm
Elbow	Ipsilateral elbow flexion	5.50°		
*The movements observed in two comparisons.				

Summary and discussion of Study 1

The study 1 identified and quantified compensatory movements of both trunk and UE when stroke participants performed the two planar motor exercises through playing the rehabilitation games of VRS. Results showed that stroke participants adopt various compensatory movements during the gameplay. The compensatory movements of trunk and shoulder were observed in both planar motor exercises of UE, whilst the compensatory movement of elbow was only observed in the shoulder flexion. The quantitative thresholds of above compensatory movements would be deployed in the compensation detector of VRS.

Compensatory movements found in the shoulder flexion exercise were similar with those observed in the repetitive reaching task. For example, McCrea et al. [13] identified that stroke individuals tend to use elbow flexion during early movements in reaching as it reduces the lever distance between the shoulder and the center of arm mass, and further reduces the need to generate the higher power to execute the movement; Fuller et al. [29] found that the stroke subjects leaned toward their non-reaching side to reduce the load on the shoulder elevator region where the most profound effects of fatigue such as muscle saturation was observed. Furthermore, Cirstea and Levin [10] pointed out that the muscle weakness of the shoulder muscle could result in an increase of trunk compensation.

Although the shoulder and trunk compensatory movements were also observed in the shoulder horizontal abduction exercise, the elbow compensatory movements was not. It could be the primary agonist muscles for horizontal abduction are around shoulder but not elbow. Then the elbow muscles were not saturated in the repetitive task of shoulder horizontal abduction, even though the elbow muscle was weak in stroke participants.

It should be noted that, during the five-minute gameplay in this study, the stroke participants firstly showed more distal CMPs and later more proximal CMPs after around three minutes. The change of CMP could be due to the repetitive motion-induced shoulder muscle fatigue, reflecting the muscle weakness in stroke participants. The time of shoulder fatigue was similar with previous study found in the repetitive shoulder reaching task [29].

Compensation detector

The objective of compensation detector is to detect above compensatory movements based on the kinematic data streamed from Kinect and then trigger the corresponding feedback in the gaming scene. The compensation detector would comprise four steps, including calibration, overall detection, detailed detection and feedback trigger.

The kinematic data collected from Kinect and the analysis data provided by the application of VMC system in Study 1 would be used to design the compensation detector. The two data were synchronized by the common time stamp. Specifically, the kinematic data collected

from Kinect included the orientations and positions of nine joints of the upper body, including the positions of spine and pelvic, the orientations and position of chest (called shoulder center in Kinect SDK), right shoulder, left shoulder, the orientations of right elbow and left elbow, and the positions of right wrist and left wrist. To be easily compared to the kinematic data, the analysis data provided by the application of VMC system were converted to the orientations and positions of same nine joints of the upper body.

Step 1: Calibration

The compensation detector firstly determines whether the calibration has been done. If done already, it will directly proceed to Step 2; if not, it needs to calibrate the initial motion state of older adult and, after calibration, quit the current process to deal with the new frame of kinematic data stream. Given each older adult with stroke has different levels of degree with paradise upper limb, the initial motion state when sitting on the chair and holding the haptic device would be different for each other. The compensation detector would guide each older adult to sit well and hold the haptic device in the correct and comfort pose during the calibration process till older adult confirms to start the motor practice. Then the compensation detector immediately captures one frame from the kinematic data stream inputted by Kinect and store this frame as the calibrated kinematic data, which would be used in calculation in Step 2 & 3 to determine compensatory movements. When designing the compensation detector, the calibrated kinematic data were chosen from one frame of the kinematic data collected by Kinect at the time stamp when the stroke participants started playing the game in Study 1.

Step 2: Overall detection

The purpose of overall detection is to find the possible compensatory movements via comparing the real-time input kinematic data with the calibrated kinematic data. Specifically, the orientations of five joints, including chest, left and right shoulder, and left and right elbows, will be deployed in the following equations 1-3. The equation 1 calculates the angle difference when one joint's orientation values are collected in real time and at the above calibration step, respectively. The equation 2 normalizes the angle difference to the range from 0 to 1, in which the constant value (here is 60) is set based on the observed maximum angle difference found in the analysis data of Study 1. The equation 3 is a linear equation to summarize the orientation difference of five joints between the two kinematic data sets, where the three constant values (40%, 20% & 5%) are the weights of contribution to the overall orientation difference of upper body.

If the overall orientation difference obtained in equation 3 is more than the predefined threshold δ , the compensation detector will proceed to Step 3 to further determine the details of compensatory movements; otherwise, the compensation detector will quit the current process to deal with the new frame of kinematic data stream. The predefined threshold δ is determined based on the minimum orientation difference value found in the kinematic data collected by the Kinect in Study 1.

$$A = \arccos(P_x \times S_x + P_y \times S_y + P_z \times S_z) \quad (1)$$

Where: A is the angle difference, P is the real-time joint orientation and S is the corresponding joint orientation in calibration, both orientations defined along x, y, z dimensions.

$$V_i = 1 - (60 - A_i) / 60 \quad \text{where } A_i < 60 \quad (2)$$

Where: V_i is the value of difference, A_i is the angle difference between two orientations of the i joint; when A_i is equal or more than 60 degree, V_i would be 1.

$$V = V_1 \times 40\% + (V_2 + V_3) \times 20\% + (V_4 + V_5) \times 5\% \quad (3)$$

Where: V is the overall difference, V_1 is the orientation difference value of Chest, V_2 and V_3 are the orientation difference value of left and right shoulder, respectively, V_4 and V_5 are the orientation difference value of left and right elbow, respectively

Step 3: Detailed detection

The purpose of detailed detection is to determine the possible compensatory movement listed in Table 3. Specifically, the compensation detector would determine the specific compensatory movement in two ways: 1) comparing the orientation of the selected joint between the real-time kinematic data and the calibrated kinematic data; 2) comparing the distance difference between the two selected joints between the real-time kinematic data and the calibrated kinematic data. The orientation or distance difference is then compared with the corresponding

threshold of compensatory movements recommended in Table 3. Lastly the compensation detector summarizes all comparisons results and labeled all detected compensatory movements for later process in Step 4.

The process to detect the contralateral trunk lateral flexion is illustrated in detail here to explain the procedure of detailed detection. Firstly, the compensation detector would calculate the orientations from spine to shoulder center via equation 4. Here the two orientations, $O_{current}$ and $O_{calibration}$, would be calculated, where the positions of spine and shoulder center would be from the current frame of kinematic data stream and the calibrated kinematic data, respectively.

$$O = \text{Vector3}(L_x - T_x, L_y - T_y, L_z - T_z) \quad (4)$$

Where: O is the orientation, L is the position of spine, T is the position of shoulder center, both positions defined along x, y, z dimensions, respectively

Then the difference of these two orientations would be calculated according to equation 1. Lastly, the orientation difference would be compared with the threshold recommend in Table 3. If the orientation difference is larger than the threshold, the corresponding compensatory movement (that is, the contralateral trunk lateral flexion) would be labeled in compensation detector.

It should be noted that, when the orientation or distance difference was applied to the comparison, the orientation or distance difference usually needs to be modified via multiplying one constant β to compensate the low accuracy of Kinect. The constant β would be varied for each comparison of the orientation or distance difference, and its value is determined based on the data collected in Study 1. Continuing the above example of detecting the contralateral trunk lateral flexion, when all contralateral trunk lateral flexion were identified in the analysis data of VMC system in Study 1, the all orientation difference could be calculated too based on the kinematic data stream input by Kinect at the same time stamps. The constant β is then determined by dividing the recommend threshold by the maximum orientation difference.

Step 4: Feedback trigger

The purpose of this step is to trigger the designed audio-visual feedback based on the labeled compensatory movements input from Step 3. Specifically, it will firstly determine whether any label is recorded. If not recorded, the process will quit immediately and the compensation detector will process the new frame of kinematic data stream; otherwise, the detected compensatory movements would be stored in database as well as displayed on the game screen. A beep sound would be played to alert the existence of compensatory movement and meanwhile, the designed audio-visual feedback based on the types of the compensatory movement would be triggered. The compensation detector would end process until the feedback shown in game scene had been completed.

Audio-visual feedback design

The audio-visual feedback aims to motivate and support older adults with stroke to be aware of and reduce compensatory movements when they respond to the feedback. Four guidelines are proposed to design the audio-visual feedback adopted in VRS.

Guideline 1: Alerting player about compensatory movements via text and audio.

This guideline aims to improve stroke elderly's awareness on compensatory movements. All compensatory movement currently detected will be displayed in game scene via Red texts with one Beep sound.

Guideline 2: Increasing the size of the player object.

This guideline focuses on supporting older adults with stroke to avoid the undesired compensatory movement. The player object in game scene is controlled by the player to accomplish the game task. The increased size of the player object can reduce the range of motion of upper limb to operate the haptic device to accomplish the game task. Thus, the player could temporally have "a rest" on shoulder movement to recover the muscle fatigue.

Guideline 3: Adding additional game objects into the game scene to induce player's shoulder movements.

This guideline is devised based on the operant conditioning [30], a behavioral psychology technique that can modify human motor behavior through reward and punishment. The additional game objects (e.g., bombs or treasure boxes) appeared at the specific positions in game scene may strengthen player's response or intention to move upper limb in the correct manner as well as overcome the compensation.

Guideline 4: Increasing or decreasing gaming grades to differentiate the desired and undesired shoulder movements.

This guideline is to indicate the performance on adapting to the correct UE movement. For example, increasing grades is to reward the desired motion in accomplishing game task, whilst decreasing grades is to punish the undesired motion. The introduction of gaming grades also helps older adults with stroke to compare their historic performances, which motivates them to achieve better gaming performance via taking correct shoulder movements.

Fig. 3 shows the timeline to trigger the gaming feedback corresponding to the detected compensatory movements as well as the design guideline. The feedback based on Guideline 1 and Guideline 4 would be triggered throughout the session to alert player to be aware of compensatory movements. The feedback based on Guideline 3 would be triggered at the first and last 10% durations of session when any compensation is detected, which considers that the player either needs time to adapt to the game at the beginning of gameplay or accumulates the muscle fatigue with shoulder after playing the game for some time.

Study 2: Preliminary Validation Of The Feasibility And Efficacy Of Vrs

Study 2 is a pilot study to validate the feasibility and efficacy of the proposed VRS when deploying it in a community elder care center.

Participants

Total 18 participants from one community rehabilitation center, who satisfied the inclusion criteria, were recruited. Participants who fulfilled the prerequisites in the screen test were allocated to the VR group (n=9), whereas the rest were consequently assigned into the conventional treatment (CT) group (n=9). During the study, a total of 3 subjects dropped out, in which 1 from CT group due to a recent diagnosis of dementia (n=1) and 2 from VR group due to uncontrolled hypertension (n=1) and hemiplegic shoulder pain secondary to non-physiotherapy related intervention (n=1) respectively. A total of 15 subjects (8 control and 7 experimental) remained at the end of the study.

Inclusion criteria:

1) age 55 years old and above, 2) at least 6-months post-stroke secondary to ischemic / hemorrhagic stroke with chronic hemiparesis, 3) discharged from acute hospital, medically stable hypertension and/or high cholesterol and/or diabetes, 4) no pre-existing shoulder joint conditions (e.g. osteoarthritis, fracture etc.) of the hemiparetic upper-extremity, 5) no ataxia and cerebellar symptoms, 6) no systemic conditions such as rheumatoid arthritis, 7) no cognitive impairments or history of psychiatric condition.

Screen test:

active range of motion (AROM) of shoulder flexion at least 45 degree, able to grip the stylus of the haptic device with affected hand, able to follow instructions, no orthopedic changes or pain on the affected upper extremity, no sensation deficit, no proprioception deficit, no visual or auditory deficit, no increase in muscle tone.

Experiment setup and procedure

The study was conducted at a room of one local rehabilitation center, as shown in Fig. 1. The setup of VRS was the same as that in Study 1, including the distances between the display and Kinect and the participant, the height of Kinect, and the sitting requirements for participants, etc.

Each group underwent 10 sessions of an additional 12 minutes of either conventional therapy or VR games on top of their usual rehabilitation schedule in a period of three months. Measurements of Wolf Motor Function Test (WMFT), Fugl-Meyer Assessment - Upper Extremity (FMA-UE), Stroke Rehabilitation Motivation Scale (SRMS), range of motion (ROM), as well as the number of compensatory movements of the subjects in the VR group and CT group (n=3) were collected through the VR system before and after the intervention for comparison. 5 of the

participants from the CT group were excluded from the measurement of number of compensatory movements due to inability to sustain grip on stylus (n=2), and keratoconjunctivitis sicca (n=1). A familiarization trial on the VR system was conducted for the VR group prior to the start of the intervention.

Participants in the VR group underwent two 3-minutes VR games with a 6-minute rest in between. To ensure safety, participants playing the VR games were informed that they should notify the experimenters immediately if symptoms of cybersickness or discomfort was experienced. In the CT group, each participant experienced an additional 3 minutes of their usual rehabilitation exercises, with a 6-minute rest in between. To make sure participants were medically stable throughout each session, vital signs were also routinely taken pre- and post-intervention.

Data analysis

Data were analysed by IBM SPSS Statistics version 21.0. As the data analysed was not normally distributed, median values and interquartile range of the scores obtained from the outcome measures were calculated. Median values of subjects' age and chronicity of stroke (in years) were used as it was more representative of the subjects, given the limited sample size. To determine if there was a significant difference in the improvements of shoulder function and quality of movements between control and experimental groups, Mann Whitney U test was used as an alternative to the independent T-test as sample size was small; Wilcoxon matched paired test was also used as an alternative to the paired t-test to compare if there were any significant improvement of shoulder function and quality of movements between pre-treatment and post-treatment. The significance level was chosen at 0.05.

Results

(1) Participants characteristics

The median age of participants was 74 years (range 63 to 79.5 years), and the median time for stroke chronicity was 2 years (range 1.5 to 5.5 years). There were no statistical differences ($p>0.05$) in baseline measures of all outcome measures and no significant differences were found between groups with respect to gender, comorbidities, affected side, handedness and stroke type, except for age ($p=0.047$). But the previous study [31] demonstrated a poor correlation between age and functional rehabilitation outcomes

Table 4

Characteristics of participants and the baseline of function status before the experiment

Characteristics	VR group (n=7)	CT group (n=8)	Baseline Function Status	VR group (n=7)	CT group (n=8)	Between Group p-value
Age in years/median	74 (63-79)	83.5 (72-85)	FMA-UE			
Stroke in years/median	2 (1-4)	2 (2-6)	Upper Extremity	31 (26.5-34)	35.5 (30-36)	0.076
Gender			Wrist	9 (6-10)	10 (5-11)	0.116
Female, n(%)	3 (20)	2 (13.33)	Hand	13 (11-14)	13 (10-14)	0.306
Male, n(%)	4 (26.7)	6 (40)	Coordination	4 (3.5-6)	5(3.5-6)	0.306
Comorbidities			Total	59 (48-61)	64 (50-65)	0.076
Hypertension, n(%)	7 (46.67)	7 (46.67)	WMFT			
Diabetes Mellitus, n(%)	5 (33.33)	1 (6.67)	FAS	69 (63.5-71.5)	72.5 (57-74.5)	0.14
Dyslipidemia, n(%)	6 (40)	3 (20)	Time in seconds	3.24 (2.71-3.45)	2.78 (1.61-3.385)	0.23
Atrial fibrillation, n(%)	0	2 (13.33)	SRMS	26 (22-27.5)	23 (20.5-23.5)	0.076
Stroke type			ROM in degree			
Ischaemic, n(%)	6 (40)	7 (46.67)	Shoulder Flexion	130 (110-132.5)	130 (110-132.5)	0.477
Haemorrhagic, n(%)	1 (6.67)	1 (6.67)	Shoulder Horizontal Abduction	20 (10-23.5)	20 (10-23.5)	0.168
Affected side			Shoulder Horizontal Adduction	95 (77-97)	95 (77-97)	0.116
Right, n(%)	0	1 (6.67)				
Left, n(%)	7 (46.67)	7 (46.67)				

in older adults with stroke. Hence, the results could reveal true effects of the interventions. The participant characteristics and baseline tests are summarized in Table 4.

(2) UE motor function

Table 5 summarizes the three major tests on UE motor functions. First, there was a statistically significant improvement in both VR (95% CI, $p=0.045$) and CT (95% CI, $p=0.044$) group in the total FMA-UE score, but there was no significant difference between both groups (95% CI, $p=0.2315$).

Table 5

Summary of test results of FMA-UE, WMFT and ROM

Upper Extremity Outcome Measure	VR Group			CT Group			Between Groups
	Median (IQR)			Median (IQR)			
	Pre-test	Post-test	p-value	Pre-test	Post-test	p-value	
FMA-UE							
26.5-34	31 (26.5-34)	33 (32-34.5)	0.0655	35.5 (30-36)	35 (31-36)	0.1425	0.168
Wrist	9 (6-9)	9 (8-9.5)	0.207	10 (5-10)	10 (8.5-10)	0.1585	0.5
Hand	14 (11-14)	14 (13-14)	0.051	13 (10-14)	14 (10.5-14)	0.168	0.4775
Coordination	4 (3.5-6)	6 (3.5-6)	0.1285	6 (3.5-6)	5.5 (3.5-6)	0.3525	0.1985
Total Score	59 (48-61)	61 (58-63)	0.045*	64 (50-65)	64.5 (53.5-66)	0.044*	0.2315
WMFT							
Functional ability score (FAS)	69 (63.5-71.5)	73 (69-73.5)	0.009*	72.5 (57-74.5)	74 (60-74.5)	0.0805	0.076
Time in seconds	3.24 (2.71-3.45)	1.95 (1.47-2.65)	0.0355*	2.78 (1.61-3.385)	1.75 (1.33-3.73)	0.0655	0.1985
Weights in lbs	7 (4-8.5)	7 (4-9.5)	0.5	8 (4-9)	8.5 (4.5-10)	0.0205*	0.0945
Grip strength in kg	10.3 (8.42-14.5)	12 (7.835-13.5)	0.376	15.5 (8.49-17.99)	16.33 (9.75-20.82)	0.181	0.1985
ROM							
Shoulder flexion in degree	130 (110-132.5)	124(108-129.5)	0.2635	124.5(108.5-133.5)	129.5(109-139.5)	0.363	0.3065
Shoulder horizontal abduction in degree	20 (10-23.5)	24 (9-25.00)	0.1165	21.5(13.5-32.5)	26 (20-27.5)	0.336	0.4335
Shoulder horizontal adduction in degree	95(77-97)	104 (89.5-107)	0.1725	100.5 (82-107)	107 (90.5-115)	0.1985	0.1915
Elbow flexion in degree	140 (134.5 - 143)	141 (135.5-144)	0.399	141 (130.5 - 142.5)	144.5 (140 - 145.5)	0.075	0.232
*p<0.05							

Second, for WMFT, participants in the VR group demonstrated a statistically significant improvement in FAS (95% CI, p=0.009) and TIME (95% CI, p=0.0355) as compared to baseline, evidently indicating that the VR intervention was beneficial in improving both functional ability and speed of timed tasks. There was no significant differences between VR and CT groups in FAS (95% CI, p=0.076) and TIME (95% CI, p=0.1985). But the box plots below (shown in Fig. 4) illustrates a trend towards greater improvements in WMFT-FAS and -TIME in the VR group, where the VR group exhibited a more improved UE functional ability with an increase in FAS median score of 4 compared to 1.5 in the CT group, and in WMFT-TIME, the VR group performed 1.29 seconds faster in task performance, as compared to 1.03 seconds in the CT group.

It was surprising to note that there was a statistically significant increase in WMFT- weights in CT group (95% CI, p=0.0205), but not in WMFT- weights (95% CI, p=0.5) in the VR group, although there were no statistically significant difference in grip strength for both the VR (95% CI, p=0.376) and CT group (95% CI, p=0.181). Further trend analysis demonstrated no decline in weight-carrying performance and grip strength post the VR intervention. In other words, the VR intervention had no negative effects on UE muscle strength and grip strength.

Lastly, there was no statistically significant improvements in the ROM of shoulder flexion, horizontal abduction and horizontal adduction, elbow flexion in both groups. Even though there were no remarkable improvements in the ROM, the VR intervention contributed to the maintenance of shoulder and elbow ROM.

(3) Quality of UE movements

The VR group demonstrated no statistical significance in the difference in total compensation numbers for the shoulder flexion exercise (Game 1) and the shoulder horizontal abduction exercise (Game 2) as shown in Table 6, indicating that there was no marked reduction in compensatory movements after the VR intervention. However, the results of Game 1 revealed a consistently decreasing trend in elbow flexion

on affected side with the median frequency showing a decrease of 8 and a boxplot converging post-intervention, indicating a decrease in variability (Fig. 5). Similarly, total median frequency of compensatory movements reduces by 14 and a converging boxplot is seen showing a decrease in variability in the post VR intervention, suggesting the improvement in reducing compensatory movements during Game 1. Likewise, for Game 2, total median values of compensatory movements was decreased by 22 (Fig. 6) in the VR group. Converging boxplots indicates a decrease in variability in VR group and thus a greater trend of improvement in reducing compensatory movements during Game 2.

Table 6

Numbers of compensatory movements for two planner motion exercises of UE in the VR group

Compensator movements	VR group		
	Pre-test	Post-test	p-value
Shoulder flexion - Game 1			
Elbow Bend on affected aside	9 (3-34)	1 (0-11)	0.088
Total Compensation	81 (54-110)	67 (22-83)	0.231
Shoulder horizontal abduction - Game 2			
Total Compensation	67 (46.67)	45 (22-74)	0.337

(4) Stroke rehabilitation motivation scale.

There was a significant (95% CI, $p=0$) increase of 28.6% in the VR group who agreed that participating in rehabilitation was exciting. The CT group paled in comparison with an increase of 25%. Despite the insignificant p-value (95% CI, $p=0.195$), the number of participants in the VR group who disagreed that their motivation for rehabilitation has gotten lower increased from 71.4% to 100% throughout these 10 sessions. In contrast, the percentage of subjects in CT group who disagreed with the statement dropped from 62.5% to 50%.

There were no significant improvements in the SRMS total score for VR group (95% CI, $p=0.0635$), CT group (95% CI, $p=0.4325$) and between groups (95% CI, $p=0.1985$). However, there was an observed increase of 3 points in the intrinsic motivation in the VR group, as compared to a 1-point increase in the CT group.

Discussion

The study 2 aims to validate the feasibility and efficacy of the developed VRS in a community setting, and the results found the improved recovery of the UE motor impairments and motor ability in older adults with stroke. Further trend analysis illustrated that a reduction in the UE compensation, as well as higher intrinsic motivation in older adults who underwent the VR intervention.

The study established that the VRS with an in-built compensation detector could be an effective adjunct in enhancing UE motor functions in older adults with stroke. The VRS could identify compensatory movements, allow older adults with stroke to independently correct their movements through the audio-visual feedback, and support them to engage in therapy even without the constant supervision from therapists. The inclusion of VR gaming provides the similar training dosage and repetitions to promote the recovery of upper- extremity motor functions as the conventional rehabilitation. This finding is important considering the high prevalence of chronic stroke patients with persistent UE impairments [4], and only 5% of them attained complete recovery of the hemiparetic upper extremity [32]. This is also extremely relevant in the current context, where there is a short supply of manpower resources and limited therapist-patient interaction time [6] in the community setting to meet the increasing demands of a rising aging population globally. Furthermore, the developed VRS has the potential to be used as a form of telerehabilitation for chronic stroke individual to take rehabilitation at home environment, in which a large amount of travelling time and cost are saved [5] and the patients could perform well in a comfortable and familiar environment during therapy time [33].

(1) Quality of UE movements

The study found that the trend towards a reduction in frequency of compensatory movements in older adults with stroke in the VR group was uplifting, even though the improvements in compensation was not significant when compared to baseline. The finding suggests that the proposed compensation detector and feedback could potentially improve the quality of UE movement, which resonated with the previous

study, for example the provision of compensatory truncal feedback in VR effectively decreasing trunk compensatory movements [30]. The finding is significant to our study as it supports the research direction that the inclusion of a compensation detector in VRS might be an appropriate treatment direction to achieve reduced compensation movements in older adults with stroke. The non-significant differences in the number of compensatory movements in the VR group, however, might be attributed to a short intervention period. The duration of 10 sessions of VR gaming might not be enough to observe a significant change in reducing the compensation, therefore the longer intervention duration (e.g 20 sessions) might be warranted to determine significant effectiveness of the developed VRS.

Specifically, the improvement in the UE movement quality might be attributed to the provision of extrinsic feedback by VRS in this study. Extrinsic feedback such as visual and auditory stimulus provided upon detection of compensatory movements allowed older adults with stroke to correct movement patterns through sensorimotor learning. Moreover, the design of some extrinsic feedback was based on the operant conditioning where rewards and punishments were given based on the detected compensatory movements or the performance in gaming. The feedback based on the operant conditioning was found to be effective in encouraging VR users to perform therapeutic exercises correctly [30]. Similarly, the feedback based on the operant conditioning might play the key role to decreasing compensatory movements in this study. The feedback gave rise to cellular and neural reorganization of the cerebral cortex and sub-cortex structures via neuroplastic processes, which is fundamental in motor relearning after stroke [34]. However, the punishment of game score designed in two games was unexpected to sometimes motivate two participants to ignore the visual compensatory feedback in their haste to obtain a higher game score, leading to a lack of self-correction and hence a non-significant reduction in compensatory movements. Therefore, the design of punishment should be carefully considered for the elderly player.

(2) UE motor function

The incorporation of the developed VRS as part of stroke rehabilitation programme was equally effective as conventional therapy in enhancing the recovery of UE motor impairments and motor ability. This is likely because the VRS provided the real-time visual feedback of their performance and results to facilitate the improvement in motor function [3], as reflected in the significant improvements of WMFT and FMA scores in the VR group. Furthermore, our results concur with contemporary findings [35], reasserting that the increase in training duration and high repetitions during VR sessions might have contributed to the improved motor ability of the hemiparetic UE.

(3) Level of intrinsic motivation

Despite non-significant differences in motivation scores for both groups, there was an observable trend demonstrating greater improvements in intrinsic motivation scores in the VR group as compared to the CT group. The results provide evidence that VR gaming could impact the intrinsic motivation of older adults with stroke, and thus influence their acceptance and adherence of therapy. Our results were consistent with the research findings in study [36] where the highest intrinsic motivation was found in subjects of the VR group after intervention. Moreover, the present VRS incorporating a goal-oriented reward scheme could help to evoke competitiveness and motivation in disengaged older adults with stroke. Despite traditional beliefs on elderly possessing negative attitudes towards technology [37], it is fair to conclude that the introduction of VR gaming has the potential to enhance engagement and motivation.

Moreover, an increased intrinsic motivation level could have possibly contributed to the significant improvement within VR group in WMFT. Levin et al. [38] suggested that VR environments increase intrinsic motivation and problem-solving ability, which helped to achieve motor relearning via adaptive neuroplasticity changes, potentially leading to gains in motor function. This might help to explain the significant improvements in UE motor ability in the VR participants, and not in the CT participants. It indicates that the VR program could be a better intervention than the conventional therapy.

Limitations

The main limitation of this study is the small sample size. The calculated sample size was 136 (G*Power Version 3.1.9.2) in the previous study that aimed to improve upper limb motor function in stroke rehabilitation through VRS [3]. In addition, the study was implemented in a single rehabilitation center, hence the results may not be a good representation of the general stroke population. The small sample size also indicates that randomized allocation of our subjects was not possible.

Another limitation of this study is the missing of resistance training exercise of VRS. Although the haptic device used in the study can provide kinesthetic feedback to users in the form of vibration and force-feedback, its range of force feedback is not comparable to the equipment for strength training in conventional therapy. Because the present VRS did not include any components of resistance training whilst the conventional therapy had in this study, it could explain that WMFT-weights was found to be significantly increased in the CT group compared

to the VR group. Nonetheless, it is encouraging to find out that there was no compromise in upper- extremity muscle strength, as well as grip strength in VR participants.

Conclusion

The present study described the development of a compensation-aware UE virtual rehabilitation system that could be deployed in the community setting, even at the home environment. Unlike the previous VRS focusing on the reaching task or other activities of daily life, the present VRS focused on two planar motion exercises of UE, shoulder flexion and shoulder horizontal abduction, to train the specific UE functions. Two studies were conducted to determine the compensatory movements and their thresholds in these two motor exercises of UE in the first study, and to preliminary test the feasibility and efficacy of the developed VRS to improve the recovery of UE motor impairments and ability as well as reduce the UE compensation. Areas requiring improvements were identified to incorporate the strength training as well as the comprehensive feedback, and the future research is needed to establish the long-term trial with more participants to determine its effectiveness in enhancing the quality of movements in older chronic stroke populations.

Declarations

Ethics approval and consent to participate

Informed consent was obtained from all participants to complete the protocol approved by the Ethics Committee of Nanyang Polytechnic(ref: SIT-2014-001), Singapore.

Consent for publication

The authors received consent for the publication of the photographs used within the manuscript.

Availability of data and materials

The datasets analysed during the current study are available from the corresponding author on reasonable request.

Competing interests

The authors declare that they have no competing interests.

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Authors' contributions

Z. Luo conceived study design, designed compensation detector, and drafted the manuscript. A. Lim designed the rehabilitation game and requirements, as well as analysed the data. P. Durairaj guided the field test in community centre. K.K. Tan designed the gaming feedback. V. Verawaty collected the data and programmed the system. All authors read and approved the final manuscript.

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Figures

Figure 1

Hardware of VRS set in a community rehabilitation centre: 1-haptic device, 2-display, 3-Kinect, 4-PC and 5-audio box

Figure 2

The two rehabilitation games: (a) the shoulder flexion game and (b) the shoulder horizontal abduction game, where the right side shows an experimenter demonstrating the game playing.

Figure 3

The timeline to trigger the game feedback corresponding to the compensatory movements, where G1, G2, G3 and G4 represents the proposed four guidelines to design the feedback.

Figure 4

WMFT-FAS (left) and WMFT-Time (right) between the VR and CT groups

Figure 5

Box-plot of the number of Elbow Flexion and total number of compensatory movements Pre- and Post-intervention in the VR group during the shoulder flexion exercise - Game 1

Figure 6

Box-plot of total number of compensatory movement Pre- and Post-intervention in the VR group during the shoulder horizontal abduction exercise - Game 2