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Rehabilitation of activities of daily living in virtual environments with intuitive user interface and force feedback

ABSTRACT

Purpose

To investigate the feasibility of using a virtual rehabilitation system with intuitive user interface and force feedback to improve the skills in activities of daily living (ADL).

Method

A virtual training system equipped with haptic devices was developed for the rehabilitation of three ADL tasks – door unlocking, water pouring and meat cutting. Twenty subjects with upper limb disabilities, supervised by two occupational therapists, received a four-session training using the system. The task completion time and the amount of water poured into a virtual glass were recorded. The performance of the three tasks in reality was assessed before and after the virtual training. Feedback of the participants was collected with questionnaires after the study.

Results

The completion time of the virtual tasks decreased during the training ($p<0.01$) while the percentage of water successfully poured increased ($p=0.051$). The score of the Borg scale of perceived exertion was 1.05 (SD=1.85; 95% CI=0.18–1.92) and that of the task specific feedback questionnaire was 31 (SD=4.85; 95% CI=28.66–33.34). The feedback of the therapists suggested a positive rehabilitation effect. The participants had positive perception towards the system.

Conclusions

The system can potentially be used as a tool to complement conventional rehabilitation approaches of ADL.

INTRODUCTION

Activities of daily living (ADL) refer to the activities carried out by people to live an independent life without assistance, e.g. grooming, preparing food or eating. Manual dexterity is needed to perform ADL properly and effectively. For people with upper limb disabilities, deficiency in the functions of their upper arm, forearms or hands limit their ability to perform ADL independently, thereby hindering self care and leading to low self esteem. According to the Centers for Disease Control and Prevention, there are at least 1,500 newborns annually in the United States of America suffering from various forms of upper limb disabilities [1]. In Hong Kong, as of 2008, 15% of the physically disabled population had motor impairment in the upper limbs [2]. This could be an issue to the healthcare system as well as the individuals and the families concerned.

Occupational therapy is an effective form of rehabilitation for people with upper limb disabilities to cope with their motor impairment and regain the ability of performing ADL and self care. The therapy caters for the specific needs of individuals and maximise the function of their affected limbs. Studies have shown that task-oriented approaches focusing on the attainment of specific goals can improve their performance in ADL [3-5]. Conventional task-oriented approach requires disabled people to perform a task repeatedly in a controlled environment, and under direct supervision of occupational therapists (OTs) who provides guidance and makes assessment during the process. The conventional approach demands considerable amount of human resource since the rehabilitation process require constant and long hours of one-to-one supervision. The therapists need to prepare the materials required for the training of ADL, set up, clean up and reset the environment again and again. In the meantime, they also evaluate the performance of the patient while making correction and providing guidance. The process is critical for effective rehabilitation but it is also demanding and laborious which limits the throughput of the training.

The rehabilitation process can potentially be computerized using virtual reality (VR) technology that can offer a solution to complement the conventional approaches and enhance the training effectiveness. In fact, VR has been regarded as an effective tool for motor and cognitive rehabilitation. VR technology encompasses the use of computer hardware and software to simulate real environments using interactive computer-generated audio, visual and haptic feedbacks, so that the users can percept and immerse in the corresponding virtual environments as if they were real. One of the major advantages of using VR systems in rehabilitation is that the training tasks can be readily custom-designed through computer programming to meet the specific needs of the target users. Besides, the automation, availability and accessibility of VR training systems enable repeated practice and self-learning that can help enhancing the proficiency of specific tasks without excessively increasing the workload of OTs. Besides, quantitative data can be recorded automatically to analyse user performance and gain insight into the training progress. For tasks that involves the manipulation of potentially hazardous materials, e.g. sharp objects or hot liquid, safety is guaranteed as training in virtual environments are harmless, and errors could be undone [6].

VR systems have been successfully implemented for the rehabilitation of different target populations, e.g. stroke patients [7-9], people with traumatic brain injury [10,11] or children with developmental disorders [12]. They have been employed to assess the performance of upper limb motor abilities of patients through real-time quantitative measures [13]. In these studies, force feedbacks were provided in the training using haptic devices, in conjunction with audio and audio feedbacks to enhance the realism of the virtual environments. Findings from previous studies consistently showed that users had a high level of satisfaction towards virtual rehabilitation systems. The advances demonstrate the potential to adopt such systems as routine training approaches in occupational therapy [14].

However, the use of VR for the rehabilitation of ADL receives relatively less attention. One example is the Virtual Life Skills [15] project which attempted to facilitate people with learning disabilities to learn the knowledge and perform the tasks necessary for independent survival in the real world, e.g. handling money and dressing, by simulating them with a virtual city. Other examples that leverage VR for the rehabilitation of ADL include the use of a virtual kitchen for training meal preparation tasks, or the use of virtual supermarket for practising shopping tasks [16], for people suffering from traumatic brain injury [17]. The emphasis of these projects was to enhance the cognitive abilities, where generic user interface devices like computer mouse or joystick were only used, and the training of manual skills involved in ADL was therefore not possible.

On the other hand, robotics has been used to develop haptic interface that is essential for the training of manual skills, e.g. HapticMaster [18,19] and ARMin [20,21], which are high performance devices, at about human height, that can guide the impaired arm or hand of users through a robotic arm. In particular, ARMin is an exoskeleton robot also equipped with actuator to assist shoulder movement. These devices can generate nominal forces of 100 N [18] and torques in the range of 2 to 20 Nm [20]. HapticMaster was used for the training of ADL like grooming, drinking, eating and playing tic-tac-toe [19]. ADL tasks like cooking, cleaning and using a ticket machine were trained using ARMin, where the assist-as-needed strategy was adopted to provide guiding forces when necessary [20].

In this study, a VR rehabilitation system was proposed as a platform to facilitate the training of the manual skills in ADL in a safe, versatile and flexible virtual environment. Unlike the robot-assisted rehabilitation approaches discussed above, the platform was realised using a relatively low cost and handy desktop haptic device to simulate force feedback interactively during virtual rehabilitation. The device comes with an intuitive pen-like stylus and has a small footprint. Given the potential of robotics approaches, the proposed platform can lower the barrier to wider adoption, thus enabling more people who suffer from upper limb disabilities to enjoy the benefits. While the haptic device employed in this study was less powerful (with a maximum output force of 3.3 N), it demonstrates the feasibility of producing forces that are involved in various ADL tasks.

To demonstrate the feasibility, the proposed VR system was implemented for the training of three common tasks of ADL, namely, door unlocking, water pouring and meat cutting. For easy reference, the three virtual tasks are referred to as Task 1, Task 2 and Task 3 in this paper. A study was conducted to evaluate the system by recruiting students with upper limb disabilities from a special school. Details of the study and the findings will be discussed in the following sections.

METHODS

Participants

Twenty students with upper limb disabilities were recruited from a special school through purposive sampling. Those who were visually impaired and the impairment could not be corrected with visual aids; in an unstable medical conditions such as frequent seizure activities; suffered from complete sensory loss of upper limbs; had severe arm pain, and manifested behavioural problems, were excluded. The study was approved by the Human Subjects Ethics Committee of the institution. Informed consents were obtained from the parents or guardians of all the subjects. Besides, two OTs responsible for the rehabilitation of the subjects were also recruited to participate in the study to perform professional assessment on the performance of the subjects and give comments on the proposed system.

Demographics

The demographic data of the twenty subjects is shown in Table I. 60% of the subjects were male. The mean age is 16.65 years (SD=4.57 years); the youngest subject was 7 years old and the eldest was 22 years old. In addition, the ability of the subjects in handing objects in ADL was identified using the manual ability classification system (MACS) [22]. The MACS level, ranging from level 1 to level 5, was rated by the two OTs responsible for providing rehabilitative care to the subjects. The higher the MACS level, the more severe the disability. In the study, 75% of the subjects were at MSCS level 3 or above. On the other hand, the two OTs are both senior occupational therapists with over 20 years of working experience in the rehabilitation of disabled students.

Insert Table I about here

The Virtual Rehabilitation System

The proposed system was developed using a desktop personal computer with an Intel Core i7-4770 3.4GHz CPU, 16GB RAM, and an NVidia GeForce GTX750Ti display card, running the Microsoft Windows 7 operating system. The computer was connected to a 22-inch Viewsonic VA2261 LED monitor which was fixed on the desk top using a flexible mount to allow for easy and ergonomic adjustment. The computer was also connected to a pair of SensAble Phantom Omni haptic devices. The complete system was installed on an Ergotron WorkFit-C movable workstation, as shown in Figure 1.

Insert Figure 1 about here.

The haptic devices employed in the study are intuitive 3D user interface equipped with a pen-like stylus. It provides 6 degrees-of-freedom inputs (3 degrees respectively for the position and orientation of the stylus endpoint) and 3 degrees-of-freedom force output. In the study, the stylus was detached and replaced by tailor-made handles fabricated using 3D printing technology. The 3D printed handles included a key for Task1, a jar for Task 2, and a piece of meat and a knife for Task 3, as shown in the middle column of Figure 1.

The software of the system was developed using the C/C++ programming language, with the OpenGL and OpenHaptics application programming interfaces adopted to render the graphic and haptic display interactively in the 3D virtual environments. For Task 1, a door with door knob and a key were rendered; for Task 2, a jar, a glass and the water were displayed; for Task 3, a virtual hand holding a piece of meat and a knife were shown. The virtual environments are shown in the right column of Figure 1. The position and orientation of the key, jar, meat and knife were rendered interactively on the screen depending how the user manoeuvred the tailor-made 3D printed handles that were mounted to the haptic devices. In addition, the locality data of the haptic devices were recorded during the process of virtual training, which could be used to plot the trajectories of hand movements in 3D space. An example of the 3D plots for the three tasks is shown in Figure 2.

Insert Figure 2 about here.

Instruments

Four instruments were used to evaluate the computerized virtual training system, including (i) the task specific feedback questionnaire (TSFQ), (ii) the Borg scale of perceived exertion (BSPE), (iii) the questionnaire on performance in simulated real tasks (QSRT), and (iv) the computer system usability questionnaire (CSUQ). The twenty subjects were requested to respond to the first two instruments, whereas the OTs were asked to complete the last two.

Task Specific Feedback Questionnaire

The TSFQ is a standardized tool used to evaluate the level of enjoyment, difficulty and the sense of control perceived by a user after performing a task in virtual environment [14]. The questionnaire consisted of 8 items, on a Likert scale from 1 (not at all) to 5 (very much). In the study, the subjects were asked to rate their overall feeling when they were performing the three virtual tasks, and also the level of realism of the virtual environments they perceived. Considering that some of the subjects were quite young, emoticons associating with the numerical choices were supplied to help them to better appreciate the extent of differences.

Borg Scale of Perceived Exertion

The BSPE measures the extent of exertion during physical exercise or sport using an 11-point Likert scale, with 0 indicating no exertion at all, to 10 indicating the maximal exertion [23]. In the study, the subjects were asked to rate the level of physical exertion they perceived during the virtual tasks. Similar to the TSFQ, emoticons associating with the numerical choices were supplied to assist the subjects in appreciating the differences.

Questionnaire on Performance in Simulated Real Tasks

The three tasks of ADL concerned in the study are conventionally assessed in the special school in *simulated* real environments designed by the OTs. The term “simulated” was specifically used here to make clear that the assessments were not conducted using the actual objects in real ADL due to safety and convenience consideration. Hence, the door opening task was simulated by asking students to open a customized miniature door put on top of a desk. Water pouring was simulated by pouring dyed water from a transparent jar into a glass put on a tray, whereas meat cutting was simulated by cutting a piece of therapy putty with a plastic knife. The simulated real tasks are shown in the left of Figure 3. Further details will be given in the next section.

Insert Figure 3 about here.

In the study, the performance of the subjects in these three simulated real tasks was assessed by the OTs, before and after the virtual training, in order to evaluate whether the proposed system can help improving the skills in reality. To this end, the QSRT was developed for the OTs to assess the performance of the subjects on the three simulated real tasks. For each task, the OTs would rate the performance of the subjects from four aspects, i.e., time taken to complete the task, the accuracy, completeness, and the overall competency of the subject. The QSRT consisted of 12 items, and adopted a 7-point Likert scale, from 1 (strongly disagree) to 7 (strongly agree).

Computer System Usability Questionnaire

The CSUQ was developed by the IBM Corporation to measure the usability of a computer system [24], on a 7-point Likert scale from 1 (strongly agree) to 7 (strongly disagree). The questionnaire contains 19 items evaluating various aspects of user perception towards the effectiveness, interface, expectations and satisfaction of a computer system. At the end of the study, the OTs accompanying the subjects during the study were asked to rate the usability of the proposed training system using the CUSQ based on their professional judgement.

Research Design

A pre-post test was conducted over a period of two months to evaluate the proposed virtual training system. The research protocol is shown in Figure 4 and the procedures are described as follows.

Insert Figure 4 about here.

Pre-test

In the pre-test, the baseline performance of the subjects in ADL was assessed by asking them to perform the three above-mentioned simulated real tasks one by one. The processes were video-recorded with a digital camera. For door opening, the task was to pick up the key, insert it into the key hole of the door knob, and then make a clockwise rotation to unlock and open the miniature door (see the top-left photo in Figure 3). For water pouring, the task started by lifting a transparent jar of dyed water and pouring it into an empty glass, until all the water was removed from the jar. The purpose of the dye was to allow the researcher and OTs to observe the process more clearly (see the middle-left photo in Figure 3)). For meat cutting, subjects were requested to hold with one hand a piece of therapy putty, in the form of a slab, and cut it with a plastic knife with the other hand by sawing back and forth until the putty was separated into two parts (see the bottom-left photo in Figure 3). The video recordings were then used by the researchers to determine the time taken by each subject to complete the individual tasks, and also reviewed by the OTs to evaluate the performance of the subjects using the QSRT.

Intervention

After the pre-test, the subjects received four sessions of virtual training using the proposed rehabilitation system, two sessions per week in four separate days. In each session, a subject used the system to perform the three tasks of ADL. For door opening, the subject used the 3D-printed key attached to the haptic device to control the virtual key (see the top-right photo in Figure 3). The virtual key was to be moved towards the door knob and inserted into the keyhole. Feedback forces were generated and felt by the hand of the subject whenever the key collided with the door or the door knob in the virtual environments. After the key was inserted and turned 90 degrees clockwise, an audio clip of the sound of door opening was played and the task was completed.

For water pouring, the 3D-printed jar was attached to the haptic device as the user interface. The subject held the ear of the jar with one hand and manoeuvred it to control the water-filled virtual jar displayed on the screen, as if they were holding a real jar (see the middle-right photo in Figure 3). Gravity was simulated such that the subject could feel the weight of the water inside the virtual jar through the haptic device, which gradually decreased as the water flowed out of the jar. In the virtual environment, an empty glass was put on a desk and the subject was required to move the mouth of the jar on top of the glass, and then tilt the jar to pour the water into the glass. The amount of water successfully poured into the virtual glass was recorded automatically by the system as a measure of accuracy. Interactive audio cues were provided such that the sound of water pouring into the glass was played when the task was being performed successfully; otherwise, the sound of water spilling over the table was played instead.

For meat cutting, a pair of haptic devices was employed for simulating the bi-manual operations required in the task. The haptic stylus of the device on the left was replaced with a 3D-printed slab to represent a piece of meat, whereas the one on the right was replaced with a 3D-printed handle of a knife (see the bottom-right photo in Figure 3). Using the two 3D-printed models, the subject manoeuvred the virtual knife to cut a piece of virtual meat. The virtual task was programmed to contain three steps. In the first step, the subjects used the left hand to move the virtual meat to a target position on the desk and pressed it downwards. Next, a guideline was displayed near the right edge of the virtual meat, as a visual cue to signify the subject to move the virtual knife towards the guideline and align accordingly. In the third step, the subject used the virtual knife to saw, along the guideline, back and forth horizontally on the meat for 10 times to complete the task. With feedback forces generated by the haptic device, the subject could feel the knife-meat friction while performing the sawing motion. On-screen message was displayed when the virtual knife was too close to the virtual left hand. An animated audio clip was played when the knife was sawing on the virtual meat.

Post-test

After the virtual training, the subjects were asked to demonstrate their skills in the three simulated real tasks as they had performed in the pre-test. Similar to the pre-test, the processes were recorded by videos which were subsequently reviewed by the researchers to determine the time spent on each of the three simulated real tasks, and by the two OTs to evaluate the performance of the subjects using the QRST. Finally, the subjects were also asked to fill in the TSFQ and BSPE, whereas the OTs were asked to complete the CSUQ.

RESULTS

Virtual training

The performance of the subjects during the four practice sessions is shown in Figure 5 and the performance in the first and the fourth session is compared in Table II. In terms of task completion time, it can be observed from the box-plots that there was apparently a decreasing trend in the median value over the four sessions for the three virtual tasks. The decrease was more conspicuous for Task 1 and Task 3. Comparing the performance in the first and last session, the results of the t-tests indicated the decrease was statistically significant, with p-values equal to 0.001, 0.007 and 0.004 for the three tasks respectively. Besides, regarding the percentage of water successfully poured into the virtual glass in Task 2, an increasing trend over the four sessions was revealed from the box-plots. The result of the t-test yielded a p-value of 0.051 for the observed increase in the amount of water filled between the first and the fourth session.

Insert Figure 5 and Table II about here

Simulated real tasks

The performance of the subjects in the simulated real tasks before and after the virtual training is shown in Figure 6 and the performance in the pre-test and post-test is compared in Table III. The average completion time for three tasks was found to decrease in the post-test but not statistically significant, with p-values equal to 0.181, 0.225 and 0.167 for Tasks 1, 2 and 3 respectively.

Insert Figure 6 and Table III about here

User evaluation

The statistical results of TSFQ, i.e. mean score, SD and 95% confidence interval (CI), are summarized in Table IV. The mean total score was 31 (SD=4.85; 95% CI=28.66 – 33.34) out of 40. The mean scores in 5 of the 8 items were above 4 (‘1’ indicating strongly *disagree* and ‘5’ strongly *agree*), whereas the mean scores of the questions regarding ‘Level of comfort’ (item no. 7) and ‘Perception of easiness’ (item no. 8) were lower than 3. On the other hand, the mean BSPE score was 1.05 (SD=1.85; 95% CI=0.18 – 1.92), with ‘0’ indicating no exertion and ‘10’ maximal exertion.

Insert Table IV about here

The proposed virtual training system was evaluated by the two OTs who supervised the four practice sessions using the CSUQ. The results are shown in Table V. Among the 19 items, the mean scores of 15 items were between 2 and 3 (‘1’ indicating strongly *agree* and ‘7’ strongly *disagree*). The items regarding ‘Simplicity of system’ (item no. 2) and ‘Satisfaction towards system interface’ (item no. 17) scored the best (1.5) while the item ‘Fulfilling expectation on function’ (item no. 18) scored less favourably (4.0). The mean overall satisfaction score is 2.5. Furthermore, the difference in score of 13 items was 1 point, indicating that the rating of the two OTs were quite consistent. However, they disagreed in some way on items concerning ‘Effectiveness in task completion’ (item no. 3) and ‘Improvements in productivity’ (item no. 8), with a difference of 3 points.

Insert Table V about here

The two OTs rated the degree of improvement in the performance of the subjects in the three simulated real tasks by reviewing videos taken in the pre-tests and post-tests. As shown in Table VI, the results are positive and the mean scores of the individual items are all within 5 and 6 (‘1’ indicating strongly *disagree* and ‘7’ strongly *agree*).

Insert Table VI about here

DISCUSSION

In this study, it is hypothesized that the proposed virtual training approach can improve the learning curve of people with upper limb disability in the acquisition of skills of ADL. The results suggest that the approach has the potential to achieve this goal. In the virtual training, the subjects were able to complete the three ADL tasks faster in the fourth practice session as compared to the first session (Table II). For the water pouring task, there was a modest reduction in completion time. This is due to the fact that, among the three virtual tasks, the design and user interface of water pouring were considered to be most intuitive by both the subjects and the OTs. Provision of instructions to the subjects was almost unnecessary. The subjects could all immerse into the virtual reality easily and quickly, naturally grasping the 3D printed jar and pour water into the glass shown on the computer screen as if they were doing so in reality. Indeed, the action of water pouring was also relatively simple and involved less dexterous manipulations when compared with the other two tasks. As a result, they could already complete the task using a short amount of time in the first session and the task completion time did not improve much further in the following sessions. Similar situation was also observed from the percentage of water successfully poured into the virtual glass, which increased moderately by about 10% over the four training sessions

Regarding the pre-post tests on the simulated real tasks, while there was a decrease in completion time after the virtual training, the difference was not significant (Table III). This could be explained by the limitation that the virtual environments and user interface of the computer-based training were not exactly identical to the setting of that in the simulated real tasks. For example, the real key used for door opening was shorter than the 3D-printed key; the tactile feeling of cutting therapy putty was different from that rendered in the virtual task.

Some adaptation was required to transfer the manual skills and experience gained from the virtual reality to the simulated real tasks. Also, the number of virtual training sessions may need to be increased in order to observe a more significant improvement in performance. Nevertheless, the subjects were mentally better prepared for the real ADL after going through the four sessions of virtual training. This is also supported by the positive results obtained from the QSRT which will be discussed below.

In fact, the subjects were quite satisfied with the proposed training system, as shown by the TSFQ scores (Table IV). However, the “Level of comfort” (item no. 7) and “Perception of easiness” (item no. 8) were rated relatively low, which, from the comments of the subjects, were due to the settings of Task 1 and Task 3. In Task 1, they found it difficult to aim the virtual key at the keyhole. Some even considered it more difficult than the real task. Although the virtual environment was rendered with 3D objects, stereoscopic effect was not available and thereby leading to the absence of depth cues. Without depth information, it was indeed difficult to judge the relative position between the key and the keyhole, even for able-bodied people. While the incorporation of stereoscopic vision in the virtual training is technically possible, it may turn out to be creating confusion, if not an additional hurdle, to the subjects who would need wear a pair of goggles and adapt to the artificially generated stereoscopic 3D environment. This is particularly non-trivial for those with multiple disabilities, as cautioned by the OTs. Nevertheless, depth cues can be provided in the virtual environment by using shadows, lighting or other rendering effects in computer graphics. On the other hand, some subjects reflected that since Task 3 was a bi-manual operation that required a higher level of coordination of both hands with the eyes, they found it relatively less comfortable and easy to perform it than the single-handed tasks.

The positive results of the CSUQ scores suggest that the tow OTs, from the perspectives of the subjects, were satisfied with the proposed computer-based virtual training system (see Table V). For the items that were rated relatively low, i.e. “Explicitness of information” (item no. 11) and “Fulfilling expectations on functions” (item no. 18), while the OTs appreciated the efforts expended to mimic the setting and situation of the real ADL tasks, they recommended further improvements to enrich the information and functions provided by the system and their manifestations. For example, the door could be made to open after unlocking, sounds of collisions between key and door knob could be simulated. Wider variety of instructions, motivation messages or alerts, presented using texts, graphics or audio speech commands, could be helpful cues to guide the users. Also, because of complexity in computer programming, Task 3 was divided into three separate steps to simply the design, and the subjects were constrained to make linear sawing motion only in the last step. It was suggested that the system could be equipped with functions to allow users to make suboptimal motions which can then be detected to produce warring signals.

The OTs also observed the issue that some of the subjects could not “immerse” into the virtual environments while performing the virtual tasks. During the virtual training of Task 3, they looked alternately at the 3D-printed handles attached to the haptic devices and the virtual objects displayed on the screen. The frequent change in gaze direction would indeed adversely affect the performance of the subjects and the training effectiveness. In some cases, a few subjects even thought that they would use the 3D-printed knife model to cut the 3D-printed “meat” model in reality, instead of performing the actions in the virtual environment. To circumvent this situation, the setup will be designed to cover the haptic user interface and the 3D-printed handed so that the users can focus on the virtual environments displayed on the screen. In the meantime, virtual hands will be rendered on the screen to serve as proxy of the real hands (currently only the hand holding the knife was rendered in Task 3), so as to improve the sense of presence of the users in the virtual environments and raise the level of immersion.

As discussed previously, the pre-post test results of the completion time of the simulated real tasks before and after the virtual training did not arrive at conclusive findings. However, the responses of the OTs to the QRST, based on their judgment by examining the videos recorded during the pre-tests and post-tests, show that they agreed that the subjects had improved their performance of all the three simulated real tasks after the virtual training, in terms of completion time, accuracy, completeness and competency.

One attractive feature of using virtual reality and haptic devices for rehabilitation is the automatic recording of the movements made by the users, which allows for objective performance assessment in terms of quantitative metrics. In addition to the task completion time measured in all the three virtual tasks and the amount of water filled in Task 2, other metrics gauging the accuracy and dexterity in performing the tasks could be included to conduct a more comprehensive evaluation. For example, as shown in Figure 2, the proposed system was able to record the position of the haptic stylus, which made possible the analysis of hand movement trajectories. Kinematic parameters such as trajectory straightness, mean distance from target, path length and jerkiness can be estimated to gain insights into the degree of paresis or loss of fractionated movement [25]. Besides, other parameters like speed and acceleration of hand movements and the amount of forces applied, as well as the number of collisions between the key and the door knob or the door in Task 1 and the number of times that the hand holding the knife is too close to the hand holding the meat in Task 3 can also be logged. Further study will be conducted using these quantitative parameters to perform kinematic assessment in the rehabilitation of ADL in the virtual training.

CONCLUSION

The present study provides insights into the use of VR technology for the teaching and learning of ADL for people with upper limb disability. The positive results suggest that the proposed computer-based training system has the potential to be used as a tool to complement the existing approaches in occupational therapy. Invaluable comments and feedback were collected from both the subjects and the OTs, based on which further effort will be made to improve the current system. In addition, the current study was a pre-post test with 20 subjects all received the virtual training with a relatively small number of practice sessions. A randomised controlled trial with a larger sample size will be conducted to investigate the performance of the subjects with and without the virtual training. Experiment with different training dosage, stratified by the MACS level, will also be administered to study the amount of training required for people of different degrees of disability to yield the optimal rehabilitation effect. Furthermore, the system will be extended for the training of other ADL.

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Declaration of interest

The authors report no conflicts of interest.

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Figures

Figure 1. The computerized virtual training system for the rehabilitation of ADL: the complete system is shown on the left; the middle column shows the stylus of the haptic device replaced with 3D-printed key (top), jar (middle), meat and knife (bottom) respectively for Task 1, Task 2 and Task 3; the corresponding virtual environments as displayed on the screen are shown on the right.

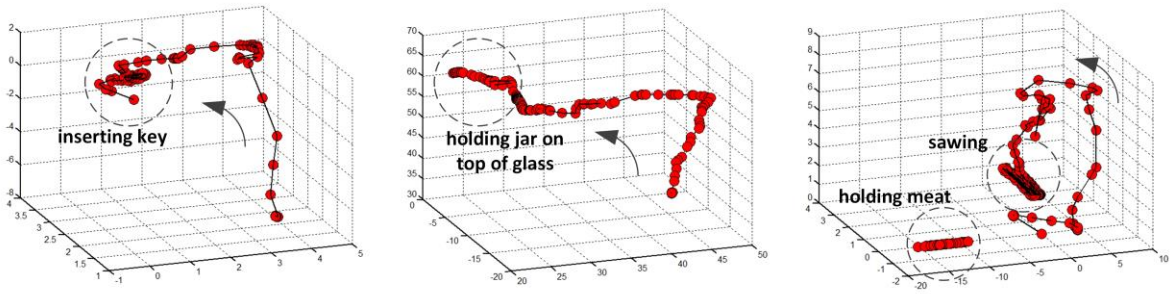

Figure 2. Trajectories of hand movements during the three virtual tasks: door unlocking (left), water pouring (middle) and meat cutting (right). Bimanual hand movements are shown in the third task, where a piece of virtual meat was being hold by the left hand and sawn by the right.

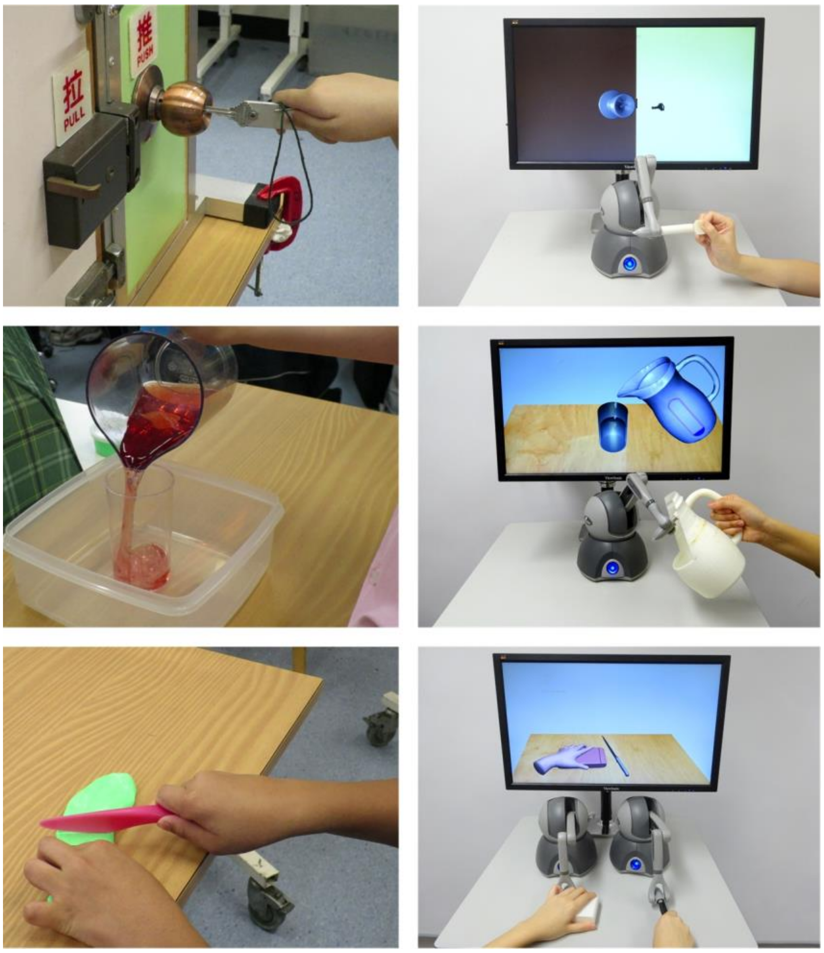

Figure 3. Simulated real tasks (left) versus the corresponding virtual tasks (right) of the three ADL in this study: door unlocking (top), water pouring (middle) and meat cutting (bottom).

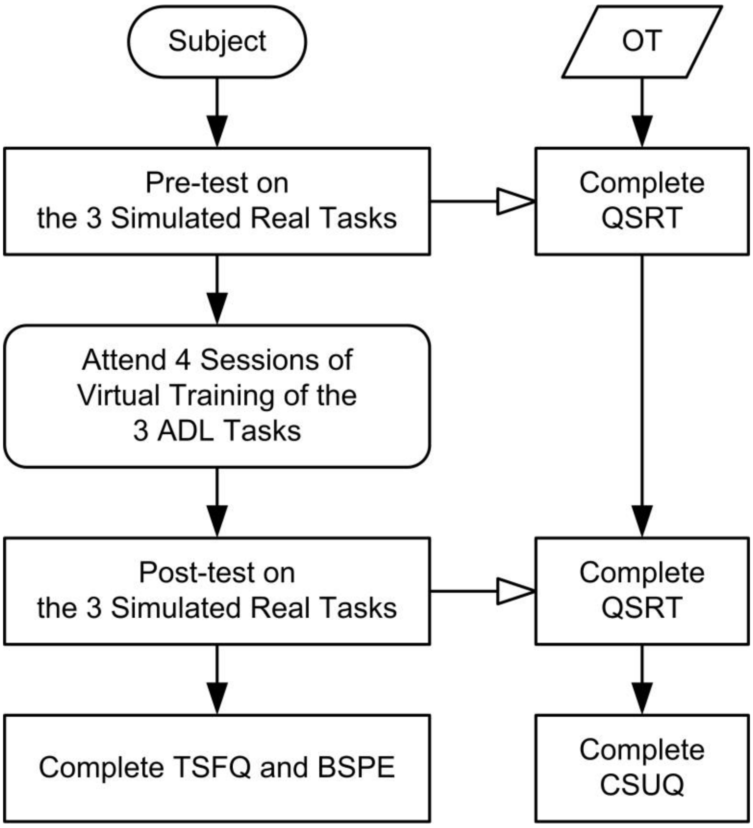

Figure 4. Research protocol.

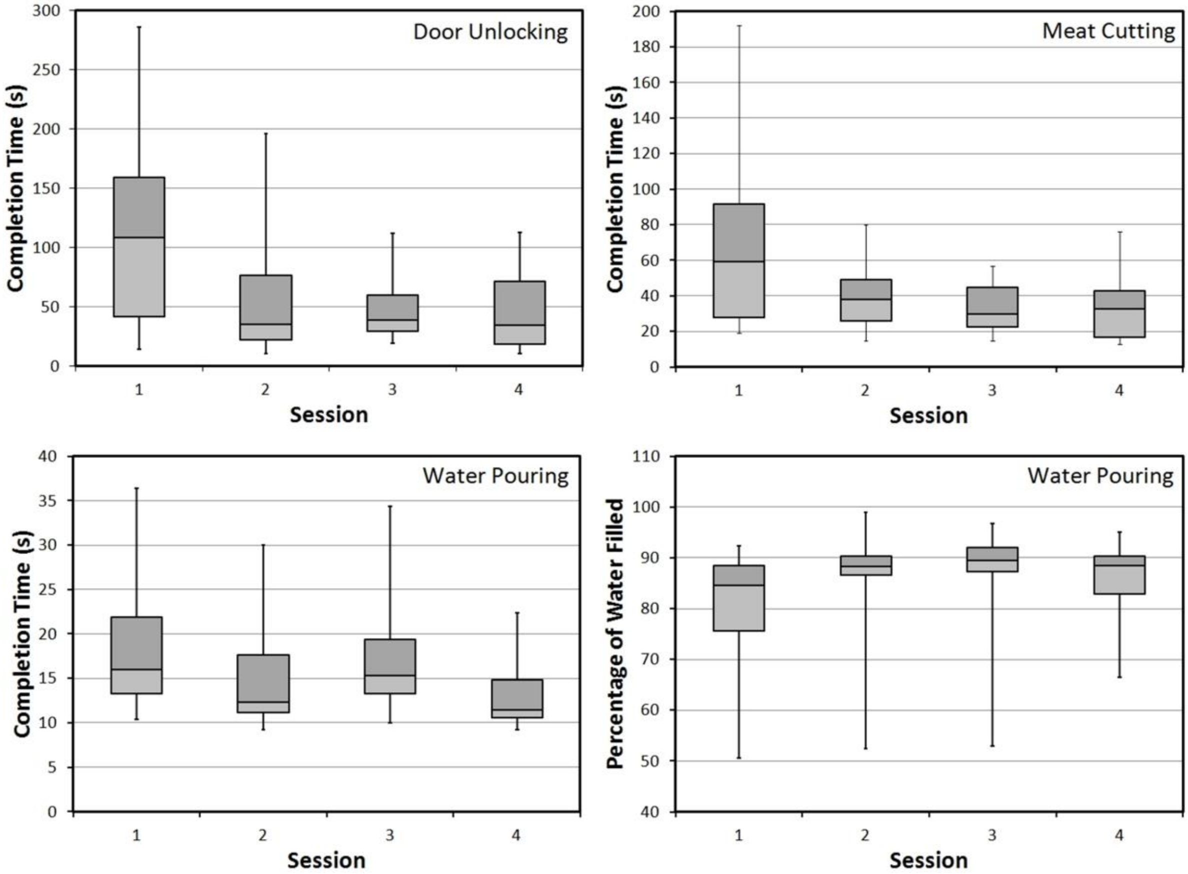

Figure 5. Performance of virtual training during the four sessions: the average complete time of Task 1 (top left), Task 2 (bottom left) and Task 3 (top right), and the average amount of water poured into the virtual glass in Task 2 (bottom right).

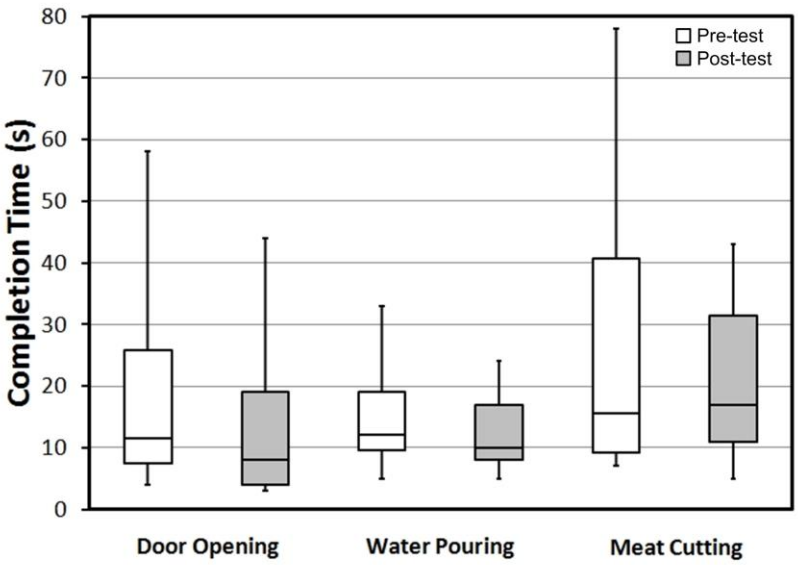

Figure 6. Performance of the simulated real tasks in the pre-post tests.

Tables

Table I. Demographic data of the subjects.

Demographics	Category	N	%
Gender	Male	12	60
	Female	8	40
Age (years)	< 13	11	55
	13 to 17	4	20
	> 17	5	25
MACS Level	1	0	0
	2	5	25
	3	7	35
	4	6	30
	5	2	10

Table II. Performance between the first and the fourth session of the virtual tasks.

Task	Completion time (s)				Percentage of water filled (%)				p-value
	Session 1		Session 4		Session 1		Session 4		
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	
Task 1	110.09	78.54	46.53	31.83	-	-	-	-	0.001
Task 2	18.73	7.76	13.29	4.15	-	-	-	-	0.007
Task 2	-	-	-	-	79.71	12.77	85.56	7.95	0.051
Task 3	73.58	54.77	34.61	19.30	-	-	-	-	0.004

Table III. Performance between the pre-test and post-test on the simulated real tasks.

Task	Completion time (s)				p-value
	Pre-test		Post-test		
	Mean	SD	Mean	SD	
Task 1	18.56	15.60	14.00	13.43	0.181
Task 2	14.44	7.76	12.74	5.73	0.225
Task 3	26.50	23.07	20.44	12.44	0.167

Table IV. TSFQ scores rated by the subjects.

No.	Item	Mean	S.D	95% CI
1	Feeling of enjoyment	4.53	0.90	4.09 – 4.96
2	Sense of being in environment	4.37	0.90	3.94 – 4.80
3	Successful feeling	4.42	0.77	4.05 – 4.79
4	Control of the system	4.37	0.96	3.91 – 4.83
5	Perception of a realistic environment	3.74	1.37	3.08 – 4.40
6	Comprehension of computer feedback	4.89	0.32	4.74 – 5.00
7	Level of comfort	2.26	1.91	1.34 – 3.18
8	Perception of easiness	2.42	1.84	1.54 – 3.31
	Total score	31.00	4.85	28.66 – 33.34

Table V. CSUQ scores rated by the two OTs.

No.	Item	OT1	OT2	Mean	Difference
1	Easiness of use	2	3	2.5	*
2	Simplicity of system	2	1	1.5	*
3	Effectiveness in task completion	1	4	2.5	***
4	Completion speed	3	2	2.5	*
5	Efficiency in task completion	1	3	2	**
6	Level of comfort	2	2	2	-
7	Easiness of learning to use	3	1	2	**
8	Improvements in productivity	1	4	2.5	***
9	Messages on fixation of errors	3	3	3	-
10	Recovery rate of system	3	3	3	-
11	Explicitness of information	4	3	3.5	*
12	Accessibility of information	2	3	2.5	*
13	Easiness in understanding of information	3	3	3	-
14	Usefulness of information	3	2	2.5	*
15	Organization of information	2	4	3	**
16	System interface	2	2	2	-
17	Satisfaction towards system interface	2	1	1.5	*
18	Fulfilling expectations on functions	3	5	4	**
19	Overall satisfaction	3	2	2.5	*

The symbols *, ** and *** denote a difference of one, two and three points respectively between the scores rated by the two OTs for an item; with dash indicating no difference.

Table VI. QSRT scores rated by the two OTs after examining the videos taken at the pre-tests and post-tests for all the subjects.

No.	Item	Task 1		Task 2		Task 3	
		Mean	SD	Mean	SD	Mean	SD
1	Improvement in completion time	5.25	1.62	5.30	1.34	5.50	1.47
2	Improvement in accuracy	5.45	1.39	5.65	1.46	5.60	1.60
3	Improvement in completeness	5.50	1.47	5.60	1.57	5.65	1.60
4	Improvement in competency	5.45	1.54	5.70	1.56	5.70	1.56