Haptic virtual rehabilitation in stroke: transferring research into clinical practice

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**Objective:** The paper will give an overview of our work with a haptic immersive workbench which can be used in different setting for rehabilitation.

**Method:** Forty-eight subjects participated in three different experiments. Twenty-nine users had a stroke and 19 were healthy individuals. The intervention in the first two experiments consisted of playing three-dimensional computer games. A computerised task was developed to assess motor movement of the affected upper extremity. In the third experiment, a computerised visuospatial neglect test was developed and compared with traditional neglect tests. The subject hand position data (haptic stylus end-point, i.e. x-, y- and z-coordinates) was measured during each trial in the different experiments.

**Results:** All experiments demonstrated that this haptic immersive workbench can provide a quantitative analysis of hand movements. The first experiment showed improvements in the computerised task. One subject improved in occupational performance, i.e. improvement reflected in activities of daily living. The second experiment was consistent with the first, but the results have extended these findings, showing that virtual rehabilitation can be beneficial not only to younger users but also to elderly people in terms of enhancing their motor performance. In the third experiment, we showed that the computerised visuospatial neglect test gave additional information compared to traditional tests. Both the subjects with neglect and the subjects clinically recovered from neglect showed aberrant search performance in the cancellation task in the virtual environment.

**Conclusion:** The haptic immersive workbench features assessment methods and three-dimensional computer games, which are adjustable with respect to degree of difficulty and users’ abilities. For the future, we propose a system for Internet based connection and communication between users and rehabilitation centres. The benefits of a system for rehabilitation after stroke, employing telemedicine, haptics, 3D-visualisation and serious-games should be more frequent exercising, better compliance with training in the home setting and improved quality of life.

**Keywords:** haptics, home care, rehabilitation, stroke, serious games, virtual reality

**Introduction**

Computer games have the potential to enhance training motivation, as illustrated by the growing interest in the field of Serious Games (www.seriousgames.org). A ‘serious game’ is a computer-based game with the goal of education and/or training in any form, as opposed to traditional computer games, which are primarily intended to entertain. The health care sector is showing steadily increasing interest in serious games. Integrating gaming features into
virtual reality environments has been reported to enhance motivation in adults undergoing physical and occupational therapy following a stroke.\textsuperscript{1,2}

We have employed contemporary information and communication technology (ICT), i.e. virtual reality (VR), haptics (allows users, for example, to identify an object, or one of its features like size, shape or weight), three-dimensional (3D) computer games and telemedicine, in studies of movement rehabilitation post-stroke. In our set-up the virtual environment consists of a haptic and stereovision immersive workbench (Fig. 1). The user stands in the real world and looks into a virtual world generated in the computer. He or she is then able to reach into a virtual space and interact with 3D objects through a handheld stylus (haptic device) positioned in the line of sight. It creates an illusion of virtual objects for the user while the only real element is the handheld stylus and the computer equipment. Using stereoscopic shuttered glasses, the user observes a 3D image displayed above the tabletop. The PHANTOM Omni haptic device (Fig. 1) from SensAble Technologies was used. This is a desktop haptic feedback device that provides single point, 3D force feedback to the user via a stylus attached to a moveable robotic arm. The position of the stylus point/fingertip is tracked, and resistive force is applied to it when the device comes into contact with the virtual model, providing force feedback. It is therefore possible to measure hand position data (haptic stylus end-point) when moving in the 3D environment. The physical working space is determined by the extent of the arm. Motor movement and assessment can be trained and recorded using the PHANTOM Omni.

Haptic interfaces include many devices such as the force-feedback stylus, which we used, data gloves with exoskeleton, and other robotic devices used by others. Haptic devices using VR have been suggested to enhance stroke rehabilitation.\textsuperscript{3–6} Research implies that haptic-based virtual rehabilitation offers a potential tool in motor and cognitive rehabilitation, with a wide range of applicability. In a recent systematic review of the effectiveness in terms of upper extremity (UE) motor recovery within VR and stroke rehabilitation the authors concluded that the evidence is limited but sufficiently encouraging to justify additional trials.\textsuperscript{7} The key factors identified among the studies were:

(i) salient task practice
(ii) high repetition intensity
(iii) training in a novel environment offers high motivation to the users
(iv) enhanced feedback about the results of performance.

In 2002, we started proof of concept studies to investigate whether computer games and haptics can be utilised as an assessment tool and training device for stroke rehabilitation.\textsuperscript{8} Stroke is a serious condition with respect to its medical features, its multitude of functional symptoms and their impact on everyday life. Common neurological phenomena are different degrees of hemiparesis and sensory impairments, aphasia, dysarthria, hemianopia, dysphagia, perceptual impairments, limited attention span and visuospatial neglect.\textsuperscript{9}

Since then procedures have been developed to assess and/or train two of these neurological phenomena, i.e. loss of UE function (hemiparesis) and visuospatial neglect. Perceived loss of UE function has been reported as a major problem in participants with stroke.\textsuperscript{10} Because a majority of users are able to perform most of their activities of daily living with their non involved UE, they tend not to use their involved less functional UE (learned-non-use).\textsuperscript{11} Learned-non-use is one of the theories behind constraint induced movement therapy (CIMT) and is based on experiments with monkeys.\textsuperscript{12} Constraint induced movement therapy is a type of treatment for hemiparetic stroke users in which the users are strongly encouraged to use the more affected paretic UE.\textsuperscript{13} Several studies have investigated the use of
CITM, and it has been shown to produce improvements in the actual amount of use of the more-affected arm-hand.\textsuperscript{14–17} Target oriented rehabilitation approaches and individually adapted training programmes seem to be essential for gaining UE recovery after stroke. Recovery of motor skill often comprises intensive training and feedback in an environment that motivates the patient to train.\textsuperscript{18} If the focus is on these aspects in rehabilitation, the design of activities should be attractive. The fact that an activity is pleasurable is important for motivating the patient. The recovery of the affected UE, as in every other training situation, is dependent on regularity and intensity in training, as well as on specificity.\textsuperscript{19} In order to stimulate recovery, the training programme must allow the individual to develop and re-establish their motor system.\textsuperscript{20}

A central component of the rehabilitation system used here is a library of games (Fig. 2a and b), intended to be simultaneously entertaining for the patient and beneficial for rehabilitation. The games train movements so that the patient can perform daily training exercises in a stimulating environment. Currently, the game library consists of a dozen games. The 3D computer games developed were adapted to address specific motor deficits common after stroke and to provide a challenging and engaging practice environment.

In this work, six different games were used. ‘Archery’ requires pulling back a string and shooting towards different targets, which move in 3D space. The difficulty level increases the more games are played. In ‘bingo’, numbers are generated at random on a bingo machine; the user has to mark the corresponding number on a bingo board. The game gradually increases by adding rows. ‘Fish tank’ requires picking up fish and lifting them out from the fish tank. Jellyfish act as bombs; by touching them the point score decreases. In ‘space tennis’ users control a racket with the haptic stylus and bounce a ball in the direction of the opponent (computer controlled). Users have to reach and intercept a ball; points are scored when one player misses a ball. In ‘memory’ users must find matching pairs on the board by touching question marks. Points are awarded when two similar pairs are singled out. In ‘Simon’ users mimic a sequence of tones; whenever a combination of tones is mimicked, a new tone is added to the sequence. In these games users have to memorise sequences. Feedback is provided to the users after the completion of each game in the form of trial success rate and total time. All games were designed to activate the affected UE and offer practice of reaching, forearm pronation and supination movements on the paretic side.

In order to assess motor movement a computerised task (Fig. 3) was developed which consists of touching round targets that appear in the virtual space.\textsuperscript{21} The targets appear one after the other on the screen and disappear when pointed at. The placement of the targets (32) in the 3D space is apparently random to the users but was actually set according to a pre-set kinematic scheme for evaluation purposes. In total, there are 32 targets to touch. Haptics are enabled for the targets as well as the enclosing walls in the
environment. The task requires the patient to perform reaching movements of the UE, as dictated by the target placement, whilst holding the haptic stylus.

After completion, the following variables are examined for the whole task and for the midpoint target-to-target movement: time (s), distance (m), hand path ratio (HPR: the quotient between actual hand trajectory and the straight-line distance between two targets) max velocity (m s\(^{-1}\)) and max acceleration (m s\(^{-2}\)). The basic pattern of stylus movement in space is visualised in Matlab (www.mathworks.com), giving an indication of how hand trajectory and movement quality change over time.21

In addition to providing the opportunity for movement repetition, the VR system used by these authors allows therapists to assess cognitive deficits, i.e. visuospatial neglect. Visuospatial neglect is an impaired ability or lost ability to react or process stimuli on the contralateral side of the brain lesion.22 A diagnosis of visuospatial neglect typically includes a number of simple and rapid tests such as figure copying, freehand drawing, line bisection, reading and writing and target cancellation tasks.23 Cancellation tasks are said to be the single most sensitive test of neglect.24 In these types of tasks users with neglect not only exhibit omissions of visual targets but also demonstrate more general deficits in their search performance.25

Relatively little is known about the spatial progression of the manual navigation throughout a cancellation test during the search for targets. For this purpose, a task was developed in the VR environment for assessing visuospatial neglect (Fig. 4). This is a cancellation task that requires visual search and coordinated eye and hand movements. The targets, which all appear in the beginning of the task, have numeric labels. The targets are marked with the digit ‘1’, and the distracters are marked with two-digit numbers. There are 60 distracters and 20 targets. The task ends when the red target in the bottom right-hand corner is touched.26 The objective of the task is to touch the targets, and to avoid the distracters. The targets change colour after being touched to avoid memorisation effects.

Stroke rehabilitation involves repetitive exercises, and demands continuous attention from the therapist – the main challenge in stroke rehabilitation is maintaining a patient’s motivation. Optimal effect is achieved when rehabilitation is fun and engaging and takes place on a daily basis and at a level adjusted to challenge maximum performance.27 The aim of this VR system is to deliver a precise quantitative assessment tool for neurological impairments, especially for stroke patients, and games in the form of a solution that aids rehabilitation in all its phases: at the hospital, at rehabilitation centres, and at home. Since the consequences of a stroke vary greatly among different users, the system is designed to be modular so that patients can use games specifically designed to deliver physical training of arm/hand movements, as well as cognitive training, according to their individual rehabilitation needs. In the following sections, we will review results from three experiments that were conducted to evaluate the potential of our software and hardware set-up for creating flexible therapy environments.

Experiments

In VR based haptic applications it is difficult to achieve realism for the user when manipulating objects without co-located representations of the objects visible on the screen. In the real world objects are usually perceived in the same location whether the sense involved is vision or haptics, but in the virtual world the perceived locations may differ. For example, if a user is manipulating a virtual model in a 3D environment, the realism of the manipulation is very high when the virtual model is co-located in space with the user’s real hand. Eye hand coordination, i.e. placing the hand in the same location as a virtual object, improves performance.28 Thus all assessments and games are co-located, i.e. co-location between the physical and virtual worlds is achieved by projecting the virtual image onto the same location as the user’s hand through the mirror setup. Thus co-location provides functional cooperation.
between motor/kinesthetic and visual brain areas during relearning in rehabilitation.

First experiment

The purpose of the first experiment was to determine the effects of motor training using VR and haptics in a group of individuals in the chronic stage post-stroke.

The intervention programme consisted of a 3D computer game; 3D Bricks. The users had to strike a virtual ball with the haptic device and knock over bricks in the virtual environment (Fig. 5). Fifteen, 45 min treatment sessions were conducted during the treatment phase.

The users were five hemi-paretic, post-stroke users with a mean age of 59 years (range 53–63 years), and were between 9 to 69 months post stroke. Four had left hemisphere brain damage and one right hemisphere brain damage. To be included in the study, users had to have a hemiparesis in one of the UEs, i.e. Box and Block Test (BBT) score lower than 55, no signs of neglect of stroke, be in a chronic stage (>6 months post stroke) and have no other neurological disease. All users were right handed and novel computer game players at the start of the study.

A single-subject design was used to provide comparison for intervention effects on the VR task. All users began with a baseline phase (A). The dependent variables were velocity ($m \cdot s^{-1}$), HPR and time (s). This was assessed with three measurements made during one session, three times during 1 week. The intervention phase (B) then started and continued for 5 weeks; measurements were made, once a week. A follow-up (C) assessment was made 12 weeks later with the same assessment procedure as used in the baseline phase. To determine if the detected change of the intervention in the VR environment was reflected in real life, functional changes were measured using the BBT and the Assessment of Motor and Process Skills (AMPS) on entry to the study and at follow-up. The BBT test evaluates gross movements of the arm and hand; it requires moving, one by one, the maximum number of blocks from one compartment of a box to another of equal size within 1 min. AMPS is a standardised assessment of occupational performance, used to observe and evaluate a user’s ability to perform activities of daily living.

After an initial introduction, all users quickly learned to use the VR system. The users reported spontaneously that the game was challenging and enjoyable to them. All users completed the VR task more rapidly as compared to baseline values. The visual analysis revealed improvements in velocity ($m \cdot s^{-1}$), time (s) and HPR after the intervention and at the follow-up assessment for all users (Fig. 6). Visual inspection of the detailed $x$, $y$, $z$-plot for the hand trajectories for one short target-to-target movement revealed a change in movement pattern. Qualitatively the trajectories post-training are more restrained, smoother and less cluttered at the end point (Fig. 7). The other outcome measures (BBT and AMPS) varied for the users. Only one user (P3) improved in the BBT on unilateral manual ability and one user (P4) on the AMPS in occupational performance. The other users did not improve in these measures, probably because the users had already acquired the capacity to manage their needs without using the affected UE.

Second experiment

In the second experiment, the VR system was placed outside the hospital in an activity centre for people with stroke. This was done to improve access to the VR technology by a wider group of stroke users to see whether it could be used in this setting and to evaluate whether playing with computer games resulted in improved motor function in this group. Further we wanted to investigate the use of a telemedical application based on Skype with a camera as an adjunct to communicate response to the intervention from the clinic to the activity centre. The intervention consisted of playing 3D computer games where the users could select various games with the haptic stylus from a game library (Fig. 2).

A pre- and post-test design with a control and reference group was employed. In this experiment, the BBT and ABILHAND were used to assess whether the detected change of the intervention in the VR environment could strengthen the results of
the quantitative data. ABILHAND is a questionnaire that measures manual ability in chronic stroke. It measures the user’s experience of problems in performing everyday tasks such as feeding, dressing or managing domestic tasks, whatever strategies are involved. All users were tested before and immediately after treatment. A semi-structured interview was used at the end of the study to assess the users’ opinions of the VR system.

Sixteen hemi-paretic (13 women and 3 men), post-stroke users with a mean age of 68 years (range 47–85) and with an average time post-stroke of 66 months (range 15–140) were recruited. Nine users had a history of right hemisphere stroke and seven had left hemisphere damage. The inclusion criteria remained the same as for the first experiment. An additional group of 11 right-handed individuals without previous history of neurological or psychiatric
illnesses served as reference users. They were recruited from the users' family members or via direct contact (person to person). The reference group consisted of three men and eight women with a mean age of 68.0 (range 61–83 years). The stroke users were matched by sex and then randomly assigned to an intervention group (n=11) or a control group (n=11). Six users (n=6) were willing to cross over between the control group and the intervention group so that they received both treatments. They started the study as control users.

The intervention group received additional VR therapy, three times a week for 45 min for 4 weeks. The control group received no additional

Figure 7 Raw data for the hand trajectories at baseline (A), end of intervention (B) and at follow-up (C). Similar short target-to-target trajectories were visualised. In this case, the start point trajectory was chosen, i.e. moving the haptic stylus from the first targets to the second target. This reflects a reaching movement in the physical environment (diagonally upwards, forwards). The viewpoint was: X from right to left, Y from up to down and Z toward to away. The visual inspection reveals a variation in movement pattern for all subjects; especially the end-point suggests a different planning process for striking the target.
rehabilitation; they participated in their usual activities such as playing games, weaving, sewing, painting or gardening. Manual ability as estimated with the BBT increased by 9% in the intervention group; from 37.5 (SD=14.6) mean performance at pre-test to 40.3 (SD=16.5) at post-test. The BBT measure in the control group did not reveal differences between pre-test, 40.2 (SD=17.2), and post-test, 40.6 (SD=16.0). No changes in the ABILHAND measures were found in the intervention group between pre-test, mean = -0.18 logits (SD=0.27), and post-test, mean = -0.17 (SD=0.13). On admission, mean performance in the control group was -0.22 (SD=1.6) and, at post-testing, was -0.16 (SD=0.20).

The results for the VR-test revealed that time (s) and HPR decreased noticeably (p<0.05, Wilcoxon signed rank test), compared to controls, but no significant difference was found for velocity (m s⁻¹) (Table 1). Overall, the mean improvement in time (m s⁻¹) was greater for the intervention group (reduced by 41%) than the control (reduced by 12%). The same tendency of improvement, although smaller, was seen for HPR (reduced by 19% and 5% for the intervention and control groups, respectively) and velocity (increased by 6 and 11% for the intervention and control groups respectively) and velocity (increased by 6 and 11% for the intervention and control groups respectively). Taken together, these results indicate that the VR-group improved their movement pattern efficiency more than the control group, so that they took less time overall to complete the task, and had less need to increase velocity of the task (unlike the control group). It is worth noting that neither the intervention nor the control group was able to match the values for the computerised task observed in the non-disabled group, taking 69 and 91% longer respectively, although HPR (intervention, 8% and control, 15% higher than the reference group) and velocity (intervention, 24% and control, 16% slower than the reference group) were considerably closer to the reference group values. The VR-training’s most prominent effect was improved and more efficient movement patterns, although time to complete the task and velocity also improved.

In the analysis of the short target-to-target movement the same tendency was observed as for the whole exercise: time (s) improved considerably (p<0.05, Wilcoxon signed rank test) in the intervention group but not in the control group. Here, also, the values were significantly different from those of the reference group. HPR improved in the intervention group, but there were no differences between pre- and post-intervention. No differences were found between pre- and post-training for the intervention and control group with respect to max velocity (m s⁻¹) and max acceleration (m s⁻²), in Table 1. The visual inspection of the target-to-target movement for the four oldest users (i.e. the detailed x-, y-, z-plot) revealed a change in movement pattern in all four (Fig. 8). Qualitatively the trajectories post-training were more restrained, smoother and less cluttered at the end point.

All users responded favourably to the use of the VR system. A change of attitude took place after the users were exposed to playing computer games. Initially, the users expressed some hesitancy about computer games; however, hands-on experience showed that more knowledge can stimulate interest and all users wanted to continue playing in the future. They stated that the games were easy to learn and enjoyable and that they would like to have the VR system as a complement to their current programme at the activity centre or in their home environment. The use of telemedicine based on Skype with a camera worked well as an adjunct while maintaining a high quality of service to the clinicians and stroke users. When problem arose, i.e. the games would not

### Table 1 Mean (SD) of the computer-based measurements in the intervention, control and reference groups

<table>
<thead>
<tr>
<th>Overall</th>
<th>Intervention (n=11)</th>
<th>Control (n=11)</th>
<th>Reference (n=11)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pre-test Mean (SD)</td>
<td>Post-test Mean (SD)</td>
<td>Mean (SD)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time (s)</td>
<td>109.81 (77.32)</td>
<td>64.84 (34.06)*</td>
<td>82.90 (72.16)</td>
</tr>
<tr>
<td>HPR</td>
<td>2.80 (0.99)</td>
<td>2.27 (0.39)*</td>
<td>2.54 (0.71)</td>
</tr>
<tr>
<td>Velocity (m s⁻¹)</td>
<td>0.18 (0.96)</td>
<td>0.19 (0.83)</td>
<td>0.19 (0.07)</td>
</tr>
<tr>
<td>Target-to-target</td>
<td></td>
<td></td>
<td>0.21 (0.07)</td>
</tr>
<tr>
<td>Time (s)</td>
<td>3.14 (2.81)</td>
<td>1.74 (1.02)*</td>
<td>1.77 (0.92)</td>
</tr>
<tr>
<td>HPR</td>
<td>2.81 (2.34)</td>
<td>1.87 (0.38)</td>
<td>2.02 (0.61)</td>
</tr>
<tr>
<td>Max velocity (m s⁻¹)</td>
<td>0.54 (0.17)</td>
<td>0.53 (0.18)</td>
<td>0.53 (0.18)</td>
</tr>
<tr>
<td>Max acceleration (m s⁻²)</td>
<td>0.16 (0.02)</td>
<td>0.16 (0.02)</td>
<td>0.16 (0.05)</td>
</tr>
</tbody>
</table>

*p<0.05 (p-value associated with Wilcoxon Signed Ranks Test).
start, the user contacted the therapist at the clinic and the problem was solved by remote instructions.

Third experiment

In the third experiment, we compared a cancellation task in a virtual environment (Fig. 4) with conventional tests of neglect (star cancellation and the baking tray task). Information was gathered with the VR cancellation task that was specific to the neglect syndrome, i.e. omissions of targets, manual search performance, start column and repeated target press. Further we wanted to describe the pattern of manual search performance and to obtain kinematic data on hand movement.

The star cancellation test is a sub-test in the Behavioural Inattention Test battery. It consists of a total of 52 large stars, 56 smaller stars, 13 letters and 10 short words, which are pseudo randomly positioned over a landscape A4 sheet. The users are asked to cross out all the small stars on the sheet with a pen. The maximum score was 54, 27 on each side of the midline (two small stars in the centre were not counted). The baking tray task is a comprehensible, simple-to-perform test for use in assessing unilateral neglect. Users have to place 16 identical items (3.5 cm wooden cubes) on a blank test board, the baking tray (75 x 100 cm), as symmetrically as possible as if they were buns on a baking tray. A normal distribution is eight cubes in each field. The cut-off is a distribution more skewed than seven items on the left half and nine items (7/9) on the right. The VR cancellation task earlier described was used (Fig. 4).

When the response pattern was analysed, the screen was divided into four columns and three rows. The maximum score was 18, nine on each side of the midline (two targets in the centre were not scored). The cut-off criterion for visual neglect was based on the normative range obtained from the reference group. Hand position data (haptic stylus end-point) were recorded in the same way as described for the UE test, i.e. time (s), distance (m), velocity (m s⁻¹) and hand path ratio (HPR).

Since healthy users typically search by rows or columns their search pattern is either horizontal (e.g. left to right) or radial (e.g. far to near) across the page. To capture this net orthogonal search pattern, all x coordinate and y coordinate values of all marked locations were measured. All x values of all marked locations relative to the order in which they were marked were plotted. The y values of marked locations were analysed in the same way. The r-value was calculated for all x values and y values. For example, starting on the left side of the page and marking by columns rightward would yield a higher r value on the x coordinate regression than on the y coordinate regression because the cancellation progress would be consistently horizontal (left-to-right) but inconsistently radial. From the two linear regressions calculated for each user, the one with the higher (‘best’) r value was selected to represent the degree to which cancellations were pursued orthogonally. In general, a highly organised approach would be reflected by a high ‘best r’.

Eight users with stroke and right brain damage were included, mean age 54 years (range 44–63) and an average time after stroke of 20 weeks (range=7–39).

The criteria for inclusion were:

(i) right-sided brain damage confirmed by CT or MRI scans
(ii) visual neglect identified by the star cancellation test and the baking tray task, 2–5 weeks post-stroke
(iii) ability to understand information
(iv) right-handed with no signs of motor impairment on the right side
(v) no pre-stroke history of visual deficits.
Eight control users were recruited; four men and four women, mean age 53 years (range 33–63). The criteria for inclusion for the controls were: right-handed; and no history of visual or neurological deficits.

Four users (n=4) who exhibited neglect on admission to the rehabilitation unit had recovered from these symptoms at the time of this assessment and they showed no omissions and no contralesional bias by either the conventional tests or the VR cancellation task. For the other users (n=4) the presence or absence of neglect was identified by using VR or the conventional neglect tests. Users with neglect (n=4) as well as users recovered from neglect (n=4) still exhibited persisting aberrant search performance in the VR task, i.e. mixed search pattern (Fig. 9, data from two users are presented), repeated target pressures, ipsilesional start of search and deviating hand movements. This finding is in accordance with a study by Pflugshaupt40 that showed that users who had recovered from neglect in conventional paper-and-pencil tests still exhibited oculomotor and exploratory deficits in novel or complex search tasks. In visual search tasks, users with neglect not only exhibit omissions of visual targets but also demonstrate more general deficits in their search performance, such as an unsystematic search pattern and re-exploration and re-marking of targets.25,41,42 Right hemisphere neglect users often start on the right side of the page (whereas control users who read left-to-right usually start on the left) and omit targets to the left of the page.25

Six of eight users had more deviations of hand movements (HPR) during the visual search compared to healthy controls. This suggests that virtual reality (VR) may be a useful tool for rehabilitation of neglect.

### Table 2 Kinematic data for the user group and healthy subjects

<table>
<thead>
<tr>
<th>Subjects</th>
<th>Best r</th>
<th>Hand path ratio</th>
<th>Time to complete the exercise (s)</th>
<th>Median velocity (m s⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Not recovered</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P1</td>
<td>-0.42</td>
<td>3.7</td>
<td>34</td>
<td>0.058</td>
</tr>
<tr>
<td>P2</td>
<td>-0.58</td>
<td>7.5</td>
<td>59</td>
<td>0.045</td>
</tr>
<tr>
<td>P3</td>
<td>-0.81</td>
<td>4.2</td>
<td>68</td>
<td>0.058</td>
</tr>
<tr>
<td>P4</td>
<td>-0.76</td>
<td>2.6</td>
<td>37</td>
<td>0.044</td>
</tr>
<tr>
<td>Clinical recovered</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P5</td>
<td>0.40</td>
<td>6.6</td>
<td>156</td>
<td>0.062</td>
</tr>
<tr>
<td>P6</td>
<td>-0.57</td>
<td>3.7</td>
<td>43</td>
<td>0.071</td>
</tr>
<tr>
<td>P7</td>
<td>-0.91</td>
<td>4.4</td>
<td>46</td>
<td>0.103</td>
</tr>
<tr>
<td>P8</td>
<td>-0.79</td>
<td>3.4</td>
<td>66</td>
<td>0.044</td>
</tr>
<tr>
<td>Healthy subjects</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C1</td>
<td>-0.80</td>
<td>2.8</td>
<td>24</td>
<td>0.072</td>
</tr>
<tr>
<td>C2</td>
<td>0.81</td>
<td>2.3</td>
<td>30</td>
<td>0.063</td>
</tr>
<tr>
<td>C3</td>
<td>-0.96</td>
<td>2.1</td>
<td>33</td>
<td>0.056</td>
</tr>
<tr>
<td>C4</td>
<td>-0.93</td>
<td>2.7</td>
<td>48</td>
<td>0.045</td>
</tr>
<tr>
<td>C5</td>
<td>0.47</td>
<td>2.0</td>
<td>32</td>
<td>0.046</td>
</tr>
<tr>
<td>C6</td>
<td>0.96</td>
<td>2.4</td>
<td>77</td>
<td>0.029</td>
</tr>
<tr>
<td>C7</td>
<td>-0.86</td>
<td>3.2</td>
<td>30</td>
<td>0.086</td>
</tr>
<tr>
<td>C8</td>
<td>0.87</td>
<td>1.7</td>
<td>18</td>
<td>0.096</td>
</tr>
</tbody>
</table>

Gray areas are subjects with values outside the 95% reference interval.
with the control group (Table 2). The velocity (m s$^{-1}$) and time (s) profile did not differ between clinically recovered users and controls. The users who had not recovered from neglect showed a lower median velocity (m s$^{-1}$). A relatively low correlation (i.e. Best r in Table 2) was observed in four of the users (P1, P2, P5 and P6) and in one of the controls (C5). The presence of chronic visuospatial neglect is more difficult to assess and rehabilitation is associated with poor outcome. Thus, it is important to establish the prevalence of chronic neglect when considering rehabilitation programmes. The data in this experiment indicate that this VR task is more informative for the identification of deviations in search performance compared to examination of search by more conventional paper and pencil tests.

**Discussion**

The overall aim of this work was to investigate whether virtual reality technology and haptics can be utilised as an assessment tool and training device for stroke rehabilitation. In the different studies included, the results indicate that the VR system with a haptic interface can function as an assessment/training tool for motor impairment and assessment tool for visuospatial neglect.

The first and second experiments show that the users made improvements in the kinematic variables measured with the VR system. In the first experiment, real life changes were reflected in two of the users, such as improvements in traditional outcome measures. The other user did not show any improvement in these measures. The third experiment (computerised neglect test) provided a quantitative analysis of detecting small variations in manual search performance otherwise not detected in standard paper-and-pencil tests. It was found that the presence or absence of visual inattention was identified for the same users either by using VR or the conventional neglect tests. In addition to providing the opportunity for movement repetition, this VR system allows users to practise improving cognitive deficits. Cirstea et al. suggest that successful motor rehabilitation may possibly involve varying degrees of cognitive processing depending on the cognitive demands of the intervention. Cognitive functioning may potentially modify training effects so that motor improvements could be related to cognitive abilities. Viau and colleagues compared movements made in a virtual environment to movements made in a real environment and suggested that VR is similar enough to reality to provide an effective training environment for rehabilitation. The ability to reach is essential for almost all activities of daily living, such as dressing, grooming and toileting. Characterising the features of reaching and quantifying specific variables allows therapists to treat specific deficits. The haptic based VR system used here is capable of designing such features. Measuring and following the performance of a user over time is another characteristic.

Further, this VR system was placed in a non-hospital environment to improve access to VR technology by a wider group of stroke users. The VR system worked without problems and made it possible to expose people that otherwise would not have had the chance to try the VR system. Adherence to the programme was excellent and may have been facilitated by the novel technique of VR: people may have wanted to try VR in the hope that it would improve their UE function. Attitudes to new technology are affected by the perceived benefits of using it, positive past experiences, quality of information about it, training and follow-up, hands-on experience, and the extent to which it meets user needs, and users’ enjoyment.

The telemedicine application used was Skype. The main reasons why Skype was chosen were that it is a solid and fully tested software suite that provides a good operating system residency, high performance and a smooth integration with other computer software at a low cost. The system was used as a therapist–patient communication tool before, after and even during the rehabilitation exercises, giving the patient the opportunity to e.g. show the therapist a sore muscle group or his motor status and ask questions. In addition, the health professionals could for example instruct the patient, make a visual examination/check the status of the patient’s motor capacity.

The clinical advantage of using such a system is considerable. The trend is toward shorter hospital stays and fewer outpatient visits. Today it is difficult to check a patient’s progress once discharged from hospital. In order to determine the patient’s progress with their training programmes new approaches must be adopted. The increasing costs of providing healthcare services to an aging population and the changing pattern of use of hospital resources, i.e. fall in the average length of stay, are shifting the focus of care from hospital to home or nearby community centres. Telemedicine systems minimise the barrier of distance, and make it possible to be able to conduct evaluation and rehabilitation programmes at rural
locations, at great distance from the clinic. This leads to speculation about the importance of developing home-based therapy systems. Home rehabilitation is a promising approach in remote training.\textsuperscript{50-56} VR training has the potential to affect a stroke user’s functional outcome by allowing him or her to continue with additional therapy past the traditional period of hospitalisation and rehabilitation. This current trend of cost containment in health care has prompted a search for innovative methods of providing quality care. A modern telemedicine communication technique has the potential to improve the communication and prolong the contact with the user after being discharged.

The VR equipment is now being implemented at different hospitals in Sweden as a new technology. The VR training probably needs to be tailored more for the needs and interests of each person. A continuous dialogue is ongoing with the developers of the training programmes.

**Future directions**

Our vision is to have a fully deployed rehabilitation organisation with clinical evaluation systems stationed at the rehabilitation centre that has bidirectional contact with the home-based units, for collection of daily assessments, game allocation and tuning of difficulty, and audiovisual communication between care providers and users or among users.\textsuperscript{27}

The therapist will be able to discuss those goals with the user via a peer-to-peer audio conferencing feature. The interface will allow users to take the initiative in setting their own goals for recovery, and then allow for further discussion and negotiation of those goals later. This would be a way of keeping the user connected to the therapist and of encouraging users to set their own goals and take greater responsibility for their own recovery. Home rehabilitation allows for great flexibility so that users can tailor their programme of rehabilitation and follow individual schedules.\textsuperscript{57} Investigations are currently underway and we are implementing this research project in a home-based rehabilitation environment. People with stroke may then participate in an intensive level of therapy several hours per week or follow a less demanding regimen for a longer period. They would then have the opportunity to immediately transfer their improvements to functional activities of daily living.

Currently we are developing procedures for introducing volume haptics and robotics, i.e. an invisible haptic guidance field guides the user’s hand through a desired movement pattern. The guidance field is designed to provide a force counteracting incorrect motion, thereby helping the user to follow a predefined pattern. Recently the traditional internet has started to evolve into a 3D internet. Along with this evolution new opportunities arise for stroke rehabilitation. For example, virtual communities could be utilised in stroke rehabilitation via an online gaming system, where the setting allows users to communicate and access each others’ information worldwide, independent of time and place, thereby encouraging them to take a more active role in their rehabilitation.

The central component of this rehabilitation system is a library of engaging activities (games) that are simultaneously entertaining for the user and beneficial for rehabilitation. Since users have different impairments and abilities, customisation of game play aspects is desirable.\textsuperscript{58} In order to efficiently use computer games to train a particular function, we need to first determine what features a computer game should have to maximally benefit the skill in question. For this we are creating a taxonomy focusing on neurological impairments, stroke rehabilitation exercises and rehabilitation goals. The taxonomy is being linked to game design patterns in an iterative process. This will enable a certain exercise and its related patterns to be identified in the taxonomy. Conversely, an existing game or game idea can be analysed to identify patterns, indicating what rehabilitation exercises in the taxonomy can be supported by the game. However, game construction for rehabilitation purposes is still an immature process. Development of a taxonomy-based model for bilateral communication between the areas of rehabilitation/neurology and game design will continue, and this model will be used to improve existing activities, design new activities, and investigate using commercial off the shelf (COTS) games in the integrated system. Applications should be developed using interdisciplinary collaboration and continuous user-centred input/evaluation methods.

**Conclusion**

The general experience of the VR application approach suggests that this intervention seems to be a promising tool in motor and cognitive rehabilitation, with a wide range of applicability. This work demonstrates that this technology can provide real-time quantitative three-dimensional task analysis and provides preliminary evidence that interactive computer use with the right training conditions may
increase stroke users’ motor and cognitive skills. Age does not seem to be a limitation. However, as a potential tool for rehabilitation, it must demonstrate its transfer to real life tasks more clearly. Developers of virtual rehabilitation tasks could benefit from examining the formulas used by game developers. Thus benefits of a system for rehabilitation after stroke, based on VR, haptics and telemedicine should be: increased quality of life, less isolation, feeling more secure, fewer tiring clinics resulting in lower transportation costs, more frequent exercise and better compliance to training. During rehabilitation after stroke, diagnosis and treatment are not the only factors of great importance. For the user, feedback is also important for further development and the progress must be controlled and documented. Contemporary ICT provides this in one package: assessment, training, control and documentation.

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References


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