Virtual Rehabilitation –
Implications for Persons with Stroke

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Implications for Persons with Stroke

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ABSTRACT

Aims: The purpose of this thesis was to investigate the effects of Virtual Reality technology and haptics for stroke rehabilitation. Aims were to assess motor training in the so called chronic phase after stroke and to evaluate whether any improvement detected in the VR environment is reflected in daily life. We wanted to establish normative kinematic reference values and to test a method for assessing visuospatial neglect.

Methods: One hundred and six subjects participated in four different studies. Twenty-nine had a stroke and 77 were healthy individuals. In paper I, a single-subject experimental design (AB) provided intervention effects on five hemiparetic stroke subjects. The intervention consisted of playing a three-dimensional computer game. Paper II was explorative and was intended to acquire normative data. Fifty-eight healthy subjects performed three-dimensional hand movements in a virtual environment using two types of handgrip postures, i.e. pen grip and cylinder grip. Paper III used a pre/post-test design with comparison with a control population. The rationale was to place a VR system in a non hospital environment to see whether playing three-dimensional computer games would improve upper extremity motor function. The intervention involved 11 stroke subjects who received extra computer training in addition to their current activities. The control group was comprised of 11 stroke subjects who continued their usual rehabilitation (no extra computer training) during this period. An additional group of 11 right-handed aged matched individuals served as reference subjects. Paper IV was explorative with comparisons with traditional neglect tests. Eight subjects with right hemisphere brain damage and eight healthy controls were included. Four stroke subjects had visuospatial neglect and four had recovered clinically from initial symptoms of visuospatial neglect. The performance of the stroke subjects was compared with that of a reference group consisting of eight subjects with no history of neurological deficits.

Results: All studies demonstrate that this VR application can provide a quantitative analysis of hand movements. In paper I, improvements in time (extension), velocity and hand trajectory (hand path ratio) for all subjects was noted. One subject improved in occupational performance, i.e. improvement reflected in activities of daily living. In paper II, we established normative kinematic values. The test-retest for the two different handgrips between two test occasions showed a high reliability for the healthy subject for the kinematic variables. There was a training effect between the first test occasion and the third test occasion. Paper III is consistent with Paper I, but the results have extended these findings, showing that virtual rehabilitation can be beneficial not only to younger participants but also to elderly people in terms of enhancing their motor performance. In Paper IV we showed that the 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, such as mixed search pattern, repeated target pressures and deviating hand movements.

Conclusion: The VR upper extremity tests take less than a minute to complete and produce objective kinematic data. The general experience using the VR application approach suggests that this intervention concept is promising in stroke rehabilitation, with a wide range of applicability.

Keywords: Haptics, Neglect, Outcome Measures, Paresis, Stroke, Rehabilitation, Virtual Reality.

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LIST OF ORIGINAL PAPERS

This thesis is based on the following papers, which will be referred to in the text by Roman numerals:

I.

Broeren, J., M. Rydmark, A. Bjorkdahl and K. S. Sunnerhagen (2007). "Assessment and training in a 3-dimensional virtual environment with haptics: a report on 5 cases of motor rehabilitation in the chronic stage after stroke." Neurorehabil Neural Repair **21**(2): 180-9.

II.

Broeren, J., K. S. Sunnerhagen and M. Rydmark (2007). "A kinematic analysis of a haptic handheld stylus in a virtual environment: a study in healthy subjects." J Neuroengineering Rehabil **4**: 13.

III.

Broeren J, L. Claesson, D. Goude, M. Rydmark, K. S. Sunnerhagen (2007). "Virtual Rehabilitation in an activity centre for community dwelling persons with stroke; the possibilities of 3D computer games." Submitted

IV.

Broeren, J., H. Samuelsson, K. Stibrant-Sunnerhagen, C. Blomstrand and M. Rydmark "Neglect assessment as an application of virtual reality (2007)." Accepted for publication in Acta Neurologica Scandinavica

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CONTENTS

ABBREVIATIONS

3D	Three-Dimensional
AMPS	Assessment of Motor and Process Skills
ADL	Activities of Daily Living
BBT	Box and Blocks Test
BNIS	Barrow Neurological Institute Screen for Higher Cerebral function
CAVE	Computer Augmented Virtual Environment
CIMT	Constraint Induced Movement Therapy
Deg	Degrees
HPR	Hand Path Ratio
HMD	Head Mounted Display
ICC	Intra class correlation coefficient
ICF	International Classification of Functioning, Disability and Health
ICT	Information and Communication Technology
OT	Occupational Therapist
SD	Standard Deviation
UE	Upper Extremity
UL	Upper Limb
VR	Virtual Reality
WHO	World Health Organization

Metric units are used, i.e. m=meter, cm=centimeter, mm=millimeter, s=second.

GLOSSARY

Term	**Explanation**
CIMT	Constrained Induced Movement Therapy, i.e. restraint of healthy limb to force the patient to use the affected limb in performing tasks.
Haptic(s)	The word haptic derives from the Greek haptesthai meaning to touch. Haptics deals with interaction of a three-dimensional environment created in a computer, which besides the visual impressions gives the user a physical interaction with an object with a force feedback device.
Hemiparesis	Weakness of one side of the body after stroke.
Immersive	Immersion is a state of being so focused on a specific experience that there are no distractions.
Telemedicine	The delivery of health care services, where distance is a critical factor, by health care professionals using information and communications technologies for the exchange of valid information for diagnosis, treatment and prevention of disease and injuries, research and evaluation, and for the continuing education of health care providers, all in the interest of advancing the health of individuals and their communities.
Virtual Rehabilitation	The provision of therapeutic interventions locally or at a distance, using Virtual Reality hardware and simulations.

INTRODUCTION

Imagine the following scenario.

The clinic supplies the patient with a computer system at the time of the discharge from the hospital. The rehabilitation system will feature a library of engaging games that are simultaneously entertaining for the patient and beneficial for rehabilitation; i.e. the games will train in this case certain movements for upper extremity rehabilitation, so the patient can perform his/her daily training in a fun and stimulating environment. This computer system creates a virtual three-dimensional world that integrates with "virtual" touch sensation or force feedback to the hands. Here one can actually feel the objects, in addition to the visual perception. The stroke patient works with tools in the hands in a realistic environment, exactly as if he/she had the hands inside the computer screen. Thus, the user can see, feel and handle virtual objects as if they were real objects. The haptic device continuously records all positions, and these data are stored in the computer for further processing, analysis and assessment. Back at home, the patient will be able to exercise freely at a time that is suitable for him/her and in a familiar environment. At specific exercise hours, the therapist can monitor and coach the patient from a distance. In this way, the health care professionals will have an opportunity for feedback about patients' rehabilitation progress and be able to make necessary adjustments to the rehabilitation program.

This scenario gives some idea of the possibilities offered by advances in Information and Communication Technology (ICT) that are creating new opportunities for stroke rehabilitation.

Rehabilitation

Rehabilitation has been defined by the World Health Organization (WHO) as a coordinated process that enhances activity and participation (WHO 2001). Rehabilitation is a process of educating the disabled person in order to support him/her in coping with family, friends, work and leisure as independently as possible (Barnes 2003). The WHO International Classification of Functioning, Disability and Health (ICF) provides a multi-dimensional framework for health and disability suited for the rehabilitation process (WHO 2001). While this framework includes body structure and function, it also focuses on 'activity' and 'participation' from both the individual and the societal perspectives. Rather than restricting itself to the treatment of the body, it embraces the psychological condition and social environment of the patient. Therefore, treatment requires a close collaboration of specialists from a variety of disciplines, such as nurse, occupational therapist, psychologist, physician, physiotherapist, social worker and speech therapist (Höök 2001; Barnes 2003). Accordingly, modern rehabilitation medicine promotes an active rather than a passive patient participation throughout the entire course of therapy. Rehabilitation does not end with discharge from the rehabilitation center: it should provide the initial impulse to put the newly found knowledge into practice at home.

Stroke

Stroke is one of our most widespread diseases in the Western world and the principal cause of permanent physical impairment in the adult population in Sweden (National Health Care Quality Register in Sweden 2004). In Sweden, the incidence of stroke is around 30,000 cases annually (Riks-Stroke 2006). The average age at the onset of the stroke is about 75 years (men 73 years, women 77 years), but 20% are under the age of 65 years and the prevalence in those patients is twice as many men than women (Johansson *et al.* 2000; Medin *et al.* 2004). The number of persons that will suffer stroke is anticipated to shift stroke from the 6th leading cause of lost disability adjusted life years to the 4th in the world by the year 2020 (Kollen 2006). Society's costs for treatment and rehabilitation and indirect costs such as loss of working capacity, which can be for the person suffering from stroke or family members who have to engage in caring, are substantial. The total costs to society in Sweden were calculated at SEK 13.5 billion in 1998 (National Board of Health and Welfare 2005).

Stroke is a comprehensive term for conditions in which a cerebrovascular accident leads to an acute infarction or haemorrhage afflicting the brain. Persons with stroke can present various neurological symptoms depending on which vessel is affected since the nutrition to the cells supplied by that vessel is abruptly stopped. Most commonly, the damage is restricted to a specific area, thus giving so called focal symptoms. This implies that the functional dysfunctions are limited, while other body functions remain intact (Höök 2001). Common neurological phenomena are different degrees of hemiparesis and sensory impairments, aphasia, dysarthria, hemianopia, dysphagia, perceptual impairments, limited attention span and visuospatial neglect. Other impairments are dizziness, disturbances in balance, memory and difficulty with planning and concentrating (Höök 2001). These activity limitations imply difficulties in the ability to manage personal care, transferring, recreational activities and home life, which in turn can lead to limitations in participation in work and social life (Tennant *et al.* 1997). During the post acute phase, most stroke survivors live in their homes or in other non hospital housing. Several studies report on persisting disability and difficulties with I-ADL activities (Thorngren *et al.* 1990; Taub *et al.* 1994; Mayo *et al.* 2002). In Sweden, 77% of stroke survivors expressed themselves to be fully or partially dependent on support from relatives (Glader *et al.* 2001) and 30% could be left alone less than half a day (Hulter-Asberg *et al.* 2005). Without rehabilitation the problems caused by the disability might persist. With rehabilitation, most persons enhance their capacity considerably, which can increase their quality of life (National Board of Health and Welfare 2005).

Occupational therapy

Occupational therapy aims to enable clients to engage in self-directed daily occupations in the areas of self-care/self-maintenance, school, work and leisure or play (American Occupational Therapy Association 1994). Thus, occupational therapy aims to promote recovery through purposeful activity; it encourages relearning through practice of functional tasks, with tasks gradually being made more difficult (Trombly *et al.* 2002).

Relearning daily life activities often comprises intensive training, feedback and training in an environment that motivates the patient to train (Carr *et al.* 1996). If the focus is on these three aspects in rehabilitation, the design of activities should be attractive. To create attractive activities it is important to understand the patient's subjective experience of the activity. Interventions that are productive, pleasurable and distracting can be efficient. Absorbing and interesting activities have a valuable effect on mood, health and recovery (Pierce 2001). The fact that an activity is pleasurable is important for motivating the patient. A well thought out mixture of the above mentioned aspects has the greatest probability for motivating the patient (Pierce 2001).

One of the most striking social consequences of stroke is a failure to resume activities that are purely for enjoyment (Greveson *et al.* 1991). In addition, enjoyable and pleasurable activities seem to be even further decreased in older adults who have experienced a stroke (Drummond 1990). This striking decrease is said to be caused by depression, upper extremity motor dysfunction or decreased visuospatial ability (Sveen *et al.* 1999). Occupational Therapists (OTs) views play/leisure as a need-fulfilling and important occupation in the life of every person (Schaaf 1990). When engaging people in occupation, the volition experience is an important factor. The term volition has been used to conceptualize motivation (Kielhofner *et al.* 1995). Kielhofner defines volition as "a system of dispositions and self-knowledge that predisposes and enables people to anticipate, choose, experience, and interpret occupational behaviour" (Kielhofner and Forsyth 1997). Volition is concerned with what one holds important and finds enjoyable and satisfying (Kielhofner and Forsyth 1997). In order for stroke survivors to benefit from play or leisure participation, OTs must aim to find occupations that bring forth volition and discover ways to stimulate motivation (Chern *et al.* 1996).

Hemiparesis: consequences and interventions

Regaining upper extremity (UE) function poses great difficulty for subjects with hemiparesis. Because a majority of subjects are able to perform most of their activities of daily living with their non involved UE, they tend not to use their involved (learned-non-use), less functional UE (Taub *et al.* 2002). Perceived loss of arm function has been reported as a major problem in subjects with stroke (Broeks *et al.* 1999). About 65% to 85 % of persons with a stroke show an initial deficit in the function of the UE (Feys *et al.* 1998; Broeks *et al.* 1999). Only 11% to 18% of those who have sustained a severe post stroke upper extremity paresis are said to achieve full upper extremity function (Nakayama *et al.* 1994; Kwakkel *et al.* 2003). It is not known whether the lack of recovery is mainly due to the damaged area itself or the extent of the influence that compensatory strategies have on the final results.

Recovery of motor skill depends on neurological recovery, adaptation and learning new strategies and motor programs. Motor learning is built on theories of the brain's own ability to relearn and re-adjust and the idea that functional training (i.e. training of motor tasks) may in itself be remedial (van der Lee *et al.* 1999; Nudo *et al.* 2001). The system model for motor control perceives the nervous system as an organization involving the interaction of many systems. This model focuses on interaction between the individual and the surrounding environment and advocates the use of a work method focused on the individual (Turner *et al.* 2002). Normal movement is goal orientated, a task carried out by an individual to reach control over motor functions. The current perspective on motor learning focuses on how feedback and training affect long term changes in the ability of movement (Carr and Shepherd 1996). When focusing on UE recovery one must discern between the recovery of use of the UE (activities) and recovery of basic motor control (function). There is a danger that therapists and subjects stop working on improving motor function in the affected UE in favour of teaching compensatory strategies using the unaffected UE (Desrosiers *et al.* 2006). Repeated failed attempts to use the affected UE might lead to learned-non-use (Desrosiers *et al.* 2006).

Learned-non-use is one of the theories behind constrained induced movement therapy (CIMT) and is based on experiments with monkeys (Taub *et al.* 1965). CIMT is a type of treatment for hemiparetic stroke subjects in whom the subjects are strongly encouraged to use the more affected paretic UE (Taub *et al.* 1993). 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 (Liepert *et al.* 1998; Taub *et al.* 2002; Pierce *et al.* 2003; Page *et al.*

2004; Wolf *et al.* 2006). Further, a multi-centre randomized controlled study by Wolf (Wolf *et al.* 2006) showed that these improvements persisted for at least one year. Target oriented rehabilitation approaches and individually adapted training programs seem to be essential for gaining recovery after stroke. In contrast, Desrosiers *et al.* (2005) evaluated the effect of an arm training programme combining repetition of unilateral and symmetrical bilateral tasks for people in the sub acute phase after stroke. They concluded that an arm training programme based on repetition of unilateral and symmetrical bilateral practice did not reduce impairment and disabilities or improve functional outcomes in the sub acute phase after stroke more than the usual therapy (Desrosiers *et al.* 2005).

Visuospatial neglect: consequences, tests and intervention

In this thesis, the term visuospatial neglect or simply neglect is used to describe the neglect syndrome. Neglect is an impaired ability to react to stimuli on the opposite side of the brain lesion (Pedersen *et al.* 1997). In its most chronic form, this disorder is most common in subjects with right hemisphere damage and is associated with poor functional outcome (Katz *et al.* 1999; Suhr *et al.* 1999; Cherney *et al.* 2001; Jehkonen *et al.* 2001; Farne *et al.* 2004).

Neglect subjects may not eat from the left part of their dish; they may bump their wheelchair into obstacles situated on their left, and have a tendency to focus their vision to the right. 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 (Halligan *et al.* 1991).

Cancellation tasks are said to be the single most sensitive test of neglect (Parton *et al.* 2004). In these tasks subjects search for and mark with a pen target items on a sheet of paper. Right hemisphere neglect subjects often start on the right side of the page (whereas control subjects who read left-to-right usually start on the left) and omit targets to the left of the page (Samuelsson *et al.* 2002). In visual search tasks subjects 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 (Samuelsson *et al.* 2002; Behrmann *et al.* 2004; Parton *et al.* 2006).

Attempts to rehabilitate neglect encourage subjects to direct their gaze towards contralesional space. Although this approach shows some success in reducing neglect within a particular task, subjects typically demonstrate little generalisation of their improved scanning behaviour to tasks outside of the training environment (Robertson and Marshall. 1993). Researchers have attempted to develop techniques that produce an automatic change in behaviour. The most promising of these approaches involves prism adaptation, using lenses that provoke a rightward horizontal displacement of subjects' visual fields (Frassinetti *et al.* 2002; Pisella *et al.* 2006; Rode *et al.* 2006). These studies suggest that the after effects of simple prism adaptation treatment may result in a long lasting improvement of neglect. Many subjects who show visuospatial neglect in the acute phase recover clinically. The presence of chronic visuospatial neglect is more difficult to assess and rehabilitation is associated with poor outcome (Katz *et al.* 1999). Thus, it is important to establish the prevalence of chronic neglect when considering rehabilitation programmes.

Virtual Reality and Haptics in rehabilitation

In the last decade of the 20th century, virtual reality technologies first began to be developed and studied as potential tools for assessment and treatment in rehabilitation (Rizzo *et al.* 2005). The number of studies with different applications is growing and diverse with the common goal to construct a simulated environment to facilitate the person's motor and/or cognitive abilities in order to improve functional ability (Weiss *et al.* 2004).

The idea behind Virtual Reality (VR) is simple; a simulated world runs on a computer system. The term VR was used for the first time in 1986 by John Lamier (Riva 2005). VR is a set of computer technologies which, when combined, provide an interactive interface to a computer generated world. This computer-based three-dimensional environment can be navigated through and interacted with and is updated in real-time (Rose *et al.* 1996; Ring 1998; Riva 1998; Szekely *et al.* 1999; Riva 2002; Tarr *et al.* 2002; Riva 2005). Several "state of the art" articles have been published in recent years. Sveistrup (2004) and Holden (2005) present both a comprehensive review of the current use of VR technology for motor rehabilitation. VR technology in brain damage rehabilitation is reviewed by Rose *et al.* (2005). Riva (2005) outlines the current state of clinical research relevant to the development of virtual environments for use in psychotherapy.

Although it is difficult to categorise all VR systems, most configurations fall into two main categories, i.e. immersive VR and non immersive VR (Sanchez-Vives *et al.* 2005). Each category can be ranked by the sense of immersion, or degree of presence it provides. Immersion or presence can be regarded as how powerfully the attention of the user is focused on the task at hand (Witmer *et al.* 1998). Immersion presence is generally believed to be the product of several parameters including level of interactivity, image complexity, stereoscopic view, and field of regard and the update rate of the display. Fully immersive VR can consist of a head mounted display (HMD), a Computer Augmented Virtual Environment (CAVE) or a large screen, which curves to some extent towards the participants producing a wide-angle view (Bowman *et al.* 2001). A computer screen often displays non immersive VR. Interaction may be by means of standard joysticks, gloves, computer mouse or gestures (video sensing that tracks user movement). VR is always associated with immersion. However, the sense of presence in a virtual world can be achieved using a conventional workstation (Sanchez-Vives and Slater 2005).

Training with haptic devices using VR has been suggested to enhance stroke rehabilitation. Bardorfer and colleagues developed a method for evaluating the functional studies of the UE in subjects with neurological diseases (Bardorfer *et al.* 2001). The Rutgers group (Jack, Boian *et al.* 2001; Boian, Sharma *et al.* 2002) developed a haptic interface called the "Rutgers Master II" force feedback glove. Broeren *et al.* (2002) identified a method to record quantitative measures of arm movements in a 3D virtual environment. Conner *et al.* (2002) used an approach to rehabilitation of cognitive deficits following stroke using haptic guided errorless learning with an active force feedback joystick and computer. In a study by Viau (2004), a VR task was validated as a tool for studying arm movements in healthy and stroke subjects by comparing the movement kinematics in a virtual environment and in the real world. Baheux and colleagues (2006) developed a 3D haptic virtual reality system to diagnose visuospatial neglect. Kim *et al.* (2004, 2007) designed a VR system to assess and train right hemisphere stroke subjects.

Employing computer games to enhance training motivation is an opportunity 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. This stands in contrast to traditional computer games, whose main purpose is to entertain. Serious games include games for learning, games for health and games for policy and social change. The health care sector is showing steadily increasing interest in serious games. Integrating gaming features into virtual environments has been reported to enhance motivation in adults undergoing physical and occupational therapy following a stroke (Jack *et al.* 2001; Kizony *et al.* 2005). According to Rizzo and Kim (2005), designers of rehabilitation tasks can benefit from enhancing motivation by leveraging gaming factors whilst presenting a patient with a repetitive series of cognitive or physical training challenges. Governing the flow and variation in stimulus pacing in a progressive goal-reward structure within an interactive and graphic-rich environment could support increased user engagement in game play and thus engagement in the rehabilitation process.

AIM

The overall aim of this thesis was to investigate whether Virtual Reality technology and haptics can be utilized as an assessment tool and training device for stroke rehabilitation.

Paper I

The aim of the study was to apply VR and haptics in the so-called chronic phase after stroke for motor training and to assess the effects. The second aim was to identify whether any improvement detected in the VR environment was reflected in activities of daily living.

Paper II

The aim of this study was to apply the haptic handheld stylus in a virtual environment in a cohort of healthy subjects in order to evaluate the test-retest reliability of a clinical procedure measuring trajectories and to establish normative data.

Paper III

The aim of this study was twofold: to assess the application of the VR system in a non hospital environment to see if it could be used there and to evaluate whether playing computer games resulted in improved motor function in persons with prior stroke.

Paper IV

The aim of this study was threefold: to apply the VR system as a tool for assessing neglect by comparing a cancellation task in a virtual environment with conventional tests of neglect, to describe the pattern of manual search performance and to obtain kinematic data on hand movement.

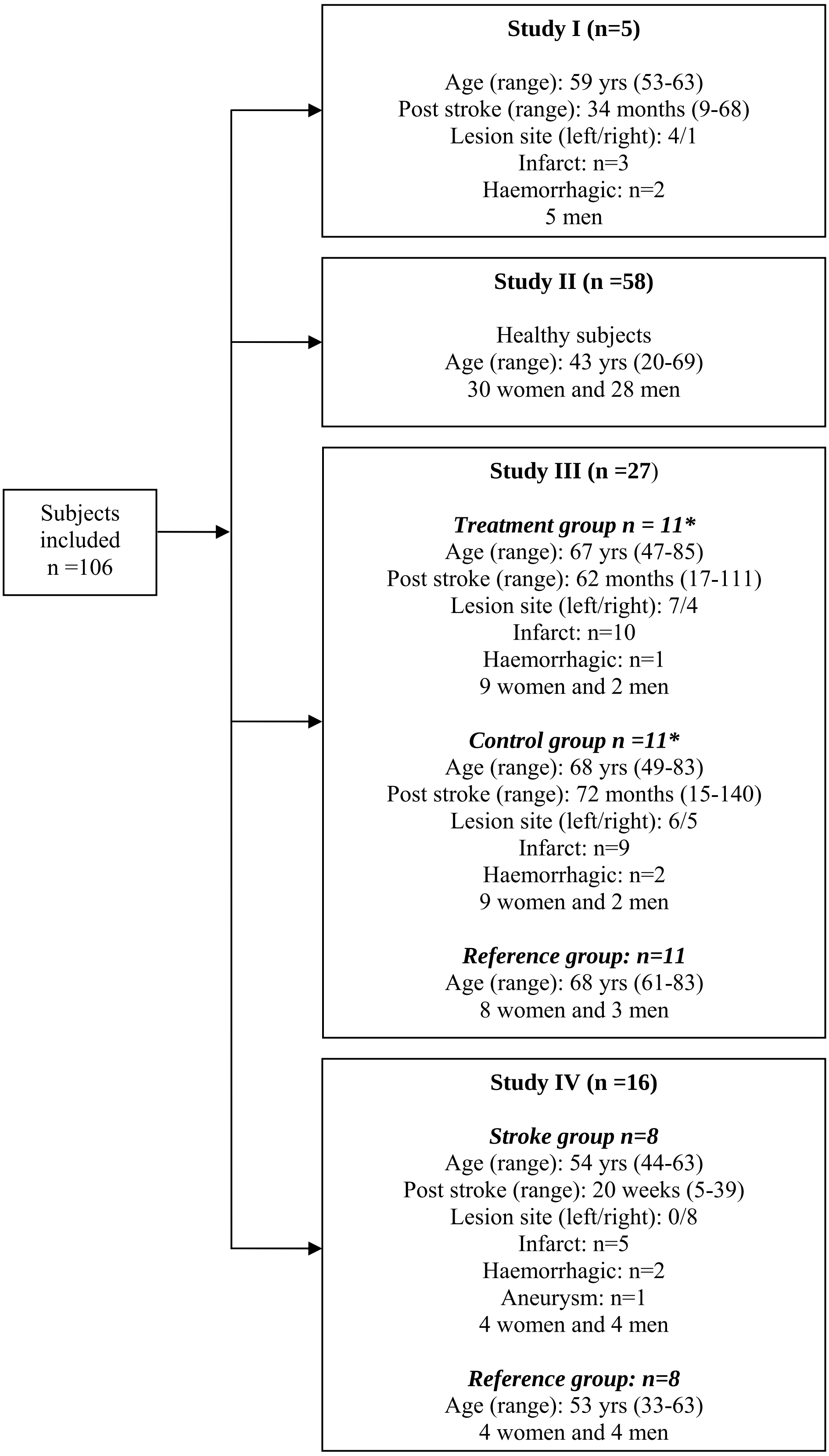
METHODS

Subjects

A total of 106 subjects were included in the different studies; 29 of them had had a stroke and 77 were healthy individuals. For a detailed overview, see figure 1. Twenty-nine stroke subjects, 17 women and 12 men aged 44-85 years, post stroke 1-140 months, participated in the different studies (I, III and IV).). In studies I and IV, the subjects underwent in- or out-patient rehabilitation at the Department of Rehabilitation Medicine at Sahlgrenska University Hospital, Göteborg, Sweden. Study III was carried out at a facility for community dwelling persons with stroke (Stroke Forum) in Göteborg, Sweden. The identification of the lesion site (left vs. right) and etiology (infarct vs. haemorrhagic) was done by magnetic resonance imaging and/or computed tomography scans by an experienced neuroradiologist and was re-evaluated by an experienced stroke neurologist. The reference groups (II, III and IV) of healthy individuals (self perceived health) comprised 42 women and 35 men aged 20-83, all right-hand dominant. Most of the subjects were hospital or university employees with varying levels of education and were recruited via direct contact, person to person, by telephone or by mail or via their work manager.

Inclusion criteria

The subjects in studies I and III were required to have a hemiparesis in one of the upper extremities, i.e. box and blocks test (BBT) score lower than 55 (Mathiowetz *et al.* 1985), no signs of neglect, to be in a chronic stage (≥ 6 months post stroke) and no other neurological disease. In study II all subjects underwent a neuropsychological examination with the Barrow Neurological Institute Screen for Higher Cerebral function (BNIS) to confirm normal cognitive function (Prigatano *et al.* 1992; Prigatano *et al.* 1995). Subjects were included if they had a score above 47 points (upper limit=50), which is considered normal cerebral function. In the fourth study (IV) the criteria for inclusion were right-sided brain damage confirmed by CT or MRI scans, visual neglect identified by the star cancellation test and the baking tray task (Halligan *et al.* 1989; Tham *et al.* 1996), 2–5 weeks post-stroke, ability to understand information, right-handed with no signs of motor impairment on the right side and no pre stroke history of visual deficits. The reference subjects in studies III and IV were included if they were healthy (self perceived health) and had a minimum age of 18 years. All subjects gave their informed consent to participate in the different studies, which were conducted in accordance with the local Ethics Committee at Göteborg University.



Subjects
included
n =106

Study I (n=5)

Age (range): 59 yrs (53-63)
Post stroke (range): 34 months (9-68)
Lesion site (left/right): 4/1
Infarct: n=3
Haemorrhagic: n=2
5 men

Study II (n =58)

Healthy subjects
Age (range): 43 yrs (20-69)
30 women and 28 men

Study III (n =27)

Treatment group n = 11*
Age (range): 67 yrs (47-85)
Post stroke (range): 62 months (17-111)
Lesion site (left/right): 7/4
Infarct: n=10
Haemorrhagic: n=1
9 women and 2 men

Control group n =11*
Age (range): 68 yrs (49-83)
Post stroke (range): 72 months (15-140)
Lesion site (left/right): 6/5
Infarct: n=9
Haemorrhagic: n=2
9 women and 2 men

Reference group: n=11
Age (range): 68 yrs (61-83)
8 women and 3 men

Study IV (n =16)

Stroke group n=8
Age (range): 54 yrs (44-63)
Post stroke (range): 20 weeks (5-39)
Lesion site (left/right): 0/8
Infarct: n=5
Haemorrhagic: n=2
Aneurysm: n=1
4 women and 4 men

Reference group: n=8
Age (range): 53 yrs (33-63)
4 women and 4 men

* Six subjects participated in both the treatment and control groups.

Figure 1. Flowchart of the subjects included.

Computer equipment

Two different pieces of computer equipment were used. A semi immersive workbench developed by Reachin (www.reachin.se) was used in studies I, II and IV (Figure 2). Study III used a semi immersive workbench developed by Sensegraphics (www.sensegraphics.se), see figure 2. The user stood in the real world and looked into a virtual world generated in the computer. He or she was then able to reach into a virtual space and interact with three-dimensional objects through a handheld stylus (haptic device) positioned in the line of sight. It created an illusion of virtual objects for the user while the only real element was the handheld stylus and the computer equipment. Using stereoscopic shuttered glasses, the user observed a 3D image displayed above the tabletop.

Figure 2. Semi immersive workbenches, Reachin (left) and Sensegraphics (right).
Pictures reproduced from 3Dcgi.com and Sensegraphics AB.

Both VR systems used a PHANTOM^{TM} from SensAble Technologies (Figure 3). This is a desktop haptic feedback device that provides single point, 3D force feedback to the user via a stylus attached to a moveable arm. The position of the stylus point/fingertip was tracked, and resistive force was applied to it when the device came into contact with the virtual model, providing force feedback. The physical working space was determined by the extent of the arm. The Reachin system used the PHANTOM^{TM} desktop and the Sensegraphics system used the PHANTOM^{TM} Omni. The force feedback work space for both systems used was ~160 mm × 120 mm × 120 mm (W/H/D).

Figure 3. PHANTOM desktop (left) and PHANTOM Omni (right).
Pictures reproduced from www.sensible.com.

In study III, telemedicine based on Skype^{TM} with a camera (software version 2.5, freely available from the internet) was used as a communication tool between the therapist and the personal at the activity centre, offering clinical and technical support.

Calibration of Measurements

Since the “virtual environment” in the Reachin system was tilted 33.78 deg with respect to the desktop, the measure front/back corresponded to the cosine (33.78) times 10 cm, that is, 8.3 cm. The angle of 33.78 deg came from the physical geometry of the immersive workbench used in these experiments, which placed a visual focal plane in front of the user that rotated 33.78 deg from the tabletop. Measurement of the distance between test points separated by 10 cm left/right and front/back, respectively, at the desktop level and at a level of 9 cm above the desktop, indicated that there were no significant differences in the mm range. The Phantom Omni device featured an auto calibration function, which was activated when the stylus was placed in its resting position. Twenty readings of a 10 cm movement centred in the haptic working space were obtained in each of the x, y and z directions. Here as well, no significant differences were found in the mm ranges.

Instruments

Computerized instruments

In study I, II and III an UE test previously developed by us was used (Broeren *et al.* 2004). The subjects had to move the haptic stylus to different targets in the virtual world (Figure 4). The targets appeared one after the other on the screen and disappeared when pointed at. The target placements (32) in the three-dimensional space were apparently random to the subjects but were actually set according to a pre set kinematic scheme for evaluation purposes. The subject had to move as accurately and quickly as possible to each target.

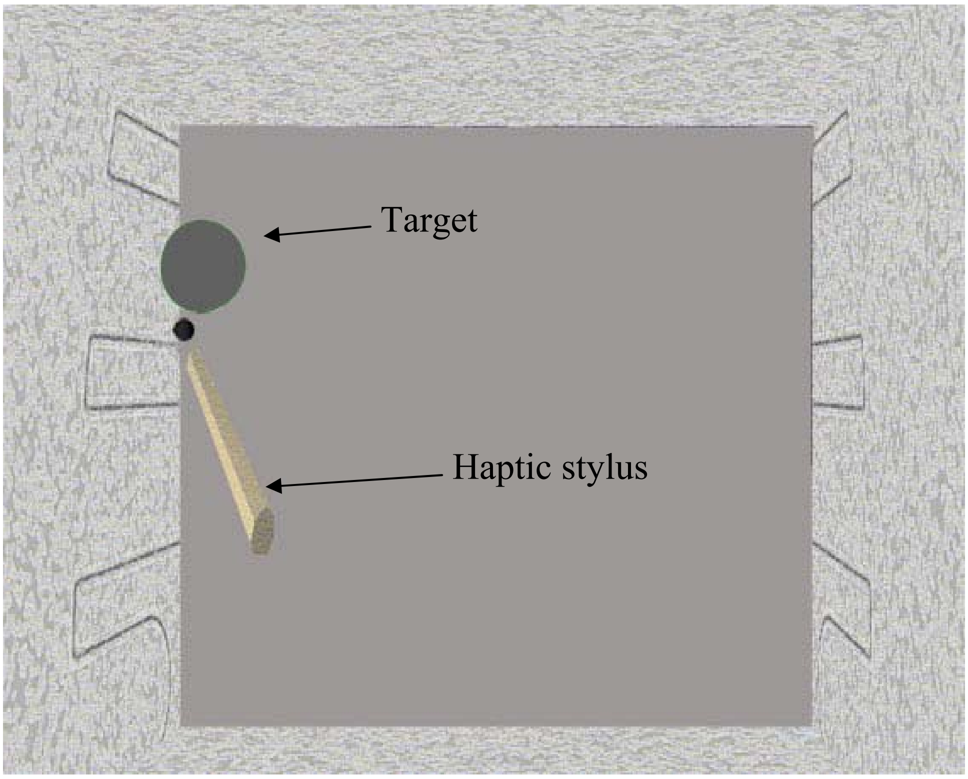


Figure 4. VR task (screenshot)

Hand position data (haptic stylus end-point) during each trial were gathered. The x-, y- and z-coordinates, which were time stamped, gave the basic pattern of hand movement. Time and distance to complete the whole exercise were recorded. From this, average velocity and HPR (hand-path ratio - the quotient between actual hand trajectory and the straight line distance between two targets) were calculated. For the short target-to-target movement (the target-to-target is one segment of motion data, separated by target presses) the following were calculated: (1) time, (2) HPR, (3) max velocity (m/s) and (4) max acceleration (m/s^2). The basic pattern of stylus movement in space was visualized in Matlab (www.mathworks.com), giving an indication of how hand trajectory and movement quality changed over time.

A cancellation test developed by our group was used in study IV (Figure 5). The VR environment consisted of 20 targets and 60 distracters (2.7 cm diameter). The target was the digit '1' and the distracters were other numbers. The targets marked with the number 1 distributed pseudo randomly on the computer screen. The subjects had to press all targets marked with the digit 1, whereby the target changed colour, and finally press the red button marked with zero (0), indicating that they had finished their search. 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.

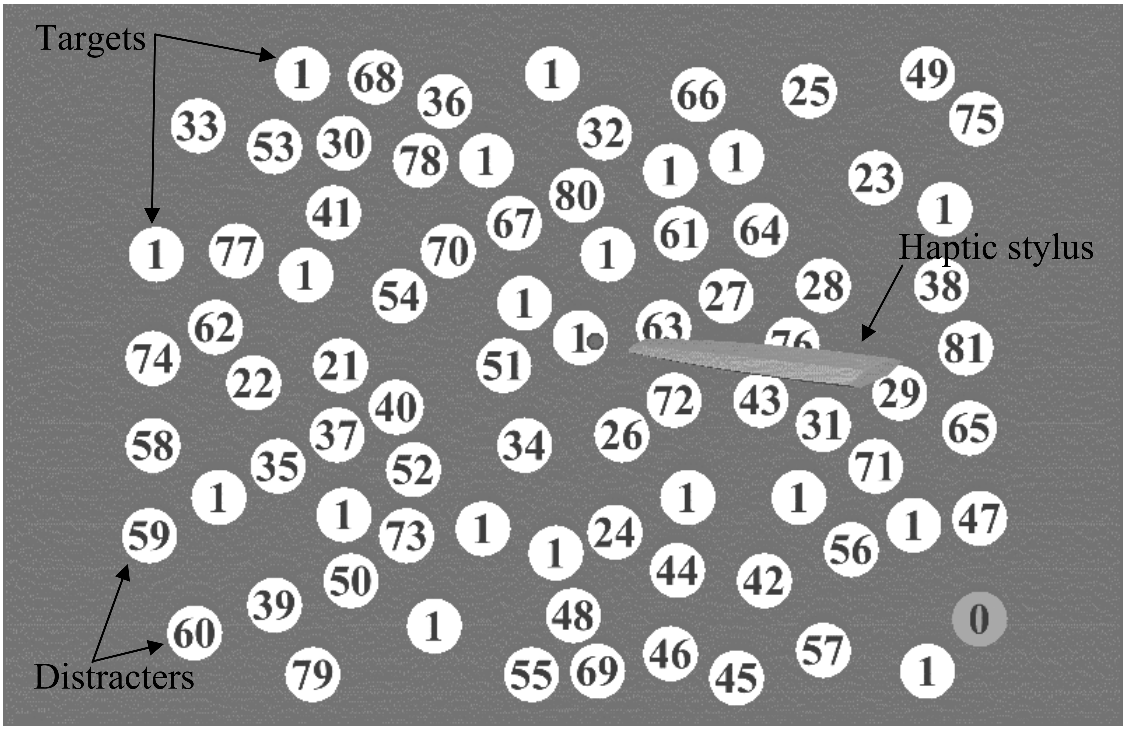


Figure 5. The VR task (screenshot). Zero (0) is the end target.

Hand position data (haptic stylus end-point) were recorded in the same way as described for the UE test, i.e. time, distance, velocity and hand path ratio (HPR). Further information was gathered that was specific for the neglect syndrome, i.e. omissions of targets, search pattern, start column and repeated target press.

Traditional instruments and what study they were employed in

The Box and Block Test (I and III), evaluates gross movements of the hand/arm (Mathiowetz *et al.* 1985; Desrosiers *et al.* 1994). The test requires moving, one by one, the maximum of blocks from one compartment of a box to another of equal size within 1 min.

The Assessment of Motor and Process Skills, AMPS (I) is an observational measure to evaluate activities of daily living. AMPS is a standardized assessment of occupational performance, used to observe and evaluate a person's ability to perform personal and instrumental ADL (Fisher 1993; Fisher 2003). It measures the quality of a person's performance during ADL tasks by evaluating 16 ADL motor skills and 20 ADL process skills. Motor skills are the observable goal-directed actions the person enacts during the performance of ADL tasks in order to move oneself or the task objects. Process skills are the observable actions of performance the person enacts to logically sequence the actions of ADL task performance over time, select and use appropriate tools and materials, and adapt his/her performance when problems are encountered (Fisher 2003). A trained and calibrated rater (calibrated to compensate for harshness or softness in the judgment of performance) scores performance in two to three tasks selected from a bank of analysed tasks. The raw scores are analysed using many-faceted Rasch analysis (Linacre 1993) to provide linear motor and process skill ability measures expressed as logistically transformed probability measures (logits) (Fisher 1993; Linacre 1993; Fisher 2003). The Assessment of Motor and Process Skills (AMPS) has been validated for use in Sweden (Bernspang *et al.* 1995). A change of 0.5 logits is considered a clinically relevant difference in the Rasch analysis (Fisher *et al.* 1992; Dickerson *et al.* 1993; Doble *et al.* 1994; Park *et al.* 1994).

The Barrow Neurological Institute Screen for Higher Cerebral function (II) is a short screening test developed to assess a variety of higher cerebral functions. The BNIS consists of 30 different items grouped together in seven clinically relevant factors. The total maximum score is 50. A high score indicates better function and a score above 47 is considered normal (Prigatano *et al.* 1992; Prigatano *et al.* 1995). The Swedish version has been validated for use in Sweden (Denvall *et al.* 2002).

ABILHAND (III) is a questionnaire whose purpose is to measure manual ability in chronic stroke. It measures the patient's experience of problems in performing everyday tasks such as feeding, dressing or managing domestic tasks, whatever strategies are involved (Penta *et al.* 1998; Penta *et al.* 2001). ABILHAND is interview based and focuses on the patient's perceived difficulty in performing everyday manual activities. ABILHAND contains 56 unimanual and bimanual activities, which the subjects are asked to judge on a four-level scale: 0=impossible, 1=very difficult, 2=difficult and 3=easy. The rating scale is accessible in ten versions, with the activities in different orders, to be administered at random. Activities not attempted during the last three months are not scored and are encoded as missing responses (Gustafsson *et al.* 2004). ABILHAND is a Rasch-based assessment (Penta *et al.* 1998). A Swedish version has been validated (Gustafsson *et al.* 2004).

The star cancellation test (IV) is a sub test in the Behavioral Inattention Test battery (Halligan *et al.* 1989). It consists of a total of 52 large stars, 56 smaller stars, 13 letters and ten short words, which are pseudo randomly positioned over a landscape A4 sheet. The subjects were 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 (IV) is a comprehensible, simple-to-perform test for use in assessing unilateral neglect. Subjects have to place 16 identical items (3.5 cm wooden cubes) on a blank test board, the baking tray (75 x 100 cm) as symmetrical 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 (Tham and Tegner 1996).

Interview

A semi-structured interview (III) was used to assess subject’s opinions about the VR system and the games, and “how” they would like to use the VR system in the future if available in regular clinical care.

Procedure and data collection

Paper I. Single-case design

A single-case design (AB design) plus a follow-up design (C) was employed.
All subjects began with a baseline phase (A). The dependent variables were velocity (m/s), hand path ratio (HPR) and time (s). This was assessed with three measurements made during one session, three times during one week. The intervention phase (B) then started and continued for five weeks; three measurements were made during one session, once a week. A follow-up (C) assessment was made 12 weeks later with the same assessment procedure as used in the baseline phase. As repeated measures over time can produce learning effects and changes in performance, the assessment of three trials with the paretic hand in the VR task was chosen. From this the mean for each session was calculated.

The intervention consisted of playing a 3D computer game (Figure 6), which entails striking a virtual ball to knock over bricks in a pile. At the start of the game, the subjects grasped (pen grip or cylinder grip) the haptic stylus with their affected UE. They obtained a view of a ball, a court filled with bricks, and a virtual bat, that is, a simulation of the haptic stylus. The ball was stationary at the start of the game. The game started when the subject struck the ball with the haptic stylus and the ball started to bounce forward and backward.

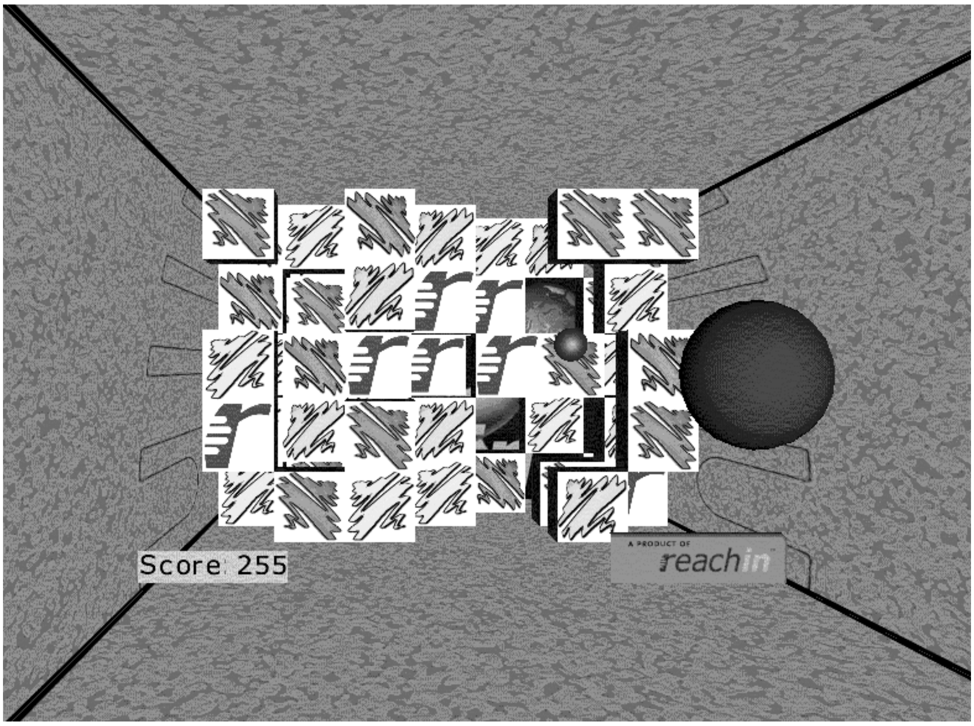


Figure 6. Screenshot of the computer game, 3D bricks.

When the ball was touched, the subject experienced a force from the haptic stylus. The subjects received credit for the bricks knocked down. On the return, when subjects missed the ball, they collected minus points. The game was customized to operate at seven different speed levels. The effect of modifying the speed from seven (easiest) to one (most difficult) caused the program to speed up the velocity of the approaching ball. All subjects started at level seven. The level of difficulty was changed after the subject had reached a predetermined score in three consecutive games. Fifteen 45-min treatment sessions were conducted over a period of five weeks. A follow-up assessment was made 12 weeks later with the same assessment procedure as used in the baseline phase.

The AMPS and BBT were used as a correlate to the quantitative kinematic information from the VR assessment in the baseline and follow-up phase. Another OT not involved in the training made AMPS and BBT assessments. The AMPS assessments were video-taped. One of the OTs, who was not present at the performance of the AMPS activity, watched the videotapes of each patient and scored performance without knowing the order in which the activity performance was shown.

Paper II. Explorative to get normative data

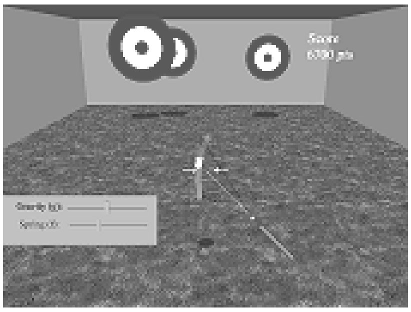
Fifty-eight subjects underwent a neuropsychological examination with the BNIS to confirm normal cognitive function. Two types of handgrip postures are studied, i.e. pen grip and cylinder grip (Figure 7). All subjects were tested in three sessions within one week with the VR assessment; each session consisted of three trials with two different handgrips. All assessments, i.e. neuropsychological test (BNIS) and the VR tests were made by a neuropsychologist.

Figure 7. Different handgrip postures, pen grip (left) and cylinder grip (right).

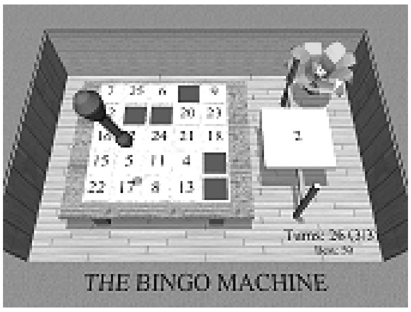
Paper III. Pre/post test design with comparison with control population

A pre and post test design was employed. All subjects were tested before and after the intervention with the VR assessment. Sixteen stroke subjects participated. Six subjects were able to participate in both groups. They started the study as control subjects. The other subjects were matched by sex and then randomly assigned to an intervention group (N=11) that received rehabilitation or a control group (N=11) that received no rehabilitation with the VR system but otherwise performed the same protocol. The intervention group received additional VR therapy three times a week for 45 minutes for four weeks. The intervention consisted of playing 3D computer games with the UE unsupported during play. The subjects could select various games with the haptic stylus from a game library (Figure 8).

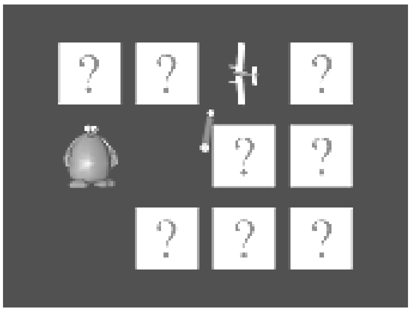
Both groups continued to participate in their usual activities at the activity centre. These activities consisted of different social activities, creative crafts and physical activities. ABILHAND and BBT were used to assess whether the detected change of the intervention in the VR environment could strengthen the results of the quantitative data. The semi structured interview was used at the end of the study to assess the subject’s opinions of the VR system. A person not responsible for the training, here the author, conducted the assessments. The rehabilitation personal at the activity centre (Stroke Forum) that prior to this had no experience of Virtual Reality conducted the training.



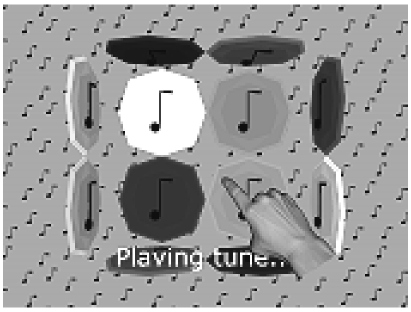
Archery: pulling back a string and shooting towards different targets, which move in 3D space. The level increases the more games that are played.



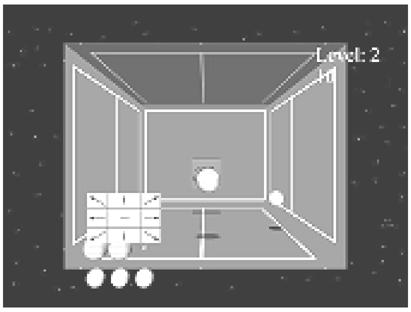
Bingo: numbers were generated in random on a bingo machine; the subject has to mark the corresponding number on a bingo board. The game gradually increases by adding rows.



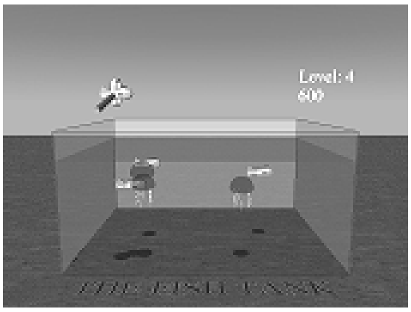
Memory: finding matching pairs on the board by touching question marks. Points are awarded when two similar pairs are singled out.



Simon: mimic a sequence of tunes; whenever a combination of tones is mimicked, a new tone is added to the sequence.



Space tennis: subjects control a racket with the haptic stylus and bounce a ball in direction of the opponent (computer controlled). Points are scored when one player misses a ball.



Fish tank: pick up fish and lift them out from the fish tank. Jellyfishes act as bombs; by touching them the point score decreases.

Figure 8. Game libery, screenshots of six different 3D computer games.

Paper IV. Explorative with comparison to traditional neglect tests

A cancellation task in a virtual environment with two conventional tests of neglect, i.e. Star cancellation and the Baking tray task, was compared. The pattern of manual search performance was described and kinematic data on hand movement were obtained. Eight stroke subjects with right brain damage and eight reference subjects participated.

Statistical analyses

The Statistical Package for the Social Sciences (SPSS) version 13.0 Software for Windows (SPSS, Chicago, IL, USA) and Microsoft Office Excel 2003 were used for statistical analysis. In papers I-IV the data derived were treated as a non-normal distribution.

In paper I, the mean and SD of each variable at baseline, during intervention and at the 12-week follow-up evaluation were calculated. Graphical representation utilized visual examination of the intervention effect for each patient individually.

In paper II, the test–retest reliability was evaluated with means per session, Intra Class Correlations (Bland *et al.* 1986) and 95% confidence intervals. The Wilcoxon signed rank test for paired scores was used to assess possible learning effects between test sessions one and three. Descriptive statistics, i.e. median and 10-25-75-90 percentiles, were calculated.

The mean and standard deviation (SD) of each variable were calculated in paper III. The Wilcoxon signed rank test was used to compare the intervention group with the control group.

One-tailed upper 97% reference limits were calculated in paper IV, i.e.: mean + 2.5 SD. Since healthy subjects 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 was 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 subject, 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" (Mark *et al.* 2004).

RESULTS AND COMMENTS

Paper I: Assessment and Training in a 3-Dimensional Virtual Environment with Haptics: A Report on 5 Cases of Motor Rehabilitation in the Chronic Stage after Stroke.

The aim of the study was to apply VR and haptics in the so-called chronic phase after stroke for motor training and assess the effects. The second aim was to identify whether any improvement detected in the VR environment was reflected in activities of daily living.

The visual analysis revealed improvements in velocity (m/s), time (s) and HPR after the intervention and at the follow-up assessment for all subjects (Figure 9.) The 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 (Figure 10).

The conventional outcome measures BBT and AMPS varied for the subjects. One subject (P3) increased considerably (23%) in unilateral manual ability. A slight increase between 2% and 6% had occurred for P1, P4 and P5, whereas P2 had a slight decrease by 3%. In activities of daily living, two subjects showed a significant difference in the AMPS motor skills. One subject (P4) showed an increase by 0.6 logits and one subject had a substantial decrease of 0.7 logits. In the performance of process skills no significant differences were found for all subjects. However, two subjects (P1 and P4) showed an improvement of 0.3 logits.

All subjects were novel computer game players at the start of the study. After an initial introduction, all subjects quickly learned to use the VR system. The subjects reported spontaneously that the game was challenging and enjoyable to them. All subjects progressed to game level 1 (most difficult) at the end of the intervention period.

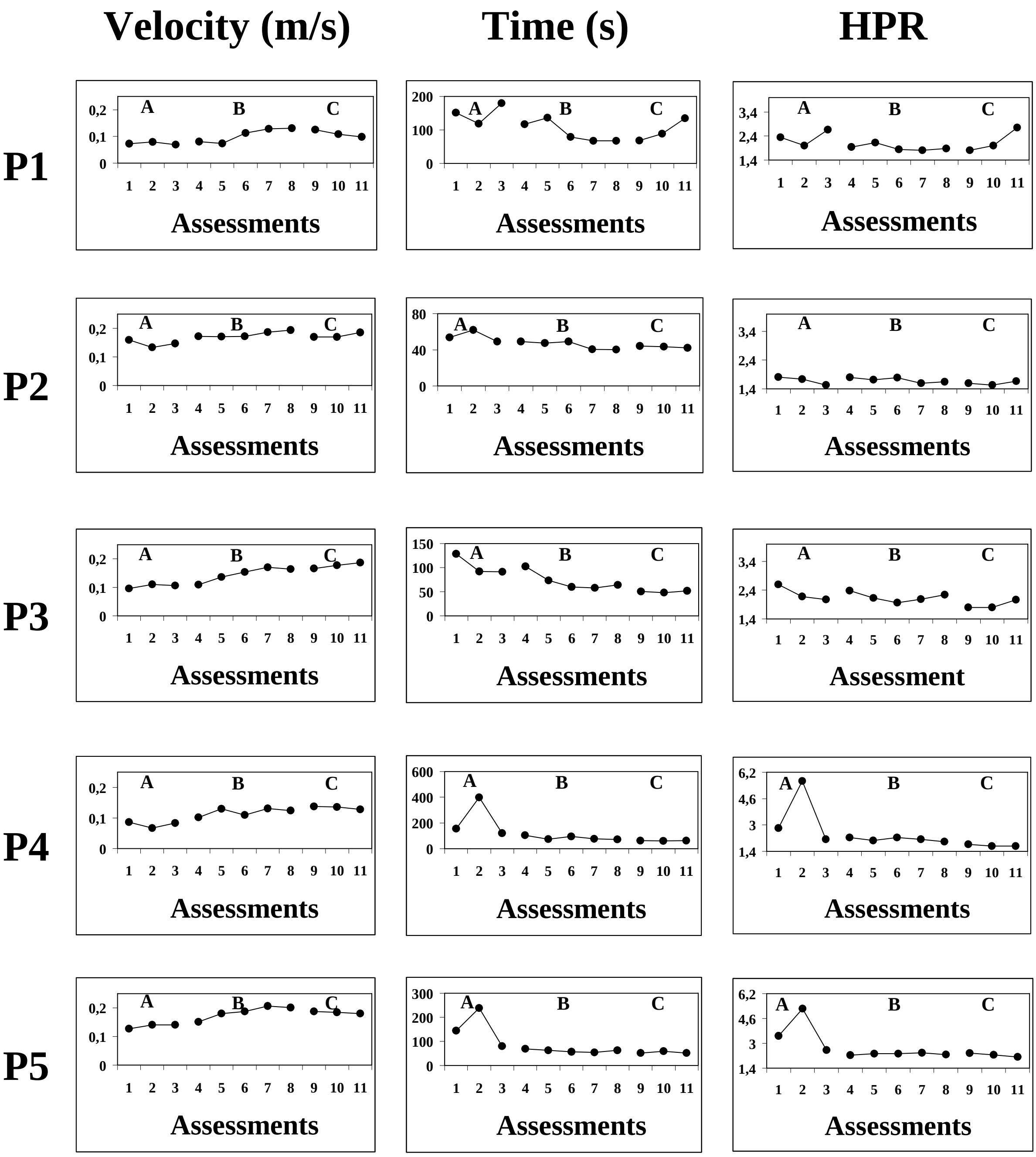


Figure 9. Mean velocity (m/s) and time (s) and HPR at assessments on the VR test for all subjects (P1–P5).

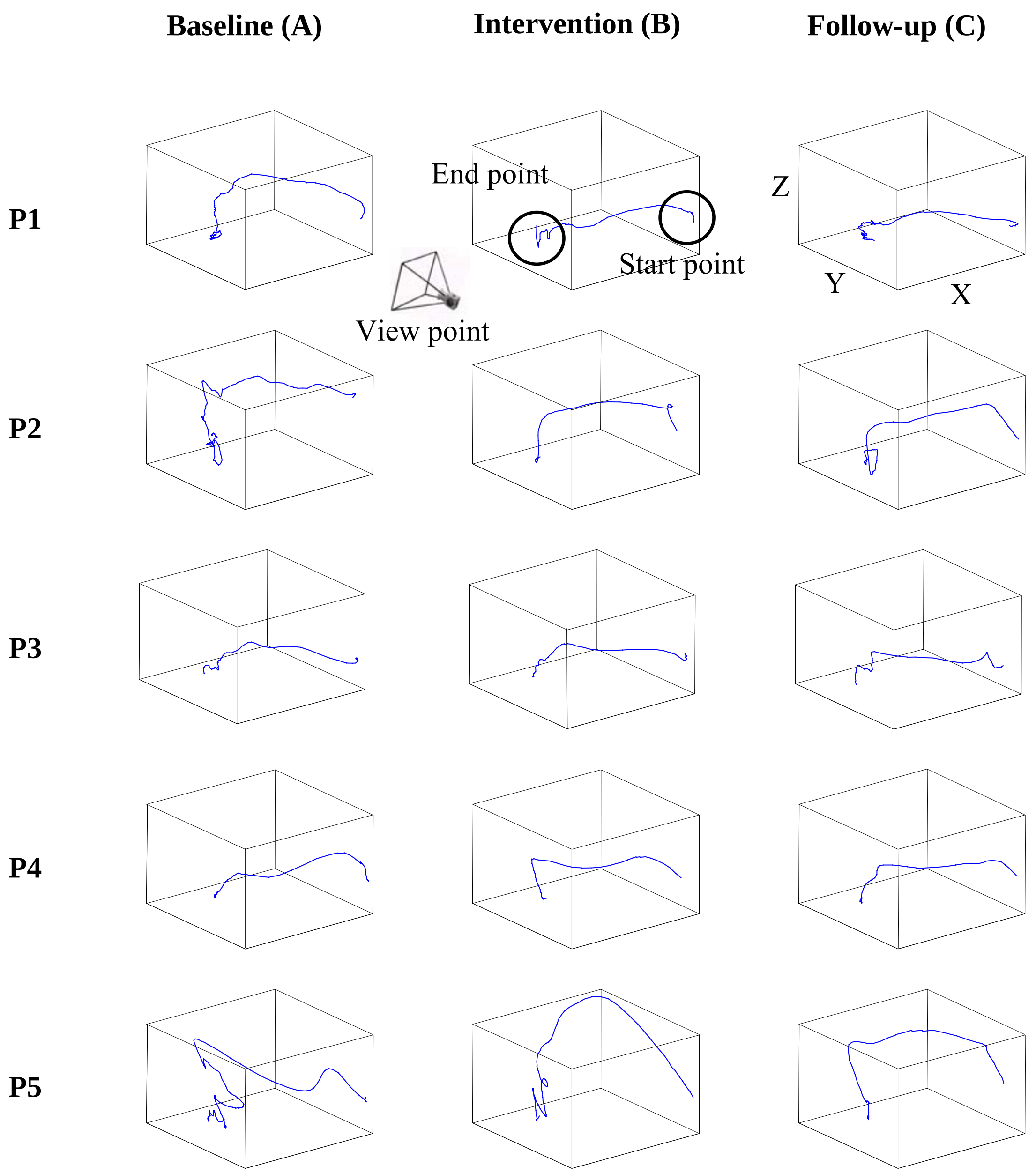


Figure 10. Raw data for the hand trajectories at baseline (A), end of intervention (B) and at follow-up (C). Similar short target-to-target trajectories were visualized. In this case the start point trajectory was chosen, i.e. moving the haptic stylus from the first targets to the second target. This 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.

Paper II: A kinematic analysis of a haptic handheld stylus in a virtual environment: a study in healthy subjects.

The aim of this study was to apply the haptic handheld stylus in a virtual environment in a cohort of healthy subjects in order to evaluate the test-retest reliability of a clinical procedure measuring trajectories and to establish normative data.

Study II resulted in a standardized test for two different grip types, i.e. cylinder and pen grip. The performance of the subjects was examined by dividing them into two different age groups, i.e. younger adults (20-44 years) and older adults (45-69). There were no significant differences in the kinematic measures between the two groups for the whole exercise; consequently the material was analysed as a single age group (Table 1).

Table 1. Changes in mean between younger adults (n=34) and older adults (n=24) for Time (s), Hand Path Ratio (HPR) and Velocity (m/s) for cylinder- and pen grip.

	Cylinder grip			Pen grip		
	Younger Mean (SD)	Older Mean (SD)	*p value*	Younger Mean (SD)	Older Mean (SD)	*p value*
Time (s)	34.97 (6.60)	36.22(12.54)	0.73	38.01 (8.54)	36,71 (11.19)	0.14
HPR	1.76 (0.37)	1,85 (0.40)	1.00	1,81 (0.50)	1.91 (0.36)	0.36
Velocity (m/s)	0.25 (0.08)	0.26 (0.08)	0.91	0.23 (0.06)	0.26 (0.08)	0.33

The test-retest reliability of the computerized test between the second and third assessments of session 1, using the ICC (Table 2, session1) was determined. There was a training effect between the first test occasion and the third test occasion (p=0.01). Test-retest reliability was once more determined for session 3 (Table 2, session 3). The accepted evaluation criteria and standards for ICC values are as follows: values of 0.75 or greater represent excellent reliability; values between 0.40 and 0.74 represent adequate reliability, and values of 0.40 or lower represent poor reliability (Salter *et al.* 2005). The ICCs for the test-retest reliability were found to be excellent or adequate for the cylinder and pen grip, see Table 2.

Table 2 Test–retest reliability for sessions 1 and 3 for the cylinder and pen grip (n=58).

		Cylinder grip		Pen grip	
		ICC*	95 % CI	ICC*	95 % CI
Session 1	Time (s)	0.80	0.74-0.85	0.73	0.65-0.79
	HPR	0.77	0.70-0.82	0.81	0.76-0.86
	Velocity (m/s)	0.84	0.82-0.89	0.88	0.84-0.91
Session 3	Time (s)	0.70	0.53-0.81	0.77	0.66-0.86
	HPR	0.73	0.59-0.83	0.74	0.74-0.91
	Velocity (m/s)	0.83	0.72-0.89	0.82	0.72-0.89

*ICC= Intra class Correlation Coefficient

The characteristics (detailed x-, y-, and z-plots) from the short target-to-target movement within the different grip types were diverse (Figure 11). It seems that the hand path trajectories with the cylinder grip were more distributed. When the subjects used the pen grip, the hand trajectories were more arched. Although this did not show in the HPR measure, there the difference between both grip types were very small and the findings in this parameter showed the same distribution. Moreover there were very small differences between the cylinder grip and pen grip regarding time (s), HPR, max velocity (m/s) and max acceleration (m/s^2). Descriptive data for time (s), HPR, average velocity (m/s) for both handgrips (whole exercise), i.e. median and percentiles (10-25-75-90), were obtained, see Figure 12. The median and percentiles (10-25-75-90) for the short target-to target movement, i.e. time(s), HPR, max velocity (m/s) and max acceleration (m/s^2), for the cylinder and pen grips are also

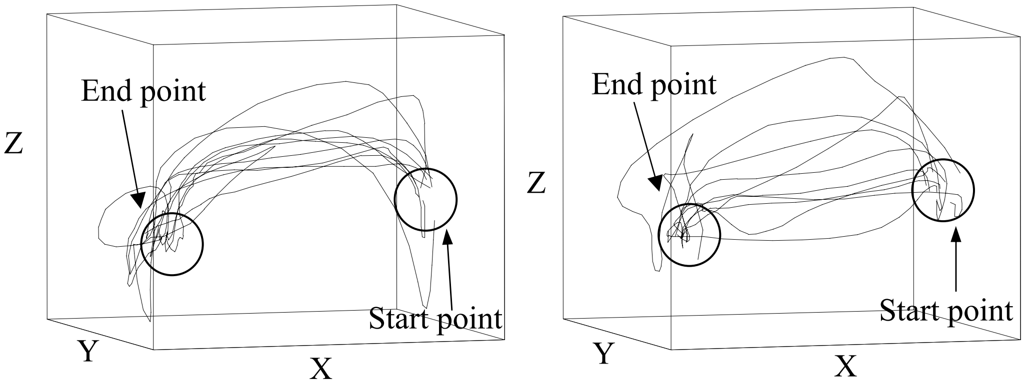


Figure 11. Detailed x-, y-, z-plots for the hand trajectories of ten subjects for one button to button movement. Left figure pen grip and right figure cylinder grip.

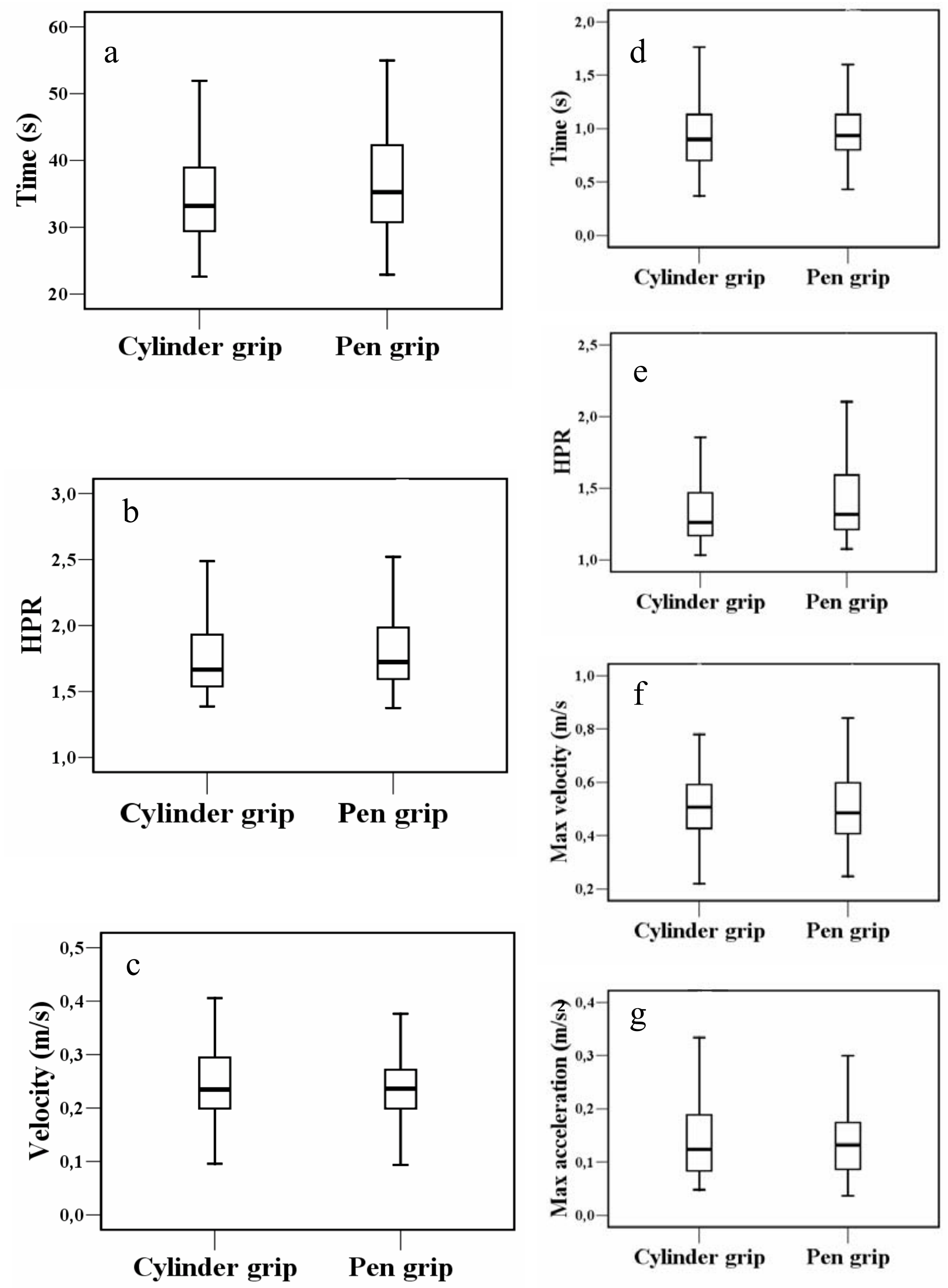


Figure 12. Kinematic data for the whole exercise (a) Time (s), (b) Hand Path Ratio and (c) velocity (m/s). Kinematic data for the short target-to-target movement (d) Time (s), (e) Hand Path Ratio, (f) Max velocity (m/s) (g) and Max Acceleration (m/s^2) shown as boxplots (10-25-75-90 percentiles) for the cylinder grip (n=58) and pen grip (n=58). The median value (thick black line) with 10th, 90th percentiles are shown at the end of the lines.

shown in figure 12. There were no differences between the cylinder grip and pen grip regarding time (s), distance (m), max velocity (m/s) and max acceleration (m/s^2).

Paper III: Virtual Rehabilitation in an activity centre for community dwelling persons with stroke; the possibilities of 3D computer games.

The aim of this study was twofold: to assess the application of the VR system in a non hospital environment to see whether it could be used there and to evaluate whether playing computer games resulted in improved motor function in persons with prior stroke.

Time (s) and HPR decreased noticeably ($p<0.05$), more than the controls, but no difference was found for velocity (m/s), see table 3. However, the time to complete the exercise was by far not close to the values of the reference group, whereas HPR and velocity (m/s) were closer to the reference group values. At the analysis of the short target-to-target movement the same tendency was observed as for the whole exercise: time (s) improved considerably ($p<0.05$) in the intervention group but not in the control group. Here as well the values were not close to the reference group. HPR improved in the intervention group, but there were no differences between pre and post intervention. No differences were found on between pre and post training for the intervention and control group with respect to max velocity (m/s) and max acceleration (m/s^2), see table 3. The visual inspection of the target-to-target movement for the four oldest subjects (i.e. the detailed *x-, y-, z- plot)* revealed a change in movement pattern in all four (Figure 13). Qualitatively the trajectories post training are more restrained, smoother and less cluttered at the end point.

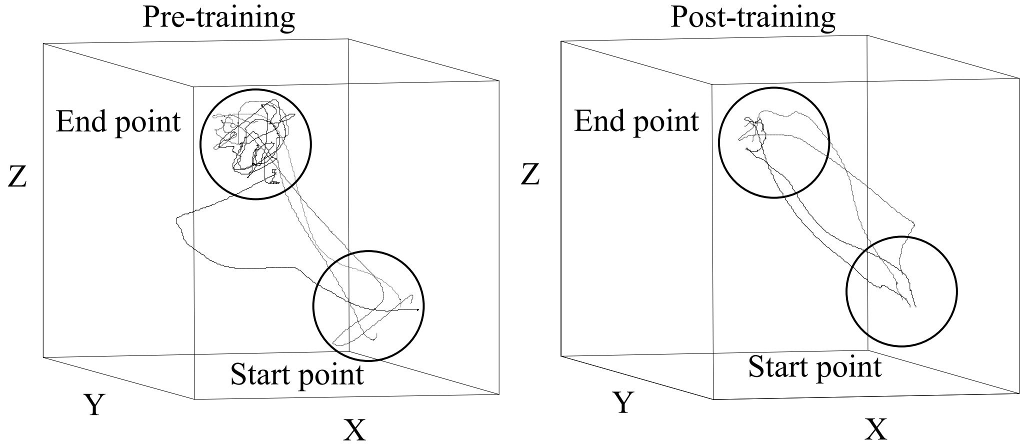


Figure 13. The raw data (x, y, and z coordinates) for the hand trajectories for one target-to-target movement for four subjects pre/post. The trajectory serves to illustrate the range of kinematic responses. The visual inspection reveals a variation in movement pattern pre and post training.

The 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 (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=0.16) and, at post testing, was -0.16 (SD=0.20).

A subjective interview was used to assess the control group's opinion of the computer training. All were novel computer game players. After the initial introduction, all quickly learned to use the VR system. All participants responded favorably to the use of the VR system. A change of attitude took place after the subjects were exposed to playing computer games. Initially, the subjects expressed some hesitancy about computer games; however, hands-on experience showed that more knowledge can stimulate interest and all subjects 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 program at the activity centre or in their home environment.

Table 3. Mean (SD) of the computer-based measurements in the intervention, control and reference groups.

	Intervention (n=11)		Control (n=11)		Reference (n=11)
	Pre test	Post test	Pre test	Post test	
Overall	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)
Time (s)	109.81 (77.32)	64.84 (34.06)*	82.90 (72.16)	73.02 (49.55)	38.3 (12.5)
HPR	2.80 (0.99)	2.27 (0.39)*	2.54 (0.71)	2.42 (0.52)	2.1 (0.3)
Velocity (m/s)	0.18 (0.96)	0.19 (0.83)	0.19 (0.07)	0.21 (0.07)	0.25 (0.1)
Target-to-target					
Time (s)	3.14 (2.81)	1.74 (1.02)*	1.77 (0.92)	1.49 (0.53)	1.13 (0.11)
HPR	2.81 (2.34)	1.87 (0.38)	2.02 (0.61)	1.83 (0.49)	1.80 (0.29)
Max velocity (m/s)	0.54 (0.17)	0.53 (0.18)	0.53 (0.18)	0.54 (0.19)	0.57 (0.14)
Max acceleration (m/s^2)	0.16 (0.02)	0.16 (0.02)	0.16 (0.05)	0.17 (0.04)	0.17 (0.03)

*p<0.05 (p-value associated with Wilcoxon Signed Ranks Test)

Paper IV: Neglect assessment as an application of virtual reality.

The aim of this study was threefold: to compare a cancellation task in a virtual environment with conventional tests of neglect, to describe the pattern of manual search performance and to obtain kinematic data on hand movement.

The presence or absence of neglect was identified for the same subjects by using the cancellation task either in the VR environment or by the conventional neglect tests. Six of eight subjects had more superfluous movements (HPR) of the hand during the visual search compared with the control group (Table 3). The velocity (m/s) and time (s) profile did not differ between clinically recovered subjects and controls. The subjects who had not recovered from neglect showed a lower median velocity (m/s). A relatively low correlation (i.e. Best r in table 3) was observed in four of the subjects (P1, P2, P5 and P6) and in one of the controls (C5).

Table 3. Kinematic data for the patient group and healthy subjects.

	Subjects	Best r	Hand Path Ratio	Time to complete the exercise (sec)	Median velocity (m/s)
Not Recovered	P1	-0.42	3.7	34	0.058
	P2	-0,58	7.5	59	0.045
	P3	-0,81	4.2	68	0.058
	P4	-0,76	2.6	37	0.044
Clinical Recovered	P5	0.40	6.6	156	0.062
	P6	-0.57	3.7	43	0.071
	P7	-0.91	4.4	46	0.103
	P8	-0.79	3.4	66	0.044
Healthy subjects	C1	-0.80	2.8	24	0.072
	C2	0.81	2.3	30	0.063
	C3	-0.96	2.1	33	0.056
	C4	-0.93	2.7	48	0.045
	C5	0.47	2.0	32	0.046
	C6	0.96	2.4	77	0.029
	C7	-0.86	3.2	30	0.086
	C8	0.87	1.7	18	0.096

Gray areas are subjects with values outside the 95% reference interval.

A further aim was to use the VR task in order to analyse the manual search performance in a virtual cancellation task. Subjects with neglect as well as subjects recovered from neglect showed aberrant search performance in the VR cancellation task, i.e. mixed search pattern (Figure 14), repeated target pressures, ipsilesional start of search and deviating hand movements. The data indicate that this VR task is more informative for deviating search performance compared to examination of search by more conventional paper and pencil tests.

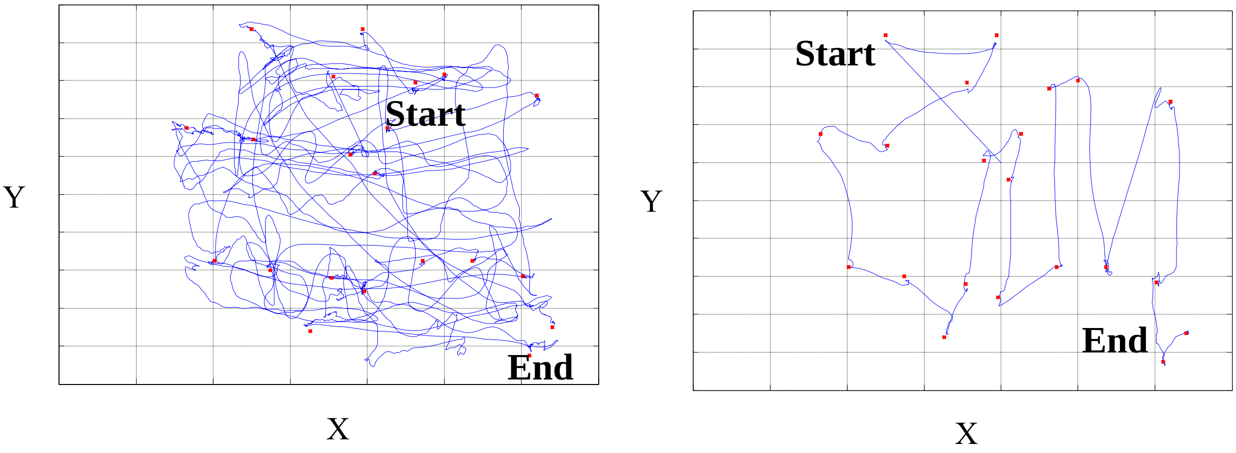


Figure 14. Data from two subjects are presented. The patient with clinical neglect (left) displays a search mixed pattern, while the control subject starts in the upper left part of the search area and has a column-by-column search strategy.

DISCUSSION

The overall aim of this thesis was to investigate whether Virtual Reality technology and haptics can be utilized as an assessment tool and training device for stroke rehabilitation. In the different studies included in this thesis, the results indicate that the VR and haptic equipment used can function as an assessment tool for motor impairment and for neglect. As for training the results are more ambiguous. Methodological limitations need to be considered to place the findings within the proper perspective. This thesis can be criticised for the small sample sizes. No information was collected on lesion size; this limits the ability to generalize to specific stroke populations and the possible impact of lesion size. No examination was made of the relation between neglect and motor performance concerning the upper extremities. No examination was made of the difference between UE deficits in subjects with left vs. right hemisphere damage and dominant vs. non dominant handedness. The study design of future studies would probably use longer training sessions to have any carry over effect into the real world and include a more homogenous group with respect to the onset of stroke and the severity of the upper extremity impairment.

Stroke is one of the most common disabling conditions and the need for effective therapies and innovative rehabilitation is clear. Most of the use of VR technologies in the motor rehabilitation field deals with stroke. In a recent systematic review of the effectiveness in terms of UE motor recovery within VR and stroke rehabilitation the authors concluded that the evidence is limited but sufficiently encouraging to justify additional trials (Henderson *et al.* 2007). The key factors identified among the studies were: (1) salient task practice; (2) high repetition intensity; (3) training in a novel environment offers high motivation to the subjects; and (4) enhanced feedback about the results of performance. Further, they considered that the level of immersion in the environment played an essential role in providing an optimal condition for task practice. The VR system used in this thesis is capable of designing such features. The intervention studies show that the subjects made improvements in the kinematic variables measured with the VR system (papers I and III). It is difficult to show that training a certain skill within a computer controlled environment transfers to real life or other simulated situations. Edmans and colleagues compared task performance in the real world and in a virtual environment (Edmans *et al.* 2006). They concluded that making a virtual hot drink was more difficult than making a hot drink in a rehabilitation kitchen and that virtual and real hot drink-making are qualitatively different tasks for stroke subjects. In paper I, real life changes were reflected in two of the subjects, such as in improvements in traditional outcome measures. The other subjects did not show any improvement in these measures (studies I and III). This may perhaps have been because they had already acquired the capacity to manage their everyday needs without using the affected UE.

Further, the VR system was placed outside the hospital to improve access to VR technology by a wider group of stroke subjects (study III). The VR system worked without problems and made it possible to expose persons 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 that would enhance their capacity for better UE function. The reason might be that the persons wanted to try the novel technique of VR with a hope for improving UE function (Barker *et al.* 2005). 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, the extent to which it meets user needs, and users' enjoyment. Irizarry and colleagues (Irizarry *et al.* 1997) showed that older people welcomed high tech products, including computer-controlled 'smart houses' of the future, but want clearer instructions about how to use them and controls that are easy to read and handle.

VR technology might be more effective if: (1) cognitive functions are involved in the tasks; (2) tasks are attractive and motivating; and (3) it is easy to understand. Haptic feedback encourages subjects to immerse themselves in the virtual environment (Sveistrup 2004). This allows the patient to interact and manipulate with virtual objects. Adding auditory feedback in addition to the visual and haptic feedback can reinforce the degree of immersion. The use of telemedicine based on Skype^{TM} with a camera was employed as an adjunct to communicate response to the intervention from the clinic to the activity centre. This increased the efficiency while maintaining a high quality of service to the personal and stroke subjects. When problem arose, i.e. the games would not start, the personal contacted the occupational therapist at the clinic and the problem was solved by remote instructions. Therapy-based rehabilitation is a promising approach in remote training (Legg *et al.* 2004; Winters *et al.* 2004).

Overall, the finding that both healthy subjects and individuals with motor deficits used similar movement strategies (figures 10, 11 and 13) in the virtual environment suggests that this standardized test is a helpful tool for studying and retraining reaching movements. Test-retest of the VR test, for two different handgrips between two test occasions, established a high reliability for the healthy subject for total time (s), HPR and average velocity (m/s) variables (study II). Two different grip types were used, i.e. the cylinder grip was chosen so that the required movement would replicate the natural world action of holding a handle. Secondly, many stroke victims' fine motor control with the hand and fingers is often impaired in the chronic stage of their disease (Hermsdorfer *et al.* 2003). The pen grip was chosen for the reason that it is a precision grip and enables the person to carry out a wide range of movements when using tools (Flanagan *et al.* 2002). The use of multiple trials was recommended by Mathiowetz *et al.* (1985) to improve test-retest reliability. The difference between sessions 1 and 3 does suggest a possible learning effect, which we consider to be advantageous. However, this effect is desirable when subjects are training, and this information thus identifies the importance of having normative data for comparison. On the basis of these analyses, the protocol demonstrates that this instrument seems to be sensitive to important change and probably suitable for demonstrating effects on UE motor performance following clinical intervention. Thus, changes in UE performance observed after intervention can likely be attributed to that intervention, and not to test-retest variability. The VR test thus seems to be a good instrument for evaluating intervention effects. Characterizing the features of reaching and quantifying specific variables allows therapists to treat specific deficits (Kamper *et al.* 2002). The ability to reach is essential for almost all activities of daily living, such as dressing, grooming and toileting (Trombly 1992). In over half of persons with stroke, the affected UE remains severely impaired despite intensive and prolonged rehabilitation (Nakayama *et al.* 1994). Similar results were found by Viau and colleagues (Viau *et al.* 2004), who compared movements made in a VE to movements made in a real environment. Their findings suggest that that both healthy subjects and individuals with motor deficits used similar movements and concluded that VR is similar enough to reality to provide an effective training environment for rehabilitation.

VR technology also appears to be beneficial for training the neglect syndrome. A few research groups have provided some evidence of the potential of virtual reality for the assessment, training and recovery of neglect. Katz *et al.* (Katz *et al.* 2005) developed a safety training VR environment in order to teach right hemisphere stroke subjects to cross streets in a safe manner. Multimodal feedback was provided to enhance careful behaviour in everyday-like situations. Subjects became progressively more able to manage complex activities not only in VR but also in a real street. Castiello and colleagues (Castiello *et al.* 2004) used a data glove device interfaced with a specially designed computer program that allowed neglect subjects to reach and grasp a real object while simultaneously observing the grasping of a virtual object located within a virtual environment by a virtual hand. After a period of training, neglect subjects coded the visual stimuli within the neglected space in an identical fashion as those presented within the preserved portions of space. It was concluded VR makes it possible to recreate links between the affected and the non affected space in neglect subjects.

The computerized neglect test provided a quantitative analysis of detecting small variations in manual search performance otherwise not detected in standard paper-and-pencil tests (study IV). It was found that the presence or absence of visual inattention was identified for the same subjects either by using VR or the conventional neglect tests. This is consistent with earlier studies where, in visual search tasks, subjects 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 (Behrmann *et al.* 2004; Parton *et al.* 2006). Further, both subjects with neglect and subjects who had recovered from neglect showed aberrant search performance in the VR task. The data indicate that this VR task is more informative for deviating search performance as compared with examination of search by more conventional paper-and-pencil tests. For example, in a search test administered in a study by Samuelsson (Samuelsson *et al.* 2002), the subjects had to search and report all numbers and letters that they could find on a test sheet. In this study, aberrant search performance was significantly associated with the presence of visuospatial neglect. Furthermore, recovery from the neglect symptoms at a six-month follow-up was followed by a return to normal search performance. However, in the present study, subjects who had recovered from neglect still exhibited persisting aberrant search. This finding is in accordance with a study by Pflugshaupt (Pflugshaupt *et al.* 2004) that showed that subjects who had recovered from neglect in conventional paper-and-pencil tests still exhibited oculomotor and exploratory deficits in novel or complex search tasks. Finally, the VR system can be used to design tasks that are otherwise impossible to construct (Baheux *et al.* 2005).

In addition to providing the opportunity for movement repetition, this VR system used in this thesis allows subjects to practice improving cognitive deficits in different virtual environments. Even though the cognitive aspects have not been addressed specifically in this thesis, computer games have the potential for therapeutic intervention of cognitive deficits. Many subjects with neglect have slack left-sided hemiplegia. UE activation is therefore unlikely to hold much rehabilitative value for this group (Cicerone *et al.* 2000). For other neglect subjects with mild to moderate pareses, encouraging the use of the left UE may give benefits for both cognitive and motor function. Nonetheless, there is some evidence to suggest that the approach may be particularly beneficial for subjects with neglect (van der Lee *et al.* 1999). According to Cicerone (Cicerone *et al.* 2000), computer-based interventions that include active therapist involvement subjects become more conscious of cognitive strengths and weaknesses. Cirstea (Cirstea *et al.* 2006) 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 (Cirstea *et al.* 2006). Westerberg (Westerberg *et al.* 2007) conducted a study of stroke subjects targeting working memory. One group played a computer game and the other did not. The intervention group improved significantly in several neuropsychological tasks, measuring such items as working memory and attentive ability. The subjects in the intervention group also reported significantly fewer symptoms of cognitive problems. VR technology can promote sustained attention, self-confidence and motivation of subjects during repetitive task training through multimodal immersive displays and interactive training programmes (Huang *et al.* 2006).

CLINICAL IMPLICATIONS AND FUTURE WORK

VR is considered an innovative technology with the potential of having a considerable impact on rehabilitation intervention over the next decade. The introduction of the VR as a medium for the assessment of stroke subjects requires careful consideration of a wide range of complex user issues. In particular, implementing this technology as part of the routine assessment procedure has implications for the health care professional. VR technology might cause a negative response from health care workers, who may feel threatened by any change in existing procedures, particularly if the current procedures are considered adequate for the task. Another important aspect is that computer technology is not an integral part of the training of health care professionals, and computer anxiety and alienation are real problems within the health care sector (Broeren 2005). The growing cost of providing health care services to an aging population and changing patterns of use of hospital resources are changing the focus of care from the hospital to the home (Broeren 2005). This leads to speculation about the importance of developing home-based therapy systems. VR training has the potential to affect a stroke subject's functional outcome by making available the ability to continue with additional therapy past the traditional period of hospitalization and rehabilitation. Stroke subjects may 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 put their improvements in impairments into functional activities of daily living.

Investigations are currently on the way to implement this research project in home-based rehabilitation. According to Fänge *et al.* (2007), a feasible approach is to set up a demonstration project. This approach gives the opportunity to try out methods and tools, aiming at signifying their effectiveness. Our vision is to have a fully deployed regional rehabilitation organisation (Figure 15) with clinical evaluation systems stationed at the rehabilitation central that has bidirectional contact with the home-based units, for collection of daily assessments, game allocation and tuning of difficulty, and audiovisual communication between therapists and subjects (Broeren *et al.* 2006; Goude *et al.* 2007; Vinnova 2007). The OT will be able to discuss those goals with the patient via a peer-to-peer audio conferencing feature. The interface will allow subjects 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 patient connected to the therapist and of encouraging subjects to set their own goals and take greater responsibility for their own recovery. Home rehabilitation allows for great flexibility so that subjects can tailor their program of rehabilitation and follow individual schedules (Rizzo *et al.* 2004).

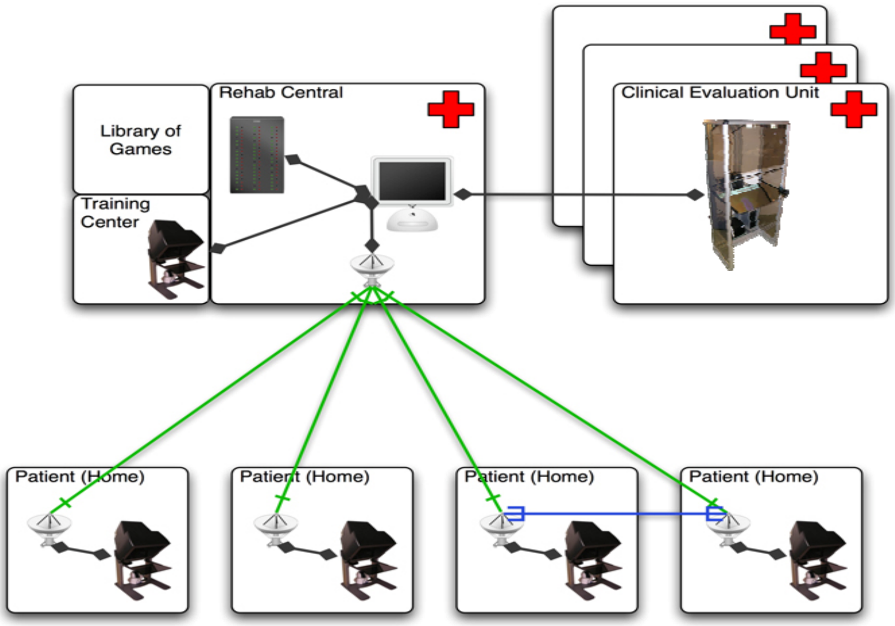


Figure 15. Regional rehabilitation organisation

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 thesis demonstrates that this technology can provide a real-time quantitative 3D task analysis and provides preliminary evidence that interactive computer use with the right training conditions may increase stroke subjects' 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. Currently, the field of virtual rehabilitation consists chiefly of proof-of-concept systems. It also lacks standardized methodologies and tools (Rizzo and Kim 2005).

POPULÄRVETENSKAPLIG SAMMANFATTNING

Slaganfall eller stroke är en av våra stora folksjukdomar och den främsta orsaken till bestående kroppsliga funktionsnedsättningar i vuxen ålder. I Sverige insjuknar cirka 25 000 – 30 000 personer i stroke varje år. Medelåldern vid insjuknandet är ca 75 år (män 73 år, kvinnor 77 år), men 20 % är yngre än 65 år. Stroke är en sammanfattande beteckning på sjukdomar till följd av blodpropp eller blödning i något av blodkärlen som försörjer delar av hjärnan. Personer med stroke kan, beroende av skadans lokalisering, bl.a. få problem med olika kroppsfunktioner. Följderna leder oftast till en skada inom ett begränsat område och ger därmed s.k. fokala symtom. Det innebär att funktionsnedsättningarna är avgränsade, och övriga förmågor verkar fungera som tidigare. Det är vanligt med förlamning och känselnedsättning i ena kroppshalvan men många får dock förändringar av flera funktioner. Vanligt är yrsel och balans-, språk-, minnes- och koncentrationssvårigheter. Strokepatienter överanvänder ofta den friska sidan för att kompensera förlusten av funktion på den drabbade sidan. Detta kan leda till problem i kroppshållning, balans, styrka och koordination, vilket kan resultera i ett avvikande rörelsemönster. Risk finns för att ett inlärt beteende kvarstår om individen endast till liten del använder den sämre sidan. En ny behandlingsmetod inom rehabilitering är VIRTUELL VERKLIGHET (Virtual Reality). I dessa studier kombinerar vi, i en datormiljö (Figur 16, VR-station), en tredimensionell virtuell värld, med känselintryck, s.k. haptik. Haptik innebär att man fysiskt kan känna på och interagera med objekten i den virtuella världen, skapad i datorn. Personen sitter framför dator och håller i en ”styrpinne” (jämför datormus) som är rörlig i det tredimensionella rummet så att den även kan flyttas på djupet. Samtidigt gör den haptiska tekniken det möjligt att röra vid virtuella objekt och man upplever känslan av kontakt med föremålet.

Figur 16. VR-stationen

Syftet med denna avhandling var att undersöka effekterna av motorisk träning av den förlamade sidan hos strokedrabbade genom att spela dataspel, att mäta handens förflyttning i den tredimensionella virtuella världen hos personer med stroke och friska personer, samt att jämföra ett datoriserat neglekttest med två befintliga tester. Personer med neglekt har svårt att uppfatta, eller ignorerar helt, saker som befinner sig till vänster om sig. Neglekt kan till exempel göra att man bara äter maten på högra sidan av tallriken eller bara rakar halva ansiktet.

I studierna deltog totalt 106 personer, varav 29 med en strokediagnos och 77 friska försökspersoner. Två datoriserade tester utvecklades, ett för att undersöka handens förflyttning i datorns tredimensionella rum (delarbete I, II och III) samt ett simulerat ”penna och papper”-test för testning av visuellt/manuellt avsökningsmönster (delarbete IV). I samtliga delarbeten undersöktes handens förflyttning i den tredimensionella virtuella världen. Följande rörelsevariabler analyserades; tid (s), hastighet (m/s) och rörelsekvalitet (ung. ett mått på överflödig rörelse).

I *delarbete I*, deltog fem personer. Interventionen bestod av att under 5 veckor, tre gånger i veckan spela ett dataspel med den förlamade handen/armen, deltagarna utgjorde sina egna kontroller. Alla deltagare förbättrades med avseende på rörelsevariablerna efter interventionen. En deltagare förbättrades med avseende på det dagliga livets aktiviteter. I *delarbete II*, deltog 58 friska personer. Syftet var att undersöka test-retest reliabiliteten av det datoriserade testet. Test-retest metoden uppskattar graden av hur testresultaten överensstämmer från ett test till nästa. Två olika handgrepp som används i dagliga livet undersöktes; helhandsgrepp och penngrepp. Det datoriserade testet visade på en hög test-retest reliabilitet. I *delarbete III* var syftet att placera VR-stationen utanför sjukhusmiljön. Sexton personer med stroke och elva friska personer deltog. Strokegruppen delades upp i två grupper varav en grupp fick extra träning (tre gånger i veckan under 4 veckor) genom att spela dataspel. Den andra gruppen fick ingen extra träning. Strokepatienter som tränade med VR-stationen förbättrades med avseende på rörelsevariablerna, i vissa fall till i närheten av normala referensvärden. I *delarbete IV* undersökte vi avsökningsstrategi hos personer med neglekt. Det datoriserade testet antydde hög sensitivitet och specificitet samt att sökstrategidefekter kunde detekteras hos personer med neglekt.

Slutsats: Bedömningsinstrumenten är kinematiska, kvantitativa och visuella, samt bedömaroberoende. Samtliga försökspersoner uppskattade att arbeta med VR-stationen. De generella erfarenheterna tyder på att VIRTUELL VERKLIGHET tycks vara ett användbart tillskott inom strokerehabilitering.

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REFERENCES

American Occupational Therapy Association (1994). "Uniform terminology for occupational therapy--third edition. ." Am J Occup Ther **48**(11): 1047-54.

Baheux, K., M. Yoshizawa, K. Seki and Y. Handa (2006). "Virtual reality pencil and paper tests for neglect: a protocol." Cyberpsychol Behav **9**(2): 192-5.

Baheux, K., M. Yoshizawa, A. Tanaka, K. Seki and Y. Handa (2005). "Diagnosis and rehabilitation of hemispatial neglect patients with virtual reality technology." Technol Health Care **13**(4): 245-60.

Bardorfer, A., M. Munih, A. Zupan and A. Primozic (2001). "Upper Limb Motion Analysis Using Haptic Interface." IEE Transactions on Mechatronics **6**(3): 253-60.

Barker, R. N. and S. G. Brauer (2005). "Upper limb recovery after stroke: the stroke survivors' perspective." Disabil Rehabil **27**(20): 1213-23.

Barnes, M. P. (2003). "Principles of neurological rehabilitation." J Neurol Neurosurg Psychiatry **74 Suppl 4**: iv3-iv7.

Behrmann, M., P. Ebert and S. E. Black (2004). "Hemispatial neglect and visual search: a large scale analysis." Cortex **40**(2): 247-63.

Bernspang, B. and A. Fisher (1995). "Validation of the Assessment of Motor and Process Skills for use in Sweden." Scand J Occup Ther **1**: 3-9.

Bland, J. M. and D. G. Altman (1986). "Statistical methods for assessing agreement between two methods of clinical measurement." Lancet **1**(8476): 307-10.

Boian, R., A. Sharma, C. Han, A. Merians, G. Burdea, S. Adamovich, M. Recce, M. Tremaine and H. Poizner (2002). "Virtual reality-based post-stroke hand rehabilitation." Stud Health Technol Inform **85**: 64-70.

Bowman, D. A., E. Kruijff, J. J. LaViola and I. Poupyrev (2001). "An Introduction to 3-D User Interface Design." Presence **10**(1): 96 -108.

Broeks, J. G., G. J. Lankhorst, K. Rumping and A. J. Prevo (1999). "The long-term outcome of arm function after stroke: results of a follow-up study." Disabil Rehabil **21**(8): 357-64.

Broeren, J. (2005). "Commentary on Holden, M.K., Virtual Environments for Motor Rehabilitation: Review." CyberPsychology & Behavior **8**(3): 212-219.

Broeren, J., A. Bjorkdahl, R. Pascher and M. Rydmark (2002). "Virtual reality and haptics as an assessment device in the postacute phase after stroke." Cyberpsychol Behav **5**(3): 207-11.

Broeren, J., M. Dixon, K. Stibrant Sunnerhagen and M. Rydmark (2006). "Rehabilitation after stroke using virtual reality, haptics (force feedback) and telemedicine." Stud Health Technol Inform **124**: 51-6.

Broeren, J., M. Rydmark and K. S. Sunnerhagen (2004). "Virtual reality and haptics as a training device for movement rehabilitation after stroke: a single-case study." Arch Phys Med Rehabil **85**(8): 1247-50.

Carr, J. and R. Shepherd (1996). A motor relearning programme for stroke. Oxford, Butterworth - Heineman.

Castiello, U., D. Lusher, C. Burton, S. Glover and P. Disler (2004). "Improving left hemispatial neglect using virtual reality." Neurology **62**(11): 1958-62.

Chern, J. S., G. Kielhofner, C. G. de las Heras and L. C. Magalhaes (1996). "The Volitional Questionnaire: psychometric development and practical use." Am J Occup Ther **50**(7): 516-25.

Cherney, L. R., A. S. Halper, C. M. Kwasnica, R. L. Harvey and M. Zhang (2001). "Recovery of functional status after right hemisphere stroke: relationship with unilateral neglect." Arch Phys Med Rehabil **82**(3): 322-8.

Cicerone, K. D., C. Dahlberg, K. Kalmar, D. M. Langenbahn, J. F. Malec, T. F. Bergquist, T. Felicetti, J. T. Giacino, J. P. Harley, D. E. Harrington, J. Herzog, S. Kneipp, L. Laatsch and P. A. Morse (2000). "Evidence-based cognitive rehabilitation: recommendations for clinical practice." Arch Phys Med Rehabil **81**(12): 1596-615.

Cirstea, C. M., A. Ptito and M. F. Levin (2006). "Feedback and cognition in arm motor skill reacquisition after stroke." Stroke **37**(5): 1237-42.

Conner, B. B., A. M. Wing, G. Humphreys, R. M. Bracewell and D. A. Harvey (2002). Errorless learning using haptic guidance: research in cognitive rehabilitation following stroke. Proc. 4th Intl Conf. Disability, Virtual Reality & Assoc. Tech., Veszprém, Hungary, University of Reading, UK.

Denvall, V., S. Elmstahl and G. P. Prigatano (2002). "Replication and construct validation of the Barrow Neurological Institute Screen for Higher Cerebral Function with a Swedish population." J Rehabil Med **34**(4): 153-7.

Desrosiers, J., D. Bourbonnais, H. Corriveau, S. Gosselin and G. Bravo (2005). "Effectiveness of unilateral and symmetrical bilateral task training for arm during the subacute phase after stroke: a randomized controlled trial." Clin Rehabil **19**(6): 581-93.

Desrosiers, J., G. Bravo, R. Hebert, E. Dutil and L. Mercier (1994). "Validation of the Box and Block Test as a measure of dexterity of elderly people: reliability, validity, and norms studies." Arch Phys Med Rehabil **75**(7): 751-5.

Desrosiers, J., L. Noreau, A. Rochette, D. Bourbonnais, G. Bravo and A. Bourget (2006). "Predictors of long-term participation after stroke." Disability & Rehabilitation **28**(4): 221 - 230.

Dickerson, A. E. and A. G. Fisher (1993). "Age differences in functional performance." Am J Occup Ther **47**(8): 686-92.

Doble, S. E., J. D. Fisk, A. G. Fisher, P. G. Ritvo and T. J. Murray (1994). "Functional competence of community-dwelling persons with multiple sclerosis using the assessment of motor and process skills." Arch Phys Med Rehabil **75**(8): 843-51.

Drummond, A. (1990). "Leisure activity after stroke." Int Disabil Stud **12**(4): 157-60.

Edmans, J. A., J. R. Gladman, S. Cobb, A. Sunderland, T. Pridmore, D. Hilton and M. F. Walker (2006). "Validity of a virtual environment for stroke rehabilitation." Stroke **37**(11): 2770-5.

Fange, A., R. Risser and S. Iwarsson (2007). "Challenges in implementation of research methodology in community-based occupational therapy: the Housing Enabler example." Scand J Occup Ther **14**(1): 54-62.

Farne, A., L. J. Buxbaum, M. Ferraro, F. Frassinetti, J. Whyte, T. Veramonti, V. Angeli, H. B. Coslett and E. Ladavas (2004). "Patterns of spontaneous recovery of neglect and associated disorders in acute right brain-damaged patients." J Neurol Neurosurg Psychiatry **75**(10): 1401-10.

Feys, H. M., W. J. De Weerdt, B. E. Selz, G. A. Cox Steck, R. Spichiger, L. E. Vereeck, K. D. Putman and G. A. Van Hoydonck (1998). "Effect of a therapeutic intervention for the hemiplegic upper limb in the acute phase after stroke: a single-blind, randomized, controlled multicenter trial." Stroke **29**(4): 785-92.

Fisher, A. G. (2003). AMPS, Assessment of Motor and Process Skills: Development, standarization, and administration manual. Fort Collins, Three Star Press.

Fisher, A. G. (1993). "The assessment of IADL motor skills: an application of many-faceted Rasch analysis." Am J Occup Ther **47**(4): 319-29.

Fisher, A. G., Y. Liu, C. A. Velozo and A. W. Pan (1992). "Cross-cultural assessment of process skills." Am J Occup Ther **46**(10): 876-85.

Flanagan, J. and R. Johansson, Eds. (2002). Hand movements Ecyclopedia of human brain. San Diego, CA, Academic Press.

Frassinetti, F., V. Angeli, F. Meneghello, S. Avanzi and E. Ladavas (2002). "Long-lasting amelioration of visuospatial neglect by prism adaptation." Brain **125**(Pt 3): 608-23.

Glader, E. L., B. Stegmayr, L. Johansson, K. Hulter-Asberg and P. O. Wester (2001). "Differences in long-term outcome between patients treated in stroke units and in general wards: a 2-year follow-up of stroke patients in sweden." Stroke **32**(9): 2124-30.

Goude, D., S. Bjork and M. Rydmark (2007). "Game design in virtual reality systems for stroke rehabilitation." Stud Health Technol Inform **125**: 146-8.

Greveson, G. and O. James (1991). "Improving long-term outcome after stroke--the views of patients and carers." Health Trends **23**(4): 161-2.

Gustafsson, S., K. S. Sunnerhagen and S. Dahlin-Ivanoff (2004). "Occupational therapists' and patients' perceptions of ABILHAND, a new assessment tool for measuring manual ability." Scandinavian Journal of Occupational Therapy **11**(3): 107 - 117.

Halligan, P. W., J. Cockburn and B. A. Wilson (1991). "The behavioural assessment of unilateral visual neglect." Neuropsychological Rehabilitation **1**(1): 5-32.

Halligan, P. W., J. C. Marshall and D. T. Wade (1989). "Visuospatial neglect: underlying factors and test sensitivity." Lancet **2**(8668): 908-11.

Henderson, A., N. Korner-Bitensky and M. Levin (2007). "Virtual reality in stroke rehabilitation: a systematic review of its effectiveness for upper limb motor recovery." Top Stroke Rehabil **14**(2): 52-61.

Hermsdorfer, J., E. Hagl, D. A. Nowak and C. Marquardt (2003). "Grip force control during object manipulation in cerebral stroke." Clin Neurophysiol **114**(5): 915-29.

Holden, M. K. (2005). "Virtual environments for motor rehabilitation: review." Cyberpsychol Behav **8**(3): 187-211.

Huang, H., S. L. Wolf and J. He (2006). "Recent developments in biofeedback for neuromotor rehabilitation." J Neuroengineering Rehabil **3**: 11.

Hulter-Asberg, K., K. Johansson, A. Staaf and B. Stegmayr (2005). "Livet efter stroke - ny nationell studie. Förnyad uppföljning av strokedrabbade visar ökande beroende av anhöriga. ." Läkartidningen **102**: 2938-41.

Höök, O. (2001). Medicinsk rehabilitering, Liber AB.

Irizarry, C., A. Downing and C. Elford (1997). "Seniors-on-line: introducing older people to technology." Australas Phys Eng Sci Med **20**(1): 39-43.

Jack, D., R. Boian, A. S. Merians, M. Tremaine, G. C. Burdea, S. V. Adamovich, M. Recce and H. Poizner (2001). "Virtual reality-enhanced stroke rehabilitation." IEEE Trans Neural Syst Rehabil Eng **9**(3): 308-18.

Jehkonen, M., J. P. Ahonen, P. Dastidar, A. M. Koivisto, P. Laippala, J. Vilkki and G. Molnar (2001). "Predictors of discharge to home during the first year after right hemisphere stroke." Acta Neurol Scand **104**(3): 136-41.

Johansson, B., B. Norrving and A. Lindgren (2000). "Increased stroke incidence in Lund-Orup, Sweden, between 1983 to 1985 and 1993 to 1995." Stroke **31**(2): 481-6.

Kamper, D. G., A. N. McKenna-Cole, L. E. Kahn and D. J. Reinkensmeyer (2002). "Alterations in reaching after stroke and their relation to movement direction and impairment severity." Arch Phys Med Rehabil **83**(5): 702-7.

Katz, N., A. Hartman-Maeir, H. Ring and N. Soroker (1999). "Functional disability and rehabilitation outcome in right hemisphere damaged patients with and without unilateral spatial neglect." Arch Phys Med Rehabil **80**(4): 379-84.

Katz, N., H. Ring, Y. Naveh, R. Kizony, U. Feintuch and P. L. Weiss (2005). "Interactive virtual environment training for safe street crossing of right hemisphere stroke patients with unilateral spatial neglect." Disabil Rehabil **27**(20): 1235-43.

Kielhofner, G., L. Borell, J. Burke, C. Helfrich and L. Nygaardt (1995). A model of human occupation: Theory and application. Baltimore, Williams & Wilkins.

Kielhofner, G. and K. Forsyth (1997). "The model of human occupation: An overview of current concepts. ." British Journal of Occupational Therapy **60**(3): 103-110.

Kim, J., K. Kim, D. Y. Kim, W. H. Chang, C. I. Park, S. H. Ohn, K. Han, J. Ku, S. W. Nam, I. Y. Kim and S. I. Kim (2007). "Virtual environment training system for rehabilitation of stroke patients with unilateral neglect: crossing the virtual street." Cyberpsychol Behav **10**(1): 7-15.

Kizony, R., L. Raz, N. Katz, H. Weingarden and P. L. Weiss (2005). "Video-capture virtual reality system for patients with paraplegic spinal cord injury." J Rehabil Res Dev **42**(5): 595-608.

Kollen, B. (2006). Recovery of gait after stroke. Rehabilitation Centre "De Hoogstraat", Rudolf Magnus Institute of Neuroscience. Utrecht, UMC Utrecht **Doctoral Dissertation:** 216.

Kwakkel, G., B. J. Kollen, J. van der Grond and A. J. Prevo (2003). "Probability of regaining dexterity in the flaccid upper limb: impact of severity of paresis and time since onset in acute stroke." Stroke **34**(9): 2181-6.

Legg, L. and P. Langhorne (2004). "Rehabilitation therapy services for stroke patients living at home: systematic review of randomised trials." Lancet **363**(9406): 352-6.

Liepert, J., W. H. Miltner, H. Bauder, M. Sommer, C. Dettmers, E. Taub and C. Weiller (1998). "Motor cortex plasticity during constraint-induced movement therapy in stroke patients." Neurosci Lett **250**(1): 5-8.

Linacre, J. (1993). Many-facted Rash measurments. Chicago, MESA Press.

Mark, V. W., A. J. Woods, K. K. Ball, D. L. Roth and M. Mennemeier (2004). "Disorganized search on cancellation is not a consequence of neglect." Neurology **63**(1): 78-84.

Mathiowetz, V., G. Volland, N. Kashman and K. Weber (1985). "Adult norms for the Box and Block Test of manual dexterity." Am J Occup Ther **39**(6): 386-91.

Mayo, N. E., S. Wood-Dauphinee, R. Cote, L. Durcan and J. Carlton (2002). "Activity, participation, and quality of life 6 months poststroke." Arch Phys Med Rehabil **83**(8): 1035-42.

Medin, J., A. Nordlund and K. Ekberg (2004). "Increasing stroke incidence in Sweden between 1989 and 2000 among persons aged 30 to 65 years: evidence from the Swedish Hospital Discharge Register." Stroke **35**(5): 1047-51.

Nakayama, H., H. S. Jorgensen, H. O. Raaschou and T. S. Olsen (1994). "Recovery of upper extremity function in stroke patients: the Copenhagen Stroke Study." Arch Phys Med Rehabil **75**(4): 394-8.

National Board of Health and Welfare. (2005). "National guidelines for Stroke 2005." Retrieved 2006-02-22, from www.socialstyrelsen.se.

National Health Care Quality Register in Sweden. (2004, 2006-02-22). "Analyserande Rapport Riks - Stroke 2004." from http://www.riks-stroke.org.

Nudo, R. J., E. J. Plautz and S. B. Frost (2001). "Role of adaptive plasticity in recovery of function after damage to motor cortex." Muscle Nerve **24**(8): 1000-19.

Page, S. J., S. Sisto, P. Levine and R. E. McGrath (2004). "Efficacy of modified constraint-induced movement therapy in chronic stroke: a single-blinded randomized controlled trial." Arch Phys Med Rehabil **85**(1): 14-8.

Park, S., A. G. Fisher and C. A. Velozo (1994). "Using the assessment of motor and process skills to compare occupational performance between clinic and home settings." Am J Occup Ther **48**(8): 697-709.

Parton, A., P. Malhotra and M. Husain (2004). "Hemispatial neglect." J Neurol Neurosurg Psychiatry **75**(1): 13-21.

Parton, A., P. Malhotra, P. Nachev, D. Ames, J. Ball, J. Chataway and M. Husain (2006). "Space re-exploration in hemispatial neglect." Neuroreport **17**(8): 833-6.

Pedersen, P. M., H. S. Jorgensen, H. Nakayama, H. O. Raaschou and T. S. Olsen (1997). "Hemineglect in acute stroke--incidence and prognostic implications. The Copenhagen Stroke Study." Am J Phys Med Rehabil **76**(2): 122-7.

Penta, M., L. Tesio, C. Arnould, A. Zancan and J. L. Thonnard (2001). "The ABILHAND questionnaire as a measure of manual ability in chronic stroke patients: Rasch-based validation and relationship to upper limb impairment." Stroke **32**(7): 1627-34.

Penta, M., J. L. Thonnard and L. Tesio (1998). "ABILHAND: a Rasch-built measure of manual ability." Arch Phys Med Rehabil **79**(9): 1038-42.

Pflugshaupt, T., S. A. Bopp, D. Heinemann, U. P. Mosimann, R. von Wartburg, T. Nyffeler, C. W. Hess and R. M. Muri (2004). "Residual oculomotor and exploratory deficits in patients with recovered hemineglect." Neuropsychologia **42**(9): 1203-11.

Pierce, D. (2001). "Occupation by design: dimensions, therapeutic power, and creative process." Am J Occup Ther **55**(3): 249-59.

Pierce, S. R., K. G. Gallagher, S. W. Schaumburg, A. M. Gershkoff, J. P. Gaughan and L. Shutter (2003). "Home forced use in an outpatient rehabilitation program for adults with hemiplegia: a pilot study." Neurorehabil Neural Repair **17**(4): 214-9.

Pisella, L., G. Rode, A. Farne, C. Tilikete and Y. Rossetti (2006). "Prism adaptation in the rehabilitation of patients with visuo-spatial cognitive disorders." Curr Opin Neurol **19**(6): 534-42.

Prigatano, G., K. Amin and L. Rosenstein (1992). "Validity studies on the BNI Screen for Higher Cerebral Functions." BNI Quarterly **9**(1): 2-9.

Prigatano, G., K. Amin and L. Rosenstein (1995). Manual for the BNI Screen for Higher Cerebral Functions. Phoenix, Arizona, Barrow Neurological Institute.

Riks-Stroke. (2006). "National Health Care Quality Registers in Sweden. Analyzed report from the National Stroke Register for the year 2005." from www.riks.stroke.org.

Ring, H. (1998). "Is neurological rehabilitation ready for 'immersion' in the world of virtual reality?" Disabil Rehabil **20**(3): 98-101.

Riva, G. (1998). "Virtual environments in neuroscience." IEEE Trans Inf Technol Biomed **2**(4): 275-81.

Riva, G. (2002). "Virtual reality for health care: the status of research." Cyberpsychol Behav **5**(3): 219-25.

Riva, G. (2005). "Virtual reality in psychotherapy: review." Cyberpsychol Behav **8**(3): 220-30; discussion 231-40.

Rizzo, A. A. and G. J. Kim (2005). "A SWOT Analysis of the Field of Virtual Rehabilitation and Therapy." In Presence: Teleoperators and Virtual Environments **Volume 14**(2): 119-146.

Rizzo, A. A., D. Strickland and S. Bouchard (2004). "The challenge of using virtual reality in telerehabilitation." Telemed J E Health **10**(2): 184-95.

Robertson IH and Marshall JC (1993). Unilateral Neglect: Clinical and Experimental Studies. Hove, Psychology Press.

Rode, G., T. Klos, S. Courtois-Jacquin, Y. Rossetti and L. Pisella (2006). "Neglect and prism adaptation: a new therapeutic tool for spatial cognition disorders." Restor Neurol Neurosci **24**(4-6): 347-56.

Rose, F. D., E. A. Attree and D. A. Johnson (1996). "Virtual reality: an assistive technology in neurological rehabilitation." Curr Opin Neurol **9**(6): 461-7.

Rose, F. D., B. M. Brooks and A. A. Rizzo (2005). "Virtual reality in brain damage rehabilitation: review." Cyberpsychol Behav **8**(3): 241-62.

Salter, K., J. W. Jutai, R. Teasell, N. C. Foley, J. Bitensky and M. Bayley (2005). "Issues for selection of outcome measures in stroke rehabilitation: ICF activity." Disabil Rehabil **27**(6): 315-40.

Samuelsson, H., E. K. Hjelmquist, C. Jensen and C. Blomstrand (2002). "Search pattern in a verbally reported visual scanning test in patients showing spatial neglect." J Int Neuropsychol Soc **8**(3): 382-94.

Sanchez-Vives, M. V. and M. Slater (2005). "From presence to consciousness through virtual reality." Nat Rev Neurosci **6**(4): 332-9.

Schaaf, R. C. (1990). "Play behavior and occupational therapy." Am J Occup Ther **44**(1): 68-75.

Suhr, J. A. and J. Grace (1999). "Brief cognitive screening of right hemisphere stroke: relation to functional outcome." Arch Phys Med Rehabil **80**(7): 773-6.

Sveen, U., E. Bautz-Holter, K. M. Sodring, T. B. Wyller and K. Laake (1999). "Association between impairments, self-care ability and social activities 1 year after stroke." Disabil Rehabil **21**(8): 372-7.

Sveistrup, H. (2004). "Motor rehabilitation using virtual reality." J Neuroengineering Rehabil **1**(1): 10.

Szekely, G. and R. M. Satava (1999). "Virtual reality in medicine. Interview by Judy Jones." Bmj **319**(7220): 1305.

Tarr, M. J. and W. H. Warren (2002). "Virtual reality in behavioral neuroscience and beyond." Nat Neurosci **5 Suppl 1**: 1089-92.

Taub, E., R. C. Bacon and A. J. Berman (1965). "Acquistion of a Trace-Conditioned Avoidance Response after Deafferentation of the Responding Limb." J Comp Physiol Psychol **59**: 275-9.

Taub, E., N. E. Miller, T. A. Novack, E. W. Cook, 3rd, W. C. Fleming, C. S. Nepomuceno, J. S. Connell and J. E. Crago (1993). "Technique to improve chronic motor deficit after stroke." Arch Phys Med Rehabil **74**(4): 347-54.

Taub, E., G. Uswatte and T. Elbert (2002). "New treatments in neurorehabilitation founded on basic research." Nat Rev Neurosci **3**(3): 228-36.

Taub, N. A., C. D. Wolfe, E. Richardson and P. G. Burney (1994). "Predicting the disability of first-time stroke sufferers at 1 year. 12-month follow-up of a population-based cohort in southeast England." Stroke **25**(2): 352-7.

Tennant, A., J. M. Geddes, J. Fear, M. Hillman and M. A. Chamberlain (1997). "Outcome following stroke." Disabil Rehabil **19**(7): 278-84.

Tham, K. and R. Tegner (1996). "The Baking Tray Task: A test of spatial neglect." Neuropsychological Rehabilitation **6**(1): 19-25.

Thorngren, M., B. Westling and B. Norrving (1990). "Outcome after stroke in patients discharged to independent living." Stroke **21**(2): 236-40.

Trombly, C. A. (1992). "Deficits of reaching in subjects with left hemiparesis: a pilot study." Am J Occup Ther **46**(10): 887-97.

Trombly, C. A. and M. Radomski (2002). Occupational therapy for physical dysfunction Philadelphia Lippincott Williams & Wilkins.

Turner, A., M. Foster and S. Jonson (2002). Occupational Therapy and Physical dysfunction: principles, skills, and practice. Edinburgh; New York, Churchill Livingstone.

van der Lee, J. H., R. C. Wagenaar, G. J. Lankhorst, T. W. Vogelaar, W. L. Deville and L. M. Bouter (1999). "Forced use of the upper extremity in chronic stroke patients: results from a single-blind randomized clinical trial." Stroke **30**(11): 2369-75.

Weiss, P., D. Rand, N. Katz and R. Kizony (2004). "Video capture virtual reality as a flexible and effective rehabilitation tool." J NeuroEngineering and Rehabil **1**(1): 12.

Westerberg, H., H. Jacobaeus, T. Hirvikoski, P. Clevberger, M. L. Ostensson, A. Bartfai and T. Klingberg (2007). "Computerized working memory training after stroke--a pilot study." Brain Inj **21**(1): 21-9.

WHO (2001). International Classification of Functioning, Disability and Health: ICF. Geneva, World Health Organization.

Viau, A., A. G. Feldman, B. J. McFadyen and M. F. Levin (2004). "Reaching in reality and virtual reality: a comparison of movement kinematics in healthy subjects and in adults with hemiparesis." J Neuroengineering Rehabil **1**(1): 11.

Vinnova. (2007). "StrokeIT - organisation av rehabilitering efter stroke, med IT-stöd." IT för sjukvård i hemmet – Projektkatalog.

Winters, J. M. and J. M. Winters (2004). "A telehomecare model for optimizing rehabilitation outcomes." Telemed J E Health **10**(2): 200-12.

Witmer, B. G. and M. J. Singer (1998). "Measuring presence in virtual environments: A Presence Questionnaire." Presence: Teleoperators and Virtual Environments **7**(3): 225-240.

Wolf, S. L., C. J. Winstein, J. P. Miller, E. Taub, G. Uswatte, D. Morris, C. Giuliani, K. E. Light and D. Nichols-Larsen (2006). "Effect of constraint-induced movement therapy on upper extremity function 3 to 9 months after stroke: the EXCITE randomized clinical trial." Jama **296**(17): 2095-104.

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