Technology-supported training of arm-hand skills in stroke

Timmermans, A.A.A.

DOI:
10.6100/IR684872

Published: 01/01/2010

Technology-Supported Training of Arm-Hand Skills in Stroke

The research described in this thesis has been funded by Philips Research Europe, Eindhoven, The Netherlands.
The research has been carried out at Adelante Rehabilitation Centre, Hoensbroek, The Netherlands.

Cover Design: Paul Verspaget

A catalogue record is available from the Eindhoven University of Technology Library.

ISBN: 978-90-386-2306-1

Technology-Supported Training of Arm-Hand Skills in Stroke

PROEFSCHRIFT

ter verkrijging van de graad van doctor aan de
Technische Universiteit Eindhoven, op gezag van de
rector magnificus, prof.dr.ir. C.J. van Duijn, voor een
commissie aangewezen door het College voor
Promoties in het openbaar te verdedigen
op donderdag 2 september 2010 om 16.00 uur

door

Annick Antoinette Alfonsine Timmermans

geboren te Hasselt, België

Dit proefschrift is goedgekeurd door de promotor:

prof.dr. H. Kingma

Copromotor:
dr. H.A.M. Seelen

To my parents,
whose love and support continue to give me strength and freedom

to Josephine and Emiel
who give and teach me more than any PhD could do

and to you Panos, most of all
because you are my soul mate,
and so much more

Contents

Chapter 1

General Introduction

Stroke pathology and epidemiology

Pathology

A stroke, or cerebrovascular accident, is a sudden problem of the blood supply to brain tissue, leading to a rapidly developing focal neurological disturbance of brain function. The vascular aetiology can be ischemic (e.g. blood vessel obstruction by thrombosis, embolism, atherosclerosis) (87%) or hemorrhagic (e.g. ruptured blood vessel) (13%). The symptoms of stroke last more than 24 hours and depend on the area of the brain that has been affected. Symptoms may include: hemiplegia, altered sensation, altered vision, decreased reflexes, balance problems, aphasia, apraxia, cognitive problems, depression, behavioural problems, spasticity and movement coordination problems. [1-3]

There are several ways to classify the lesion location. Bamford et al [4] describe a classification of 4 clinically identifiable subtypes of cerebral infarction based on the location in the brain that is affected: total anterior circulation infarcts (TACI, 17%, cortical and subcortical), partial anterior circulation infarcts (PACI, 34%, mostly cortical), posterior circulation infarcts (POCI, 24%, vertebrobasilar artery territory) and lacunar infarcts (LACI, 25%, deep perforating arteries). Prognosis for survival and functional recovery, as well as symptoms differ markedly in these groups. Patients in the TACI group present with a combination of higher cerebral dysfunction (e.g. dysphagia, dyscalculia), visual field defect, and ipsilateral motor and/or sensory deficit of at least two areas of the arm, face, and leg. They have poor functional recovery and a high chance on mortality. Patients in the PACI group present with only one or two of the three components of the TACI group and are likely to have an early recurrent stroke. Patients in the POCI group are at greater risk of a recurrent stroke in the first year after the initial event but have the best chance of a good functional outcome. They present with any of the following symptoms: ipsilateral cranial nerve palsy with contralateral motor and/or sensory deficit, bilateral motor and/or sensory deficit, disorder of conjugate eye movement, cerebellar dysfunction without ipsilateral long-tract deficit, or visual field defects. In the LACI group, patients present with a pure motor stroke, pure sensory stroke, sensori-motor stroke, or ataxic hemiparesis. Many LACI patients are left with substantial functional limitations.[4] Other classifications are the one by Adams et al [5] and by Kang et al [6]. Adams et al [5] propose the TOAST classification of subtypes of acute ischemic stroke in five categories according to the etiology of the stroke: 1) large-artery atherosclerosis, 2) cardioembolism, 3) small-artery occlusion (lacune), 4) stroke of other determined etiology, and 5) stroke of undetermined etiology. Kang et al [6] classify lesions in the following categories: single lesions (cortico-subcortical, cortical, subcortical $\geq$15 mm, or subcortical < 15 mm), scattered lesions in one vascular territory (small scattered lesions or confluent with additional lesions), and multiple lesions in multiple vascular territories (in the unilateral anterior circulation, in the posterior circulation, in bilateral anterior circulations, or in anterior and posterior circulations). Kang et al [6] found an association between the proposed lesion patterns and the specific stroke causes as presented in the TOAST classification.

Incidence and prevalence

Worldwide, stroke is the leading cause of morbidity (the first cause of motor problems and the second cause of dementia)[7, 8] and the second leading cause of mortality[9]. There are approximately 4.5 million deaths per year from stroke and over 9 million stroke survivors [2].
Large differences in stroke prevalence and incidence exist across different countries [7]. Stroke is the third cause of death in the USA and Europe and is also a cause of serious long-term disability for its survivors [3, 8, 9]. The stroke incidence in USA in 2006 was 759,000 and the prevalence was 6.5 million (2.9%) in 2006 [3]. There is a trend towards a raise in stroke incidence in the last decade. This is caused by an increase of the number of persons above 65 years of age due to 1) the increasing life expectancy because of better medical care, improved nutrition and better hygiene, and 2) the ageing of the baby boomers. Truelsen et al.[10] reported, based on WHO estimates, that stroke incidence in Europe will change from 1.1 million per year in 2000 to more than 1.5 million per year by 2025. The number of stroke patients in the Netherlands and their related health care costs are expected to increase by 15% until 2020 as a result of the aging of the population [11]. In the mid-nineties, stroke incidence in the Netherlands was approximately 1.7 (men) to 1.9 (women) per 1000 [12]. The incidence of stroke in the Netherlands in the year 2000 had increased to 2.2 per 1000 [11]. In the year 2008 stroke incidence was 2.6 per 1000 [13].

Arm-hand performance problems after stroke

Approximately 80% of acute stroke patients suffer from acute hemiparesis [14, 15]. This unilateral motor deficit leads in about 40% of stroke patients to chronic upper extremity impairment, limiting functional use as well as engagement in community life [2, 14, 16-18]. Six months after the stroke event, arm-hand function has recovered completely in only 5-20 % of patients and only 33% of patients can be classified as being independent [19]. Although posture and gait tend to improve, recovery of arm-hand function is notoriously poor and strongly lags behind recovery of other functions [16, 20]. Six months after a stroke, only 15% of stroke survivors are unable to walk indoors independently, while 33% need help with feeding, 31% need help with dressing and 49% need help with bathing [2]. Impaired arm-hand performance is a serious and underestimated problem that is associated with poor quality of life after stroke [21]. Four years after stroke, 67% of stroke patients still experience non-use or disuse of the affected arm as a major problem [22].

Motor rehabilitation of the arm and hand after stroke

General trend towards task-oriented client-centred training

The motor rehabilitation approach for arm-hand performance after stroke has been changing substantially over the last decades. At first, treatment approaches have been mainly targeting the ICF (International Classification of Functioning, Disability and Health [23]) function level. Treatment of the arm and hand has been aimed to influence the joint capsular and ligamentous structures (e.g. aiming to alter the joint rest position through bracing), and the muscles (e.g. aiming to influence muscle tone through spasticity reduction, or muscle strength through training of muscle groups, or both through neurofacilitation techniques) [24]. Conventional treatment approaches for hemiplegic patients have been used for many years, even though they were not evidence-based and their neurophysiological background was poorly investigated [25]. Butefish et al [25] found that, after training of repetitive hand and finger movements against various loads (twice daily for 15 minute periods), hemiparetic patients improved significantly with regard to grip strength and peak force, peak acceleration and contraction velocity of hand extensions. Contrary to the expectation, the rapid muscle contractions did lead to a decrease in muscle tone and less associated movements. The persons in the control group did not show any improvement after a traditional approach consisting of muscle tone reduction and TENS. Since Butefish et al [25] challenged conventional approaches that focus on spasticity reduction, a new focus has been placed on addressing paresis and impaired motor control [26-28]. New training approaches have emerged. Well explored and investigated examples of such training approaches are task-oriented training [29], mental practice [30] and constraint-induced movement therapy (CIMT)[31]. Task-oriented training [32] and CIMT [33] focus on both the ICF activity level and the ICF participation level [23]. In the Netherlands, traditional exercise concepts for stroke rehabilitation are still used by a large number of physiotherapists, even though task-oriented training has proven to have a faster and better treatment outcome [34]. Van Peppen et al [35], in a systematic review, showed that more evidence for a positive functional treatment outcome after task-oriented approaches exists than after e.g. muscle strength training. This is logical from the point of view that training effects are specific, with less effects in movements or tasks that are not included in the training [36, 37]. Patients learn by solving specific problems, such as anticipatory locomotor adjustments, cognitive processing, and learning efficient goal-oriented movement strategies [38]. Positive transfer of the learned skill to other skills occurs when similarities are present with the learned skill (identical elements theory) [37].

Whereas 'mental practice' and 'constraint induced movement therapy' are very well defined treatment approaches, until now 'task-oriented training' is poorly defined. This is reflected in the different kinds of interventions that are used in different studies aiming to perform skill training. Whereas in some studies [39] analytical single plane movements (e.g. reaching or pointing) are used and considered to be task-oriented, other studies [40] on task-oriented training use a variety of meaningful movements with real life object manipulation in real life environments. In the latter studies, task-specific movement strategies may be acquired because task-related problem solving strategies are practiced and learned [20]. A generally accepted definition on task-oriented training seems to be lacking. However, a uniform definition is necessary in order to enable comparison across different interventions. In this thesis the following definition of task-oriented training is proposed: "Task-oriented training is a repetitive training of functional, i.e. skill-related, tasks that are relevant to the patient. Task-oriented training includes the use of real-life objects in a natural environmental context". Apart from the problem described above with regard to the definition of task-oriented training, it is also not known what the relative contribution is of different characteristics of task-oriented training to any treatment effect size. It is important to know on which characteristics to place an emphasis in order to optimise training outcome. In this thesis, task-oriented training will be further operationalized with 15 training characteristics. The relative contribution of these characteristics to training effect sizes is studied (chapter 3).

An advantage of task-oriented training is that the patient can choose to train skills that are relevant to his/her personal every day life. The fact that the training goals are meaningful will increase the intrinsic motivation of the patient for the training [26], which in turn is of great benefit for motor learning [41, 42] and exercise compliance [43, 44]. In the last decade rehabilitation aims have become more client-centred, i.e. treatment has become focused on goals that are chosen and set by the patient. The goal-setting is supported by the help of an expert professional (usually an occupational therapist) to accommodate the personal needs of the patient and his/her family [45, 46]. It was found that with the long-time used curative model, in which the health care professional was setting treatment goals in the patient's best interests, patients were sub-adequately prepared for community life [45]. Patients felt that physical issues of their condition and basic care needs had been addressed, but often they did not feel adequately prepared for the real life outside the hospital or rehabilitation clinic [45]. Client-centred goal-setting does encourage patient motivation and self-regulation processes. It also provides a means for patient progress assessment (e.g. via goal attainment scaling [47]) and patient-tailored rehabilitation in which treatment goals can be prioritised, individualised and co-ordinated for the different medical and paramedical disciplines that work with the patient [46].

Technology-supported training: needs and challenges

Current outpatient physiotherapy rehabilitation is typically provided only 2-3 times per week [48]. It is known that more training leads to more improvement of arm-hand performance after stroke [49] and also that guided home rehabilitation after discharge leads to further improvement [50]. In the past it has been (incorrectly) assumed that motor recovery generally levels around 3-6 months after stroke (i.e. no more functional recovery occurs) [26]. At present, the reasons for the apparent cessation of recovery also include, next to the patient's physical potential, factors like the therapist's knowledge base, therapist's experience and treatment repertoire as well as moral influences, regulatory influences and service limitations [51]. Lai et al [16] found that some stroke patients, who are discharged from further therapy, still suffer from severely affected hand function, severely affected activities of daily living, severely affected participation and severely affected overall physical functioning compared with stroke-free community dwellers. In many cases, stroke patients seem not to have reached their full potential when they are discharged from the hospital [52], which is also corroborated by the progress reported in studies with chronic stroke patients that have been discharged [53-55]. However, after discharge there seem to be few therapy and care services available for stroke patients, leading to high levels of patient dissatisfaction [56]. Reasons for the lack of therapy services were, amongst others, that therapists did not belief therapy after discharge could lead to further recovery. Therapy goals did not reach beyond basic ADL activities, although patients did feel that further recovery on participation level would benefit their quality of life [56].

As stroke incidence is increasing quite fast, because of demographic changes, and as a large number of patients seem to benefit from motor rehabilitation for improving arm-hand performance in the chronic stage as well as in the acute and subacute stages after stroke, the question arises if the health care services will be able to keep up with rising demands [57]. Technology-supported training may offer at least four important advantages to support therapy. *Firstly*, the patient can train more often. A multicenter prospective controlled study by Shiel et al [58] and a systematic review by Kwakkel et al [49] showed that augmented therapy leads to better outcome of arm-hand performance, faster progress in motor learning and higher independence for ADL activities. There was no ceiling effect after which no further improvements were possible [58]. However, augmented exercise is not always possible in regular treatment circumstances, given the budgetary constraints of health care services. Technology-support may offer valuable opportunities. *Secondly*, a different kind of training input is delivered. Page et al [59] suggest that insufficient variety in exercise regimes and exercise conditions may be responsible for a stagnation in motor recovery. Different exercises and especially a different way of exercising may shift the motor recovery plateau to a much later stage when patients have achieved a much higher level of recovery. *Thirdly*, as ease of use of rehabilitation technology is envisioned to improve in future, the patient can train without therapist help in a comfortable home setting. *Fourthly*, the work load of paramedical staff may be relieved partly, which may reduce costs for health care services. In the last 15 years, multidisciplinary efforts involving neurologists, movement scientist, therapists, engineers, and computer programming experts have led to a variety of new training possibilities, such as systems for robotic rehabilitation [60-63], sensor-based training systems [64], and gravity compensation systems [65].

Riener et al [66] classified the robotic systems into three categories, i.e. passive (no actuation, limbs are passively stabilised), active (equipped with electromechanical, pneumatic, hydrolic and other drives to move patient limbs) and interactive systems (equipped with actuators, but also with sophisticated impedance and other control strategies that allow reaction to the patient efforts). The first rehabilitation system to support upper extremity training for stroke patients was a robotic system, called MIT-Manus [67], which has been extensively tested in clinical trials [54, 68-70]. It is also one of the first rehabilitation systems to be tested in a large multicentre randomized clinical trial [71]. Other robotic systems that have been developed and evaluated through clinical trials are: MIME [72, 73], BI-MANU-TRAC [74], BATRAC [75], ARMin [62, 76], NeReBot [77, 78], Active Joint Brace [79], T-WREX [80], UniTherapy [81, 82], Haptic Master [60, 83], Arm-Guide [84, 85] and Rutgers Master II glove[86].

As to sensor systems supporting arm-hand skills training in stroke, very few systems are available that have been clinically tested. So far only the AUTOCITE [53, 87], the H-CAD [88] and the Philips Stroke Rehabilitation Exerciser [64, 89-91] have been clinically tested for stroke patients.
Gravity compensation systems, e.g. Freebal [65], are designed to allow stroke patients with reduced muscle power and abnormal movement patterns to increase their range of arm movement and normalize abnormal coupling of movements through increment of activity in prime movers [92, 93].
Technology-supported training systems have been combined with functional electrical stimulation[94], virtual reality (VR) environments[95], and telerehabilitation[88]. Functional electrical stimulation may, especially in combination with voluntary movement, improve muscle strength and cortical excitability [94, 96]. Broeren et al [95] have combined VR with the PHANToM Haptic Device and found, in a single case experiment, that 4 weeks of training with PHANToM may improve fine manual dexterity, grip force and motor control in stroke. Research with the PHANToM also indicates that this VR system may be suitable for the assessment of neglect in stroke patients [97]. Several studies describe the use of telerehabilitation in combination with robotic systems [98, 99] or sensor-based systems[53] in stroke. Through telerehabilitation, not only communication between the therapist and the patient may occur, but also communication between different health professionals at different locations and even peer communication between patients are possible [88, 98, 100-102].
The development of rehabilitation technology is still in its very early stages [103, 104], and large scale clinical trials, although gradually appearing [71, 80], are needed before such technologies can be used widespread by stroke patients. Whereas task-oriented training has already shown to augment skilled arm-hand performance [31, 40], to date technology-supported training fails to do so [105-107]. It is essential to find out whether the available technologies have been following the trends in the field of rehabilitation, i.e. by moving from both doctor-centred and function level treatment approaches towards client-centred treatment approaches that include task-oriented training as well as training of basic functions that support skill performance. Furthermore, it is not clear which criteria should be taken into account to judge the strengths of different systems. The latter issues were studied in a review in the present thesis.
When treatment goals are formulated in a regular therapy setting, a rehabilitation professional (typically an occupational therapist) can define client-centred treatment goals through outcome assessment (e.g. Canadian Occupational Performance Measure [108] and/or Goal Attainment Scaling [47]). In contrast, technology-supported training has a fixed set of exercises that support certain treatment goals. Therefore, when using technology-supported rehabilitation, the exercises on offer should be as close as possible to the general needs of the target users / patient population. In the present thesis, subacute and chronic stroke patients were interviewed to investigate their training preferences, in order to implement exercises that support skills that are of interest to the stroke patient.
Whereas it is not too difficult to implement exercises that consist of single plane movements, it is harder to support exercises that cover multiple movement planes and happen through multiple degrees of freedom, especially when supported by individual feedback on the movement. In this thesis, a training method was developed, called T-

TOAT (Technology-supported Task-oriented Arm Training). It allows for the implementation of exercises, supporting multiplanar skills. T-TOAT exercises have been implemented in a sensor-based system (Philips Stroke Rehabilitation Exerciser, Philips Research Europe) and in a robot system (Haptic Master, Moog, NL). In this thesis, the effects of an 8 week training intervention with a sensor-based training system on arm-hand performance, and the results on system usability and patient motivation are reported. The randomized clinical trial, evaluating the additional value of Haptic Master for task-oriented arm training in stroke patients, is still ongoing.
A large variety of technological systems have been developed to support arm-hand performance training after stroke. It is until today not known, which of all these systems, having different strengths and offering different opportunities, are best suited for which patients (depending on functional and/or cognitive level, post-stroke time, etc…). Due to the lack of standardized outcome assessment and the lack of standardized training used in clinical trials, it remains very difficult to map strengths of different systems and to benchmark solutions. In this thesis, a first step towards standardized use of outcome measures is made by proposing a concept that guides the choice of measurement instruments to be used when evaluating arm-hand performance after task-oriented training.

Thesis outline

The main aims of this thesis are: 1) to provide criteria that may be used to chart strengths of existing rehabilitation technologies for arm-hand training after stroke, and to contribute to the future possibility of benchmarking solutions for different patient categories through a concept that may guide in the standardization of the choices regarding outcome measurement; 2) to define and operationalize a task-oriented training approach and investigate the relative contribution of specific training characteristics to treatment effect sizes; 3) to investigate the feasibility of technology-supported client-centred task-oriented arm training and 4) to investigate possible effects of technology-supported task-oriented training on arm-hand skill performance in persons with chronic stroke.
Chapter 2 describes a literature review in which criteria are identified that rehabilitation technology should meet in order to offer arm-hand training to stroke patients, based on recent principles of motor learning and recent clinical trial evidence on treatment approaches. Comparison of clinically tested arm rehabilitation systems for stroke patients to the proposed guidelines shows that technological systems for supporting upper limb training after stroke need to align with the evolution in rehabilitation approaches of the last decade.
Chapter 3, containing a systematic review, reports on the influence of task-oriented training content on skilled arm-hand performance of stroke patients. This review operationalizes task-oriented training with 15 underlying training components and assesses the effects of these components on skilled arm-hand performance in patients after stroke.
Chapter 4 presents a concept to guide the choice of measurement instruments for the evaluation of technology-supported task-oriented training interventions.

Chapter 5 reports on semi-structured interviews in 40 stroke patients to inventory the skills that persons after stroke prefer to train on. The list can be used for the implementation of exercises in rehabilitation technology in order to enable a choice of exercises on offer that are close to what patients prefer to train on. This research contributes to the concept of enabling ‘client-centeredness’ in technology-supported training.
Chapter 6 presents T-TOAT, a method that enables the implementation of personalized task-oriented arm training exercises for stroke patients in rehabilitation technology. An example of such implementation in a sensor-based system and in a robot system is given.
Chapter 7 describes a study evaluating treatment outcome, patient motivation and system usability after sensor-based arm skill training. A clinical study was performed in which chronic stroke patients trained with the T-TOAT method developed earlier, incorporated in a sensor-based training system. Patients trained for 8 weeks (4 times per week, 2 times 30 minutes per day). Training results are presented and discussed.
Chapter 8 (general discussion) discusses and integrates the findings presented in the different chapters of this thesis. The importance of the findings for the research fields of rehabilitation and rehabilitation technology is elaborated on. Suggestions for future research are given.

References

1. World Health Organisation. WHO infobase stroke. 2010
2. Wolfe CD. The impact of stroke. Br Med Bull. 2000;56:275-286
3. American Heart Association. Heart disease and stroke statistics - 2009 update. 2010
4. Bamford J, Sandercock P, Dennis M, Burn J, Warlow C. Classification and natural history of clinically identifiable subtypes of cerebral infarction. Lancet. 1991;337:1521-1526
5. Adams HP, Bendixen BH, Kappelle LJ, Biller J, Love BB, Gordon DL, Marsh EE, 3rd. Classification of subtype of acute ischemic stroke. Definitions for use in a multicenter clinical trial Toast. Stroke. 1993;24:35-41
6. Kang DW, Chalela JA, Ezzeddine MA, Warach S. Association of ischemic lesion patterns on early diffusion-weighted imaging with toast stroke subtypes. Arch N*eurol*. 2003;60:1730-1734
7. Ali M, Atula S, Bath PM, Grotta J, Hacke W, Lyden P, Marler JR, Sacco RL, Lees KR. Stroke outcome in clinical trial patients deriving from different countries. *Stroke*. 2009;40:35-40
8. Bejot Y, Benatru I, Rouaud O, Fromont A, Besancenot JP, Moreau T, Giroud M. Epidemiology of stroke in Europe: Geographic and environmental differences. *J Neurol Sci*. 2007;262:85-88
9. Rothwell PM, Coull AJ, Giles MF, Howard SC, Silver LE, Bull LM, Gutnikov SA, Edwards P, Mant D, Sackley CM, Farmer A, Sandercock PA, Dennis MS, Warlow CP, Bamford JM, Anslow P. Change in stroke incidence, mortality, case-fatality, severity, and risk factors in Oxfordshire, UK from 1981 to 2004 (Oxford vascular study). *Lancet*. 2004;363:1925-1933
10. Truelsen T, Piechowski-Jozwiak B, Bonita R, Mathers C, Bogousslavsky J, Boysen G. Stroke incidence and prevalence in Europe: A review of available data. *Eur J Neurol*. 2006;13:581-598
11. Struijs JN, van Genugten ML, Evers SM, Ament AJ, Baan CA, van den Bos GA. Modeling the future burden of stroke in the Netherlands: Impact of aging, smoking, and hypertension. *Stroke*. 2005;36:1648-1655
12. RIVM. Nationaal kompas volksgezondheid, versie 3.20 [in dutch]. 2009
13. Prismant. Landelijke LMR-informatie-diagnosen [in dutch]. 2010
14. Pang MY, Harris JE, Eng JJ. A community-based upper-extremity group exercise program improves motor function and performance of functional activities in chronic stroke: A randomized controlled trial. *Arch Phys Med Rehabil*. 2006;87:1-9
15. Langhorne P, Coupar F, Pollock A. Motor recovery after stroke: A systematic review. *Lancet Neurol*. 2009;8:741-754
16. Lai SM, Studenski S, Duncan PW, Perera S. Persisting consequences of stroke measured by the stroke impact scale. *Stroke*. 2002;33:1840-1844
17. Johansson A, Mishina E, Ivanov A, Bjorklund A. Activities of daily living among St Petersburg women after mild stroke. *Occup Ther Int*. 2007;14:170-182
18. WHO. Stroke1989. Recommendations on stroke prevention, diagnosis, and therapy. Report of the who task force on stroke and other cerebrovascular disorders. *Stroke*. 1989;20:1407-1431
19. Kwakkel G, Kollen BJ, van der Grond J, Prevo AJ. Probability of regaining dexterity in the flaccid upper limb: Impact of severity of paresis and time since onset in acute stroke. *Stroke*. 2003;34:2181-2186
20. Feys HM, De Weerdt WJ, Selz BE, Cox Steck GA, Spichiger R, Vereeck LE, Putman KD, Van Hoydonck GA. Effect of a therapeutic intervention for the hemiplegic upper limb in the acute phase after stroke: A single-blind, randomized, controlled multicenter trial. *Stroke*. 1998;29:785-792
21. Nichols-Larsen DS, Clark PC, Zeringue A, Greenspan A, Blanton S. Factors influencing stroke survivors' quality of life during subacute recovery. *Stroke*. 2005;36:1480-1484
22. Broeks JG, Lankhorst GJ, Rumping K, Prevo AJ. The long-term outcome of arm function after stroke: Results of a follow-up study. *Disabil Rehabil*. 1999;21:357-364
23. World Health Organization. International classification of functioning, disability and health: ICF 2001

24. Gordon J. Assumptions underlying physical therapy intervention: Theoretical and historical perspectives. In: Carr J, Shepherd R, eds. *Movement science, foundations for physical therapy in rehabilitation*. Gaithersburg, Maryland: Aspen Publishers, Incl; 2000.
25. Butefisch C, Hummelsheim H, Denzler P, Mauritz KH. Repetitive training of isolated movements improves the outcome of motor rehabilitation of the centrally paretic hand. *J Neurol Sci*. 1995;130:59-68
26. Dobkin BH. Strategies for stroke rehabilitation. *Lancet Neurol*. 2004;3:528-536
27. Shephard R, Carr J. Bridging the gap between theory and practice. In: Refshauge Kathryn, ed. *Science-based rehabilitation - theories into practice*. Edinburgh: Butterworth-Heinemann; 2005:1-13.
28. Sterr A, Szameitat A, Shen S, Freivogel S. Application of the CIT concept in the clinical environment: Hurdles, practicalities, and clinical benefits. *Cogn Behav Neurol*. 2006;19:48-54
29. French B, Thomas LH, Leathley MJ, Sutton CJ, McAdam J, Forster A, Langhorne P, Price CI, Walker A, Watkins CL. Repetitive task training for improving functional ability after stroke. *Stroke*. 2009
30. Verbunt JA, Seelen HA, Ramos FP, Michielsen BH, Wetzelaer WL, Moennekens M. Mental practice-based rehabilitation training to improve arm function and daily activity performance in stroke patients: A randomized clinical trial. *BMC Neurol*. 2008;8:7
31. Wolf SL, Winstein CJ, Miller JP, Thompson PA, Taub E, Uswatte G, Morris D, Blanton S, Nichols-Larsen D, Clark PC. Retention of upper limb function in stroke survivors who have received constraint-induced movement therapy: The excite randomised trial. *Lancet Neurol*. 2008;7:33-40
32. Holmqvist LW, von Koch L, Kostulas V, Holm M, Widsell G, Tegler H, Johansson K, Almazan J, de Pedro-Cuesta J. A randomized controlled trial of rehabilitation at home after stroke in southwest Stockholm. *Stroke* 1998;29:591-597
33. Blanton S, Wilsey H, Wolf SL. Constraint-induced movement therapy in stroke rehabilitation: Perspectives on future clinical applications. *NeuroRehabilitation*. 2008;23:15-28
34. Langhammer B, Stanghelle JK. Bobath or motor relearning programme? A comparison of two different approaches of physiotherapy in stroke rehabilitation: A randomized controlled study. *Clin Rehabil*. 2000;14:361-369
35. Van Peppen RP, Kwakkel G, Wood-Dauphinee S, Hendriks HJ, Van der Wees PJ, Dekker J. The impact of physical therapy on functional outcomes after stroke: What's the evidence? *Clin Rehabil*. 2004;18:833-862
36. Kwakkel G, Kollen B, Wagenaar R. Therapy impact on functional recovery in stroke rehabilitation: A critical view of the literature. *Physiotherapy*. 1999;13:457
37. Magill R. Transfer of learning. *Motor learning and control. Concepts and applications*. Boston: Mc Graw Hill; 2007:290-306.
38. Timmermans AA, Seelen HA, Willmann RD, Kingma H. Technology-assisted training of arm-hand skills in stroke: Concepts on reacquisition of motor control and therapist guidelines for rehabilitation technology design. *J Neuroeng Rehabil*. 2009;6:1
39. Michaelsen SM, Dannenbaum R, Levin MF. Task-specific training with trunk restraint on arm recovery in stroke: Randomized control trial. *Stroke*. 2006;37:186-192
40. Baskett JJ, Broad JB, Reekie G, Hocking C, Green G. Shared responsibility for ongoing rehabilitation: A new approach to home-based therapy after stroke. *Clinical rehabil*. 1999;13:23-33
41. Darling WG, Pizzimenti MA, Rotella DL, Hynes SM, Ge J, Stilwell-Morecraft KS, Vanadurongvan T, McNeal DW, Solon-Cline KM, Morecraft RJ. Minimal forced use without constraint stimulates spontaneous use of the impaired upper extremity following motor cortex injury. *Exp Brain Res*. 2010
42. Maclean N, Pound P, Wolfe C, Rudd A. Qualitative analysis of stroke patients' motivation for rehabilitation. *BMJ*. 2000;321:1051-1054
43. Bach-y-Rita P. Theoretical and practical considerations in the restoration of function after stroke. *Top Stroke Rehabil*. 2001;8:1-15
44. Bach-y-Rita P, Wood S, Leder R, Paredes O, Bahr D, Bach-y-Rita E, Murillo N. Rehabilitation for institutional, home, and educational late stroke programs. *Top Stroke Rehabil*. 2002;8:1-10

45. Cott CA. Client-centred rehabilitation: Client perspectives. *Disabil Rehabil*. 2004;26:1411-1422
46. Siegert RJ, McPherson KM, Taylor WJ. Toward a cognitive-affective model of goal-setting in rehabilitation: Is self-regulation theory a key step? *Disabil Rehabil*. 2004;26:1175-1183
47. Bravo G, Dubois M, Roy P. Improving the quality of residential care using goal attainment scaling. *J Am Med Dir Assoc*. 2005;6:173-180
48. Zheng H, Davies R, Black N. Web-based monitoring system for home-based rehabilitation with stroke patients. *Eighteenth IEEE symposium on computer-based medical system*. 2005: 419-424.
49. Kwakkel G, van Peppen R, Wagenaar RC, Wood Dauphinee S, Richards C, Ashburn A, Miller K, Lincoln N, Partridge C, Wellwood I, Langhorne P. Effects of augmented exercise therapy time after stroke: A meta-analysis. *Stroke*. 2004;35:2529-2539
50. Duncan P, Richards L, Wallace D, Stoker-Yates J, Pohl P, Luchies C, Ogle A, Studenski S. A randomized, controlled pilot study of a home-based exercise program for individuals with mild and moderate stroke. *Stroke*. 1998;29:2055-2060
51. Demain S, Wiles R, Roberts L, McPherson K. Recovery plateau following stroke: Fact or fiction? *Disabil Rehabil*. 2006;28:815-821
52. Malouin F RC. Assessment and training of locomotion after stroke: Evolving concepts. In: Refshauge Kathryn, ed. *Science-based rehabilitation. Theories into practice.* Edinburgh: Butterworth Heinemann; 2005:185-222.
53. Lum PS, Uswatte G, Taub E, Hardin P, Mark VW. A telerehabilitation approach to delivery of constraint-induced movement therapy. *J Rehabil Res Dev*. 2006;43:391-400
54. Fasoli SE, Krebs HI, Stein J, Frontera WR, Hogan N. Effects of robotic therapy on motor impairment and recovery in chronic stroke. *Arch Phys Med Rehabil*. 2003;84:477-482
55. van der Lee JH, Wagenaar RC, Lankhorst GJ, Vogelaar TW, Deville WL, Bouter LM. Forced use of the upper extremity in chronic stroke patients: Results from a single-blind randomized clinical trial. *Stroke*. 1999;30:2369-2375
56. Tyson S, Turner G. Discharge and follow-up for people with stroke: What happens and why. *Clin Rehabil*. 2000;14:381-392
57. Carignan CR, Krebs HI. Telerehabilitation robotics: Bright lights, big future? *J Rehabil Res Dev*. 2006;43:695-710
58. Shiel A, Burn JP, Henry D, Clark J, Wilson BA, Burnett ME, McLellan DL. The effects of increased rehabilitation therapy after brain injury: Results of a prospective controlled trial. *Clin Rehabil*. 2001;15:501-514
59. Page SJ, Gater DR, Bach YRP. Reconsidering the motor recovery plateau in stroke rehabilitation. *Arch Phys Med Rehabil*. 2004;85:1377-1381
60. Seelen HAM, Geers RPJ, Soede M, Spauwen LWL. Training of arm-hand kinaesthetics in subacute stroke patients using robotics. *Journal of Biomechanics*. 2007;40:S645
61. Krebs HI, Ferraro M, Buerger SP, Newbery MJ, Makiyama A, Sandmann M, Lynch D, Volpe BT, Hogan N. Rehabilitation robotics: Pilot trial of a spatial extension for MIT-manus. *J Neuroeng Rehabil*. 2004;1:5
62. Nef T, Guidali M, Riener R. Armin III - arm therapy exoskeleton with an ergonomic shoulder actuation. *Applied Bionics and Biomechanics*. 2009;6:127-142
63. Sanchez RJ, Liu J, Rao S, Shah P, Smith R, Rahman T, Cramer SC, Bobrow JE, Reinkensmeyer DJ. Automating arm movement training following severe stroke: Functional exercises with quantitative feedback in a gravity-reduced environment. *IEEE Trans Neural Syst Rehabil Eng*. 2006;14:378-389
64. Willmann RD, Lanfermann G, Saini P, Timmermans A, te Vrugt J, Winter S. Home stroke rehabilitation for the upper limbs. *Conf Proc IEEE Eng Med Biol Soc*. 2007;2007:4015-4018
65. Stienen A, Hekman E, Van der Helm F, Prange G, Jannink M, Aalsma A, Van der Kooi H. Freebal: Dedicated gravity compensation for the upper extremities. *10th International Conference on Rehabilitation Robotics (ICORR)*. 2007:804-808
66. Riener R, Nef T, Colombo G. Robot-aided neurorehabilitation of the upper extremities. *Med Biol Eng Comput*. 2005;43:2-10
67. Krebs HI, Hogan N, Aisen ML, Volpe BT. Robot-aided neurorehabilitation. *IEEE Trans Rehabil Eng*. 1998;6:75-87

68. Krebs HI, Mernoff S, Fasoli SE, Hughes R, Stein J, Hogan N. A comparison of functional and impairment-based robotic training in severe to moderate chronic stroke: A pilot study. *NeuroRehabilitation*. 2008;23:81-87
69. Volpe BT, Lynch D, Rykman-Berland A, Ferraro M, Galgano M, Hogan N, Krebs HI. Intensive sensorimotor arm training mediated by therapist or robot improves hemiparesis in patients with chronic stroke. *Neurorehabil Neural Repair*. 2008
70. Ferraro M, Palazzolo JJ, Krol J, Krebs HI, Hogan N, Volpe BT. Robot-aided sensorimotor arm training improves outcome in patients with chronic stroke. *Neurology*. 2003;61:1604-1607
71. Lo AC, Guarino P, Krebs HI, Volpe BT, Bever CT, Duncan PW, Ringer RJ, Wagner TH, Richards LG, Bravata DM, Haselkorn JK, Wittenberg GF, Federman DG, Corn BH, Maffucci AD, Peduzzi P. Multicenter randomized trial of robot-assisted rehabilitation for chronic stroke: Methods and entry characteristics for va robotics. *Neurorehabil Neural Repair*. 2009;23:775-783
72. Burgar CG, Lum PS, Shor PC, Machiel Van der Loos HF. Development of robots for rehabilitation therapy: The Palo Alto VA/Stanford experience. *J Rehabil Res Dev*. 2000;37:663-673
73. Lum PS, Burgar CG, Shor PC, Majmundar M, Van der Loos M. Robot-assisted movement training compared with conventional therapy techniques for the rehabilitation of upper-limb motor function after stroke. *Arch Phys Med Rehabil*. 2002;83:952-959
74. Hesse S, Schulte-Tigges G, Konrad M, Bardeleben A, Werner C. Robot-assisted arm trainer for the passive and active practice of bilateral forearm and wrist movements in hemiparetic subjects. *Arch Phys Med Rehabil*. 2003;84:915-920
75. Whitall J, McCombe Waller S, Silver KH, Macko RF. Repetitive bilateral arm training with rhythmic auditory cueing improves motor function in chronic hemiparetic stroke. *Stroke*. 2000;31:2390-2395
76. Staubli P, Nef T, Klamroth-Marganska V, Riener R. Effects of intensive arm training with the rehabilitation robot armin II in chronic stroke patients: Four single-cases. *J Neuroeng Rehabil*. 2009;6:46
77. Fanin C, Gallina P, Rossi A, Zannatta U, Masiero S. NeReBot: A wire-based robot for neurorehabilitation. *8th International Conference of Rehabilitation Robotics ICORR*. 2003:23-27
78. Masiero S, Celia A, Rosati G, Armani M. Robotic-assisted rehabilitation of the upper limb after acute stroke. *Arch Phys Med Rehabil*. 2007;88:142-149
79. Stein J, Narendran K, McBean J, Krebs K, Hughes R. Electromyography-controlled exoskeletal upper-limb-powered orthosis for exercise training after stroke. *Am J Phys Med Rehabil*. 2007;86:255-261
80. Housman SJ, Scott KM, Reinkensmeyer DJ. A randomized controlled trial of gravity-supported, computer-enhanced arm exercise for individuals with severe hemiparesis. *Neurorehabil Neural Repair*. 2009;23:505-514
81. Feng X, Johnson M, Johnson L, Winters J. A suite of computer-assisted techniques for assessing upper-extremity motor impairments. *Conf Proc IEEE Eng Med Biol Soc*. 2005;7:6867-6870
82. Johnson MJ, Feng X, Johnson LM, Winters JM. Potential of a suite of robot/computer-assisted motivating systems for personalized, home-based, stroke rehabilitation. *J Neuroengineering Rehabil*. 2007;4:6
83. Johnson M, Wisneski K, Anderson J, Nathan D, Smith R. Development of ADLER: The activities of daily living exercise robot. *BioRob2006. The first IEEE/RAS-EMBS International Conference on Biomedical Robotics and Biomechatronics*. 2006:881-886
84. Kahn LE, Rymer WZ, Reinkensmeyer DJ. Adaptive assistance for guided force training in chronic stroke. *Conf Proc IEEE Eng Med Biol Soc*. 2004;4:2722-2725
85. Kahn LE, Lum PS, Rymer WZ, Reinkensmeyer DJ. Robot-assisted movement training for the stroke-impaired arm: Does it matter what the robot does? *J Rehabil Res Dev*. 2006;43:619-630
86. Boian R, Sharma A, Han C, Merians A, Burdea C, Adamovich D, Recce M, Tremaine M, Poizner H. Virtual reality-based post-stroke hand rehabilitation. *Medicine Meets Virtual Reality 2002 Conference*. 2002:64-70
87. Lum PS, Taub E, Schwandt D, Postman M, Hardin P, Uswatte G. Automated constraint-induced therapy extension (Autocite) for movement deficits after stroke. *J Rehabil Res Dev*. 2004;41:249-258

88. Zampolini M, Todeschini E, Bernabeu Guitart M, Hermens H, Ilsbroukx S, Macellari V, Magni R, Rogante M, Scattareggia Marchese S, Vollenbroek M, Giacomozzi C. Tele-rehabilitation: Present and future. *Ann Ist Super Sanita*. 2008;44:125-134
89. van Acht V, Bongers E, Lambert N, Verberne R. Miniature wireless inertial sensor for measuring human motions. *Conf Proc IEEE Eng Med Biol Soc*. 2007;2007:6279-6282
90. Lanfermann G, Willmann R, te Vrugt J, Timmermans A, Bongers E, Lambert N, van Acht V. Philips stroke rehabilitation exerciser. *Technical Aids for Rehabilitation - TAR 2007*. 2007
91. Timmermans AAA, Seelen HAM, Geers RPJ, Saini PK, Winter S, Te Vrugt J, Kingma H. Sensor-based skill training in chronic stroke patients: Results on treatment outcome, patient motivation and system usability. *IEEE Trans Neural Syst Rehabil Eng*. 2010; 18 (3): 284-292.
92. Prange GB, Jannink MJ, Stienen AH, van der Kooij H, Ijzerman MJ, Hermens HJ. Influence of gravity compensation on muscle activation patterns during different temporal phases of arm movements of stroke patients. *Neurorehabil Neural Repair*. 2009;23:478-485
93. Prange GB, Jannink MJ, Stienen AH, van der Kooij H, Ijzerman MJ, Hermens HJ. An explorative, cross-sectional study into abnormal muscular coupling during reach in chronic stroke patients. *J Neuroeng Rehabil*. 2010;7:14
94. Freeman CT, Hughes AM, Burridge JH, Chappell PH, Lewin PL, Rogers E. A robotic workstation for stroke rehabilitation of the upper extremity using FES. *Med Eng Phys*. 2009;31:364-373
95. Broeren J, Rydmark M, Sunnerhagen KS. Virtual reality and haptics as a training device for movement rehabilitation after stroke: A single-case study. *Arch Phys Med Rehabil*. 2004;85:1247-1250
96. Hughes AM, Freeman CT, Burridge JH, Chappell PH, Lewin PL, Rogers E. Feasibility of iterative learning control mediated by functional electrical stimulation for reaching after stroke. *Neurorehabil Neural Repair*. 2009;23:559-568
97. Broeren J, Samuelsson H, Stibrant-Sunnerhagen K, Blomstrand C, Rydmark M. Neglect assessment as an application of virtual reality. *Acta Neurol Scand*. 2007;116:157-163
98. Johnson MJ, Loureiro RCV, Harwin WS. Collaborative tele-rehabilitation and robot-mediated therapy for stroke rehabilitation at home or clinic. *Intel Serv Robotics*. 2008;1:109-121
99. Broeren J, Dixon M, Sunnerhagen KS, Rydmark M. Rehabilitation after stroke using virtual reality, haptics (force feedback) and telemedicine. *Stud Health Technol Inform*. 2006;124:51-56
100. Hoenig H, Sanford JA, Butterfield T, Griffiths PC, Richardson P, Hargraves K. Development of a teletechnology protocol for in-home rehabilitation. *J Rehabil Res Dev*. 2006;43:287-298
101. Huis in 't Veld MH, van Dijk H, Hermens HJ, Vollenbroek-Hutten MM. A systematic review of the methodology of telemedicine evaluation in patients with postural and movement disorders. *J Telemed Telecare*. 2006;12:289-297
102. van Dijk H, Hermens HJ. Distance training for the restoration of motor function. *J Telemed Telecare*. 2004;10:63-71
103. Krebs HI, Carrozza MC. Guest editorial: Special issue on rehabilitation robotics: From bench to bedside to community care. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*. 2007;15:325-326
104. Gelderblom GJ, De Wilt M, Cremers G, Rensma A. Rehabilitation robotics in robotics for healthcare; a roadmap study for the European commission. *11th International Conference on Rehabilitation Robotics (ICORR). Kyoto, Japan*. 2009:834-838
105. Prange GB, Jannink MJ, Groothuis-Oudshoorn CG, Hermens HJ, Ijzerman MJ. Systematic review of the effect of robot-aided therapy on recovery of the hemiparetic arm after stroke. *J Rehabil Res Dev*. 2006;43:171-184
106. Kwakkel G, Kollen BJ, Krebs HI. Effects of robot-assisted therapy on upper limb recovery after stroke: A systematic review. *Neurorehabil Neural Repair*. 2008;22:111-121
107. Mehrholz J, Platz T, Kugler J, Pohl M. Electromechanical and robot-assisted arm training for improving arm function and activities of daily living after stroke. *Stroke*. 2009
108. Law M, Baptiste S, McColl M, Opzoomer A, Polatajko H, Pollock N. The Canadian occupational performance measure: An outcome measure for occupational therapy. *Can J Occup Ther*. 1990;57:82-87

Chapter 2

Technology-assisted training of arm-hand skills in stroke: concepts on reacquisition of motor control and therapist guidelines for rehabilitation technology design

Timmermans AA, Seelen HA, Willmann RD, Kingma H. Technology-assisted training of arm-hand skills in stroke: Concepts on reacquisition of motor control and therapist guidelines for rehabilitation technology design. *J Neuroeng Rehabil*. 2009; 6:1

Abstract

Background: It is the purpose of this chapter to identify and review criteria that rehabilitation technology should meet in order to offer arm-hand training to stroke patients, based on recent principles of motor learning.
Methods: A literature search was conducted in PubMed, MEDLINE, CINAHL, and EMBASE (1997-2007).
Results: One hundred and eighty seven scientific papers/book references were identified as being relevant. Rehabilitation approaches for upper limb training after stroke show to have shifted in the last decade from being analytical towards being focussed on environmentally contextual skill training (task-oriented training). Training programmes for enhancing motor skills use patient and goal-tailored exercise schedules and individual feedback on exercise performance. Therapist criteria for upper limb rehabilitation technology are suggested which are used to evaluate the strengths and weaknesses of a number of current technological systems.
Conclusion: This review shows that technology for supporting upper limb training after stroke needs to align with the evolution in rehabilitation training approaches of the last decade. A major challenge for related technological developments is to provide engaging patient-tailored task oriented arm-hand training in natural environments with patient-tailored feedback to support (re)learning of motor skills.

Background

Stroke is the third leading cause of death in the USA and may cause serious long-term disabilities for its survivors [1]. The World Health Organisation (WHO) estimates that stroke events in EU countries are likely to increase by 30% between 2000 and 2025 [2]. Stroke patients may be classified as being in an acute, subacute or chronic stage after stroke. Although several restorative processes can occur together in different stages after stroke (figure 1), it can be said that spontaneous recovery through restitution of the ischemic penumbra and resolution of diaschisis takes place more in the acute stage after stroke (especially in the first four weeks [3]). Repair through reorganisation, supporting true recovery or, alternatively, compensation, may also take place in the

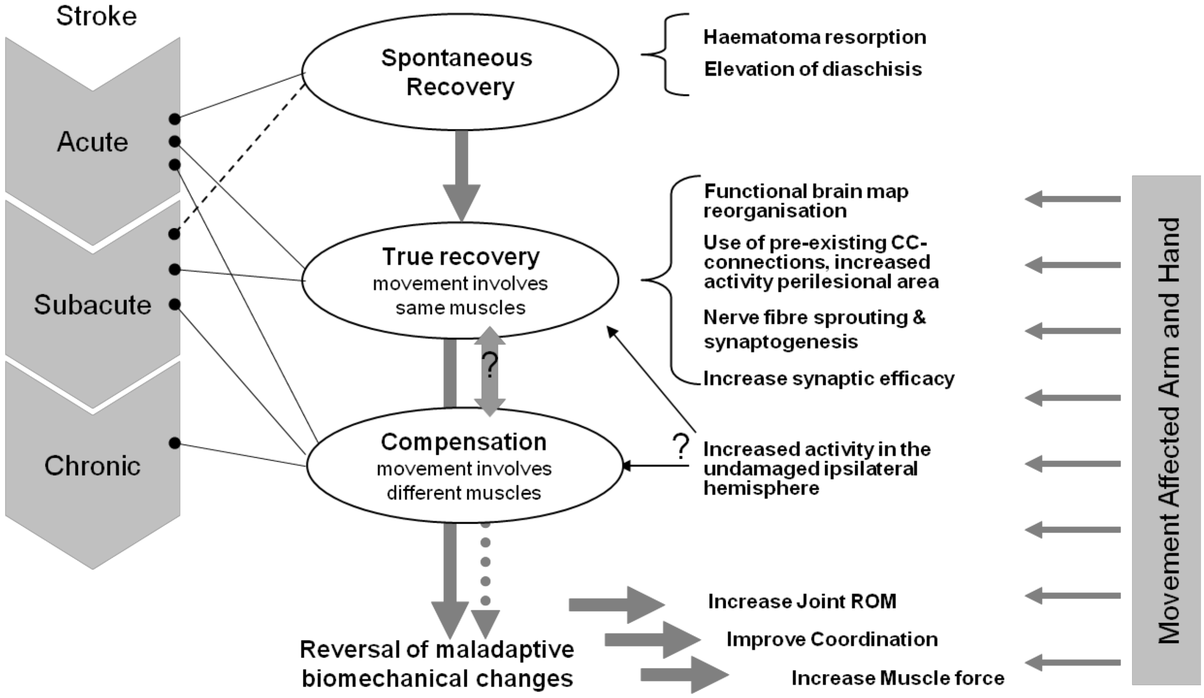

Fig. 1: Declarative model of motor recovery after stroke (CC=corticocortical)

subacute and chronic phase after stroke [3]. In true recovery, the same muscles as before the injury are recruited through functional reorganisation in the undamaged motor cortex or through recruitment of undamaged redundant cortico-cortical connections [4]. In compensation strategies, alternative muscle coalitions are used for skill performance. To date, central nervous system adaptations behind compensation strategies have not been clarified. In any case, learning is a necessary condition for true recovery as well as for compensation [3] and can be stimulated and shaped by rehabilitation; and this most, but not solely, in the first 6 months after the stroke event [5]. However, little is currently known about how different therapy modalities and therapy designs can influence brain reorganisation to support true recovery or compensation.

Persons who suffer from functional impairment after stroke often have not reached their full potential for recovery when they are discharged from hospital, where they receive initial rehabilitation [6-8]. This is especially the case for the recovery of arm-hand function, which lags behind recovery of other functions [9]. A major obstacle for rehabilitation after hospital discharge is geographical distance between patients and therapists as well as limited availability of personnel [10]. This leads to high levels of patient dissatisfaction for not receiving adequate and sufficient training possibilities after discharge from hospital [11]. Four years after stroke, only 6% of stroke patients are satisfied with the functionality of their impaired arm [8].

As therapy demand is expected to increase in future, an important role emerges for technology that will allow patients to perform training with minimal therapist time consumption [12-14]. With such technology patients can train much more often, which leads to better results and faster progress in motor (re) learning [15]. There is scientific evidence that guided home rehabilitation prevents patients from deteriorating in their

ability to undertake activities of daily living [16,17], may lead to functional improvement [6, 16, 18-20], higher social participation and lower rates of depression [20].
This setting has motivated multidisciplinary efforts for the development of rehabilitation robotics, virtual reality applications, monitoring of movement/force application and telerehabilitation.
The aim of this chapter is:

1. to bring together a list of criteria for the development of optimal upper limb rehabilitation technology that is derived from the fields of rehabilitation and motor control, and
2. to review literature as to what extent current technological applications have followed the evolution in rehabilitation approaches in the last decade. While a wealth of technologies is currently under development and shows a lot of promise, it is not the aim of this article to give an inventory of technology described in engineering databases. For an overview of such work, readers are referred to Riener et al. [21]. As this article is written from a therapy perspective, only technology that has been tested through clinical trial(s) will be evaluated.

This information may guide persons that are active in the domain of rehabilitation technology development in the conceptualisation and design of technology-based training systems.

Methods

A literature search was conducted using the following databases: PubMed, MEDLINE, CINAHL, and EMBASE. The database search is chosen to be clinically oriented, as it is the authors aim to

1. gather guidelines for technology design from the fields of motor learning/rehabilitation, and
2. to evaluate technology that has been tested through clinical trial(s).

Papers published in 1997- 2007 were reviewed. The following MeSH keywords were used in several combinations: “Cerebrovascular Accident” not “Cerebral Palsy”, “Exercise Therapy”, “Rehabilitation”, “Physical Therapy” not “Electric Stimulation Therapy”, “Occupational Therapy”, “Movement”, “Upper Extremity”, “Exercise”, “Motor Skills” or “Motor Skill Disorders”, “Biomedical Technology” or “Technology”, “Automation”, “Feedback”, “Knowledge of Results”, “Tele-rehabilitation” as well as spelling variations of these terms. Additionally, information from relevant references cited in the articles selected was used. After evaluation of the content relevance of the articles that resulted from the search described above, 187 journal papers or book chapters were finally selected, forming the basis of this paper.

Results

State-of-the-art approaches in motor (re)learning in stroke and criteria for rehabilitation technology design

General

The International Classification of Functioning, Disability and Health (ICF) [22,23] classifies health and disease at three levels:

1. Function level (aimed at body structures and function),
2. Activity level (aimed at skills, task execution and activity completion), and
3. Participation level (focussed on how a person takes up his/her role in society).

This classification has brought about awareness that addressing "health "goes further than merely addressing "function level", as has been the case in healthcare until the middle of the last decade.
Rehabilitation after stroke has evolved during the last 15 years from mostly analytical rehabilitation methods to also including task-oriented training approaches. Analytical methods address localised joint movements that are not linked to skills, but to function level. Task-oriented approaches involve training of skills and activities aimed at increasing subject's participation. Since Butefisch et al [24] started challenging conventional physiotherapy approaches that focus on spasticity reduction, a new focus on addressing paresis and disordered motor control has emerged [25-28]. Several authors advocate the use rehabilitation methods that include repetition of meaningful and engaging movements in order to induce changes in the cerebral cortex that support motor recovery (brain plasticity) [29-32].
Knowing that training effects are task-specific [33] and that to obtain improvement in "health" an improvement on different levels of functioning is required [22], it is now generally accepted that sensory-motor training is a total package, consisting of several stages: a) training of basic functions (e.g. muscle force, range of motion, tonus, coordination) prerequisite to skill training, b) skill training (cognitive, associative and autonomous phase) and c) improvement of endurance on muscular and/or cardiovascular level [34].
Apart from active therapy approaches where a patient consciously participates in a motor activity, also recent views on therapy goal setting, motivation aspects of therapy and feedback delivery on exercise performance are discussed and used for setting therapist criteria for rehabilitation technology (for an overview see table 3). Where possible, the authors aim to link training methods to neurophysiologic recovery processes.

Active therapy approaches

To determine the evidence for physical therapy interventions aimed at improving functional outcome after stroke, Van Peppen et al. [27] conducted a systematic literature review including one hundred twenty three randomised controlled clinical trials and

28 controlled clinical trials. They found that treatment focussing only on function level, as does muscle strengthening and/or nerve stimulation, has significant effects on function level but fails to influence the activity level. So, even if e.g. strength is an essential basis for good skill performance [35], more aspects involved in efficient movement strategies need to be addressed in order to train optimal motor control. Active training approaches with most evidence of impact on functional outcome after stroke are: task-oriented training, constrained induced movement therapy and bilateral arm training [27].

Task-oriented training stands for a repetitive training of functional (=skill-related) tasks. Task-oriented training has been clinically tested mostly for training locomotion [34, 36-38] and balance [39]. It is, however, also known to positively affect arm-hand function recovery, motor control and strength in stroke patients [9, 27, 40-46]. The value of task-oriented training is seen in the fact that movement is defined by its environmental context. Patients learn by solving problems that are task-specific, such as anticipatory locomotor adjustments, cognitive processing, and finding efficient goal-oriented movement strategies. Efficient movement strategies are motor strategies used by an individual to master redundant degrees of freedom of his/her voluntary movement so that movement occurs in a way that is as economic as possible for the human body, given the fact that the activity result needs to be achieved to the best of the patient's ability. Training effects are task specific, with reduced effects in untrained tasks that are similar [3, 33, 47, 48]. At the same time, impairments that hinder functional movement are resolved or reduced. All of these aspects contribute to more efficient movement strategies for skill performance [7, 26, 34, 48, 49].

Task-oriented training approaches are consistent with the ICF [22, 50] as function level is addressed, as well as activity and participation level. Task-oriented training is proven to result in a faster and better treatment outcome than traditional methods, like Bobath therapy, in the acute phase after stroke [51]. Without further therapy input however, this differential effect is not maintained, suggesting that training needs to continue beyond the acute phase in order for its positive effect not to deteriorate [52]. *Constrained Induced Movement Therapy (CIMT)* is a specialised task-oriented training approach that has proven to improve arm hand function for stroke patients through several randomised clinical trials involving a large number of patients [53-61]. The effects of CIMT training have been found to persist even 1-2 years after the training was stopped [57]. CIMT comprises several treatment components such as functional training of the affected arm with gradually increasing difficulty levels, immobilisation of the patient's non-affected arm for 90% of waking hours and a focus on the use of the more affected arm in different everyday life activities, guided by shaping [56,62]. Shaping consists of consistent reward of performance, making use of the possibility of operant conditioning [3], which is an implicit or non-declarative learning process through association [63].

A disadvantage of CIMT training is that it requires extensive therapist guidance as well as an intensive patient practise schedule, which present obstacles for its wider acceptance by patients and therapists [64]. Efforts are currently undertaken to further develop automation of CIMT (AutoCITE therapy) [56].

Bilateral arm training includes simultaneous active movement of the paretic and the non-affected arm [65]. Bilateral arm training is a recent training method that, through

randomised clinical trials, has proven to augment range of movement, grip strength and dexterity of the paretic arm [27,65-67].
It still is not fully understood which neurophysiological processes (fig.1) support the positive clinical outcomes of rehabilitation approaches, not even in e.g. CIMT, an approach extensively investigated [3,68]. Sensorimotor integration has been proven to be an important condition for motor learning [69]. Functional neuroimaging studies suggest that increased activity in the ipsilesional sensorimotor and primary motor cortex may play a role in the improvement of functional outcome after task-specific rehabilitation [68,70], such as task-oriented training [71,72] and CIMT [73,74]. Other study results suggest that motor recovery after CIMT training may occur because of a shift of balance in the motor cortical recruitment towards the undamaged hemisphere [68]. The latter rehabilitation-induced gains may be a progression in the cortical processes (e.g. by unmasking existing, less active motor pathways) that support motor recovery in earlier phases after stroke [68]. Alternatively, increased ipsilateral motor cortex involvement may occur because of the subject engaging in more complex or precise movements. Ipsilateral motor cortex involvement may also facilitate compensation strategies for motor performance [68,70]. It is thought that patients who have substantial corticospinal tract damage are more likely to restore sensorimotor functionality by compensation through use of functionally related systems, whereas patients with partial damage are likely to recover through extension of residual areas [70]. Unfortunately, although it is well known that stroke patients may show true recovery as well as behavioural compensation [5], the phasing and interaction of both in any functional recovery process after stroke remains to be clarified. Outcome scales used in clinical rehabilitation trials do not allow the distinction between true recovery (same muscles as before lesion are involved in task performance) and compensation (different muscle coalitions are used for task performance) [3]. Future studies that combine electromyography and neuro-imaging of the central nervous system could shed light on these processes.
Regardless of the therapy approach used, the *training load* should be tailored to individual patient’s capabilities and to treatment goals that are defined prior to training. Training goals can be, e.g. to increase muscle strength, endurance or co-ordination [75,76]. To obtain an improved muscle performance, training load needs to exceed the person’s metabolic muscle capacity (overload principle) [77]. The training load for the patient is determined by the total time spent on therapeutic activity, the number of repetitions, the difficulty of the activity in terms of co-ordination, muscle activity type and resistance load, and the intensity, i.e. number of repetitions per time unit [78, 79]. When, e.g. improvement of muscle strength is the goal of a set of exercises, the training load should be such that fatigue is induced after 6 to 12 exercise repetitions. This training load will be different for different patients and needs to be individually determined. When training muscle endurance or coordination is the goal, many repetitions are used (40-50 or more) against a submaximal load [79]. Distributed practice (a practice schedule with frequent rest periods) and random ordering of task-related exercises improves performance and learning [3, 80]. A good interchange between loading and adequate rest intervals is necessary for the body to recuperate from acute effects of exercise such as muscle fatigue [79]. Also variability in exercises when training a certain task improves retention of learning effects [3].

Training schedules, although very much determinant for training effects, are too often determined on an empirical basis [78].
In line with rehabilitation, rehabilitation technologies should address all levels of the ICF classification. Upper limb skill training should, where possible, happen in an environment that is natural for the specific task that is trained, as motor skills are shown to improve more than when trained out of context [81, 82]. Training programs on offer should support individual training goals by offering a personalized training load [77, 79]. Also, the more differentiated and varied training programs can be offered to the patient, the better retention of learning effects and the higher the chance that a patient can and will choose the one that fits him/her best[3, 35, 49].

Personal goal Setting

Active training approaches allow patients to take an active role in the rehabilitation process. This is especially stimulated when patients can exercise with some self-selected, well-defined and individually meaningful functional goals in mind (goal-directed approach). Personal goal setting encourages patient motivation, treatment adherence and self-regulation processes. It also provides a means for patient progress assessment (are goals attained and to which extent?- or not) and patient-tailored rehabilitation [83-86]. The tasks that are selected to work on, should be within the patient capabilities, so that self-efficacy and problem solving can be stimulated, even though exercising might be difficult initially [85, 87].
A goal-directed approach includes several essential components: 1. selection of patient's goal from a choice that is guided to be "SMART" (= Specific, Measurable, Attainable, Realistic and Time specified), 2. analysis of patient's task performance regarding the selected goal, 3. both identification of the variables that limit patient's performance and identification of patient constraints as a basis of treatment strategy selection, 4. analysis of the intervention and patient's performance leads to structurally offered feedback that supports motor learning (described infra), 5. conscious involvement of the patient to learn from feedback via restoration of cognitive processes that are associated with functional movement, and 6. finding strategies to determine individually which are the most effective solutions [85]. Goal attainment scaling (GAS) is an effective tool for the above described process and evaluation of training outcome. In GAS the patient defines a goal as well as a range of possible outcomes for it on a scale from 0 (expected result) +/-2. This implies that patient's progress is rated relative to the goal set at baseline [85,88]. For more information about goal setting and goal attainment scaling, the authors refer to Kiresuk et al [88].
It should be clear to the patient at every stage of the training which movements support which goals to avoid goal-confusion. To set up the exercise environment in a natural or realistic manner will support the latter [87].
It also is important that technology provides the opportunity for the patient to have an active role in his rehabilitation process through personal treatment goal setting.

Motivation, patient empowerment, gaming and support from friends/family

Overprotection of persons after stroke by family caregivers may lead to more depression and less motivation to engage in physical therapy programs [89]. But also overprotection by the therapist undermines the active role a patient can have in his rehabilitation process [83, 90]. Motor skill learning and retention of motor skills can be enhanced if a patient assumes control over practice conditions, e.g. timing of exercise instructions and feedback [91]. As reflection and attention are both important factors for explicit (declarative) motor learning [63], patients should be able to control that instructions and feedback are offered when they are able to learn from it. A balance has to be found between freedom and guidance to accommodate different stages of learning (cognitive, associative and autonomous stages of learning [92]). Bach-y-Rita et al. [93, 94] supported, through a literature review, the introduction of therapy for persons after stroke that is engaging and motivating in order to obtain patient alertness and full participation that optimises motor (re)learning. Improvement of arm-hand function in case-studies support the use of computer-assisted motivating rehabilitation as an inexpensive and engaging way to train [95] where joy of participation in the training should compensate its hardship [94, 95]. As an increase in therapy time after stroke has been proven to favour ADL outcome [38], it is important that patients are motivated to comply. To stimulate exercise compliance, family support and social isolation are issues to be addressed [96].

Feedback

General

It is important that feedback of exercise performance is given based on motor control knowledge, as this enhances motor learning and positively influences motivation, self-efficacy and compliance [97-100]. Feedback on correct motor performance enhances motivation [80], while feedback on incorrect exercise performance is more effective in facilitating skill improvement [101,102].
Feedback from any skill performance is acquired through task-intrinsic feedback mechanisms and task-extrinsic feedback. Task-intrinsic feedback is provided through visual, tactile, proprioceptive and auditory cues to a person who performs the task. Task-extrinsic feedback or augmented feedback includes verbal encouragement, charts, tones, video camera material, computer generated kinematic characteristics (e.g. avatar)(fig 2).
Brain damage often impairs intrinsic feedback mechanisms of stroke patients, which means that they have to rely more on extrinsic feedback for motor learning. Although rather well understood for healthy subjects, information on the efficiency of augmented feedback in motor skill learning after stroke is scarce [100].
Extrinsic feedback can be categorised as knowledge of results (KR) or knowledge of performance (KP), summary feedback (overview of results of previous trials) or average feedback (average of results of previous trials), bandwidth feedback, qualitative or quantitative feedback and can be given concurrently or at the end of task performance (terminal feedback) (fig 3) [34, 100,103]. KR is externally presented information about out-

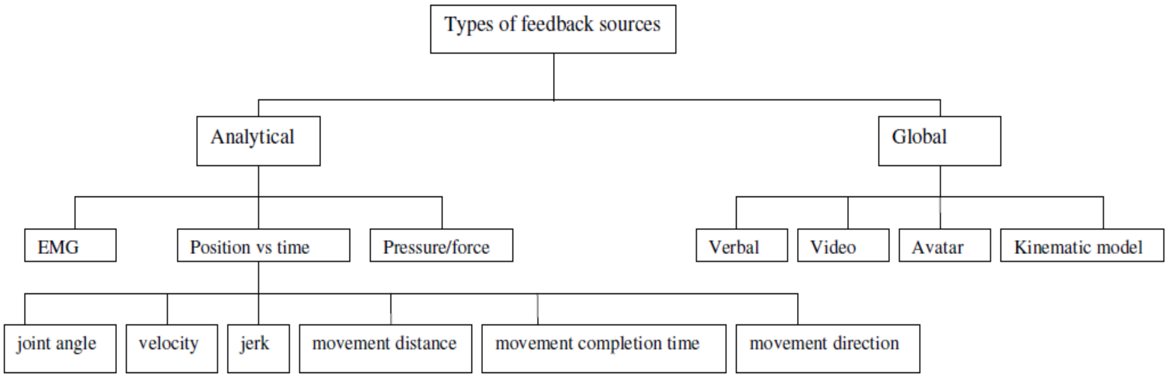

Fig. 2: Schematic presentation of types of augmented feedback sources for motor performance

come of skill performance or about goal achievement. KP is information about movement characteristics that led to the performance [80].
Both kinds of feedback are valuable [102,104,105], although there is some evidence that, for skill learning in general [106,107] and also specifically for persons after stroke [108], the use of KP during repetitive movement practice results in better motor outcomes.
Van Dijk et al [109] performed a systematic literature search to assess effectiveness of augmented feedback (i.e. electromyographic biofeedback, kinetic feedback, kinematic feedback or knowledge of results). They found little evidence for differences in effectiveness amongst the different forms of augmented feedback.

Nature and timing of feedback addresses different stages of motor learning.

Feedback needs to be tailored to the skill level of its receiver. Bandwidth feedback is a useful way of tailoring the feedback frequency to the individual patient, whereby the patients only receive a feedback signal when the amount of error is greater than a preset error range [80].
Beginners need simple information to help them approximate the required movement; more experienced persons need more specific information [100,110]. Novices seem to benefit more from prescriptive KP (stating the error and how to correct it), while for

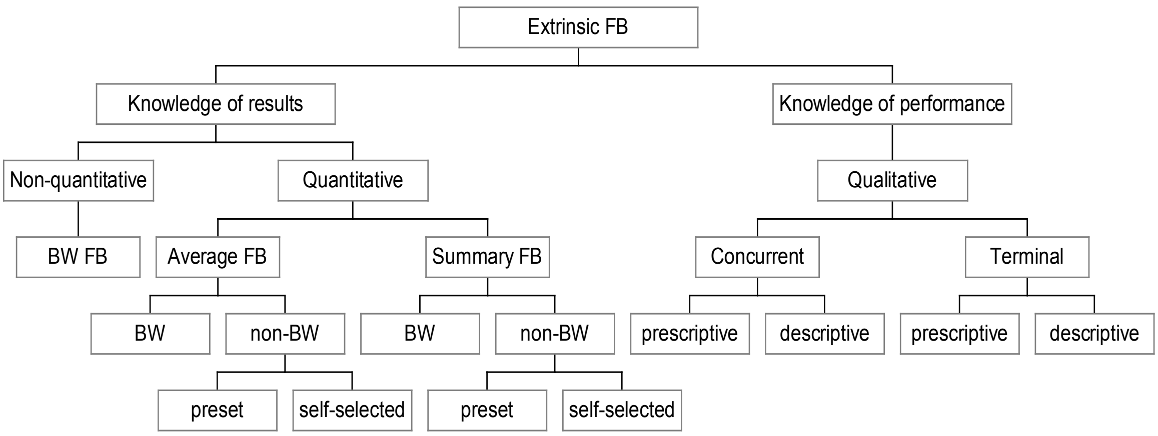

Fig. 3: Schematic presentation of extrinsic feedback components for motor performance (FB=feedback, BW=bandwidth)

more advanced persons descriptive KP (stating the error) seems to suffice [80].
Two major systems in the brain, implicit and explicit learning/memory, can both contribute to motor learning [111]. Prescriptive feedback can make use of declarative or explicit learning processes, resulting in factual knowledge that can be consciously recalled from the long-term memory [34]. Vidoni et al [111] state that "explicit awareness of task characteristics may shape performance". Specific information may be offered as a sequence of 2 or more movement components (such as: keep your trunk stable against the back of your chair, then lower your shoulder girdle, then reach out for the cup, finally concentrate on grasping the cup). Declarative or explicit learning requires attention and awareness to enable information storage in the long-term memory, involving neural pathways from frontal brain areas, hippocampus and medial temporal lobe structures [34,111].
Descriptive feedback (e.g. "concentrate on movement selectivity") assumes that the patient has some experience with performing the movement and has learned by repetition how to correct through implicit or non-declarative learning strategies, such as associative learning (classical and operant conditioning) and/or procedural learning (skills and habits). Non-declarative learning occurs in the cerebellum (movement conditioning), the amygdala (involvement of emotion), and the lateral dorsal premotor areas (association of sensory input with movement). The information is stored in the long-term memory [34, 63].
Choosing appropriate and patient-customised feedback is very complex and depends on the location and the type of the brain lesion [34, 112]. Although frequently used by therapists, the use of declarative instructions/feedback for motor learning is questionable, especially when used in combination with non-declarative instructions/feedback [111,113]. Both learning mechanisms may compete for the use of memory processing capacity [111]. This may be the reason for the finding that feedback that is provided concurrently to movement (as in online feedback) has not been found to support motor learning as the learning effect does not persist after feedback is removed [114]. Also feedback that is given immediately after completion of movement may impede the use of intrinsic feedback for task performance analysis [100,115]. There is no experimental evidence for the optimal feedback delay after movement performance [34,80]. It has been shown that the KR delay should not be filled with other motor or cognitive skills that may interfere with learning of target movements [116,117]. Also the finding that subjective performance evaluation or estimation of specific characteristics of some of the movement-related components of a performed skill before and after KR/KP seem to benefit motor learning [115,118], is in support of these findings. Wulf [91] advocates allowing patients to choose the time of feedback delivery. This gives patients control, which can enhance motivation, potentially improving retention and transfer effects [91].
It seems more effective to give average or summary feedback than to give feedback after each trial [119,120] as the latter discourages variety in learning strategies (e.g. active problem solving-activities), leads to feedback dependency and possibly also to an attention-capacity overload [121]. The optimal number of trials summarised depends on the complexity of the task in relation to the performer's skill level [122]. Progressively reducing the feedback frequency (fading schedule strategy) might have a better retention of learning effects and better transfer effects, as the dependency of the performance on feedback decreases [34,100,120].

In summary, it can be stated that rehabilitation technology should provide both knowledge of results as well as knowledge of performance. A combination of error-based augmented feedback and feedback on correct movement characteristics of the performed movement is advisable to enhance learning and motivation. Active engagement of the patient in the feedback process is to be encouraged, by subjective performance evaluation and using the information for planning the next movement. Careful use of feedback that uses declarative learning is warranted.

Technology supporting training of arm-hand performance after stroke

For upper limb rehabilitation after stroke, two categories of rehabilitation systems will be described: robotic training systems and sensor-based training systems.
A wide variety of systems have been developed. Only those for which clinical data have been presented are discussed in this paper. These technologies may all be further enhanced using virtual reality techniques. However, it is not in the scope of this paper to discuss all virtual reality applications for stroke rehabilitation (for an overview see Sveistrup [123]).
Thirty four studies, involving in total 755 patients, report testing in stroke patients of thirteen arm-hand-training systems. A short description is given for each of these systems. The number of clinical trials will be mentioned for each system, as well as the kind of trial and the total number of patients involved. More information (e.g. on the number of patients involved in each trial and outcome measures that were used) can be found in table 1 and in table 3. For information about the quality aspects of the RCTs that are mentioned, the authors refer to a systematic review by Kwakkel et al [124].

Robotic training systems

Therapeutic robotics development started about 15 years ago at which time scientific evidence supporting rehabilitation approaches was much sparser. This has been a difficulty for development of technological rehabilitation systems in the past [125].
The upper limb robotic systems that exist until today can roughly be classified in passive systems (stabilising limb), active systems (actuators moving limb) and interactive systems [21]. Interactive systems are equipped with actuators as well as with impedance and control strategies to allow reacting on patient actions [21]. The interactive systems can be classified by the degrees of freedom (DOF) in which they allow movement to occur.
Existing interactive one-degree of freedom systems are e.g. Hesse's Bi-Manu-Track, Rolling Pin, Push and Pull [126,127], BATRAC [65] and the Cozens arm robot [128]. These systems are useful for stroke patients with lower functional levels (=proficiency level for skill related movement). Multi-degrees of freedom interactive robotic systems may be useful for patients with lower as well as higher functional levels.
One of the first robotic rehabilitation systems for upper limb training after stroke is **MIT-Manus** developed by Krebs et al [12]. It allows for training wrist, elbow and

shoulder movements by moving to targets, tracing figures and virtual reality task-oriented training. The robot has two degrees of freedom. This enables training at patient function level, improving e.g. movement range and strength. The patient can train in passive, active and interactive (movement triggered or EMG-triggered) training modes. Patients with all levels of muscle strength can use the system. Visual, tactile and auditory feedback during movement is provided [12,125, 129-133]. MIT-Manus has been shown to improve motor function in the hemiparetic upper extremity of acute, subacute and chronic stroke patients in 5 clinical trials (CTs) [130,134-137] and 5 randomized clinical trials (RCTs) [138-142] In total 372 persons were tested. This is close to half of the total number of stroke patients tested in technology-supported arm training trials until the end of 2007.

MIME (Mirror Image Movement Enhancer) [131,143-145] consists of a six degrees of freedom robot manipulator, which applies forces (assistance or resistance as needed) to a patient's hand through a handle that is connected to the end-effector of the robot. This robot treatment focuses on shoulder and elbow function. The MIME system can work in pre-programmed position and orientation trajectories. It can also be used in a configuration where the affected arm is to perform a mirror movement of the movement defined by the intact arm. The forearm can be positioned in a large range of positions and has therefore the possibility to let the patient exercise in complex movement patterns. Four modes of robot-assisted movement are available: passive, active-assisted, active-constrained and bimanual mode. The MIME system has been validated through 1 CT [146] and 3 RCTs [144,145,147], involving 76 chronic stroke patients.

BI-MANU-TRACK is a one degree of freedom system, designed by Hesse et al [126,127,148] to train forearm pro-/supination and wrist flexion/extension. Training is done bilaterally in a passive or active training mode. No feedback is given to the patient. BI-MANU-TRACK has been validated for subacute and chronic stroke patients in two CTs [148, 126] and one RCT [127]. In total 66 persons after stroke were tested.

BATRAC [65] is an apparatus comprising of 2 independent T-bar handles that can be moved by the patient's hands (through shoulder and elbow flexion/extension) in a horizontal plane. Repetitive bilateral arm training is supported by rhythmic cueing and, where necessary, by assistance of movement. No patient feedback is provided. BATRAC has been tested for chronic stroke patients in one CT [65] and one RCT [67]. In total 37 patients were involved.

ARMin [149-152] is a semi-exoskeleton for movement in shoulder (3DOF), elbow (1DOF), forearm (1DOF) and wrist (1DOF). Position, force and torque sensors deliver patient-assistive arm therapy supporting the patient when his/her abilities to move are inadequate. The combination of a haptic system with an audiovisual display is used to present the movement task to the patient. One small-scale CT [153] tested the clinical outcome of arm hand function in 3 chronic stroke patients after training with ARMin.

NeReBot [154, 155] is a 3-degree of freedom robot, comprising of an easy to transport aluminum frame and motor controlled nylon wires. The end of each wire is linked to the patient's arm by means of a rigid orthosis, supporting the forearm. The desired movement is first stored into the system, by moving the patient's arm in a "learning phase" mode . Visual feedback comprises of a graphical interface providing a 3D-image of a virtual upper limb on which 3 arrows show the desired movement direction

during movement. Auditory feedback accompanies the start and end of the exercise. NeReBot has been clinically tested in a RCT [155] involving 35 acute stroke patients.
AJB or Active Joint Brace [156] is a light-weight exoskeletal robotic brace that is controlled by means of surface EMG from affected elbow flexor and extensor muscles. It allows for assistance of movement in the elbow joint (1DOF). No feedback about exercise performance is provided. The AJB has been tested in a small clinical study, involving 6 chronic stroke patients [156].
T-WREX is based on **Java Therapy**, that was developed by Reinkensmeyer et al [132]. T-WREX can train increased range of movement and more degrees of freedom, allowing for more functional exercising than Java Therapy does [19]. An additional orthosis can be used to assist in arm movement across a large, although not fully functional, workspace, with elastic bands to counterbalance arm weight. This makes it suitable for usage by patients with low muscle strength. Position sensors and grip sensors allow feedback on movement [132] and grip force [19]. T-Wrex aims to offer training of e.g. following activities: shopping, cleaning the stove, cracking eggs, washing the arm, eating, making lemonade. Limitations in movement of the shoulder (especially rotations) and forearm (no pro- or supination) cause a discrepancy between functional relevance of the exercise that is instructed and the actual movement that is performed.
Patients and therapists are presented with three types of progress charts:

1. frequency of system usage;
2. performed activity in comparison with customisable target score, average past performance and previous score; and
3. progress overview, which displays a graphical history of the user's scores on a particular activity [19,129,132]. T-Wrex has been validated through a clinical trial, involving 9 chronic stroke patients [19].

UniTherapy [157, 158] is a computer-assisted neurorehabilitation tool for teleassessment and telerehabilitation of the upper extremity function in stroke patients. It makes use of a force-feedback joystick, a modified joystick therapy platform (TheraJoy) and a force-feedback steering wheel (TheraDrive).
Four operational modes are used: assessment mode; passive training mode; interactive mode (interaction with telepractitioner) and bimanual mode (use of two force devices simultaneously).
UniTherapy provides visual and auditive cues in response to success/failure. Although very engaging, UniTherapy offers movement therapy that is not task-oriented. Apart from moving a car steering wheel, as practised in TheraDrive (Driver's SEAT) [159,160], one can question transfer to skilled performance that is needed in everyday life.
UniTherapy has been validated for chronic stroke patients in one CT [160] and one CCT [14], involving a total of 23 patients.
Haptic Master [143] is a three degrees of freedom robot, equipped with force and position sensors, that has been used for training arm movements of stroke patients [161-163]. A robotic wrist joint that provides one additional active and two passive degrees of freedom can extend it. All exercises are performed in a virtual environment. Performance feedback is provided. The therapist can create virtual tasks. Three different therapy modes are implemented: the Patient Passive mode, the Patient Active Assisted mode and the Patient Active Mode. Therapy focuses, among others, on task-oriented

training in a 3D virtual environment, like in the GENTLE/S project (reaching to a supermarket shelf, pouring a drink) [163] or on task-oriented training with real object manipulation as done with ADLER (Activity of Daily Living Exercise Robot) [162]. A limiting factor for task-oriented training is the device's small range of motion. Two clinical trials provide evidence for improvement of arm hand function after use of haptic master training in subacute and chronic stroke patients [161, 163]. In total 46 patients have been tested.
Assisted Rehabilitation and Measurement Guide (ArmGuide) is a 4 degrees of freedom robotic device, developed by Kahn et al [164-167] to provide arm reaching therapy for patients with chronic hemiparesis. An actuator controls the position of the subject's arm, which is coupled to the device through a hand piece. This hand piece slides along a linear track in the reaching direction. Real time visual feedback of the location of the arm (along the track, elevation angles of track, target location) is given to the patient. ArmGuide has been tested in three clinical studies, involving in total 41 chronic stroke patients [164, 166, 167].
Virtual reality-based hand training systems that have been developed by Burdea et al. are **Rutgers Master II glove and Cyber Glove** [15, 168, 169]. Patients practise by doing one to four hand exercise programs through computer games. Each program focuses on different aspects of hand movement: range of movement, speed of movement, individual finger movement or finger strengthening. The exercises are aiming to have a task-oriented component (e.g. grasp virtual ball, piano), but are mostly analytic. Patients receive concurrent haptic feedback, visual feedback and auditory feedback on exercise performance. Also feedback about speed, range, and strength are provided real-time. In total, seven patients were included in two small scale clinical trials [15, 169].

Sensor-based training systems

Bonato [170] addressed the importance of developing wearable miniature monitoring devices, facilitating functional movement assessment in natural settings in an unobtrusive way.
To date, although in full development (e.g. [171-173]), no such systems exist that have been clinically validated.
AutoCITE is a device that has been developed to automate constrained induced movement therapy [174, 175]. It consists of a computer, a chair and 8 task devices (for reaching, tracing, peg board use, supination/pronation, threading, arc-and-rings, finger tapping, and object flipping) that are organised on 4 work surfaces and are contained in a cabinet. The patient is guided through exercise instructions on the computer monitor. Performance variables are measured through built-in sensors [56]. Videoconferencing equipment provides the patient with exercise instruction and bidirectional audio communication between therapist and participant. The patient receives prescriptive and descriptive, concurrent and terminal feedback of performance. Also reinforcing or encouraging feedback is given to address the motivational component of the training. The tool does allow for training at home by the patient, although some (remote) therapist supervision is still needed during training [174,175]. Thirty-four patients are involved in total in one controlled clinical trial and one clinical trial.

Table 1: Overview of sensor technology used in stroke rehabilitation

Name	Body area trained	Sensor-type	PA	FB	TDL	CT, CCT RCT (n patients)	OCM	Phase
Auto CITE (34)	shoulder elbow forearm wrist hand	several sensors built into workstation	CIMT	KR: number of successful repetitions KP Encouragement	1	CCT (27)[56] CT (7)[175]	MAL, WMFT MAL, WMFT JHFT	chronic chronic

Abbreviations: FB= feedback; PA= Physiotherapy Approach; CIMT= constrained induced movement therapy; TDL= therapist dependency level: 0=no, 1=minimal, 2=fully dependent; OCM= outcome measure; CT= clinical trial; CCT= controlled clinical trial; WMFT =Wolf Motor Function Test; MAL= Motor Activity Log.

Discussion: Does technology use current insights in state-of-the-art approaches for motor (re)learning?

There has been a large evolution in rehabilitation technology in the last decade that has created a vast spectrum of new opportunities for patients and therapists. In order to evaluate this progress, strengths and weaknesses of current technology are assessed for each of the criteria that were presented in this paper (for an overview of the criteria, the authors refer to table 2).

Criteria relating to therapy aspects

Addressing function, activity and participation level

Most of rehabilitation technology has been developed based on existing (physical) interaction modes between therapist and patient [131]. Although task-oriented approaches are accepted as beneficial by persons who are involved in development of robotics [152, 162] and are mentioned as a wishful trend for future technology development [97], most rehabilitation systems support analytical training methods (function level). To date, only T-WREX, ADLER, TheraDrive, ARMin and AutoCITE aim to offer task-oriented training for the upper extremity. Reviewing the results of clinical trials on training with robotics, substantial improvements in short-term and long-term strength and analytical upper limb movements have been shown in stroke patients. However, while waiting for more clinical trial results of robotics that include task oriented training, experimental evidence indicates that, to date, robotic upper limb training fails to transfer to improvement of the activity level [19,136,176]. From evidence obtained via functional neuroimaging it is known that functional recovery from stroke is positively influenced by task-specific sensorimotor input through training [72] or everyday use [73,74] of the arm and hand. It seems that the impact of rehabilitation technology on functional outcome may be optimised by offering more chances to the nervous system to experience “real” activity-related sensorimotor input during training of upper limb movement.

In any case, the state-of-the-art robotic upper extremity training in stroke patients can play a very important role in alleviating therapists from administering repetitive analytical exercises and can be useful in combination with other conventional treatment [155]. Hesse [177] advocates robotics as an ideal means of training for severely affected patients where external assistance such as actuator assistance to movement and/or exoskeleton support may overcome problems of muscle weakness. Mildly affected patients do not need such assistance and benefit more from task-oriented training approaches.
Most robotic systems to date focus on the proximal part of the upper limb (MIME, T-Wrex, and ArmGuide). Rutgers Master II focuses exclusively on hand and fingers.
Of the current robotic systems, only ADLER allows for training of the entire arm (shoulder, elbow, forearm, wrist) and hand, which means that for most robotic systems it is difficult to train meaningful upper extremity skills as they occur in every day life [131,176]. The MIT-MANUS team is developing a hand module to complete the existing upper limb robot [125]. MIT-MANUS will be allowing training of the upper extremity over all its joints, although it is not possible to train all joints of the upper extremity at the same time. This implies that training a skill is only possible in some of its broken down components.
Also training in full range of joint motion and with all necessary degrees of freedom is not possible with any of the existing robotic systems; which is, again, a limiting factor of current robotic systems for allowing task-oriented training.
Different robotic systems train different body areas, with different kind of exercises and feedback. Therefore, the concept of Krebs [125] to have a “gym” or exercise room in which patients can use several kinds of robotics to train, or the concept of Johnson [158] to have an “integrated suite of low-cost robotic/computer assistive technologies” is a good approach. This kind of training does practise very essential components of movement, such as muscle strength and range of movement and can be very useful in support of training in a rehabilitation setting. However, this solution is still not offering training of movement strategies that enable learning of skilled arm-hand performance, as is the purpose of task-oriented training. For practical reasons (e.g. patient independence for use) and cost reasons it is also unlikely to become a solution for the home environment.
Sensor-based solutions have potential to offer treatment that may influence impairment, activity and participation level. These possibilities have though not been fully used so far. AutoCITE does provide skill training, albeit, to date, for a limited number of skills (threading, tracing, reaching, object flipping, displacement of pegs), and has proven to influence activity level [175].

Offering environmentally contextual training

Kahn et al [41] found better outcome effects after training chronic stroke patients for reaching movements without use of robotics than for patients who actually practised

with robotics. These findings promote systems that allow training of skills in their natural environment. In this sense, sensor-based solutions can potentially support environmentally contextual training more than robotics do. The robotic system that allows most for environmentally contextual training is ADLER [162], as the hand is left free to allow for object manipulation. This feature is missing in e.g. T-WREX [19] where forces are applied on a handgrip. To provide realistic sensorimotor input and encourage task-related problem solving, robotic systems research may benefit from the use of mixed reality systems (e.g. concept of Edmans et al [178]), where movement sensitive objects and machine vision allow for a virtual reality environment that is steered by "real" object manipulation.
The sensor system AutoCITE allows for object manipulation, although it is limited to chair seated training in front of work surfaces in a cabinet, which may hinder transfer effects to "everyday situations". On the other hand, the progress of seven chronic stroke patients on Motor Activity Log testing after training with AutoCITE as reported by Lum et al does suggest positive effects on everyday life use and usefulness of the affected limb [175].

Inclusion of frequent movement repetition

Robotics are very suitable for facilitating repetitive training in stroke patients with all functional levels [155], which has proven to address brain plasticity and to improve function [9]. For sensor-based solutions, only stroke patients who have a certain level of endurance and muscle strength (should be able to move against gravity) can be instructed to repeat a movement frequently.

Patient and goal-tailored training load & exercise variability

Most robotic systems (especially MIT-Manus, Haptic Master and MIME) are very suitable for delivering a patient-tailored and goal-tailored training load. Actuators can deliver assistance for movement execution where necessary and resistance where possible. This makes robotic systems very valuable for arm and hand function training of patients with lower functional levels. Fine-tuned assistance encourages patients to use all their capabilities to progress movement performance. Such strong feature is absent in sensor-based solutions.
As for training variability, robotics do provide a large variability for analytical exercises. Exercise variability is currently especially limited for stroke patients with higher functional levels, who need more challenge. Also sensor-based solutions, although having a large potential for variability of patient-tailored functional exercises, seem not to have been able to date to actually offer this to patients yet.

Criteria related to motivational aspects

Gaming

All robotic systems described in this paper include gaming aspects in their upper limb rehabilitation for stroke patients. Current sensor-based training systems are (still) focussing mostly on instruction of analytical movement.

Therapist independence

Most of the current technological solutions still need therapist help to attach the technology to the patient, and/or to operate the technology. In practice this means that these technologies can be useful in rehabilitation centres allowing a therapist to supervise several patients at the same time. But as the duration of hospitalisation or stay at

Table 2: Checklist of criteria/guidelines for robotic and sensor rehabilitation technology, based on motor learning principles

Criteria related to therapy approaches
Training should address function, activity and participation levels by offering strength training, task-oriented/CIMT training, bilateral training.
Training should happen in the natural environmental context.
Frequent movement repetition should be included.
Training load should be patient and goal-tailored (differentiating strength, endurance, co-ordination).
Exercise variability should be on offer.
Distributed and random practise should be included.
Criteria related to motivational aspects
Training should include fun & gaming, should be engaging
The active role of the patient in rehabilitation should be stimulated by:
therapist independence on system use.
individual goal setting that is guided to be realistic.
self-control on time of delivery exercise instructions and by feedback that is guided to support motor learning.
control in training protocol: exercise, exercise material, etc.
Criteria related to feedback on exercise performance
KR (average & summary feedback) and KP should be available (objective standardised assessment of exercise per formance is necessity).
Progress Components:
fading frequency schedule (from short to long summary/average lengths)
from prescriptive to descriptive feedback
from general (e.g. sequencing right components) to more specific feedback (range of movement, force application, etc)
from simple to more complex feedback (according to cognitive level).
Empty time slot for performance evaluation before and for planning of next performance after giving feedback.
Guided self-control on timing delivery feedback.
Feedback on error and correct performance.

rehabilitation centre becomes compressed, patients are increasingly left "home alone".

Active role of the patient in rehabilitation

There is strong evidence that specific and difficult goals can improve patient performance [84]. Patient customisation of treatment refers to exercises that are meaningful to the patient [179] and to a training load that is tailored to patient capabilities (percentage of repetition maximum (RM) of the patient [79, 180]) as well as to treatment goals (increase of muscle force, endurance, coordination) [79]. Technology should be able to offer exercises that are close to what the patient prefers to train on [179]. Few applications offer enough exercise variability to support individual goal setting according to individual needs. From the description in the related articles, it cannot be derived which training load (e.g. maximum load that a patient can perform a certain number of times before needing a rest [79, 180]) has been applied and how this has been customised to the patient.

Even when the treatment on offer is patient-customised, the principles that exercise programs are based on should be generic, allowing for inter-individual comparison. Examples of such principles are: a) the method for setting treatment goals (e.g. goal attainment scaling [88]), b) exercise programs that are designed for certain treatment goals [79], and c) the use of uniform and appropriate assessment tools [23, 181, 182]. When these are taken into account, treatment can be evaluated to give adequate patient feedback on individual progress, as well as allowing for clinical research into the effect of customised treatment methods, whether they are technology-supported or not.

Criteria related to feedback on exercise performance

Most technological applications provide good assessment of exercise performance; allowing for objective and valid feedback. It is not always clear from the description in articles how this assessment of performance is used in order to give feedback. Another problem to be identified here is, that most assessment is done at the function level only (UniTherapy, MIT Manus, MIME) and can therefore only be used to limited extent as feedback for skill training.

Most systems provide the patient with feedback, either during exercise performance (MIT Manus) or as terminal feedback (T-WREX, UniTherapy) or both (AUTOCITE, Rutgers Master II & CyberGlove).

Conclusion

In view of the fast developments in rehabilitation technology, it is useful to reflect on guidelines that allow future technologies to offer engaging rehabilitation with optimal training possibilities. This review confirms the commentary of Johnson [97] that technology for supporting upper limb training after stroke needs to align with the evolution in the field of rehabilitation towards functionally oriented approaches that influence function level, activity level and participation level. The review offers an

inventory of points to focus on for development of future and/or adaptation of current rehabilitation technology.
Motor learning may be further improved when feedback progress criteria could be fitted to certain patient types, depending on type and lesion location and to the different phases of motor learning (e.g. as described by Fitts and Possner [92]), thus facilitating feedback delivery most appropriate for the patient.
According to the present literature, it is not yet understood how different rehabilitation approaches contribute to restorative processes of the central nervous system after stroke. A contributing factor to the success of task-oriented approaches may be found in the task-specific sensorimotor input that shapes brain reorganisation in such a way that it can support restitution or substitution of skilled arm hand function. Research, as currently ongoing in, e.g., the EXPLICIT-stroke trials [183-185], will shed more light on training related neurologic changes that are responsible for the improvement of function and activity after stroke.
Although a number of rehabilitation technology approaches show promising results in small-scale studies, it will be interesting to have results from large scale clinical trials. It is advocated that future trials include outcome assessment of arm-hand function on all ICF-levels [23,181, 182] to give evidence for the influence of technology-supported training on skilled arm-hand function and patient participation, as well as on function level. Future trials should also report the patients' goals that are trained on and the individual patient training load and exercise programs that are used in order to allow for comparison between different studies.
Finally it must be mentioned that rehabilitation technology that has not been clinically reported until 2007 and therefore was not reviewed in this study, represents a lot of potential for rehabilitation in the future.

Table 3: Overview of robotics that have proven to be valid through CCTs

Name (n patients tested)	**body area trained**	**modalities**	**DF**	**P-A**	**FB**	**TDL**	**CT, CCT, RCT, (n patients)**	**OCM**	**acute subacute chronic patients**
MIT-Manus (372)	shoulder, elbow, wrist, hand	passive, active, interactive: movement- or emg-triggered	2	A	concurrent FB (visual, tactile, auditory)	2	CT (30) [134]	FM,FIM, MP,MSS	chronic
							CT (30) [135]	MSS,FM,WMFT	chronic
							CT (15) [136]	FM,MP,WMFT, SIS,KM	chronic
							CT(3) [130]	EMG	subacute
							CT(117) [137]	FM, KM	chronic
							RCT(20) [138]	FM,FIM	acute
							RCT (56)[139]	FM,FIM,MSS, MPS	acute
							RCT(12)[140]	AMAT, FM, KM	chronic
							RCT(42)[186]	AS,MRC FM,MSS	chronic
							RCT(47) [142]	FM,KM	chronic

MIME (76)	shoulder, elbow, forearm	passive active-assisted active-constrained bimanual	6	A	none	2	CT (13) [146] RCT (21)[145] RCT (27)[144] RCT (15)[147]	KM FM FM, FIM FM, FIM	chronic chronic chronic subacute
BI-MANU-TRACK (66)	forearm, wrist	bimanual: passive or active	1	A	none	1	CT (10) [148] CT(12) [126] RCT(44)[127]	FM MAS, RMA FM, AS, MRC	subacute chronic subacute
BATRAC (37)	shoulder , elbow	active active assisted	1	A	none	1	CT (16) [65] RCT (21) [67]	FM, WMFT, UMAQS FM, WMFT, UMAQS, fMRI, EMG	chronic chronic
ARM-in (3)	shoulder, elbow, forearm, wrist	active, passive, interactive	6	T (A)	position force	2	CT (3) [153]	FM, KM	chronic
NeReBot (35)	shoulder elbow	active, active assisted, passive	3	A	visual auditory KP	2	RCT (35)[155]	FM MRC, FIM, TCT, MAS	acute
AJB (6)	elbow	active, active assisted	1	A	-	1	CT (6) [156]	FM, MAS	chronic
T-Wrex (9)	shoulder elbow forearm wrist	passive, interactive, active, active-assisted, re-sisted	2	T (A)	position, grip force, coordination, speed	1-2	CT (9) [19]	FM, BBT, MBBT, RFT	chronic
UniTherapy (23)	shoulder, elbow forearm	passive, interac-tive: active, active-assisted, resisted	2	A	terminal FB (visual audi-tory)		CCT (16) [14] CT (7) [160]	FM, KM, EMG FM, KM	chronic chronic
Haptic Master (46)	shoulder, elbow, fo-rearm	passive, interactive: active, active-assisted, resisted	3 +3	T (A)	_	2	CT (31) [163] CT (15)[161]	FM, MAS MRC, KM	chronic subacute
ArmGuide (41)	shoulder	passive, active, active assisted, resisted	4	A	concurrent FB (visual)	2	CT (1) [166] CT (19) [167] RCT (21)[187]	KM RFT, CMM, KM FM, WMFT, RLA	? chronic chronic
RM II (7)	hand	interactive: active, active-resisted		A (T)	terminal KR & KP; concurrent force, auditory visual FB	0	CT (4) [169] CT (3) [15]	KM, JT KM, JT	chronic chronic

Abbreviations: FB= feedback, DF= Degrees of freedom, PA= Physiotherapy Approach, A= Analytical, T= Task-oriented, TDL= therapist dependency level: 0=no, 1=minimal 2=fully dependent, OCM= outcome measure, CT= clinical trial, CCT= controlled clinical trial, RCT= randomized controlled clinical trial, AS=Ashworth Scale, FM=Fugl Meyer Assessment, FIM= Functional Independence Measure, MRC=Medical Research Council motor power score, MSS=Motor Status Scale, MPS=Motor Power Scale, AMAT=Arm Motor Ability Test, WMFT=Wolf Motor Function Test, SIS=Stroke Impact Scale, RMA= Rivermead Motor Assessment, TCT= Trunk Control Test, RFT= Rancho Functional Test, CMM= Chedoke-McMaster test, EMG= electromyography, BBT = Box and Block test, mBBT= modified Box and Block test, JT= Jebson Test, UMAQS= University of Maryland Arm Questionnaire, KM= kinematic information.

Acknowledgements

The research described in this chapter was funded by grants from Philips Research Europe (Media Interaction Department, Eindhoven).
Dr. G. Lanfermann and Dr. S. Winter (Philips Research Europe, Medical Signal Processing Department, Aachen) are acknowledged for their valuable comments on reviewing this chapter.

References

1. American Heart Association. Heart disease and stroke statistics - 2004 update. 2007
2. Truelsen T, Piechowski-Jozwiak B, Bonita R, Mathers C, Bogousslavsky J, Boysen G. Stroke incidence and prevalence in europe: A review of available data. *Eur J Neurol*. 2006;13:581-598
3. Krakauer JW. Motor learning: Its relevance to stroke recovery and neurorehabilitation. *Curr Opin Neurol*. 2006;19:84-90
4. Jacobs KM, Donoghue JP. Reshaping the cortical motor map by unmasking latent intracortical connections. *Science*. 1991;251:944-947
5. Kwakkel G, Kollen B, Lindeman E. Understanding the pattern of functional recovery after stroke: Facts and theories. *Restor Neurol Neurosci*. 2004;22:281-299
6. Duncan P, Studenski S, Richards L, Gollub S, Lai SM, Reker D, Perera S, Yates J, Koch V, Rigler S, Johnson D. Randomized clinical trial of therapeutic exercise in subacute stroke. *Stroke*. 2003;34:2173-2180
7. Malouin F. Assessment and training of locomotion after stroke: Evolving concepts. In: Refshauge Kathryn, ed. *Science-based rehabilitation. Theories into practice.* Edinburgh: Butterworth Heinemann; 2005:185-222.
8. Broeks JG, Lankhorst GJ, Rumping K, Prevo AJ. The long-term outcome of arm function after stroke: Results of a follow-up study. *Disabil Rehabil*. 1999;21:357-364
9. Feys HM, De Weerdt WJ, Selz BE, Cox Steck GA, Spichiger R, Vereeck LE, Putman KD, Van Hoydonck GA. Effect of a therapeutic intervention for the hemiplegic upper limb in the acute phase after stroke: A single-blind, randomized, controlled multicenter trial. *Stroke*. 1998;29:785-792
10. Hoenig H, Sanford JA, Butterfield T, Griffiths PC, Richardson P, Hargraves K. Development of a teletechnology protocol for in-home rehabilitation. *J Rehabil Res Dev*. 2006;43:287-298
11. Tyson S, Turner G. Discharge and follow-up for people with stroke: What happens and why. *Clin Rehabil*. 2000;14:381-392
12. Krebs HI, Hogan N, Aisen ML, Volpe BT. Robot-aided neurorehabilitation. *IEEE Trans Rehabil Eng*. 1998;6:75-87
13. Krebs HI, Dipietro L, Ferraro M, Volpe BT, Hogan,N. Rehabilitation robotics: Performance-based progressive robot-assisted therapy. *Autonomous Robots*. 2003;15:7-20
14. Johnson MJ, Van der Loos HF, Burgar CG, Shor P, Leifer LJ. Experimental results using force-feedback cueing in robot-assisted stroke therapy. *IEEE Trans Neural Syst Rehabil Eng*. 2005;13:335-348
15. Merians AS, Jack D, Boian R, Tremaine M, Burdea GC, Adamovich SV, Recce M, Poizner H. Virtual reality-augmented rehabilitation for patients following stroke. *Phys Ther*. 2002;82:898-915
16. Legg L, Langhorne P. Rehabilitation therapy services for stroke patients living at home: Systematic review of randomised trials. *Lancet*. 2004;363:352-356
17. Legg L, Langhorne P. Therapy-based rehabilitation for stroke patients living at home. *Stroke*. 2004; 35:1022
18. Duncan P, Richards L, Wallace D, Stoker-Yates J, Pohl P, Luchies C, Ogle A, Studenski S. A randomized, controlled pilot study of a home-based exercise program for individuals with mild and moderate stroke. *Stroke*. 1998;29:2055-2060
19. Sanchez RJ, Liu J, Rao S, Shah P, Smith R, Rahman T, Cramer SC, Bobrow JE, Reinkensmeyer DJ. Automating arm movement training following severe stroke: Functional exercises with quantitative feedback in a gravity-reduced environment. *IEEE Trans Neural Syst Rehabil Eng*. 2006;14:378-389
20. Ryan T, Enderby P, Rigby AS. A randomized controlled trial to evaluate intensity of community-based rehabilitation provision following stroke or hip fracture in old age. *Clin Rehabil*. 2006;20:123-131
21. Riener R, Nef T, Colombo G. Robot-aided neurorehabilitation of the upper extremities. *Med Biol Eng Comput*. 2005;43:2-10

22. World Health Organization. Towards a common language for functioning, disability and health: ICF. 2002
23. Salter K, Jutai JW, Teasell R, Foley NC, Bitensky J. Issues for selection of outcome measures in stroke rehabilitation: ICF body functions. *Disabil Rehabil*. 2005;27:191-207
24. Butefisch C, Hummelsheim H, Denzler P, Mauritz KH. Repetitive training of isolated movements improves the outcome of motor rehabilitation of the centrally paretic hand. *J Neurol Sci*. 1995;130:59-68
25. Dobkin BH. Strategies for stroke rehabilitation. *Lancet Neurol*. 2004;3:528-536
26. Shephard RC, J. Bridging the gap between theory and practice. In: Refshauge Kathryn ALaEE, ed. *Science-based rehabilitation - theories into practice*. Edinburgh: Butterworth-Heinemann; 2005:1-13.
27. Van Peppen RP, Kwakkel G, Wood-Dauphinee S, Hendriks HJ, Van der Wees PJ, Dekker J. The impact of physical therapy on functional outcomes after stroke: What's the evidence? *Clin Rehabil*. 2004;18:833-862
28. Sterr A, Szameitat A, Shen S, Freivogel S. Application of the cit concept in the clinical environment: Hurdles, practicalities, and clinical benefits. *Cogn Behav Neurol*. 2006;19:48-54
29. Wade DT. Personal context as a focus for rehabilitation. *Clin Rehabil*. 2000;14:115-118
30. Woldag H, Hummelsheim H. Evidence-based physiotherapeutic concepts for improving arm and hand function in stroke patients: A review. *J Neurol*. 2002;249:518-528
31. Fisher BE, Sullivan KJ. Activity-dependent factors affecting poststroke functional outcomes. *Top Stroke Rehabil*. 2001;8:31-44
32. Teasell R, Bayona N, Salter K, Hellings C, Bitensky J. Progress in clinical neurosciences: Stroke recovery and rehabilitation. *Can J Neurol Sci*. 2006;33:357-364
33. Kwakkel G, Wagenaar R. Therapy impact on functional recovery in stroke rehabilitation: A critical view of the literature. *Physiotherapy*. 1999;13:457
34. Shumway-Cook A . *Motor control. Translating research into clinical practice*. Wolters Kluwer/ Lippincott Williams & Wilkins; 2007.
35. Whitall J. Stroke rehabilitation research: Time to answer more specific questions? *Neurorehabil Neural Repair*. 2004;18:3-8; author reply 9-11
36. Dean CMR, Malouin,F. Task-related circuit training improves performance of locomotor tasks in chronic stroke: A randomized, controlled pilot trial. *Arch Phys Med Rehabil*. 2000;81:409-417
37. Salbach N, Wood-Dauphinee S, Hanley J, Richards C, Cote R. A task-oriented intervention enhances walking distance and speed in the first year post stroke: A randomized controlled trial. *Clin Rehabil*. 2004;18:509-519
38. Kwakkel G, van Peppen R, Wagenaar RC, Wood Dauphinee S, Richards C, Ashburn A, Miller K, Lincoln N, Partridge C, Wellwood I, Langhorne P. Effects of augmented exercise therapy time after stroke: A meta-analysis. *Stroke*. 2004;35:2529-2539
39. Bayouk JB, Leroux,A. Balance training following stroke: Effects of task-oriented exercises with and without altered sensory input. *International Journal of Rehabilitation Research*. 2006;29:51-59
40. Andrews AW, Bohannon RW. Short-term recovery of limb muscle strength after acute stroke. *Arch Phys Med Rehabil*. 2003;84:125-130
41. Kahn LE, Zygman ML, Rymer WZ, Reinkensmeyer DJ. Robot-assisted reaching exercise promotes arm movement recovery in chronic hemiparetic stroke: A randomized controlled pilot study. *J Neuroengineering Rehabil*. 2006;3:12
42. Mathiowetz VWD. Task constraints and functional motor performance of individuals with and without multiple sclerosis. *Ecological Psychology*. 1995;7:99-123
43. Sunderland A, Fletcher D, Bradley L, Tinson D, Hewer RL, Wade DT. Enhanced physical therapy for arm function after stroke: A one year follow up study. *J Neurol Neurosurg Psychiatry*. 1994;57:856-858
44. Sunderland A, Tinson DJ, Bradley EL, Fletcher D, Langton Hewer R, Wade DT. Enhanced physical therapy improves recovery of arm function after stroke. A randomised controlled trial. *J Neurol Neurosurg Psychiatry*. 1992;55:530-535
45. Royal College of Physicians of London. Uk clinical guidelines for stroke - second version. 2004:146

46. Butler AJ, Blanton S, Rowe VT, Wolf SL, Higgins J, Salbach NM, et al. Attempting to improve function and quality of life using the ftm protocol: Case report. *Phys Ther*. 2006:148-156
47. Morrissey MC, Harman EA, Johnson MJ. Resistance training modes: Specificity and effectiveness. *Med Sci Sports Exerc*. 1995;27:648-660
48. van Peppen R, Harmeling-van der Wel B et al. KNGF-richtlijn beroerte. *Nederlands Tijdschrift voor Fysiotherapie*. 2004;114:82
49. Krebs HI, Volpe BT, Ferraro M, Fasoli S, Palazzolo J, Rohrer B, Edelstein L, Hogan N. Robot-aided neurorehabilitation: From evidence-based to science-based rehabilitation. *Top Stroke Rehabil*. 2002;8:54-70
50. World Health Organization. International classification of functioning, disability and health: Icf. 2001
51. Langhammer B, Stanghelle JK. Bobath or motor relearning programme? A comparison of two different approaches of physiotherapy in stroke rehabilitation: A randomized controlled study. *Clin Rehabil*. 2000;14:361-369
52. Langhammer B, Stanghelle JK. Bobath or motor relearning programme? A follow-up one and four years post stroke. *Clin Rehabil*. 2003;17:731-734
53. Wolf SL, Winstein CJ, Miller JP, Taub E, Uswatte G, Morris D, Giuliani C, Light KE, Nichols-Larsen D. Effect of constraint-induced movement therapy on upper extremity function 3 to 9 months after stroke: The excite randomized clinical trial. *Jama*. 2006;296:2095-2104
54. Bonifer NM, Anderson KM, Arciniegas DB. Constraint-induced movement therapy after stroke: Efficacy for patients with minimal upper-extremity motor ability. *Arch Phys Med Rehabil*. 2005;86:1867-1873
55. van der Lee JH, Wagenaar RC, Lankhorst GJ, Vogelaar TW, Deville WL, Bouter LM. Forced use of the upper extremity in chronic stroke patients: Results from a single-blind randomized clinical trial. *Stroke*. 1999;30:2369-2375
56. Taub E, Lum PS, Hardin P, Mark VW, Uswatte G. Autocite: Automated delivery of CI therapy with reduced effort by therapists. *Stroke*. 2005;36:1301-1304
57. Taub E, Uswatte G, King DK, Morris D, Crago JE, Chatterjee A. A placebo-controlled trial of constraint-induced movement therapy for upper extremity after stroke. *Stroke*. 2006;37:1045-1049
58. Tarkka IM, Pitkanen K, Sivenius J. Paretic hand rehabilitation with constraint-induced movement therapy after stroke. *Am J Phys Med Rehabil*. 2005;84:501-505
59. Brogardh C, Sjolund BH. Constraint-induced movement therapy in patients with stroke: A pilot study on effects of small group training and of extended mitt use. *Clin Rehabil*. 2006;20:218-227
60. Hakkennes S, Keating JL. Constraint-induced movement therapy following stroke: A systematic review of randomised controlled trials. *Aust J Physiother*. 2005;51:221-231
61. Teasell RW, Foley NC, Bhogal SK, Speechley MR. An evidence-based review of stroke rehabilitation. *Top Stroke Rehabil*. 2003;10:29-58
62. Taub E, Uswatte G, Mark VW, Morris DM. The learned nonuse phenomenon: Implications for rehabilitation. *Eura Medicophys*. 2006;42:241-256
63. Kandel E, Kupfermann I, Iversen S. Learning and memory. In: Kandel ER SJ, Jessell TM, ed. *Principles of neural science*. New York: McGraw-Hill; 2000:1227-1246.
64. Page SJ, Levine P, Sisto S, Bond Q, Johnston MV. Stroke patients' and therapists' opinions of constraint-induced movement therapy. *Clin Rehabil*. 2002;16:55-60
65. Whitall J, McCombe Waller S, Silver KH, Macko RF. Repetitive bilateral arm training with rhythmic auditory cueing improves motor function in chronic hemiparetic stroke. *Stroke*. 2000;31:2390-2395
66. Chang JJ, Tung WL, Wu WL, Su FC. Effect of bilateral reaching on affected arm motor control in stroke--with and without loading on unaffected arm. *Disabil Rehabil*. 2006;28:1507-1516
67. Luft AR, McCombe-Waller S, Whitall J, Forrester LW, Macko R, Sorkin JD, Schulz JB, Goldberg AP, Hanley DF. Repetitive bilateral arm training and motor cortex activation in chronic stroke: A randomized controlled trial. *Jama*. 2004;292:1853-1861
68. Schaechter JD. Motor rehabilitation and brain plasticity after hemiparetic stroke. *Prog Neurobiol*. 2004;73:61-72

69. Pavlides C, Miyashita E, Asanuma H. Projection from the sensory to the motor cortex is important in learning motor skills in the monkey. *J Neurophysiol*. 1993;70:733-741
70. Rossini PM, Dal Forno G. Neuronal post-stroke plasticity in the adult. *Restor Neurol Neurosci*. 2004;22:193-206
71. Nelles G, Jentzen W, Jueptner M, Muller S, Diener HC. Arm training induced brain plasticity in stroke studied with serial positron emission tomography. *Neuroimage*. 2001;13:1146-1154
72. Jang SH, Kim YH, Cho SH, Lee JH, Park JW, Kwon YH. Cortical reorganization induced by task-oriented training in chronic hemiplegic stroke patients. *Neuroreport*. 2003;14:137-141
73. Liepert J, Uhde I, Graf S, Leidner O, Weiller C. Motor cortex plasticity during forced-use therapy in stroke patients: A preliminary study. *J Neurol*. 2001;248:315-321
74. Wittenberg GF, Chen R, Ishii K, Bushara KO, Eckloff S, Croarkin E, Taub E, Gerber LH, Hallett M, Cohen LG. Constraint-induced therapy in stroke: Magnetic-stimulation motor maps and cerebral activation. *Neurorehabil Neural Repair*. 2003;17:48-57
75. Kerr K. Exercise in rehabilitation. In: Pitt-Brooke Judith HR, Lockwood Jane, Kate Kerr, ed. *Rehabilitation of movement: Theoretical basis of clinical practice*. London: W.B.Saunders; 1998:423-457
76. Mangine RH, TP ; Eldridge VL. Improving strength, endurance, and power. In: Scully RBM, ed. *Physical therapy*. Philadelphia: Lippincott Company; 1989:739-762
77. McArdle WD, Katch FI, Katch VL. *Essentials of exercise physiology*. Philadelphia: Lippincott Williams & Wilkins; 2000
78. Dromerick AW, Lum PS, Hidler J. Activity-based therapies. *NeuroRx*. 2006;3:428-438
79. Kisner C, Colby L. *Therapeutic exercise: Foundations and techniques*. Philadelphia: F.A. Davis Company; 2007
80. Magill R. *Motor learning and control, concepts and applications*. New York: The McGraw-Hill Companies; 2007
81. Ma HI, Trombly CA, Robinson-Podolski C. The effect of context on skill acquisition and transfer. *Am J Occup Ther*. 1999;53:138-144
82. Wu C, Trombly CA, Lin K, Tickle-Degnen L. A kinematic study of contextual effects on reaching performance in persons with and without stroke: Influences of object availability. *Arch Phys Med Rehabil*. 2000;81:95-101
83. Pomeroy V. Facilitating independence, motivation and motor learning. *Physiotherapy*. 2007
84. Levack WM, Taylor K, Siegert RJ, Dean SG, McPherson KM, Weatherall M. Is goal planning in rehabilitation effective? A systematic review. *Clin Rehabil*. 2006;20:739-755
85. Mastos M, Miller K, Eliasson AC, Imms C. Goal-directed training: Linking theories of treatment to clinical practice for improved functional activities in daily life. *Clin Rehabil*. 2007;21:47-55
86. Siegert RJ, McPherson KM, Taylor WJ. Toward a cognitive-affective model of goal-setting in rehabilitation: Is self-regulation theory a key step? *Disabil Rehabil*. 2004;26:1175-1183
87. Gentile AM. Skill acquisition: Action, movement, and neuromotor processes. In: Carr JS, R, ed. *Movement science. Foundations for physical therapy in rehabilitation*. Gaithersburg,Maryland: Aspen Publishers,Inc; 2000:111-187
88. Kiresuk T, Smith A, Cardillo J. *Goal attainment scaling: Applications, theory, and measurement*. Hillsdale, New Jersey: Lawrence Erlbaum Associates, Publishers; 1994
89. Thompson SC, Galbraith M, Thomas C, Swan J, Vrungos S. Caregivers of stroke patient family members: Behavioral and attitudinal indicators of overprotective care. *Psychology and Health*. 2002;17:297-312
90. Maclean N, Pound P, Wolfe C, Rudd A. Qualitative analysis of stroke patients' motivation for rehabilitation. *Bmj*. 2000;321:1051-1054
91. Wulf G. Self-controlled practice enhances motor learning: Implications for physiotherapy. *Physiotherapy*. 2007; 93,2:96-101
92. Fitts PP, MI. *Human performance*. Belmont,CA: Brooks/Cole; 1967
93. Bach-y-Rita P. Theoretical and practical considerations in the restoration of function after stroke. *Top Stroke Rehabil*. 2001;8:1-15
94. Bach-y-Rita PW, Leder R, Paredes O, Bahr D, Bach-y-Rita E, Murillo N. Rehabilitation (CAMR) for institutional, home, and educational late stroke programs. *Top Stroke Rehabil*. 2002;8:1-10

95. Wood S, Bach-y-Rita P, Leder R, Marks J, Page S. Motivating, game-based rehabilitation: A brief report. *Top Stroke Rehabil*. 2003;10:134-140
96. Gordon NF, Gulanick M, Costa F, Fletcher G, Franklin BA, Roth EJ, Shephard T. Physical activity and exercise recommendations for stroke survivors: An american heart association scientific statement from the council on clinical cardiology, subcommittee on exercise, cardiac rehabilitation, and prevention; the council on cardiovascular nursing; the council on nutrition, physical activity, and metabolism; and the stroke council. *Stroke*. 2004;35:1230-1240
97. Johnson MJ. Recent trends in robot-assisted therapy environments to improve real-life functional performance after stroke. *J Neuroengineering Rehabil*. 2006;3:29
98. Annesi JJ. Effects of computer feedback on adherence to exercise. *Percept Mot Skills*. 1998;87:723-730
99. Jones F. Strategies to enhance chronic disease self-management: How can we apply this to stroke? *Disabil Rehabil*. 2006;28:841-847
100. van Vliet PM, Wulf G. Extrinsic feedback for motor learning after stroke: What is the evidence? *Disabil Rehabil*. 2006;28:831-840
101. Lintern G. Transfer of landing skill after training with supplementary visual cues. *Hum Factors*. 1980;22:81-88
102. Wallace S. Knowledge of performance and the learning of a closed motor skill. *Research Quarterly*. 1979;50:265-271
103. Carr J, Shephard R. *Stroke rehabilitation. Guidelines for exercise and training to optimize motor skill.* Edinburgh: Butterworth Heinemann. Elsevier Science Limited.; 2003
104. Bilodeau E, Schumsky D. Some effects of introducing and withdrawing knowledge of results early and late in practice. *Journal of Experimental Psychology*. 1959;58:142-144
105. Silverman S, Subramaniam P. Feedback and practice in physical education: Interrelationships with task structures and student skill level. *J Human Mov Stud*. 1999;36:203-224
106. Kernodle MW, Carlton LG. Information feedback and the learning multiple-degree-of-freedom activities. *J Mot Behav*. 1992;24:187-196
107. Zubiaur M, Ona A, Delgado J. Learning volleyball serves: A preliminary study of the effects of knowledge of performance and of results. *Percept Mot Skills*. 1999;89:223-232
108. Cirstea CM, Ptito A, Levin MF. Feedback and cognition in arm motor skill reacquisition after stroke. *Stroke*. 2006;37:1237-1242
109. van Dijk H, Jannink MJ, Hermens HJ. Effect of augmented feedback on motor function of the affected upper extremity in rehabilitation patients: A systematic review of randomized controlled trials. *J Rehabil Med*. 2005;37:202-211
110. Gentile AM. Skill acquisition: Action, movement and neuromotor processes. In: Carr J and Shepherd R, ed. *Movement science: Foundations for physical therapy in rehabilitation.* London: Heinemann Physiotherapy; 1987.
111. Vidoni ED, Boyd LA. Achieving enlightenment: What do we know about the implicit learning system and its interaction with explicit knowledge? *J Neurol Phys Ther*. 2007;31:145-154
112. Boyd LA, Winstein CJ. Impact of explicit information on implicit motor-sequence learning following middle cerebral artery stroke. *Phys Ther*. 2003;83:976-989
113. Boyd L, Winstein C. Explicit information interferes with implicit motor learning of both continuous and discrete movement tasks after stroke. *J Neurol Phys Ther*. 2006;30:46-57; discussion 58-49
114. Verschueren SM, Swinnen SP, Dom R, De Weerdt W. Interlimb coordination in patients with parkinson's disease: Motor learning deficits and the importance of augmented information feedback. *Exp Brain Res*. 1997;113:497-508
115. Swinnen S, Nicholson D, Shapiro D. Information feedback for skill acquisition: Instantaneous knowledge of results degrades learning. *J Exp Psychol*. 1990;16:706-716
116. Marteniuk RG. Information processes in movement learning: Capacity and structural interference. *Journal of Motor Behavior*. 1986;5:249-259
117. Swinnen SP. Interpolated activities during the knowledge of results delay and postknowledge of results interval: Effects of performance and learning. *J Exp Psychol Learn Mem Cogn*. 1990;16:692-705

118. Liu J, Wrisberg CA. The effect of knowledge of results delay and the subjective estimation of movement form on the acquisition and retention of a motor skill. *Res Q Exerc Sport*. 1997;68:145-151
119. Wulf G, Schmidt R, Deubel H. Reduced feedback frequency enhances generalized motor program learning but not parameterization learning. *J Exp Psychol Learn Mem Cogn*. 1993;19:1134-1150
120. Winstein C, Schmidt R. Reduced frequency of knowledge of results enhances motor skill learning. *J Exp Psychol Learn Mem Cogn*. 1990;16:677-691
121. Winstein CJ, Pohl PS, Lewthwaite R. Effects of physical guidance and knowledge of results on motor learning: Support for the guidance hypothesis. *Res Q Exerc Sport*. 1994;65:316-323
122. Guadagnoli MA, Dornier LA, Tandy RD. Optimal length for summary knowledge of results: The influence of task-related experience and complexity. *Res Q Exerc Sport*. 1996;67:239-248
123. Sveistrup H. Motor rehabilitation using virtual reality. *J. NeuroEng Rehabil*. 2004;1:1-8
124. Kwakkel G, Kollen BJ, Krebs HI. Effects of robot-assisted therapy on upper limb recovery after stroke: A systematic review. *Neurorehabil Neural Repair*. 2008;22:111-121
125. Krebs HI. Robot-mediated movement therapy: A tool for training and evaluation. *European Symposium Technical Aids for Rehabilitation – TAR 2007*. 2007
126. Hesse S, Schulte-Tigges G, Konrad M, Bardeleben A, Werner C. Robot-assisted arm trainer for the passive and active practice of bilateral forearm and wrist movements in hemiparetic subjects. *Arch Phys Med Rehabil*. 2003;84:915-920
127. Hesse S, Werner C, Pohl M, Rueckriem S, Mehrholz J, Lingnau ML. Computerized arm training improves the motor control of the severely affected arm after stroke: A single-blinded randomized trial in two centers. *Stroke*. 2005;36:1960-1966
128. Cozens JA. Robotic assistance of an active upper limb exercise in neurologically impaired patients. *IEEE Trans Rehabil Eng*. 1999;7:254-256
129. Carignan CR, Krebs HI. Telerehabilitation robotics: Bright lights, big future? *J Rehabil Res Dev*. 2006;43:695-710
130. Dipietro L, Ferraro M, Palazzolo JJ, Krebs HI, Volpe BT, Hogan N. Customized interactive robotic treatment for stroke: EMG-triggered therapy. *IEEE Trans Neural Syst Rehabil Eng*. 2005;13:325-334
131. Lum P, Reinkensmeyer D, Mahoney R, Rymer WZ, Burgar C. Robotic devices for movement therapy after stroke: Current status and challenges to clinical acceptance. *Top Stroke Rehabil*. 2002;8:40-53
132. Reinkensmeyer DJ, Pang CT, Nessler JA, Painter CC. Web-based telerehabilitation for the upper extremity after stroke. *IEEE Trans Neural Syst Rehabil Eng*. 2002;10:102-108
133. Krebs HI, Ferraro M, Buerger SP, Newbery MJ, Makiyama A, Sandmann M, Lynch D, Volpe BT, Hogan N. Rehabilitation robotics: Pilot trial of a spatial extension for mit-manus. *J Neuroengineering Rehabil*. 2004;1:5
134. Ferraro M, Palazzolo JJ, Krol J, Krebs HI, Hogan N, Volpe BT. Robot-aided sensorimotor arm training improves outcome in patients with chronic stroke. *Neurology*. 2003;61:1604-1607
135. Macclellan L, Bradham D, Whitall J, Wilson P, Ohlhoff J, Meister C, Hogan N, Krebs HI, Bever C. Robotic upper extremity neurorehabilitation in chronic stroke patients. *Journal of Rehabilitation Research and Development*. 2005;42:717-722
136. Finley MA, Fasoli SE, Dipietro L, Ohlhoff J, Macclellan L, Meister C, Whitall J, Macko R, Bever CT, Krebs HI, Hogan N. Short-duration robotic therapy in stroke patients with severe upper-limb motor impairment. *J Rehabil Res Dev*. 2005;42:683-692
137. Dipietro L, Krebs HI, Fasoli SE, Volpe BT, Stein J, Bever C, Hogan N. Changing motor synergies in chronic stroke. *J Neurophysiol*. 2007;98:757-768
138. Aisen ML, Krebs HI, Hogan N, McDowell F, Volpe BT. The effect of robot-assisted therapy and rehabilitative training on motor recovery following stroke. *Arch Neurol*. 1997;54:443-446
139. Volpe BT, Krebs HI, Hogan N, Edelstein L, Diels C, Aisen ML. A novel approach to stroke rehabilitation: Robot-aided sensorimotor stimulation. *Neurology*. 2000;54:1938-1944
140. Daly JJ, Hogan N, Perepezko EM, Krebs HI, Rogers JM, Goyal KS, Dohring ME, Fredrickson E, Nethery J, Ruff RL. Response to upper-limb robotics and functional neuromuscular stimulation following stroke. *J Rehabil Res Dev*. 2005;42:723-736

141. Fasoli SE, Krebs HI, Hogan N. Robotic technology and stroke rehabilitation: Translating research into practice. *Top Stroke Rehabil*. 2004;11:11-19
142. Stein J, Krebs HI, Frontera WR, Fasoli SE, Hughes R, Hogan N. Comparison of two techniques of robot-aided upper limb exercise training after stroke. *Am J Phys Med Rehabil*. 2004;83:720-728
143. Loureiro RA, Topping M, Driessen B, Harwin W. Upper limb robot mediated stroke therapy - gentle/s approach. *Autonomous Robots*. 2003;15:35-51
144. Lum PS, Burgar CG, Shor PC, Majmundar M, Van der Loos M. Robot-assisted movement training compared with conventional therapy techniques for the rehabilitation of upper-limb motor function after stroke. *Arch Phys Med Rehabil*. 2002;83:952-959
145. Burgar CG, Lum PS, Shor PC, Machiel Van der Loos HF. Development of robots for rehabilitation therapy: The palo alto va/stanford experience. *J Rehabil Res Dev*. 2000;37:663-673
146. Lum PS, Burgar CG, Shor PC. Evidence for improved muscle activation patterns after retraining of reaching movements with the mime robotic system in subjects with post-stroke hemiparesis. *IEEE Trans Neural Syst Rehabil Eng*. 2004;12:186-194
147. Lum PS, Burgar CG, Van der Loos M, Shor PC, Majmundar M, Yap R. Mime robotic device for upper-limb neurorehabilitation in subacute stroke subjects: A follow-up study. *J Rehabil Res Dev*. 2006;43:631-642
148. Hesse S, Werner C, Schonhardt EM, Bardeleben A, Jenrich W, Kirker SG. Combined transcranial direct current stimulation and robot-assisted arm training in subacute stroke patients: A pilot study. *Restor Neurol Neurosci*. 2007;25:9-15
149. Nef T, Mihelj M, Riener R. Armin: A robot for patient-cooperative arm therapy. *Med Biol Eng Comput*. 2007;45:887-900
150. Dobkin BH. Confounders in rehabilitation trials of task-oriented training: Lessons from the designs of the excite and scilt multicenter trials. *Neurorehabil Neural Repair*. 2007;21:3-13
151. Mihelj M, Nef T, Riener R. Armin - toward a six dof upper limb rehabilitation robot. *IEEE/RAS-EMBS International Conference on Biomedical Robotics and Biomechatronics*. 2006
152. MIhelj M, Riener R. Armin ii - 7 dof rehabilitation robot: Mechanisms and kinematics. *IEEE International conference on Robotics and Automation*. 2007;FrC8.1:4120-4125
153. Nef TM M, Kiefer G, Perndl C, Muller R, Riener R. Armin- exoskeleton for arm therapy in stroke patients. *IEEE 10th International Conference on Rehabilitation Robotics*. 2007:68-74
154. Fanin C, Gallina P, Rossi A, Zannatta U, Masiero S. Nerebot: A wire-based robot for neurorehabilitation. *8th International Conference of Rehabilitation Robotics ICORR*. 2003:23-27
155. Masiero S, Celia A, Rosati G, Armani M. Robotic-assisted rehabilitation of the upper limb after acute stroke. *Arch Phys Med Rehabil*. 2007;88:142-149
156. Stein J, Narendran K, McBean J, Krebs K, Hughes R. Electromyography-controlled exoskeletal upper-limb-powered orthosis for exercise training after stroke. *Am J Phys Med Rehabil*. 2007;86:255-261
157. Feng X, Johnson M, Johnson L, Winters J. A suite of computer-assisted techniques for assessing upper-extremity motor impairments. *Conf Proc IEEE Eng Med Biol Soc*. 2005;7:6867-6870
158. Johnson MJ, Feng X, Johnson LM, Winters JM. Potential of a suite of robot/computer-assisted motivating systems for personalized, home-based, stroke rehabilitation. *J Neuroengineering Rehabil*. 2007;4:6
159. Johnson MJ, Trickey M, Brauer E, Feng X. Theradrive: A new stroke therapy concept for home-based, computer-assisted motivating rehabilitation. *Conf Proc IEEE Eng Med Biol Soc*. 2004;7:4844-4847
160. Johnson MJ, Ramachandran B, Paranjape RP, Kosasih JB. Feasibility study of theradrive: A low-cost game-based environment for the delivery of upper arm stroke therapy. *Conf Proc IEEE Eng Med Biol Soc*. 2006;1:695-698
161. Seelen HAM, Geers RPJ, Soede M, Spauwen LWL. Training of arm-hand kinaesthetics in subacute stroke patients using robotics. *Journal of Biomechanics*. 2007;40:S645
162. Johnson M, Anderson J, Nathan D, Smith RO. Development of ADLER: The activities of daily living exercise robot. *BioRob2006. The first IEEE/RAS-EMBS International Conference on Biomedical Robotics and Biomechatronics*. 2006:881-886

163. Amirabdollahian F, Loureiro R, Gradwell E, Collin C, Harwin W, Johnson G. Multivariate analysis of the fugl-meyer outcome measures assessing the effectiveness of gentle/s robot-mediated stroke therapy. *J Neuroengineering Rehabil*. 2007;4:4
164. Kahn LE, Rymer,W, Reinkensmeyer D. Effect of robot-assisted and unassisted exercise on functional reaching in chronic stroke hemiparesis. *23rd EMBS International Conference*. 2001
165. Kahn LE, Reinkensmeyer DJ. Selection of robotic therapy algorithms for the upper extremity in chronic stroke: Insights from mime and arm guide results. *ICORR Conference*. 2003
166. Kahn LE, Rymer WZ, Reinkensmeyer DJ. Adaptive assistance for guided force training in chronic stroke. *Conf Proc IEEE Eng Med Biol Soc*. 2004;4:2722-2725
167. Kahn LE, Lum PS, Rymer WZ, Reinkensmeyer DJ. Robot-assisted movement training for the stroke-impaired arm: Does it matter what the robot does? *J Rehabil Res Dev*. 2006;43:619-630
168. Burdea G, Popescu V, Hentz V, Colbert K. Virtual reality-based orthopedic telerehabilitation. *IEEE Trans Rehabil Eng*. 2000;8:430-432
169. Boian RS, A. ; Han,C. ; Merians,A. ; Burdea,C. ; Adamovich,D. ; Recce,M. ; Tremaine,M. ; Poizner,H. Virtual reality-based post-stroke hand rehabilitation. *Medicine Meets Virtual Reality 2002 Conference*. 2002:64-70
170. Bonato P. Advances in wearable technology and applications in physical medicine and rehabilitation. *J Neuroengineering Rehabil*. 2005;2:2
171. Mountain GW, Hammerton, J, Mawson S.J, Zheng H, Davies R, Black N, Zhou H, Hu H, Harris N; Eccleston C. The smart project: A user led approach to developing and testing technological applications for domiciliary stroke rehabilitation. In: Robinson P, ed. *Designing accessible technology*. London: Springer; 2006
172. Willmann RL, Lanfermann G, Saini P, Timmermans A, TeVrugt J, Winter S. Home stroke rehabilitation for the upper limbs. *EMBC 2007; 29th Ann. Int. Conf. IEEE Engineering in Medicine and Biology Society*. 2007:4015-4018
173. Lanfermann G, Willmann R, te Vrugt J, Timmermans,A, Bongers E, Lambert N, van Acht,V ;. Philips stroke rehabilitation exerciser. *Technical Aids for Rehabilitation - TAR 2007*. 2007
174. Lum PS, Taub E, Schwandt D, Postman M, Hardin P, Uswatte G. Automated constraint-induced therapy extension (autocite) for movement deficits after stroke. *J Rehabil Res Dev*. 2004;41:249-258
175. Lum PS, Uswatte G, Taub E, Hardin P, Mark VW. A telerehabilitation approach to delivery of constraint-induced movement therapy. *J Rehabil Res Dev*. 2006;43:391-400
176. Prange GB, Jannink MJ, Groothuis-Oudshoorn CG, Hermens HJ, Ijzerman MJ. Systematic review of the effect of robot-aided therapy on recovery of the hemiparetic arm after stroke. *J Rehabil Res Dev*. 2006;43:171-184
177. Hesse S. What does the clinician expect from machines and robots in neurorehabilitation? *European Symposium Technical Aids for Rehabilitation – TAR 2007*. 2007
178. Edmans JA, Gladman JR, Walker M, Sunderland A, Porter A, Fraser DS. Mixed reality environments in stroke rehabilitation: Development as rehabilitation tools. *5th International Conference of Disability, Virtual Reality & Assoc. Tech. (ICDVRAT)*. 2004
179. Timmermans AAA, Seelen HAM, Willmann RD, Bakx W, de Ruyter B, Lanfermann G, Kingma H. Arm and hand skills: Training preferences after stroke. *Disabil. Rehabil*. 2009; 31 (16): 1344-1352.
180. Delorme TL, Watkins AL. Technics of progressive resistance exercise. *Arch Phys Med Rehabil*. 1948;29:263-273
181. Salter K, Jutai JW, Teasell R, Foley NC, Bitensky J, Bayley M. Issues for selection of outcome measures in stroke rehabilitation: Icf activity. *Disabil Rehabil*. 2005;27:315-340
182. Salter K, Jutai JW, Teasell R, Foley NC, Bitensky J, Bayley M. Issues for selection of outcome measures in stroke rehabilitation: Icf participation. *Disabil Rehabil*. 2005;27:507-528
183. van Kordelaar J, Nijland R, van Wegen EEH, et al. Investigating behavioral strategies underlying recovery of the upper paretic limb after stroke: The explicit - stroke program. *Ageing, 3rd Dutch-UK Rehabilitation Meeting*. 2008
184. van der Krogt JM, Klomp A, Meskers CGM, et al. Understanding neuromechanics in post-stroke recovery: The explicit-stroke program. *Ageing: 3rd Dutch-UK Rehabilitation Meeting*. 2008

185. van Wegen EEH, van Kordelaar J, Nijland R, van de Krogt JM, Meskers CGM, van Kuijk A, Bakker C, Buma F, Visser-Meily JMA, Geurts AC, Lindeman E, Arendzen JH, Kwakkel G. Explaining plasticity after stroke. *Ageing: 3rd Dutch-UK Rehabilitation Meeting*. 2008
186. Fasoli SE, Krebs HI, Stein J, Frontera WR, Hughes R, Hogan N. Robotic therapy for chronic motor impairments after stroke: Follow-up results. *Arch Phys Med Rehabil*. 2004;85:1106-1111
187. Fischer H, Kahn LE, Pelosin E, Roth H, Barbas J, Rymer WZ, Reinkensmeyer D. Can robot-assisted therapy promote generalization of motor learning following stroke?: Preliminary results. *BioRob*. 2006:865-868

Chapter 3

Influence of task-oriented training content on skilled arm-hand performance in stroke: a systematic review

Timmermans A, Spooren A, Kingma H, Seelen H. Influence of task-oriented training content on skilled arm-hand performance in stroke: a systematic review. *Neurorehabil Neural Repair*. 2010. In press

Abstract

Objective: This review evaluates the underlying training components currently used in task-oriented training and assesses the effects of these components on skilled arm-hand performance in patients after a stroke.
Methods: A computerized systematic literature search in 5 databases (PubMed, CINAHL, EMBASE, PEDro, and Cochrane) identified randomized clinical trials, published until March 2009, evaluating the effects of task-oriented training. Relevant article references listed in included publications were also screened. The methodological quality of the selected studies was assessed with the Van Tulder Checklist. For each functional outcome measure used, the effect size (bias corrected Hedges's g) was calculated.
Results: The intervention results in 528 patients (16 studies) were studied. From these, fifteen components were identified to characterize task-oriented training. An average of 7.8 (SD=2.1) components were used in the included trials. There was no correlation between the number of task-oriented training components used in a study and the treatment effect size. 'Distributed practice' and 'feedback' were associated with the largest post-intervention effect sizes. 'Random practice' and 'use of clear functional goals' were associated with the largest follow-up effect sizes.
Conclusion: The task-oriented training approach was operationalized with 15 components. The number of components used in an intervention aimed at improving arm-hand performance after stroke was not associated with the post-treatment effect size. Certain components, which optimize storage of learned motor performance in the long-term memory, occurred more in studies with larger treatment effects.

Introduction

Stroke leaves approximately 50 % of its survivors disabled as to arm-hand performance, often for the rest of their lives [1, 2]. With stroke incidence and prevalence increasing [3], arm-hand performance problems are likely to occur more frequent and enlarge the burden on the health system substantially in the next decades.
Rehabilitation after stroke has evolved in the last 15 years from analytical training approaches to task-oriented training approaches that involve training of 'basic functions', 'skills' and 'endurance (at a muscular and cardiovascular level)' [4]. The task-

oriented training approach matches patient training preferences [5] and has been proven to be effective for the improvement of skilled arm-hand performance after stroke [6, 7]. However, French et al [8] did not find supporting evidence for repetitive task training of the paretic upper limb.
'Task-oriented training' is, to date, a poorly defined concept. For occupational therapy, Legg et al [9] mention that the exact nature of a successful intervention is vague and the same holds for task-oriented training specifically. Studies reporting on 'task training' of the upper extremity after stroke use different intervention durations and intensities, and include different kinds of interventions which makes comparison of their treatment effects difficult. Some studies consider the instruction of single-joint and/or single-plane movements to be task-oriented (e.g. reaching, pointing) [10]; whereas other studies consider task-oriented training to focus on meaningful complex movements with real life object manipulation in a real life environment[11]. This finding emphasizes the need for an operationalization of task-oriented training to define its key characteristics.
Training may consist of different training components, used in several unique combinations. In this chapter, a 'training component' refers to a task-oriented training characteristic with a specific effect on motor learning. For example, 'random practice' is a training component that has proven to have positive effects on retention of learned motor actions [12, 13].
In order to optimize training programs, it is important that components of task-oriented training are identified and that their importance for task-oriented training effects is known so they can be used in evidence-based therapies by clinicians and patients. While the merit of most training components for motor learning has been scientifically investigated in isolated studies, it is unknown what the relative importance is of the components for post-intervention and follow-up effect sizes. The authors of the current paper hypothesize that the success of task-oriented training may, next to factors like intensity [14-16] and duration of training [17], depend on the use of specific ' training components'.
For future interventions, it is also interesting to know if training effects are larger if more components are used in an intervention. It is possible that 'more is better' because training effects caused by individual components add up.
The main objective of this review is

1. to identify task-oriented components that have been used for task-oriented training in randomized clinical trials,
2. to investigate if a relation exists between the number of task-oriented components used in a training intervention and the treatment effect size (ES) of the training intervention and
3. to investigate the influence of each task-oriented arm training component on the functional outcome, i.e. skill or activity level.

Methods

Literature search strategy

The systematic review is based on articles published until March 2009 that were selected after a computerized search strategy in the following databases: PubMed, EMBASE, CINAHL, PEDro and Cochrane. The following Medical Subject Headings (MeSH) were used: *("stroke") AND (("exercise movement techniques" OR "occupational therapy" OR "task performance and analysis" OR "exercise therapy" OR "exercise")) AND ("clinical trial") AND ("upper extremity" OR ("activities of daily living" NOT "lower extremity") OR ("motor skills" OR "motor skill disorders"))*. The abstracts were screened by two independent reviewers (AT & AS). In case of disagreement, the opinion of a third reviewer (MM) was asked. Only references that fulfilled inclusion criteria were selected for further analysis and use in this review.
In addition to the database search, articles in the selected papers' reference list that were found to be relevant were checked.

Eligible studies

Inclusion criteria were:

1. The study described should be a randomized clinical trial (RCT),
2. At least one condition of the trial had to include active task-oriented arm-hand training in (hemorrhagic or ischemic) stroke patients. Constraint-induced movement therapy (CIMT) trials were not considered for the present systematic review, because of the lack of comparability with the included trials, since CIMT is characterized by constraining the non-paretic arm and focuses on practice by the affected arm only (the non-affected arm may serve as a support). Much of the CIMT practice can, however, be considered task-oriented[18] and for activities that are important to the patient, can induce cortical reorganization[19],
3. The task-oriented training should be well described in the article (general descriptions like 'occupational therapy' and 'physiotherapy' were not included as they could not be used for training component identification),
4. The studies should use outcome measures at activity level by means of a) registration of kinematic parameters measured during skilled arm-hand performance, or b) arm-hand performance tests on activity level,
5. Articles had to be written in Dutch, French, English or German,
6. A minimum of 10 stroke patients had to be included

Identification of task-oriented training type

Two reviewers (AT, AS) independently identified fifteen training components. Interrater reliability of individual components that were matched to a training intervention

was tested with Cohen's kappa statistic (SPSS). The results of both researchers were compared and consensus was reached after discussion on the differences.
It was agreed to use the following components to mark the interventions that were described in the included articles, namely the exercises presented can be:

1. functional,
2. directed towards a clear functional or everyday life activity (ADL) goal [20],
3. client-centred [21],
4. repeated frequently (over learning [22] and overload [23] principle),
5. used with real life object manipulation,
6. performed in a context specific environment [13],
7. performed in increasing difficulty levels (exercise progression) [24],
8. varied (within one task) [13],
9. followed by feedback on the exercise performance [25],
10. exercised in multiple movement planes,
11. including total skill performance [26],
12. patient customized for training load [27],
13. offered in random practice [13],
14. occur through distributed practice [22] and
15. composed of bimanual tasks [28].

A more extensive explanation of the categories can be found in table 4. These 15 components were selected, because they were thought to contain the most important contributors to support motor learning during (and after) task-oriented training.

Methodological quality assessment

The methodological quality of the studies was rated using the Van Tulder's quality assessment system [29, 30] and was scored by two independent reviewers (AT and AS). The Van Tulder list consists of internal validity criteria, descriptive criteria and statistical criteria. The internal validity criteria refer to characteristics of the study that might be related to selection bias, performance bias, attrition bias and detection bias, and should be used to define methodological quality in the meta-analysis. The descriptive criteria refer to the external validity of the study and may be used for the subgroup and sensitivity analyses. The statistical criteria indicate whether calculations can be made and conclusions can be drawn independently of the opinion of the authors of the original study [29]. Interrater reliability of individual items was tested with Cohen's kappa statistic (SPSS). In case of disagreement, a third reviewer (HS) made the final decision. Using the consensus method, the total Van Tulder score was calculated.

Quantitative analysis

Hedges' g [31] was chosen to calculate the effect size of the different studies selected, because of its good properties for small samples when multiplied by a correction factor that adjusts for small sample bias [32]. Hedges' g was established by calculating the

difference between means of the baseline values and post-intervention measurement divided by the pooled standard deviation (SD). In cases where means and standard deviations were not provided in the paper, the respective authors of the papers were contacted by email and data were asked for.
Given the selected studies, a correlation coefficient (Spearman's rho) was calculated between the number of task-oriented components that were used in the studies and the effect size reported. In case multiple measurement instruments were used, the outcome measurement providing the largest effect size after intervention administration was used. Choosing the largest effect size allows components to be linked to their maximal possible treatment effect, which is also in line with the ultimate goal of each therapist.
An inventory was made of the highest effect sizes for each study that the component was used in. Subsequently a *median effect size (MES)* across studies was calculated to enable comparison between components with regard to their relation to treatment outcome. Non-parametric descriptive values were used as the data were not normally distributed. The more a component was used in an intervention with a large ES, the larger the MES will be that is matched to a component.
Based on the classification of Cohen, effect sizes <0.2 were classified as small, between 0.2 and 0.5 as medium, and >0.5 as large [33]. According to this classification, it was assessed if training components were linked to small, moderate or large effect sizes both for post-intervention and follow-up.
As the first component 'functional' was an inclusion criterion for this review, this component is present in all included interventions. The median linked to this component therefore served as a reference value to which the median values of the other studies were compared. A *'relative median effect size (RMES) per component'* was calculated by subtracting the MES attributed to the component 'functional' from the MES that was attributed to that component and by dividing this difference by the MES of the component 'functional'.
To assess the influence of post-stroke time, training duration and training intensity, categories were made and median effect sizes of all interventions belonging to a category were calculated. In case of differences in MES between categories, it was assessed if components were spread over the categories (or not). To assess the influence of post-stroke time on the conclusions drawn, post-stroke time was categorized as follows:

1. acute (between 0-30 days post-stroke),
2. subacute (between 30 days and 6 months post stroke) and
3. chronic (+6 months post-stroke).

To assess the influence of training duration on the results of this study, median effect sizes of studies belonging to following categories were calculated:

1. 3-4 weeks training,
2. 5-6 weeks training,
3. +12 weeks of training.

To assess the influence of the training intensity on the results of this study, median effect sizes of studies belonging to following categories were calculated:

1. training less than 3 hours per week,
2. training between 3-4 hours per week,
3. training more than 5 hours per week.

Results

Selection of studies

The article selection process and results are shown in figure 1. From 362 papers resulting from a literature search, finally 16 papers[11, 15, 16, 34-46] were selected and analysed. In 2 papers [36,37], both control and intervention groups were offered task-oriented training. One paper [16] reported the follow-up results from another included study [15], both studies were further treated as one single study for data-extraction. Therefore, a total of 17 interventions were analysed with regard to task-oriented training type. Three studies (four papers) [15, 16, 40, 47] did not report the mean and SD information of the results that was needed for effect size calculation. As a result, from only 14 interventions effect size calculation could be performed.

Patient characteristics of included studies

In total, the intervention results of 528 patients were studied. All patients had suffered from ischemic or haemorrhagic stroke. The average age of the patients was 68.9 (ranging between 38.4-95.1 years). The number of days since stroke on inclusion to the study varied between 5 and 546 days (average=71.63 days). The average sample size of the group studied was 31 persons (SD=15.8). More detailed information about characteristics of the patients that were participating in the included studies is provided in table 1.

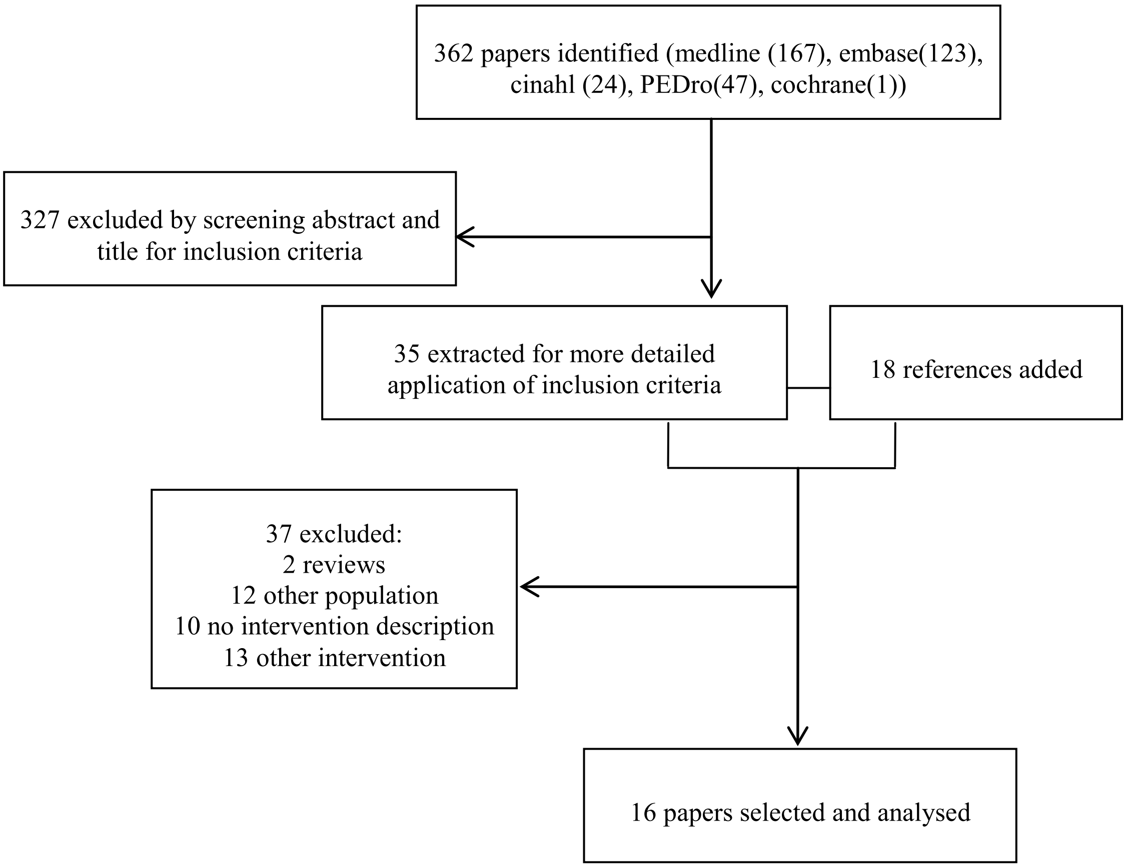

Fig. 1: Process of article selection

Methodological quality judgement

In table 2, the Van Tulder scores are presented for the 15 studies that are included in this review.
The two coders disagreed on 20 of the 204 Van Tulder items, resulting in a mean Cohen's kappa score of 0.79, which was considered good48. After obtaining consensus on the differences in Van Tulder scores, the mean Van Tulder score of all included studies was 13.6 (SD=1.7).
All studies were of acceptable methodological quality, as the lowest Van Tulder score equalled 11, which is well above the by Van Tulder suggested cut-off point of 50% (= 9.5) 29.
The mean internal validity score for all studies was 7.2 (out of 10) (SD=1.4). The mean descriptive score for all studies was 4.6 (out of 6)(SD=0.8). Twelve out of the fifteen studies had full scores for statistical criteria. The mean statistical score was 1.8 (SD=0.4).

Table 1: Overview of patient characteristics, training content, measurement instruments and effect size.

	Patients			**Intervention**					**Measurement**	**Results**	
Reference	**mean age (SD)**	**days since stroke (SD)**	**n**	**Training**	**N weeks**	**Freq/week**	**Freq/day**	**Min/session**	**Instruments**	**PI-ES**	**FU-ES**
Alon 2008	66.46	23.8 (10.9)	13	task-specific training: grasping, holding, moving and placing objects	12	5	2	30	BBT, JTT, FM	4.19	
Baskett 1999	67.8	38.6 (28.1)	50	individual home exercise program instructed by therapist, but patient trained by himself (no daily supervision of therapists at home)	12	7	try several	choice patient	MAS, MBI, NHPT, FAT, grip strength (JAMAR)	0.59	
Blennerhasset 2004	56.3	50.1 (49.2)	15	circuit of 10 five-minute workstations (under supervision) including warm-up, functional tasks to improve reach, grasp, hand-eye coordination, stretches (if needed therapist assisted exercises)	4	5	1	60	JTT, MAS	1.07	1.09
Chan 2006	53.8 (15.4)	117,7	33	program in 4 steps: 1)identification missing performance components,2) training using remedial exercises,3) training using functional tasks components,4)training functional skills	6	3	1	120	FIM , IADL, CIQ	2.19	
	54.4 (13.7)	88,8	33	no identification of missing components, training remedial tasks and training functional task without reinforcement of missing components.						0.46	
Desrosiers 2005	72.2	34.2 (34.4)	20	symmetrical and asymmetrical bilateral tasks, unilateral task of affected and less affected side	5	3-4	1	45	BBT, PPT, TEMPA, FIM, AMPS, grip strength (MartinVigorometer)	1.02	
		35.4 (33.7)	21	functional activities and exercise to enhance strength, active, assisted and passive movements and sensorimotor skills of the arm						0.78	
Duncan 2003	68.5	77.5 (28.7)	44	exercise program to improve strength, balance, endurance and to encourage use of affected extremity	12	3		90	WMFT, FM, grip strength (JAMAR)	NA	
Higgins 2006	73	217	47	therapy session + home program: training tasks based on daily problems including e.g. manipulating playing cards, clothes pins, writing	6	3 (home ex)	1	90 (+15 home ex)	BBT, NHPT, TEMPA, BI, IADL, SF-36, grip strength (JAMAR)	0.18	

Holmqvist 1998	70.8 (7.6)	5	41	individual tailor-made therapy at home with therapist	12-16				BI, NHPT, LMC, Katz, FAI, SIP	NA	
Kwakkel 1999-2002	69 (9.8)	7.2 (2.8)	33	functional exercises that facilitated forced arm and hand activities such as leaning, punching a ball, grasping and moving objects	20	5		30	BI, ARAT, FAI, NTHP, SIP	NA	
Liu 2004	72.7 (9.4)	15.4 (12.2)	20	3 sets of daily tasks with 5 tasks in each set (e.g. folding laundry, to do shopping, taking transportation)	3	5		60	Performance of tasks, FM	0.59	
McDonnell 2007	60.1 (10.5)	138 (78)	10	identification of impairment; strategies to reduce these impairments ; task specific training including reaching, wrist extension against resistance, performing fine motor skills	3	3	1	60	Grip-Lift Task, ARAT, FM, MAL, Pinch Grip, Tapping speed	0.79	4.01
Michaelsen 2006	69.4 (10.8)	546 (321)	15	object-related reach-to-grasp training	5	3	1	30	Tempa, BBT, kinematic outcomes, FM	0.58	0.71
Morris 2008	67.8 (9.9)	47 (9-284)	50	bilateral training including 4 core tasks: move a doweling peg, move a block from the table, grasp and empty glass, point targets	6	5		20	BI, ARAT, NHPT, RMA,NTHP	1.72	1.4
Sackley 2006	88.6 (6.5)	? Residence care	63	targeted towards ADL activities, e.g. feeding, dressing, bathing, transferring and mobilizing	12	choice patient			BI, RMA	2.99	0.05
Winstein 2004	95% 35-75	15.5 (6.0)	20	standard care like muscle facilitation, stretching, self care plus task-specific functional training such as pointing, grasping, stirring	4			60	FTHUE, FIM, FM, muscle strength arm-hand (Chatillon force gauge)	5.15	4.51

Abbreviations: SD: Standard deviation, PI- ES: Post-intervention effect size, FU-ES: Follow-up effect size, BBT: Box and Blox Test, JJT: Jebsen-Taylor Test, MAS: Motor Assessment Scale, MBI: Modified Barthel Index of activities of daily living, NHPT: Nine Hole Peg Test, NTHP: Nottingham Health Profile, FAT: Frenchay Arm Test, FAI: Frenchay Arm Index, FIM: Functional Independence Measure, IADL: Instrumental Activities of Daily Living, PPT: Purdue Pegboard Test, AMPS: The Assessment of Motor and Process Skills, WMFT: Wolf Motor Function Test, LMCA: Lindmark Motor Capacity Assessment, ARAT: Action Research Arm Test, RMA: Rivermead Motor Assessment upper-limb scale, FTHUE: Functional Test for hemiparetic upper extremity, FM: Fugl Meyer Assessment, CIQ: Community Integration Questionnaire, SIP: Sickness Impact Profile

Table 2: Van Tulder Score

References	Internal validity score	Descriptive score	Statistical score	Total Score
Alon 2008	4	5	2	11
Baskett 1999	8	4	1	13
Blennerhassett 2004	7	4	2	13
Chan 2006	6	4	2	12
Desrosiers 2005	7	4	2	13
Duncan 2003	9	5	2	16
Higgins 2006	8	4	2	14
Holmqvist 1998	6	6	1	13
Kwakkel 1999-2002	10	6	2	18
Liu 2004	6	4	2	12
McDonnell 2007	8	4	1	13
Michaelsen 2006	7	4	2	13
Morris 2007	8	4	2	14
Sackley 2006	8	5	2	15
Winstein 2004	7	6	2	15

Use of components in task-oriented training intervention and their relation to intervention effect size

The two coders disagreed on 12 of the 255 components rated (255=17 interventions x 15 components), resulting in a mean Cohen's kappa score of 0.88 (SD=0.15), which was considered excellent [48].
The articles included in this study used between 3 [15, 16] and 11 [36] training components. The average amount of training components used was 7.8 (SD=2.1). An overview of the training components that were used in each study can be found in table 3.
Six components, i.e. 'training that was functional', 'use of a clear ADL goal', 'use of real object manipulation', 'use of exercise progression', 'involving multiple movement planes' and 'total skill practise', were included in at least 12 of the 17 interventions.
Two components were included in between 9 to 11 of the 17 interventions: 'use of a patient customized training load' and 'inclusion of bimanual task practice'.
Seven components were included in less than 9 of the 17 interventions studied: 'client-centred training', 'use of frequent repetitions', 'training in a context specific environment', 'exercise variety', 'feedback on motor performance', 'random' and 'distributed practise'.
No relation was found between the number of components used in a training intervention for improving arm hand performance after stroke and the post-intervention effect size (r=0.12).

Table 3: Total number of components used per study and frequency of component use

	used to calculate ES	Functional	Clear functional goal	Client-centred	Overload	Real object	Context specific	Exercise progression	Exercise variety	Feedback	Multiple movement	Total skill	Customized training load	Random practice	Distributed practice	Bimanual tasks included	total components
Alon 2008	v	1	0	0	0	1	0	1	1	0	1	1	1	0	1	0	8
Baskett 1999	v	1	1	1	1	1	1	0	0	0	1	1	1	0	0	1	10
Blennerhassett 2004	v	1	0	0	0	0	0	1	0	0	1	0	1	0	0	0	4
Chan 2006 (A)	v	1	1	0	1	1	0	1	1	1	1	1	1	0	0	1	11
Chan 2006 (B)	v	1	1	0	1	1	0	1	0	0	1	1	1	0	0	1	9
Desrosiers 2005 (A)	v	1	1	0	1	1	0	0	1	0	1	1	1	1	0	1	10
Desrosiers 2005 (B)	v	1	1	0	0	1	0	0	0	0	1	1	1	0	0	1	7
Duncan 2003	0	1	1	0	0	1	1	1	0	0	1	1	0	0	0	1	8
Higgins 2006	v	1	1	1	0	1	0	1	0	0	1	1	1	0	0	1	9
Holmqvist 1998	0	1	1	1	0	1	1	0	0	0	1	1	0	0	0	0	7
Kwakkel1999&2002	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	1	3
Liu 2004	v	1	1	0	0	1	1	1	0	0	1	1	0	0	0	1	8
McDonnell 2007	v	1	1	0	0	1	1	1	0	1	1	1	0	0	0	0	8
Michaelsen 2006	v	1	0	0	1	0	0	1	1	1	1	0	0	0	0	1	7
Morris 2007	v	1	0	0	1	1	0	1	1	1	1	0	1	1	0	0	9
Sackley 2006	v	1	1	1	0	1	1	1	0	1	1	1	0	0	0	1	10
Winstein 2004	v	1	1	0	1	0	0	1	0	1	0	0	0	1	0	0	6
Frequency		**17**	**12**	**4**	**7**	**13**	**6**	**12**	**5**	**6**	**16**	**12**	**9**	**3**	**1**	**11**	

All but 3 components were associated with large post-intervention and follow-up Median effect sizes (Cohen>0.5 [33]). Only client-centred training, bimanual training and total skill training were associated with medium effect sizes (Cohen 0.2-0.5 [33]).

As explained before in the methodology section, the component 'functional' (MES=0.9) can be considered as a measure of comparison for the MESs of the other components. The components that were associated with the largest post-intervention ES are (non-relative values): 'distributed practice' (MES=2.39) and 'feedback' (MES=1.95). Also scoring high were: 'within-task exercise variability' (MES=1.72) and 'random practice' (MES=1.72). An overview of the 'relative median effect size per component' is given in figure 2 for post-intervention and in figure 3 for follow-up.

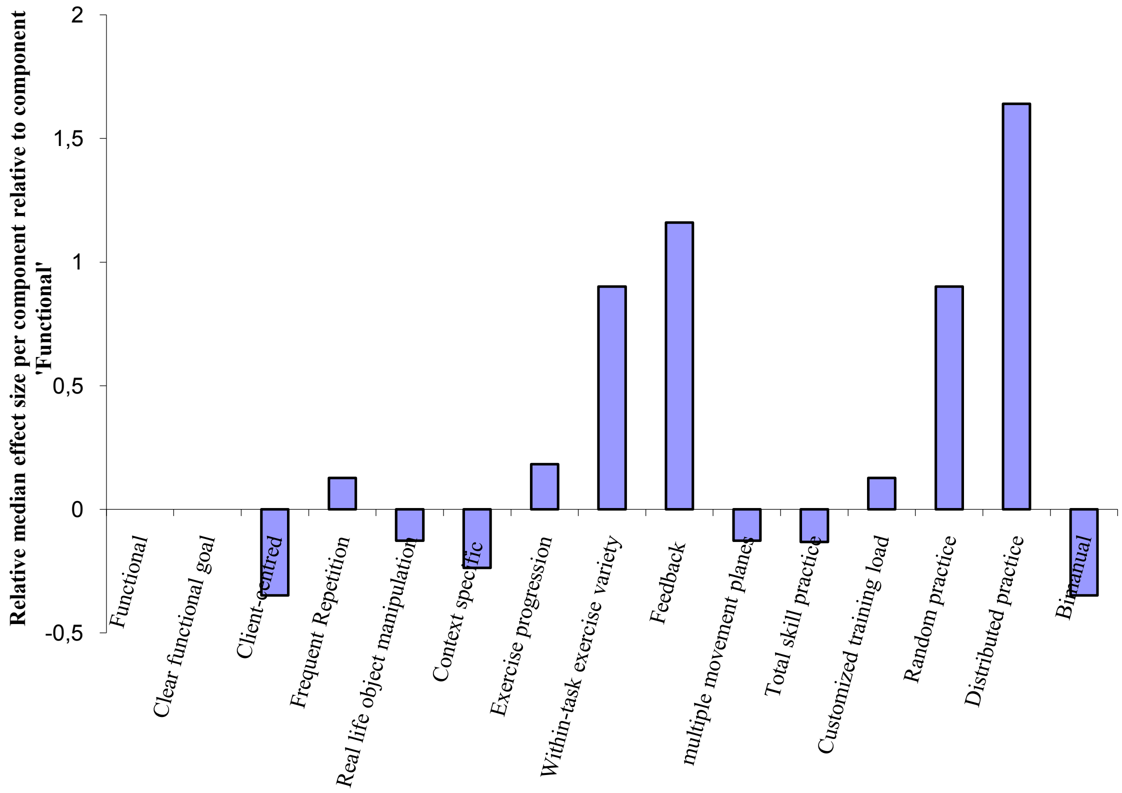

Fig. 2: Relative median effect size per component (post-intervention)

For follow-up ES the median value of the component ‘functional’ equals 1.24. The components that scored highest on follow-up effect size (compared to baseline values) were ‘use of clear functional goals’ (MES=4.01) and ‘random practice’ (MES=2.95). Also scoring high were ‘context specific environment’ (MES=2.03), ‘frequent movement repetition’ (MES=1.4) and ‘feedback’ (MES=1.4).

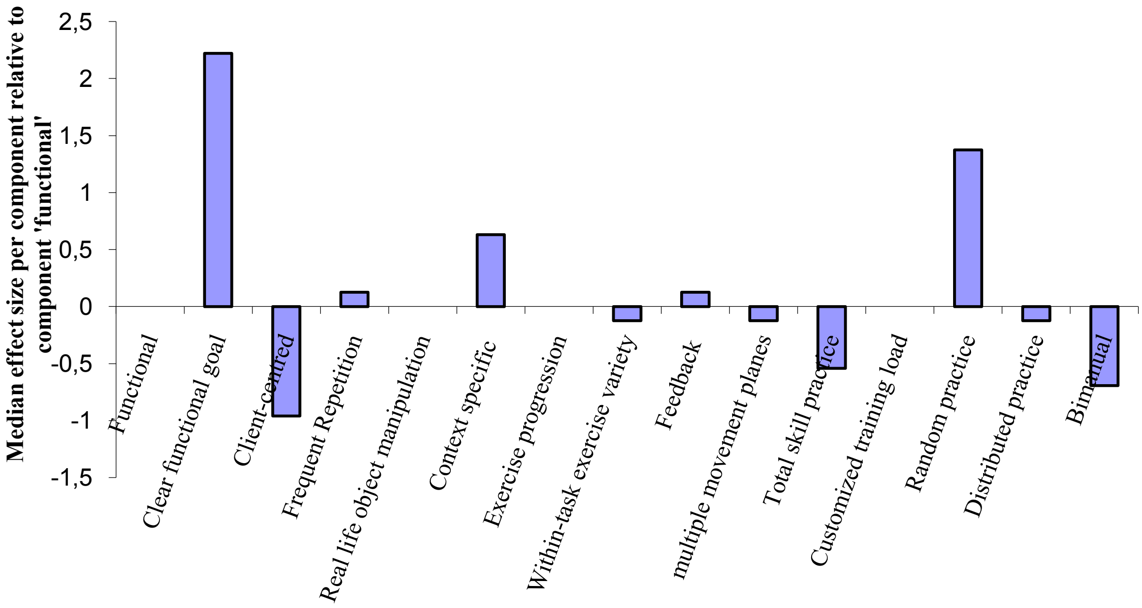

Fig. 3: Relative median effect size per component (follow-up)

The studies that were training with acute stroke patients were associated with a median effect size (MES = 4.19) that was almost 4 times larger than the median effect size associated with studies that were training subacute (MES=1.04) and chronic (MES= 1.17) stroke patients. However, three components that were linked to large effect sizes (feedback, random practice and use of clear functional goals) were linked to studies with acute, subacute and chronic patients. Therefore it can be concluded that post-stroke time did not influence the results presented for these components in this study. The component 'distributed practice' only occurred in the category of acute stroke patients.

The following median effect size values were found for the training duration categories:

1. 3-4 weeks training (MES=0.93, SD=2.17),
2. 5-6 weeks training (MES=1.17, SD=0.62),
3. +12 weeks of training (MES=2.99, SD=1.8).

Longer intervention duration does influence the median effect size, which is consistent with earlier results found in other task-oriented training interventions [6]. However, three out of four components were well distributed over the different categories. The result for the component 'distributed practice' may have been influenced by training duration as it only occurred in the category training of 12 weeks.

The median effect size values of the training intensity categories were:

1. training less than 3 hours per week (MES=1.1, SD=0.8),
2. training between 3-4 hours per week (MES=1.02, SD=0.2) and
3. training more than 5 hours per week (MES=1.6, SD=1.9).

One study [45] left the training intensity up to the patient, and could therefore not contribute to this analysis. The components 'clear functional goal', 'feedback' and 'random practise' were equally distributed along the different categories. However, the component 'distributed practise' did only occur in the highest intensity category and may therefore have been influenced by this factor.

Discussion

The aim of this systematic review was

1. to identify task-oriented training components,
2. to assess whether the number of task-oriented components that were used in a training intervention is related to the treatment effect size, and
3. to assess the possible influence of task-oriented training components on the treatment effect size.

Although the use of more task-oriented training components did not lead to higher treatment effect sizes, several components could be identified that were used more frequently in interventions with a larger treatment effect size than other components, namely 'feedback' and 'distributed practice' (post-intervention) and 'clear functional goal' and 'random practice' (follow-up). Substantial evidence exists for the positive effects of distributed practice [49], random practice[12], feedback[10, 50] and clear functional goals [6, 51] for motor skill learning after stroke. However, there has been no research to date that compares their importance for training outcome. It is good to raise awareness for the importance of these components in a task-oriented training program as especially feedback, random and distributed practice were reported in very few of the included studies (in only 6, 3 and 1 out of the 17 studies respectively) (table 3).

The finding that *distributed* practice improves post-intervention performance and *random practise* is linked to high follow-up outcome, is supported by previous research [13, 22]. Distributed practice has been shown to result in better motor learning than massing practise sessions [49]. Possible explanations for the distributed practice benefit are that: 1. less fatigue occurs than in mass practice, 2. the amount of cognitive effort that one is prepared to put is higher and 3. there is more opportunity for memory consolidation processes [22]. Random practice leads to better retention of learned motor performance through the contextual interference effect (memory and performance disruption that lead to a learning benefit [12]). *Feedback* is known to have positive effects on motor learning, although limited evidence is available for stroke patients[50]. The choice of appropriate and patient-customized feedback is very complex and depends on location and type of the brain lesion [52, 53] and the stage of learning the patient is in [54]. The way feedback was delivered was poorly described in many intervention reports. For example, it is known that progressively reducing feedback frequency leads to a better retention of learning effects and better transfer effects [25, 52, 55]. It was not clear at all if this strategy was used. A *'clear functional goal'* is identified as an important component for treatment outcome at follow-up. Working with a clear functional goal is a manner of goal setting which may increase the efficiency and the effectiveness of rehabilitation [56]. Even after finishing the training, patients are more likely to keep on doing these functional goals and therefore obtain better results at follow-up.

A common feature of the four components linked to the highest effect size is that they all optimize the storage of learned 'skilled' (clear functional goal) motor performance in the long-term memory (see reasons given in discussion above). This may be the reason for their contribution to high treatment outcome.

The effect sizes that were linked to 'client-centred training' were lower than expected. It is known that client-centred training increases the level of 'active' participation of the patient in the rehabilitation process [57]. This has a positive influence on patient motivation, which is an important factor for motor learning as attention during training is enhanced and exercise repetition and treatment compliance are stimulated [25, 58]. The poor result for 'client-centred training' in this review may be attributed to the fact that the above benefits could not be materialized during the clinical trial interventions, e.g. because there was little control from therapists during home-training, or by restricting the amount of repetitions or exercise duration to the one described in the exercise protocol or by not making use of the benefit from enhanced attention to 'learn' (=store information in short and long term memory), e.g. through too fast follow-up of exercises. Another cause for the poor result of this factor may be that client-centred treatment focuses on very specific goals (e.g. progressions in the real life objects used) that are not always measurable with the tests that were used in the included studies.

This emphasizes the need for theoretical frameworks to formalize client-centred treatment and to guide the application of client-centred care into clinical practice [59, 60]. Although there is not enough evidence for this component to be contributing to large treatment effects, it may be too early to dismiss it because of the early stages client-centred training is in with regard to its implementation in training interventions.

Methodological considerations

Studies could not be compared between each other with regard to effect sizes, because of different training duration, different dosage of task practice, different severity at inclusion and different post-stroke time (table 1). The authors chose to investigate which MES corresponded to each component. In this case the differences that occurred between studies were similar for all components, apart from the results of the component 'distributed practice' that may have been influenced by post-stroke time, training duration and training intensity. It was impossible to assess the influence of stroke severity on the results of this study, as different baseline measurements and inclusion criteria were used in the studies included in the analysis.

The effect sizes reported were not only influenced by the training content, but also by the use of different measurement instruments (18 different outcome measures in 16 interventions). Although these effects are well spread over the different studies, standardisation of intervention protocols (outcome measurement and training intervention) in future would highly benefit the collection of scientifically supported knowledge.

The extent to which training components that were identified actually were used (and evaluated) in the study could not be assessed. For example, feedback was mentioned to be used in several studies, but it was not described which kind of feedback was given (knowledge of performance or knowledge of results feedback, visual or auditive or haptic feedback), the frequency of feedback delivery (after each exercise or summary feedback), the schedule (fading frequency schedules, feedback delay), etc.

Several studies were excluded from this systematic review because the task-oriented training was not specified enough. These studies may have added interesting information to the current review article. Also studies using constraint-induced movement therapy were not included in this review. In CIMT trials the patient inclusion criteria and the manner in which task practice is taught to the patient (shaping principles [61]) are very well specified. The baseline characteristics of the participants that were studied in the included trials of the present review could not always be identified, especially with regard to their impairment and activity levels. Also the way of task training delivery was generally not specified in relation to the problem solving strategies that were stimulated. Because of the lack of comparability with the included trials, the CIMT randomized clinical trials were not included in this review.

It must be noted that studies using technology-supported training (robotics, sensor technology) were not excluded from this systematic review. Only, there were no publications of randomized clinical trials with technology-supported training available that matched the inclusion criteria for this study. It will be very interesting to repeat this review when the results of ongoing research are published.

It was not within the scope of this review to find out which training components are leading to larger effect sizes for different patient groups, e.g. with regard to degree of impairment in function/performance. This would however be an interesting topic of future research.
In the light of the importance of several training components highlighted in this article, the authors advocate a detailed description of the training intervention, including a description of training content, training intensity and training load.
This systematic review suggests that it is important to include 'random and distributed practice', 'feedback' and 'clear functional goals' in task-oriented arm training for persons after stroke to augment post-intervention and follow-up outcome of skilled arm-hand performance.

Table 4: Brief explanation of task oriented training components.

Functional movements : a movement involving task execution that is not directed towards a clear ADL-goal (e.g. moving blocks from one location to another, stacking rings over a cone) (as opposed to analytical movements, which are movements without a goal, usually occurring in one single movement plane and often occurring in single joints, e.g. shoulder flexion)
Clear functional goal: a goal that is set during everyday-life activities, hobbies (e.g. washing dishes, grooming activity, dressing oneself, playing golf) [20]
Client-centred patient-goal: therapy goals that are set through the involvement of the patient him/herself in the therapy goal decision process. The goals respect patient's values, preferences, expressed needs and recognize the clients' experience and knowledge [21].
Overload: training that exceeds the patient's metabolic muscle capacity [23]. Overload is determined by the total time spent on therapeutic activity, the number of repetitions, the difficulty of the activity in terms of coordination, muscle activity type and resistance load, and the intensity, i.e. number of repetitions per time unit [23]. In this review we have scored a high amount of repetitions as determining factor for the presence of overload, as the other factors are rarely described in intervention descriptions.
Real life object manipulation: manipulation that makes use of objects that are handled in normal everyday-life activities (e.g. cutlery, hairbrush…).
Context-specific environment: a training environment (supporting surface, objects, people, room,…) that equals or mimics the natural environment for a specific task execution, in order to include task characteristic sensory/perceptual information, task specific context characteristics and cognitive processes involved [13].
Exercise progression: Exercises on offer have an increasing difficulty level that is in line with the increasing abilities of the patient, in order to keep the demands of the exercises and challenges optimal for motor learning [24].
Exercise variety: A variety of exercises was offered to support motor skill learning of a certain task because of the person experiencing different movement and context characteristics (within task variety) and problem solving strategies[13].
Feedback: specific information on the patient's motor performance that enhances motor learning and positively influences patient motivation (for more information, the authors refer to [25]).
Multiple movement planes: Movement that uses more than one degree of freedom of a joint, therefore occurring around multiple joint axes.
Total skill practise: The skill is practiced in toto, with or without preceding skill component training (e.g. via chaining) [26].
Patient customized training load: A training load that suits the individualized treatment targets (e.g. endurance, coordination or strength training [27]) as well as the patient's capabilities (e.g. 65% of 1 repetition maximum or 85% of 1 repetition maximum for the specific patient).
Random practice: Each practice session, the exercises are randomly ordered [13]
Distributed practice: A practice schedule with relatively long rest periods [22]
Bimanual practice: tasks where both arms and hands are involved are included [28].

Acknowledgements

This research was funded by Philips Research Europe (Department of Biomedical Sensor Systems, Eindhoven).
The authors thank Maurice Monfrance for his help in setting up the search strategy, and for his help in screening of abstracts to identify appropriate articles (opinion third reviewer).

References

1. Broeks JG, Lankhorst GJ, Rumping K, Prevo AJ. The long-term outcome of arm function after stroke: Results of a follow-up study. *Disabil Rehabil*. 1999;21:357-364
2. Shelton FN, Reding MJ. Effect of lesion location on upper limb motor recovery after stroke. *Stroke*. 2001;32:107-112
3. Truelsen T, Piechowski-Jozwiak B, Bonita R, Mathers C, Bogousslavsky J, Boysen G. Stroke incidence and prevalence in europe: A review of available data. *Eur J Neurol*. 2006;13:581-598
4. Shumway-Cook A, Woollacott M. A conceptual framework for clinical practice. *In: Motor control. Translating research into clinical practice.* Philadelphia: Lippincott Williams & Wilkins; 2007:136-153
5. Timmermans AA, Seelen HA, Willmann RD, Bakx W, de Ruyter B, Lanfermann G, Kingma H. Arm and hand skills: Training preferences after stroke. *Disabil Rehabil*. 2009:1-9
6. Timmermans AA, Seelen HA, Geers RPJ, Saini PK, Winter S, Te Vrugt J, Kingma H. Sensor-based skill training in chronic stroke patients: Results on treatment outcome, patient motivation and system usability. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*. 2010; IEEE Trans Neural Syst Rehabil Engin. 18,3:284-292
7. Van Peppen RP, Kwakkel G, Wood-Dauphinee S, Hendriks HJ, Van der Wees PJ, Dekker J. The impact of physical therapy on functional outcomes after stroke: What's the evidence? *Clin Rehabil*. 2004;18:833-862
8. French B, Thomas LH, Leathley MJ, Sutton CJ, McAdam J, Forster A, Langhorne P, Price CI, Walker A, Watkins CL. Repetitive task training for improving functional ability after stroke. *Stroke*. 2009
9. Legg LA, Drummond AE, Langhorne P. Occupational therapy for patients with problems in activities of daily living after stroke. *Cochrane Database Syst Rev*. 2006:CD003585
10. Cirstea CM, Ptito A, Levin MF. Feedback and cognition in arm motor skill reacquisition after stroke. *Stroke*. 2006;37:1237-1242
11. Baskett JJ, Broad JB, Reekie G, Hocking C, Green G. Shared responsibility for ongoing rehabilitation: A new approach to home-based therapy after stroke. *Clin Rehabil*. 1999;13:23-33
12. Shea CH, Morgan RL. Contextual interference effects on the acquisition, retention, and transfer of a motor skill. *J Expl Psychol: Hum Learn Mem*. 1979;5:179-187
13. Magill R. Practice variability and specificity. *In: Motor learning and control*. Boston: Mc Graw Hill; 2007:368-389.
14. Kwakkel G, Wagenaar RC, Koelman TW, Lankhorst GJ, Koetsier JC. Effects of intensity of rehabilitation after stroke. A research synthesis. *Stroke*. 1997;28:1550-1556
15. Kwakkel G, Wagenaar RC, Twisk JW, Lankhorst GJ, Koetsier JC. Intensity of leg and arm training after primary middle-cerebral-artery stroke: A randomised trial. *Lancet*. 1999;354:191-196
16. Kwakkel G, Kollen BJ, Wagenaar RC. Long term effects of intensity of upper and lower limb training after stroke: A randomised trial. *J Neurol Neurosurg Psychiatry*. 2002;72:473-479
17. Kwakkel G, van Peppen R, Wagenaar RC, Wood Dauphinee S, Richards C, Ashburn A, Miller K, Lincoln N, Partridge C, Wellwood I, Langhorne P. Effects of augmented exercise therapy time after stroke: A meta-analysis. *Stroke*. 2004;35:2529-2539

18. Dobkin BH. Confounders in rehabilitation trials of task-oriented training: Lessons from the designs of the excite and scilt multicenter trials. *Neurorehabil Neural Repair*. 2007;21:3-13
19. Liepert J, Hamzei F, Weiller C. Lesion-induced and training-induced brain reorganization. *Restor Neurol Neurosci*. 2004;22:269-277
20. Duff J, Evans MJ, Kennedy P. Goal planning: A retrospective audit of rehabilitation process and outcome. *Clin Rehabil*. 2004;18:275-286
21. Cott CA. Client-centred rehabilitation: Client perspectives. *Disabil Rehabil*. 2004;26:1411-1422
22. Magill R. The amount and distribution of practice. *Motor learning and control. Concepts and applications.* Boston: Mc Graw Hill; 2007:390-404.
23. Kisner C, Colby L. Resistance exercise for impaired muscle performance. *Therapeutic exercise. Foundations and techniques*. Philadelphia: F.A. Davis Company; 2007:150.
24. Conroy B, Earle R. Bone,muscle,and connective tissue adaptations to physical activity. In: Beachle TR, Earle RW, Wathen D, eds. *Essentials of strength training and conditioning*. Champaign: Human Kinetics; 2008:57-73.
25. Timmermans AA, Seelen HA, Willmann RD, Kingma H. Technology-assisted training of arm-hand skills in stroke: Concepts on reacquisition of motor control and therapist guidelines for rehabilitation technology design. *J Neuroeng Rehabil*. 2009;6:1
26. Magill R. Whole and part practice. *Motor learning and control*. Boston: Mc Graw Hill; 2007:405-420.
27. Mangine RH, TP ; Eldridge VL. Improving strength, endurance, and power. In: Scully RBM, ed. *Physical therapy*. Philadelphia: Lippincott Company; 1989:739-762.
28. Whitall J, McCombe Waller S, Silver KH, Macko RF. Repetitive bilateral arm training with rhythmic auditory cueing improves motor function in chronic hemiparetic stroke. *Stroke*. 2000;31:2390-2395
29. van Tulder MW, Assendelft WJ, Koes BW, Bouter LM. Method guidelines for systematic reviews in the cochrane collaboration back review group for spinal disorders. *Spine (Phila Pa 1976)*. 1997;22:2323-2330
30. van Tulder M, Furlan A, Bombardier C, Bouter L. Updated method guidelines for systematic reviews in the cochrane collaboration back review group. *Spine (Phila Pa 1976)*. 2003;28:1290-1299
31. Hedges LV, Olkin I. Nonparametric estimators of effect size in meta-analysis. *Psychological Bulletin*. 1984;96:573-580
32. Kampenes VB, Dyba T, Hannay JE, Sjoberg DI. A systematic review of effect size in software engineering experiments. *Information and Software Technology*. 2007;49:1073-1086
33. Cohen J. The t-test for means. *Statistical power analysis for the behavioral sciences* Hillsdale, NJ: Lawrence Earlbaum Associates; 1988:p25-26.
34. Alon G, Levitt AF, McCarthy PA. Functional electrical stimulation (fes) may modify the poor prognosis of stroke survivors with severe motor loss of the upper extremity: A preliminary study. *Am J Phys Med Rehabil*. 2008;87:627-636
35. Blennerhassett J, Dite W. Additional task-related practice improves mobility and upper limb function early after stroke: A randomised controlled trial. *Aust J Physiother*. 2004;50:219-224
36. Chan DYL, Chan CCH, Au DKS. Motor relearning programme for stroke patients: A randomized controlled trial. *Clin Rehabil*. 2006;20:191-200
37. Desrosiers J, Bourbonnais D, Corriveau H, Gosselin S, Bravo G. Effectiveness of unilateral and symmetrical bilateral task training for arm during the subacute phase after stroke: A randomized controlled trial. *Clin Rehabil*. 2005;19:581-593
38. Duncan P, Studenski S, Richards L, Gollub S, Lai SM, Reker D, Perera S, Yates J, Koch V, Rigler S, Johnson D. Randomized clinical trial of therapeutic exercise in subacute stroke. *Stroke*. 2003;34:2173-2180
39. Higgins J, Salbach NM, Wood-Dauphinee S, Richards CL, Cote R, Mayo NE. The effect of a task-oriented intervention on arm function in people with stroke: A randomized controlled trial. *Clin Rehabil*. 2006;20:296-310
40. Holmqvist LW, von Koch L, Kostulas V, Holm M, Widsell G, Tegler H, Johansson K, Almazan J, de Pedro-Cuesta J. A randomized controlled trial of rehabilitation at home after stroke in southwest stockholm. *Stroke* 1998;29:591-597

41. Liu KP, Chan CC, Lee TM, Hui-Chan CW. Mental imagery for promoting relearning for people after stroke: A randomized controlled trial. *Arch Phys Med Rehabil*. 2004;85:1403-1408
42. McDonnell MN, Hillier SL, Miles TS, Thompson PD, Ridding MC. Influence of combined afferent stimulation and task-specific training following stroke: A pilot randomized controlled trial. *Neurorehabil and Neural Repair*. 2007;21:435-443
43. Michaelsen SM, Dannenbaum R, Levin MF. Task-specific training with trunk restraint on arm recovery in stroke: Randomized control trial. *Stroke*. 2006;37:186-192
44. Morris JH, van Wijck F, Joice S, Ogston SA, Cole I, MacWalter RS. A comparison of bilateral and unilateral upper-limb task training in early poststroke rehabilitation: A randomized controlled trial. *Arch Phys Med Rehabil*. 2008;89:1237-1245
45. Sackley C, Wade DT, Mant D, Atkinson JC, Yudkin P, Cardoso K, Levin S, Lee VB, Reel K. Cluster randomized pilot controlled trial of an occupational therapy intervention for residents with stroke in uk care homes. *Stroke*. 2006;37:2336-2341
46. Winstein CJ, Rose DK, Tan SM, Lewthwaite R, Chui HC, Azen SP. A randomized controlled comparison of upper-extremity rehabilitation strategies in acute stroke: A pilot study of immediate and long-term outcomes. *Arch Phys Med Rehabil*. 2004;85:620-628
47. Duncan P, Studenski S, Richards L, Gollub S, Lai SM, Reker D, Perera S, Yates J, Koch V, Rigler S, Johnson D. Randomized clinical trial of therapeutic exercise in subacute stroke. *Stroke; a journal of cerebral circulation*. 2003;34:2173-2180
48. Landis JR, Koch GG. The measurement of observer agreement for categorical data. *Biometrics*. 1977;33:159-174
49. Shea CH, Lai Q, Black C, Park J. Spacing practice sessions across across days benefits the learning of motor skills. *Human Movement Science*. 2000;19:737-760
50. van Vliet PM, Wulf G. Extrinsic feedback for motor learning after stroke: What is the evidence? *Disabil Rehabil*. 2006;28:831-840
51. Wolf SL, Winstein CJ, Miller JP, Taub E, Uswatte G, Morris D, Giuliani C, Light KE, Nichols-Larsen D. Effect of constraint-induced movement therapy on upper extremity function 3 to 9 months after stroke: The excite randomized clinical trial. *Jama*. 2006;296:2095-2104
52. Shumway-Cook A, Woollacott M. Motor learning and recovery of function. *In: Motor control. Translating research into clinical practice*. Philadelphia: Lippincott Williams & Wilkins; 2007:21-45.
53. Boyd LA, Winstein CJ. Impact of explicit information on implicit motor-sequence learning following middle cerebral artery stroke. *Phys Ther*. 2003;83:976-989
54. Kisner C, Colby L. Strategies for effective exercise and task-specific instruction. *Therapeutic exercise. Foundations and techniques.* Philadelphia: F.A. Davis Company; 2007:29.
55. Winstein CJS, R.A. Reduced frequency of knowledge of results enhances motor skill learning. *Journal of Experimental Psychology: Learning, Memory, and Cognition*. 1990;16:677-691
56. Wade DT. Goal setting in rehabilitation: An overview of what, why and how. *Clin Rehabil*. 2009;23:291-295
57. Wressle E, Eeg-Olofsson AM, Marcusson J, Henriksson C. Improved client participation in the rehabilitation process using a client-centred goal formulation structure. *J Rehabil Med*. 2002;34:5-11
58. Timmermans A, Seelen H, Kingma H. Task-oriented training: An essential element in technology-supported rehabilitation of skilled arm-hand performance after stroke. *IEEE-EMBS Benelux Chapter Symposium*. 2009:63-66
59. Leach E, Cornwell P, Fleming J, Haines T. Patient centered goal-setting in a subacute rehabilitation setting. *Disabil Rehabil*. 2009:1-14
60. Playford ED, Siegert R, Levack W, Freeman J. Areas of consensus and controversy about goal setting in rehabilitation: A conference report. *Clin Rehabil*. 2009;23:334-344
61. Taub E, Uswatte G, King DK, Morris D, Crago JE, Chatterjee A. A placebo-controlled trial of constraint-induced movement therapy for upper extremity after stroke. *Stroke*. 2006;37:1045-1049

Chapter 4

A concept for selecting arm-hand measurement instruments for evaluation of technology-supported task-oriented training in stroke

Timmermans A.A.A., Spooren A.I.F., Kingma H, Seelen H.A.M. Submitted.

Abstract

Introduction: There is a growing interest in the development of rehabilitation technology to support task-oriented training. To identify benefits across different training systems, common outcome measures, representative of essential arm-hand skill performance (AHSP) should be used. This paper describes a conceptual framework that may guide the choice of outcome measures to be used in technology-supported training interventions.
Methods: A systematic literature search identified RCTs evaluating the effects of task-oriented arm-training on AHSP after stroke. Two reviewers independently identified components, representative for AHSP, which can be measured as separate entities through outcome measurement.
Results: The outcome measures in sixteen interventions were studied. Twenty-eight assessment tools were used, averaging 4 per study. The concept comprised of eight identified arm-hand skill assessment components, i.e.: assessment of

1. function,
2. complex skills,
3. arm skills,
4. hand skills,
5. participation,
6. bilateral skills,
7. exact measures, and
8. real-life relevance.

On average 5.7 (SD=1.4) components per study were measured. Each treatment addressed, on average, 4 (SD=1.3) components. In 10 studies similar components for both, evaluation and training, were used. Generalized effects were most frequently evaluated for complex skills (7 studies) and function (7 studies). Most used outcome measures were Barthel Index (n=6), grip strength measurement (n=5), Fugl-Meyer Test (n=5), Nine-Hole-Peg Test (n=4) and Box-and-Block Test (n=4).
Conclusion: A concept was developed to guide the choice of measurement instruments for a specific intervention. Current AHSP assessment includes the evaluation of both generalized and training-specific effects. A challenge remains to include 'real-life relevant' measures and 'technology-supported assessment on activity and participation level'.

Introduction

As a result of the aging of the population, the number of stroke patients in Europe and the related healthcare costs are expected to increase by more than 30% [1]. Approximately 50% of persons who have suffered from stroke face arm-hand performance problems that may last for the rest of their lives [2, 3]. The recovery of upper limb performance often lags behind recovery of lower limb function [4], which may lead to disappointment and distress in patients when discharge from physiotherapy occurs before achievement of optimal arm-hand performance [5].
However, new chances for therapy emerge. A large number of rehabilitation technology systems have been developed, from which a substantial proportion has been shown to improve arm-hand performance after stroke [6-8]. Many of these systems have great potential by offering therapy that is engaging, motivating and supportive of motor (re)learning of skilled arm-hand performance after stroke [9].
Most rehabilitation technology is still in a research or predevelopment phase and only few systems are currently used by clinicians [10]. An important obstacle for clinical adoption of such systems is that it is very difficult to compare different technological systems with regard to training effects, and that it is virtually impossible to know which system is the best one to use for different patient categories [9]. A similar problem has been reported regarding clinical interventions for stroke patients that do not rely on technology use [11-13]. It has been argued that standardized research protocols should be developed in order to allow for comparable evidence on the benefits of the applications of robotics in healthcare [14]. Clearly this conclusion also applies to rehabilitation technology in general. Protocols on outcome assessment are a first step in standardizing the evaluation of rehabilitation technology. The interpretation of outcome assessment in stroke is very difficult due to the diverse aetiologies of stroke, the heterogeneity of symptoms, the variability in stroke severity, and the possibility of spontaneous recovery after stroke [15]. Also the large number of test batteries available and the lack of guidelines for their use make it hard to choose the most suitable instrument. These challenges are reflected in the wide range of outcome measures that are used between different studies [11,13, 16, 17 25].
Task-oriented training has been shown to improve arm-hand performance in stroke patients [18] and may match patient training preferences [19]. However, it is only in the last five years that this training approach has started to be applied in technology-supported training [6, 7, 20-22]. Evaluation of task-oriented training should encompass assessment of all ICF levels, i.e. function, activity and participation level [17, 23]. Since no single test can evaluate all levels simultaneously, clinicians usually assemble a battery of tests for the evaluation of skilled arm-hand performance[23]. The choice of measurement instruments is currently guided by patient-related factors (e.g. age, diagnosis, level of function of the patient) [23], the need for performance-based or self-reported information [23], the purpose of the examination (discriminate, evaluate, or predict) [15], psychometric properties (sensitivity to change, floor- and ceiling effects, reliability, validity, and specificity) [15, 24] and the level of the ICF classification one aims to assess [11,15, 17, 24, 25]. While these factors are useful and important, a content-driven conceptualisation of which aspects of arm-hand performance exactly are measured by tests has an added value and may further support the decision process as to the choice of test

instruments. This is especially of importance for the evaluation of technology-supported training, as a large variety of systems (each with their own training approach) is available.

In order to evaluate training-specific effects of an intervention, the characteristics of the assessment tool are to be matched to the characteristics of that intervention (if e.g. basic hand skills are trained, the test should measure these). Motor skill training may not only improve the performance of that specific skill, but may also improve functions (e.g. muscle strength), other skills (transfer effect), participation, etc. To map these generalized training effects, one may choose to use additional measurement instruments that assess different characteristics of training to other skill components. A choice of assessment tools according to the aforementioned concept would allow for evidence-based conclusions to be drawn on a wider range of arm-hand performance aspects related to (technology-assisted) training, and thus would contribute to cross-link multiple intervention outcomes. This, in turn, would help the clinician to choose which intervention best fits the needs of his/her patient.

It is the aim of this review

1. to inventorize the outcome measures that are used in randomized clinical trials focusing on task-oriented arm-hand training after stroke and that also may be appropriate for use in technology-assisted rehabilitation,
2. to introduce a conceptual framework to classify and choose outcome measures to evaluate (technology-supported) task-oriented training, and
3. to assess to which extent training-specific and/or generalized training effects are evaluated in task-oriented arm-hand training interventions in stroke patients.

Methods

Parts of the methods described below have also been reported earlier by the authors[26].

Literature search strategy

The systematic review is based on articles published until March 2009 that were selected after a computerized search strategy in the following databases: PubMed, EMBASE, CINAHL, PEDro and Cochrane. The following Medical Subject Headings (MeSH) were used: *("stroke") AND (("exercise movement techniques" OR "occupational therapy" OR "task performance and analysis" OR "exercise therapy" OR "exercise")) AND ("clinical trial") AND ("upper extremity" OR ("activities of daily living" NOT "lower extremity") OR ("motor skills" OR "motor skill disorders"))*. The abstracts were screened by two independent reviewers (AT and AS). In case of disagreement, a decision was made by a third reviewer (MM). In addition to the database search, articles in the selected papers' reference lists that were found to be relevant were checked.

Eligible studies

Inclusion criteria were:

1. The study described should be a randomized clinical trial (RCT);
2. At least one condition of the trial should be focussed on active task-oriented arm-hand training in (hemorrhagic or ischemic) stroke patients. Constraint-induced movement therapy (CIMT) trials were excluded from the present systematic review, because of the lack of comparability with the included trials, since CIMT is characterized by constraining the non-paretic arm and focuses on practice by the affected arm only (although the non-affected arm may serve as a support). Much of the CIMT practice can, however, be considered task-oriented [27]and for activities that are important to the patient, can induce cortical reorganization [28];
3. The task-oriented training should be well described in the article. Papers reporting general descriptions like ‘occupational therapy’ and ‘physiotherapy’ were not included as they could not be used for training component identification;
4. The studies should use outcome measures at activity level by means of a) registration of kinematic parameters measured during skilled arm-hand performance, or b) arm-hand performance tests at activity level;
5. Articles should be written in Dutch, French, English or German;
6. A minimum number of 10 stroke patients should be included.

Conceptual framework consisting of arm-hand skill ‘assessment components’

Two reviewers (AT and AS) independently identified 8 components that, in addition to the ICF classification, characterized arm-hand skill performance assessment used in the included articles. These 8 components can be measured as separate entities and can be represented by means of outcome measures. They will further be named ‘arm-hand skill assessment components’ in this text. The results of both researchers were compared and consensus was reached after discussion on differences.
The following arm-hand skill assessment components were identified:

1. measurement of ‘arm-hand function’ (i.e. physiological function and body structures) [11]
2. measurement of ‘complex arm-hand activity’(complex skills are defined as skills in which the whole body is used) [29],
3. measurement of ‘basic arm activity’ (proximal joints play a key role in the task execution)[29],
4. measurement of ‘basic hand activity’ (the wrist/hand plays a key role in the task execution)[29],
5. measurement of ‘participation’ (involvement in social activities: hobbies, work, etc.) [30],
6. measurement of ‘bilateral (bimanual) arm-hand performance’ is included,
7. ‘exact measurement of arm-hand performance’ is included (i.e. quantitative objective measurement, e.g. time measurement),

8. 'assessment of real-life relevance'(day-to-day performance in the person's normal environment is assessed, as opposed to observation in test conditions) [31].

The above mentioned components may serve as elements in a framework for choosing the optimal measurement instrument(s). To do so, it has to be known which arm-hand skill components are featured in the different measurement instruments. Therefore two authors (AT and AS) independently classified the measurement instruments used in the studies reviewed according to the eight arm-hand skill assessment components that were identified. For each measurement instrument, the two coders marked which arm-hand skill assessment components were evaluated. Interrater reliability was tested with Cohen's kappa statistic. Differences between the two authors were discussed until a consensus was reached.

For the evaluation of training-specific changes in arm-hand skilled performance, the measurement instrument should be matched to training content. This is the minimum requirement that has to be fulfilled to evaluate the effects of a training intervention (and to allow for comparison between similar interventions used in different studies). But it is advocated to also add additional measurements (representing additional skill assessment components) for the evaluation of generalized training effects (e.g. for task-oriented training: tests that measure the influence of the training at participation level). This can map the strengths of different interventions and systems. Furthermore it can benchmark solutions.

The use of exact measures is strongly recommended as they allow best for objective comparisons across different studies (and different systems).

Methodological quality assessment

The methodological quality of the studies was rated using the Van Tulder quality assessment system [32, 33] and was scored by two independent reviewers (AT and AS). In case of disagreement, a third reviewer (HS) made the final decision. Using the consensus method, the total Van Tulder score was calculated. Interrater reliability of individual items was tested with Cohen's kappa statistic.

Quantitative analysis

For each measurement instrument, the number of studies that used it was calculated.

Also the number of times an assessment component was used in (the measurement instruments of) each study was calculated.

A Spearman correlation coefficient was calculated between the number of studies that assessed a certain component and the number of studies that included the same component in the treatment.

Next to the assessment of training specific treatment effects (i.e. when the components that were present in the training were evaluated), it was investigated if (additional) measurement instruments were used that evaluated generalized treatment effects. For this, the number of studies that included certain components in the assessment without including them in the treatment intervention was calculated.

Results

Selection of studies

The article selection process is depicted in figure 1. From the 362 papers initially identified in the literature search, 16 papers were finally selected and analysed [34-49]. In 2 papers [37, 38], both control and intervention groups were offered task-oriented training. One paper [43] reported the follow-up results from another study [42]. As to the latter, both studies were further treated as a single study during data-extraction, thus resulting in 15 studies. In all, a total of 17 interventions were analysed with regards to task-oriented training content.

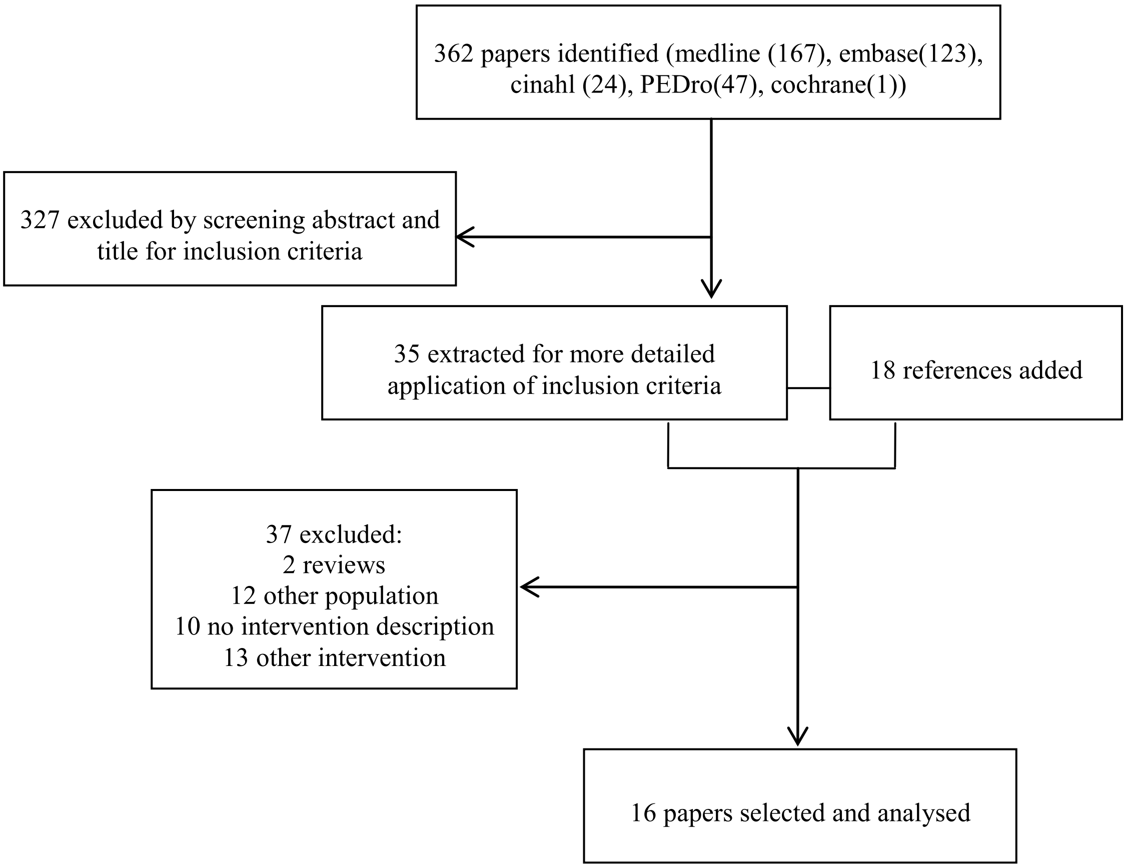

Fig. 1: Process of article selection

Patient characteristics of the studies included

In total, the intervention results of 528 patients were studied. All patients had suffered from ischemic or haemorrhagic stroke. The average age of the patients was 68.9 years (ranging between 38.4 and 95.1 years). Post-stroke time upon inclusion in the various studies was between 5 and 546 days (average=71.63 days). The average sample size of the group studied was 31 persons (SD=15.8). The characteristics of the patients that were participating in the included studies are presented in table 1.

Table 1: Overview of patient characteristics, training content, assessment components and measurement instruments

	Patients			Intervention		UE-Measurement
Reference	**Mean age (SD)**	**days since stroke (SD)**	**N**	**Training**	**Assessment components present in treatment**	**Instruments**
Alon 2008	66.46	23.8 (10.9)	13	task-specific training: grasping, holding, moving and placing objects	function, complex activity, basic arm, basic hand , participation, bilateral training, real-life relevance	BBT, JTT, FM
Baskett 1999	67.8	38.6 (28.1)	50	individual home exercise program instructed by therapist, but patient trained by himself (no daily supervision of therapists at home)	complex activity, basic arm, basic hand, bilateral training, real-life relevance	MAS, MBI, NHPT, FAT, grip strength (JAMAR)
Blennerhasset 2004	56.3	50.1 (49.2)	15	circuit of 10 five-minute workstations (under supervision) including warm-up, functional tasks to improve reach, grasp, hand-eye coordination, stretches (if needed therapist assisted exercises)	function, basic arm, basic hand	JTT, MAS
Chan 2006	53.8 (15.4)	117,7	33	program in 4 steps: 1)identification missing performance components,2) training using remedial exercises,3) training using functional tasks components,4)training functional skills	complex activity, basic arm, basic hand, bilateral training, real-life relevance	FIM , IADL, CIQ
	54.4 (13.7)	88,8	33	no identification of missing components, training remedial tasks and training functional task without reinforcement of missing components.		
Desrosiers 2005	72.2	34.2 (34.4)	20	symmetrical and asymmetrical bilateral tasks, unilateral task of affected and less affected side	basic arm, basic hand, bilateral training, real-life relevance	BBT, PPT, TEMPA, FIM, AMPS, grip strength (Martin Vigorometer)
		35.4 (33.7)	21	functional activities and exercise to enhance strength, active, assisted and passive movements and sensorimotor skills of the arm		
Duncan 2003	68.5	77.5 (28.7)	44	exercise program to improve strength, balance, endurance and to encourage use of affected extremity	basic arm, basic hand, bilateral training, real-life relevance	WMFT, FM, grip strength (JAMAR)
Higgins 2006	73	217	47	therapy session + home program: training tasks based on daily problems including e.g. manipulating playing cards, clothes pins, writing	basic arm, basic hand and real-life relevance	BBT, NHPT, TEMPA, BI, IADL, SF-36, grip strength (JAMAR)
Holmqvist 1998	70.8 (7.6)	5	41	individual tailor-made therapy at home with therapist	complex activity, basic hand, participation, bilateral training, real-life relevance	BI, NHPT, LMC, Katz, FAI, SIP

Kwakkel 1999-2002	69 (9.8)	7.2 (2.8)	33	functional exercises that facilitated forced arm and hand activities such as leaning, punching a ball, grasping and moving objects	basic arm, basic hand	BI, ARAT, FAI, NTHP, SIP
Liu 2004	72.7 (9.4)	15.4 (12.2)	20	3 sets of daily tasks with 5 tasks in each set (e.g. folding laundry, to do shopping, taking transportation)	complex activity, basic arm, basic hand, participation, bilateral training, real-life relevance	Performance of tasks, FM
McDonnell 2007	60.1 (10.5)	138 (78)	10	identification of impairment; strategies to reduce these impairments ; task specific training including reaching, wrist extension against resistance, performing fine motor skills	function, basic arm, basic hand	Grip-Lift Task, ARAT, FM, MAL, Pinch Grip, Tapping speed
Michaelsen 2006	69.4 (10.8)	546 (321)	15	object-related reach-to-grasp training	basic arm, basic hand, bilateral training	Tempa, BBT, kinematic outcomes, FM
Morris 2008	67.8 (9.9)	47 (9-284)	50	bilateral training including 4 core tasks: move a doweling peg, move a block from the table, grasp and empty glass, point targets	function, basic arm, basic hand	BI, ARAT, NHPT, RMA,NTHP
Sackley 2006	88.6 (6.5)	? Residence care	63	targeted towards ADL activities, e.g. feeding, dressing, bathing, transfering and mobilizing	complex activity, basic arm, basic hand, bilateral training, real-life relevance	BI, RMA
Winstein 2004	95% 35-75	15.5 (6.0)	20	standard care like muscle facilitation, stretching, self care plus task-specific functional training such as pointing, grasping, stirring	function, basic arm, basic hand	FTHUE, FIM, FM, muscle strength arm-hand (Chatillon force gauge)

Abbreviations: SD: Standard deviation, UE: Upper Extremity, BBT: Box and Block Test, JTT: Jebsen-Taylor Test, FM: Fugl Meyer Test, MAS: Motor Assessment Scale, MBI: Modified Barthel Index of activities of daily living, NHPT: Nine Hole Peg Test, NTHP: Nottingham Health Profile, FAT: Frenchay Arm Test, FAI: Frenchay Activities Index, FIM: Functional Independence Measure, IADL: Instrumental Activities of Daily Living, CIQ: Community Integration Questionnaire , PPT: Purdue Pegboard Test, AMPS: The Assessment of Motor and Process Skills, WMFT: Wolf Motor Function Test, LMCA: Lindmark Motor Capacity Assessment, ARAT: Action Research Arm Test, RMA: Rivermead Motor Assessment upper-limb scale, FTHUE: Functional Test for hemiparetic upper extremity, SIP: Sickness Impact Profile.

Methodological quality

In table 2, the Van Tulder scores are presented for the 15 studies that are included in this review.

The two coders disagreed on 20 out of the 204 Van Tulder items, resulting in a mean Cohen's kappa score of 0.79, which is considered good [50]. After obtaining consensus on the Van Tulder scores, the mean Van Tulder score of all included studies was 13.6 (SD=1.7).

All studies were of acceptable methodological quality, as the lowest Van Tulder score equalled 11, which is well above the cut-off point of 50% (= 9.5) suggested by Van Tulder[32].

The mean internal validity score was 7.2 (out of 10) (SD=1.4). The mean descriptive score was 4.6 (out of 6)(SD=0.8). Twelve out of the fifteen studies had full scores for statistical criteria. The mean statistical score was 1.8 (SD=0.4).

Table 2: Van Tulder Score

Reference	Internal validity score	Descriptive score	Statistical score	Total Score
Alon 2008	4	5	2	11
Baskett 1999	8	4	1	13
Blennerhassett 2004	7	4	2	13
Chan 2006	6	4	2	12
Desrosiers 2005	7	4	2	13
Duncan 2003	9	5	2	16
Higgins 2006	8	4	2	14
Holmqvist 1998	6	6	1	13
Kwakkel 1999-2002	10	6	2	18
Liu 2004	6	4	2	12
McDonnell 2007	8	4	1	13
Michaelsen 2006	7	4	2	13
Morris 2007	8	4	2	14
Sackley 2006	8	5	2	15
Winstein 2004	7	6	2	15

Assessment in task-oriented training interventions after stroke

In the present review, twenty-eight assessment tools were reported, averaging 4 per study. On average 5.7 (SD=1.4) arm-hand skill assessment components were measured per study, while on average treatments addressed 4 of these arm-hand skill components (SD=1.3). The most used outcome measures were Barthel Index (n=6), grip strength measurement (n=5), Fugl-Meyer (n=5), Box-and-Block Test (n=4), and Nine-Hole-Peg-Test (n=4). An overview of the classification concept and the categorisation of the outcome measures according to the proposed concept is presented in table 3. The two coders disagreed on 24 out of the 224 items (8 components x 28 measurement instruments), resulting in a mean Cohen's Kappa score of 0.74 (SD=0.14), which is a substantial agreement according to Landis and Koch [50].

Table 3: Overview of the arm-hand skill assessment concept components and marking of measurement instruments used in the interventions

Arm-Hand Skill Assessment Component OCM	Arm-hand Function	Complex AH-act	Basic Arm-act	Basic Hand-act	Participation	Bilateral AH-act	Exact measure	Real-life relevance	Frequency of use in review articles
BBT			V	V			V		4
JTT			V	V			V		2
MAS		V	V	V					2
MBI		V				V		V	6
NHPT				V			V		4
FAT			V	V		V			1
FIM		V				V		V	3
IADL		V			V	V		V	2
PPT				V			V		1
TEMPA		V	V	V		V	V		3
AMPS		V	V	V		V		V	1
WMFT			V	V		V	V		1
ARAT			V	V			V		3
TP		V				V			1
GLT	V						V		1
RMA	V	V	V	V		V			2
FTHUE			V	V		V			1
LMC	V								1
Katz		V				V		V	1
FM	V								5
GSM	V						V		5
CIQ					V				1
SF-36		V			V				1
FAI					V			V	2
NTHP					V				1
MAL		V	V	V				V	1
KM	V						V		2
SIP		V			V				2
	n=6	**n=12**	**n=11**	**n=13**	**n=6**	**n=11**	**n=10**	**n=7**	**(Average=2.1, SD= 1.4)**

Abbreviations: OCM= outcome measure, V= concept component is present, AH: Arm-hand, act: Activity, BBT: Box and Block Test, JTT: Jebsen-Taylor Test, MAS: Motor Assessment Scale, MBI: Modified Barthel Index of activities of daily living, NHPT: Nine Hole Peg Test, FAT: Frenchay Arm Test, FIM: Functional Independence Measure, IADL: Instrumental Activities of Daily Living, PPT: Purdue Pegboard Test, AMPS: The Assessment of Motor and Process Skills, WMFT: Wolf Motor Function Test, LMC: Lindmark Motor Capacity Assessment, Katz: Katz ADL index, ARAT: Action Research Arm Test, RMA: Rivermead Motor Assessment upper limb scale, MAL: Motor Activity Log, FTHUE: Functional Test for hemiparetic upper extremity, FM: Fugl Meyer Test, GSM: Grip Strength Measurement, FAI: Frenchay Activities Index, CIQ: Community Integration Questionnaire, NTHP: Nottingham Health Profile, GLT: Grip Lift Task, TP: Task Performance, KM: Kinematic Measures, SIP: Sickness Impact Profile.

To use table 3 for the evaluation of AHSP in a specific intervention (e.g. task-oriented training by means of sensor-technology [6]), one first has to determine which components are apparent in the training (e.g. an intervention addressing 'basic arm activity', 'basic hand activity' and 'real life relevance'). One then chooses one or more measurement instrument(s) from table 3 that capture these components to the extent relevant to the intervention, to evaluate training specific effects (e.g. Action Research Arm Test and Motor Activity Log). The presence of the 'exact measurement' skill assessment component is a valuable added aspect. Furthermore, one can choose to assess other assessment components that measure generalized training effects (e.g. on the level of function and participation, resulting in e.g. use of Fugl-Meyer Test and SF-36).

Regarding specific measurements of skilled arm-hand performance, 10 studies showed agreement between arm-hand components used in both assessment and in training. An overview of the number of studies that evaluated and treated each of the proposed concept components is given in table 4. There was no significant correlation between the number of studies that assessed a certain component and the number of studies that included the same component in the treatment (r=0.6). The number of studies that used a component in the treatment, but did not evaluate it was low (average=1.5 studies per component, SD=0.9). 'Real life relevance' was the component that was least frequently evaluated while being present in the treatment (3 studies [34, 39, 44]).

Table 4: Relationship between the content of the assessment used and the administered treatment

Arm-hand (AH) skill assessment components	**Number of studies that measure the component**	**Number of studies treating the component**	**Number of studies that treat, but not evaluate the component**	**Number of studies that evaluate, but not treat the component**
AH-function	11	5	1	7
Complex AH-activity	12	6	1	7
Basic arm activity	12	14	2	0
Basic hand activity	13	15	2	0
Participation	5	3	2	4
Bilateral AHP	11	9	1	3
Exact measurement	12	0	0	12
Real-life relevance	10	9	3	4
Average (SD)	-	-	1.5 (0.9)	4.6 (3.9)

The number of studies that evaluate certain components without specifically targeting them during treatment was calculated. This number gives an impression how often possible generalized effects of the training were measured. Scoring highest was 'the assessment of complex skills' (n=7 studies) and 'the assessment of function' (n=7).

'Exact measurement' was used mostly to objectify another measurement component (i.e. 'time measurement', 'strength measurement', and 'movement analysis') (see also table 5) instead of being a component that treatment focused on.

Table 5: Use of exact measurements in assessment of task-oriented training

1) Time measurement
- as test performance deadline: Box and Blocks Test, Purdue Pegboard Test - as outcome measurement: Jebson Taylor Test, Nine-Hole Peg Test, Wolf Motor Function Test, Tempa, Action Research Arm Test
2) Strength measurement -Jamar dynamometer, Chatillon Force Gauge, Martin Vigorometer.
3) Movement analysis - joint movement (range,velocity,jerk, trajectory straightness): Optotrak (Northern Digital) - relationship grasp/lift force: Grip Lift Test (lightweight load cells) - tapping speed: load cell

Discussion

It was the aim of this review to

1. inventorize the outcome measures that were used in randomized clinical trials that use task-oriented training to influence arm-hand performance after stroke,
2. to introduce a concept that can serve as a framework to classify and choose outcome measures and
3. to assess the extent to which training specific and/or generalized training effects were evaluated in arm-hand task-oriented training interventions after stroke.

Inventory of outcome measures that were used in task-oriented training interventions

Our systematic review revealed that the Barthel Index, grip strength measurement and the Fugl-Meyer-Test were the *tests that were used* most frequently.
Also other studies found that the Barthel Index was the most often [13, 25] (or second most often [51]) used outcome measurement. The Barthel Index measures total body activity (self-care and mobility) [52]. Besides being widespread, it is easy to administer (it doesn't take training); and it takes as little as 2-5 minutes to complete [17]. However, the Barthel Index does also have important weaknesses, i.e. ceiling effect in stroke patients with mild deficits, insensitivity to change and lack of comprehensiveness [15-17, 53].
The Box-and-Block-Test and Nine-Hole-Peg-Test were the specific arm-hand activity level measures that were most frequently used. These tests do measure gross manual dexterity (BBT) and fine manual dexterity (NHPT) [40]. However, they hardly relate to activities of daily life. The activity level assessment methods that were used in CIMT (a more specific task-oriented training approach), namely Wolf Motor Function Test and Motor Activity Log[54], were used infrequently (both only once) to evaluate task-oriented training in the present review. Ashford et al [31], in their systematic review, identified ABILHAND [55] and MAL [56] as valid and reliable assessment tools reflective of 'real-life' higher active function. However, among the RCTs that were included in the present systematic review only one used MAL [45]. Remarkably, LASIS and ABILHAND were not used at all. It is hypothesized that the reason for the limited use

of more specific motor function tests (e.g. Wolf Motor Function test), instrumental activities of daily living tests (e.g. Frenchay Arm Test), and 'real life reflecting measures' (MAL, ABILHAND, LASIS) is that these instruments are still not known enough amongst clinicians and, although very useful and complementary[57], they currently do not match the longer and more widespread used generic ADL measures: Barthel Index and FIM.
Whereas time and strength measurement were used by most clinicians for outcome measurement (see also table 1 and 5), the movement analysis methods were mostly limited to a research environment. With the use of technology-supported rehabilitation, a wider range of technology-assisted evaluation methods will become more available to clinicians in the near future. It is advocated that they will be used as objective, reliable, and time-saving methods for outcome assessment. Robotic and sensor technology may, next to their role as training tools, also play an increasingly important role in future outcome assessment, as kinematic outcome assessment allows for differentiation between true recovery and/or adaptive strategies of motor learning [58, 59]. Bosecker et al [60] have developed models to calculate the outcome on Fugl-Meyer, Motor Status score, and motor power from the MIT-Manus robot derived metrics . Although these models have only investigated the potential for predicting arm-hand (ICF) function level outcome, they could prove valuable for offering reliable outcome assessment that may reduce therapist assessment time in future. Research of technology-supported arm-hand performance evaluation on activity and participation level has to date been focusing on the measurement of arm-hand activity (the ratio of impaired versus non-impaired arm use) by means of accelerometry in real life and has been validated against real life clinical outcome measures (Motor Activity Log) [61]. However, although very promising these methods are still only used in research rather than in clinical practice due to the limited ease of use of the assessment tool.

Conceptual framework to guide the choice of outcome measures

There are no large-scale randomized clinical studies available that investigate the effects of technology-supported task-oriented training. Therefore the *conceptual framework* presented in this manuscript has been developed, based on evidence from non-technology supported trials. Identification and conceptualisation of outcome measures on the basis of ICF has been found useful by several authors [11, 25], but as there is still a multitude of tests available in each of the ICF categories, ICF does not suffice for guiding test choice. The field of rehabilitation technology needs more standardization on outcome measure use in clinical trials in order to enable comparison across systems [14]. Wade has emphasized that it is essential to base test choice on what really needs to be measured [62]. A framework to classify measurement instruments according to aspects of upper extremity performance that can be measured, may be a first step towards the standardized use of 'evidence-based' outcome assessment measures.
Geyh et al [25] had also identified constructs contained in outcome measures. However, these constructs (n=191) were outnumbering the number of different outcome measures that were used in stroke trials and can therefore not be used as a basis for outcome measure choice. The concept that is presented in this paper presents a classifica-

tion of test batteries according to 8 arm-hand skill assessment components. These 8 arm-hand skill assessment components refer to five levels of content assessment:

1. the ICF classification,
2. evaluation of complex and/or basic skills,
3. exact measurement or not,
4. measurement reflecting real-life relevance or not and
5. whether bilateral task evaluation was included or not.

The first level, namely the classification of test batteries according to the ICF framework is well supported by literature [15-17, 25]. Spooren et al [29] have further subdivided the ICF activity level in basic (arm and hand) and complex skills (the second level of content assessment) in their investigation of outcome measures used for the evaluation of upper extremity motor training in tetraplegic patients. A more detailed content-based conceptual framework that may be used for outcome measure choice is to the authors' knowledge not available. The concept that is outlined in the present paper may guide the clinician/researcher further. Once (s)he has decided which arm-hand skill (assessment) components are best mapping onto the training content, the concept (table 3) can show the measurement instrument(s) that contain(s) most of these components and is therefore best suitable to evaluate the training intervention. Next it has to be decided if/for which other components generalized effects are to be measured.

Specific and generalized training effects

The systematic review showed that *training specific effects* on arm-hand performance as well as *generalized effects* to non-trained (assessment) components were measured in the included clinical trials. In the systematic review 'grip strength' and 'Fugl Meyer' were the assessments that were most often used to assess generalized effects of the training, namely on the function level. Evaluation of impairment is often preferred, because the associated measurement instruments are objective and easy to use [63]. Impairment measures are useful to measure prognosis and to track process effects of interventions [64]. However, also activity level measurement should be included as it is more relevant for what patients are concerned with [16 64].
Also the effect of task-oriented training at the participation level was studied in more than 30% (5 out of 15) of the included RCT studies. This was much more than the 5.4% that was found by Salter et al [65] who studied 491 RCT's (between 1968 and 2005) evaluating the effectiveness of interventions in stroke rehabilitation. Salter et al [65] do mention that in recent years, the importance of understanding the effect of training interventions on the participation of an individual in society has gained much attention. The different percentage in their study compared to the percentage that is found by the present systematic review, may be attributed to the fact that only task-oriented training interventions were included in the current systematic review. This training approach and the studies included in this review are fairly recent (studies dated between 1998 and 2009).

Methodological considerations and future research

No randomized clinical trials are available that evaluate technology-supported task-oriented training. Technology-supported outcome assessment has rarely been used in the studies covered by this systematic review. When available in future, a review on technology-supported outcome measurement of task-oriented training will complement the conceptual framework presented in this study.

The concept presented in this study contributes to standardisation of outcome assessment as it guides persons that use similar interventions towards the choice of similar measurement instruments. However, the model is only a first step. In the 'basic' conceptual model that is proposed in the present study, a skill assessment component was assigned to test batteries if the component was apparent, even if it was only for a very small part of the test. Therefore, an important next step is to attribute for each test a weighing for the skill assessment components that are related to that test. This may guide the user of the model further in choosing the appropriate test. Future research should also integrate this concept in a more elaborated guiding model, including also other factors that guide clinicians towards the choice of a measurement instrument, namely patient-related factors (age, diagnosis, performance level), need for performance-based or self-reported evaluation, purpose of examination and psychometric properties. Besides the specific and general arm-hand skill outcome measures that are represented in the proposed conceptual model, also measures that detect changes that are important to each individual patient [66] should be added. 'Individualized outcome measurement' was not a component that was apparent in the measurement instruments used in the present review, but may be a meaningful skill assessment component to be included in a next version of the currently proposed model. In the present study we only included randomized clinical trials as we wanted to start from the highest level of clinical studies. A necessary next step would be to complement this research, also including the non-randomized clinical trials in a similar approach to investigate how this changes and/or adds to the list of tests used and the analysis of additional tests with regard to the components proposed in this study. As mentioned in the discussion above, very valuable measurement instruments exist for evaluation of skilled arm hand performance (e.g. ABILHAND), that are not included in the current model.

Another step for future research comprises of the development of conceptual guidelines for training protocols that can be adopted in clinical trials using rehabilitation technology. Furthermore, it would be most interesting if these conceptual guidelines for outcome assessment and training protocols could be developed across different neurological disease categories as common denominators for conceptual outcome measurement and intervention frameworks can enable comparisons between intervention types, dosage, and suitability for different (neurological) patients [67].

Conclusion

An initial concept was introduced to classify measurement instruments and guide the choice for evaluation of arm-hand performance after a specific intervention. AHSP assessment in task-oriented training includes the evaluation of both training specific and generalized effects. At activity level, generic measures are mostly used, while measures reflecting 'real-life activities' were least frequently used. Whereas technology-supported assessment of arm-hand performance has been used quite extensively at function level, a major challenge exists to extend technology-supported outcome assessment towards activity and participation level.

Acknowledgements

This research was funded by Philips Research Europe (Department of Biomedical Sensor Systems, Eindhoven, The Netherlands).
The authors thank M. Monfrance for his help in setting up the search strategy, and the screening of the abstracts to identify appropriate articles (opinion third reviewer).

References

1. Truelsen T, Piechowski-Jozwiak B, Bonita R, Mathers C, Bogousslavsky J, Boysen G. Stroke incidence and prevalence in Europe: A review of available data. *Eur J Neurol*. 2006;13:581-598
2. Andersen HE, Eriksen K, Brown A, Schultz-Larsen K, Forchhammer BH. Follow-up services for stroke survivors after hospital discharge--a randomized control study. *Clin Rehabil*. 2002;16:593-603
3. Broeks JG, Lankhorst GJ, Rumping K, Prevo AJ. The long-term outcome of arm function after stroke: Results of a follow-up study. *Disabil Rehabil*. 1999;21:357-364
4. Feys HM, De Weerdt WJ, Selz BE, Cox Steck GA, Spichiger R, Vereeck LE, Putman KD, Van Hoydonck GA. Effect of a therapeutic intervention for the hemiplegic upper limb in the acute phase after stroke: A single-blind, randomized, controlled multicenter trial. *Stroke*. 1998;29:785-792
5. Wiles R, Ashburn A, Payne S, Murphy C. Discharge from physiotherapy following stroke: The management of disappointment. *Soc Sci Med*. 2004;59:1263-1273
6. Timmermans AAA, Seelen HAM, Geers RPJ, Saini PK, Winter S, Te Vrugt J, Kingma H. Sensor-based skill training in chronic stroke patients: Results on treatment outcome, patient motivation and system usability. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*. 2010; Vol 18, 3, 284-292
7. Timmermans AA, Seelen HA, Willmann RD, Kingma H. Technology-assisted training of arm-hand skills in stroke: Concepts on reacquisition of motor control and therapist guidelines for rehabilitation technology design. *J Neuroeng Rehabil*. 2009;6:1
8. Riener R, Nef T, Colombo G. Robot-aided neurorehabilitation of the upper extremities. *Med Biol Eng Comput*. 2005;43:2-10
9. Timmermans A, Seelen H, Kingma H. Task-oriented training: An essential element in technology-supported rehabilitation of skilled arm-hand performance after stroke. *IEEE-EMBS Benelux Chapter Symposium*. 2009:63-66
10. Gelderblom GJ, De Wilt M, Cremers G, Rensma A. Rehabilitation robotics in robotics for healthcare; a roadmap study for the european commission. *11th International Conference on Rehabilitation Robotics (ICORR). Kyoto, Japan*. 2009:834-838
11. Salter K, Jutai JW, Teasell R, Foley NC, Bitensky J. Issues for selection of outcome measures in stroke rehabilitation: Icf body functions. *Disabil Rehabil*. 2005;27:191-207
12. Jutai JW, Teasell R. The necessity and limitations of evidence-based practice in stroke rehabilitation. *Topics in Stroke Rehabilitation*. 2003;10:71-78
13. Salter KL, Teasell RW, Foley NC, Jutai JW. Outcome assessment in randomized controlled trials of stroke rehabilitation. *Am J Phys Med Rehabil*. 2007;86:1007-1012
14. Butter M, Rensma A, van Boxtel J, Kalisingh S, Schoone M, Leis M, Gelderblom G, Cremer G, de Wilt M, Kortekaas W, Thielmann A, Cuhls K, Sachinopoulou A, Korhonen I. Robotics for healthcare: Final report. Edited by european commission, dg information society. *5.0*. 2008:1-179
15. Barak S, Duncan PW. Issues in selecting outcome measures to assess functional recovery after stroke. *NeuroRx*. 2006;3:505-524
16. Duncan PW, Jorgensen HS, Wade DT. Outcome measures in acute stroke trials: A systematic review and some recommendations to improve practice. *Stroke*. 2000;31:1429-1438
17. Salter K, Jutai JW, Teasell R, Foley NC, Bitensky J, Bayley M. Issues for selection of outcome measures in stroke rehabilitation: Icf activity. *Disabil Rehabil*. 2005;27:315-340
18. Van Peppen RP, Kwakkel G, Wood-Dauphinee S, Hendriks HJ, Van der Wees PJ, Dekker J. The impact of physical therapy on functional outcomes after stroke: What's the evidence? *Clin Rehabil*. 2004;18:833-862
19. Timmermans AA, Seelen HA, Willmann RD, Bakx W, de Ruyter B, Lanfermann G, Kingma H. Arm and hand skills: Training preferences after stroke. *Disabil Rehabil*. 2009:1-9

20. Lum PS, Uswatte G, Taub E, Hardin P, Mark VW. A telerehabilitation approach to delivery of constraint-induced movement therapy. *J Rehabil Res Dev*. 2006;43:391-400
21. Johnson MW, KJ. ; Anderson,J. ; Nathan,D. ; Smith,RO. Development of adler: The activities of daily living exercise robot. *BioRob2006. The first IEEE/RAS-EMBS International Conference on Biomedical Robotics and Biomechatronics*. 2006:881-886
22. Timmermans AAA, Geers RPJ, Franck JA, Dobbelsteijn P, Spooren AIF, Kingma H, Seelen HAM. T-toat: A method of task-oriented arm training for stroke patients suitable for implementation of exercises in rehabilitation technology. *IEEE 11th International Conference on Rehabilitation Robotics*. 2009:98-102
23. Shumway-Cook A, Woollacott M. A conceptual framework for clinical practice. *In: Motor control. Translating research into clinical practice.* Philadelphia: Lippincott Williams & Wilkins; 2007:136-153.
24. Andresen EM. Criteria for assessing the tools of disability outcomes research. *Arch Phys Med Rehabil*. 2000;81:S15-20
25. Geyh S, Kurt T, Brockow T, Cieza A, Ewert T, Omar Z, Resch KL. Identifying the concepts contained in outcome measures of clinical trials on stroke using the international classification of functioning, disability and health as a reference. *J Rehabil Med*. 2004:56-62
26. Timmermans AAA, Spooren AIF, Kingma H, Seelen HAM. Influence of task-oriented training content on skilled arm-hand performance in stroke: A systematic review. *Neurorehabil Neural Repair*. 2010. In press
27. Dobkin BH. Confounders in rehabilitation trials of task-oriented training: Lessons from the designs of the excite and scilt multicenter trials. *Neurorehabil Neural Repair*. 2007;21:3-13
28. Liepert J, Hamzei F, Weiller C. Lesion-induced and training-induced brain reorganization. *Restor Neurol Neurosci*. 2004;22:269-277
29. Spooren AI, Janssen-Potten YJ, Kerckhofs E, Seelen HA. Outcome of motor training programmes on arm and hand functioning in patients with cervical spinal cord injury according to different levels of the ICF: A systematic review. *J Rehabil Med*. 2009;41:497-505
30. Salter K, Jutai JW, Teasell R, Foley NC, Bitensky J, Bayley M. Issues for selection of outcome measures in stroke rehabilitation: Icf participation. *Disabil Rehabil*. 2005;27:507-528
31. Ashford S, Slade M, Malaprade F, Turner-Stokes L. Evaluation of functional outcome measures for the hemiparetic upper limb: A systematic review. *J Rehabil Med*. 2008;40:787-795
32. van Tulder MW, Assendelft WJ, Koes BW, Bouter LM. Method guidelines for systematic reviews in the cochrane collaboration back review group for spinal disorders. *Spine*. 1997;22:2323-2330
33. van Tulder M, Furlan A, Bombardier C, Bouter L. Updated method guidelines for systematic reviews in the cochrane collaboration back review group. *Spine*. 2003;28:1290-1299
34. Alon G, Levitt AF, McCarthy PA. Functional electrical stimulation (fes) may modify the poor prognosis of stroke survivors with severe motor loss of the upper extremity: A preliminary study. *Am J Phys Med Rehabil*. 2008; 87:627-636
35. Baskett JJ, Broad JB, Reekie G, Hocking C, Green G. Shared responsibility for ongoing rehabilitation: A new approach to home-based therapy after stroke. *Clin Rehabil*. 1999;13: 23-33
36. Blennerhassett J, Dite W. Additional task-related practice improves mobility and upper limb function early after stroke: A randomised controlled trial. *Aust J Physiother*. 2004; 50:219-224
37. Chan DYL, Chan CCH, Au DKS. Motor relearning programme for stroke patients: A randomized controlled trial. *Clin Rehabil*. 2006;20:191-200
38. Desrosiers J, Bourbonnais D, Corriveau H, Gosselin S, Bravo G. Effectiveness of unilateral and symmetrical bilateral task training for arm during the subacute phase after stroke: A randomized controlled trial. *Clin Rehabil*. 2005;19:581-593
39. Duncan P, Studenski S, Richards L, Gollub S, Lai SM, Reker D, Perera S, Yates J, Koch V, Rigler S, Johnson D. Randomized clinical trial of therapeutic exercise in subacute stroke. *Stroke*. 2003;34:2173-2180
40. Higgins J, Salbach NM, Wood-Dauphinee S, Richards CL, Cote R, Mayo NE. The effect of a task-oriented intervention on arm function in people with stroke: A randomized controlled trial [with consumer summary]. *Clin Rehabil*. 2006;20:296-310

41. Holmqvist LW, von Koch L, Kostulas V, Holm M, Widsell G, Tegler H, Johansson K, Almazan J, de Pedro-Cuesta J. A randomized controlled trial of rehabilitation at home after stroke in southwest stockholm. *Stroke* 1998;29:591-597
42. Kwakkel G, Wagenaar RC, Twisk JW, Lankhorst GJ, Koetsier JC. Intensity of leg and arm training after primary middle-cerebral-artery stroke: A randomised trial. *Lancet*. 1999;354:191-196
43. Kwakkel G, Kollen BJ, Wagenaar RC. Long term effects of intensity of upper and lower limb training after stroke: A randomised trial. *J Neurol Neurosurg Psychiatry*. 2002;72:473-479
44. Liu KP, Chan CC, Lee TM, Hui-Chan CW. Mental imagery for promoting relearning for people after stroke: A randomized controlled trial. *Arch Phys Med Rehabil*. 2004;85:1403-1408
45. McDonnell MN, Hillier SL, Miles TS, Thompson PD, Ridding MC. Influence of combined afferent stimulation and task-specific training following stroke: A pilot randomized controlled trial. *Neurorehabil and Neural Repair*. 2007;21:435-443
46. Michaelsen SM, Dannenbaum R, Levin MF. Task-specific training with trunk restraint on arm recovery in stroke: Randomized control trial. *Stroke*. 2006;37:186-192
47. Morris JH, van Wijck F, Joice S, Ogston SA, Cole I, MacWalter RS. A comparison of bilateral and unilateral upper-limb task training in early poststroke rehabilitation: A randomized controlled trial. *Arch Phys Med Rehabil*. 2008;89:1237-1245
48. Sackley C, Wade DT, Mant D, Atkinson JC, Yudkin P, Cardoso K, Levin S, Lee VB, Reel K. Cluster randomized pilot controlled trial of an occupational therapy intervention for residents with stroke in uk care homes. *Stroke*. 2006;37:2336-2341
49. Winstein CJ, Rose DK, Tan SM, Lewthwaite R, Chui HC, Azen SP. A randomized controlled comparison of upper-extremity rehabilitation strategies in acute stroke: A pilot study of immediate and long-term outcomes. *Arch Phys Med Rehabil*. 2004;85:620-628
50. Landis JR, Koch GG. The measurement of observer agreement for categorical data. *Biometrics*. 1977;33:159-174
51. Haigh R, Tennant A, Biering-Sorensen F, Grimby G, Marincek C, Phillips S, Ring H, Tesio L, Thonnard JL. The use of outcome measures in physical medicine and rehabilitation within europe. *J Rehabil Med*. 2001;33:273-278
52. Sulter G, Steen C, De Keyser J. Use of the barthel index and modified rankin scale in acute stroke trials. *Stroke*. 1999;30:1538-1541
53. Johnston MV, Keith RA, Hinderer SR. Measurement standards for interdisciplinary medical rehabilitation. *Arch Phys Med Rehabil*. 1992;73:S3-23
54. Wolf SL, Winstein CJ, Miller JP, Thompson PA, Taub E, Uswatte G, Morris D, Blanton S, Nichols-Larsen D, Clark PC. Retention of upper limb function in stroke survivors who have received constraint-induced movement therapy: The excite randomised trial. *Lancet Neurol*. 2008;7:33-40
55. Penta M, Tesio L, Arnould C, Zancan A, Thonnard JL. The abilhand questionnaire as a measure of manual ability in chronic stroke patients: Rasch-based validation and relationship to upper limb impairment. *Stroke*. 2001;32:1627-1634
56. Uswatte G, Taub E, Morris D, Light K, Thompson PA. The motor activity log-28: Assessing daily use of the hemiparetic arm after stroke. *Neurology*. 2006;67:1189-1194
57. Dromerick AW, Lang CE, Birkenmeier R, Hahn MG, Sahrmann SA, Edwards DF. Relationships between upper-limb functional limitation and self-reported disability 3 months after stroke. *J Rehabil Res Dev*. 2006;43:401-408
58. Bartolo M, Don R, Ranavolo A, Serrao M, Sandrini G. Kinematic and neurophysiological models: Future applications in neurorehabilitation. *J Rehabil Med*. 2009;41:986-987
59. Kalra L. Stroke rehabilitation 2009: Old chestnuts and new insights. *Stroke*.41:e88-90
60. Bosecker C, Dipietro L, Volpe B, Krebs HI. Kinematic robot-based evaluation scales and clinical counterparts to measure upper limb motor performance in patients with chronic stroke. *Neurorehabil Neural Repair*. 2010;24:62-69
61. Taub E, Uswatte G, King DK, Morris D, Crago JE, Chatterjee A. A placebo-controlled trial of constraint-induced movement therapy for upper extremity after stroke. *Stroke*. 2006;37:1045-1049
62. Wade DT. Measurement in neurologic rehabilitation. *Curr Opin Neurol*. 1993;6:778-784

63. Roberts L, Counsell C. Assessment of clinical outcomes in acute stroke trials. *Stroke*. 1998;29:986-991
64. Wade D. Generic or global outcome measures in rehabilitation: Are they appropriate for measuring (and improving) service quality? *Clin Rehabil*. 2009;23:867-872
65. Salter KL, Foley NC, Jutai JW, Teasell RW. Assessment of participation outcomes in randomized controlled trials of stroke rehabilitation interventions. *Int J Rehabil Res*. 2007;30:339-342
66. Hurn J, Kneebone I, Cropley M. Goal setting as an outcome measure: A systematic review. *Clin Rehabil*. 2006;20:756-772
67. Dobkin BH. Motor rehabilitation after stroke, traumatic brain, and spinal cord injury: Common denominators within recent clinical trials. *Curr Opin Neurol*. 2009

Chapter 5

Arm and hand skills: training preferences after stroke

Timmermans AA, Seelen HA, Willmann RD, Bakx W, de Ruyter B, Lanfermann G, Kingma H. Arm and hand skills: Training preferences after stroke. *Disabil Rehabil*. 2009; 31(16):1344-1352

Abstract

Purpose: An increasing demand for training after stroke has brought about the need to develop rehabilitation technology. This paper reports an inquiry into skill preferences of persons after stroke regarding arm-hand training and examines the relationship between the use of the affected arm and the patient's training preference.
Method: Data collection involved a semi-structured interview of 20 persons in the subacute and 20 persons in the chronic stage after stroke, based on an adaptation of the Motor Activity Log.
Results: Subacute and chronic patients after stroke agreed on seven out of ten most preferred training skills. Patient preferences related mostly to 'manipulation in combination with positioning' and 'manipulation'. Eight motivation aspects for skill training were identified as being important. A positive correlation was found between skill preference scores and use of the impaired arm ($r=0.64$) ($p<0.001$).
Conclusions: This study has resulted in an inventory of skills that persons after stroke prefer to train on. This list can be used for implementation of exercises in rehabilitation technology. Motivation for skill training pertains to optimising participation level, rather than function or activity level. This study suggests that client-centred assessment is advocated in order to set therapy goals that match patient training preferences.

Introduction

Approximately 50% of stroke survivors experience considerable disability of arm and hand function after discharge from hospital or rehabilitation clinics, which may last for the rest of their lives [1-3]. Training after hospital or rehabilitation care can improve arm hand function further; even in chronic stages after stroke [4-11].
The expected increase of stroke events [12], and the knowledge that prolonged rehabilitation leads to improved arm and hand function in persons after stroke[4] has increased the demand for rehabilitation services. This is expected to increase pressure on the health system considerably. The development of smart rehabilitation technology that can allow patients to train their arm (semi-) independent from a therapist is an opportunity if not a necessity for future stroke patient care [13].
Most robotic (actuator driven) [14] and sensor (movement/activity registration) systems [15], that are available nowadays for training arm and hand function in persons after

stroke support training that involves practise of movements in single joints and along single movement planes. This approach may be effective in reducing motor impairment, but does not lead to corresponding benefits regarding every day life activities [16-18]. Arguably, impairment-oriented training is not a sound approach. Richards et al.[19] found that the more time is spent on training higher level skills in patients after stroke, the more successful the rehabilitation outcome will be. This was also confirmed by the literature review by Van Peppen et al.[20] who found that most evidence for influencing functional outcome after stroke exists for task-oriented training approaches. In the context of face to face contact between therapist and patient, it is not necessary to know a-priori patient training preferences as exercises can be matched by the therapist to the needs of the patient [21].
However, task-oriented approaches are finding their way towards rehabilitation technology, although to date they are applied in few systems [22-26]. When developing rehabilitation technology it is essential to know in advance which skills are of interest to persons after stroke to ensure that technology will support these skills. Firstly because training effects are context and task-specific and improvement after training a certain skill cannot be assumed to transfer to other functional activities [27, 28]. Therefore, software (exercises, feedback on exercises) and training objects accompanying a robotic or sensor-based rehabilitation system should be as specific as possible for the skills that are trained. Secondly, it is important to allow patients to choose from skills that are close to what they want/need to train. Patient tailored rehabilitation allows patients to have an active role in their rehabilitation process, which stimulates motivation and treatment adherence [29-32].

This study aimed to assess a) skill training preferences of subacute and chronic persons after stroke and b) whether patients prefer to train on their most impaired functions (or not) and c) which are their main motives for skill training preferences.

Methods

Study design

A cross-sectional survey involving a semi-structured interview of subacute and chronic patients after stroke was conducted. The Medical Ethics Committee of Stichting Revalidatie Limburg in Hoensbroek (the Netherlands) has approved this study.

Subjects

Twenty subacute and twenty chronic patients after stroke were recruited from the Hoensbroek Rehabilitation Centre in Hoensbroek (NL) over a period of 5 months.
Inclusion criteria were:

1. a first ever supratentorial stroke,
2. age ≥18 years,

3. clinically diagnosed with central paresis of the arm/hand,
4. a post-stroke time of either 3-26 weeks (subacute group) or >12 months (chronic group),
5. a fair cognitive level, i.e. MMSE score ≥ 26 [33],
6. ability to read and
7. understand the Dutch language.

Exclusion criteria were:

1. severe neglect in the near extra personal space [34], established by the letter cancellation test [35] and Bell's test (quantitative evaluation) [36] with a minimum omission score of 15%[37],
2. severe spasticity (Modified Ashworth Scale total arm, measuring spasticity of Shoulder adductors, Elbow Flexors and Wrist Flexor Musculature >4),
3. severe additional neurological, orthopaedic or rheumatoid impairments prior to stroke that may interfere with task performance,
4. Broca aphasia, Wernicke aphasia, global aphasia: as determined by Akense Afasie Test (AAT) [38], and
5. severe apraxia as measured by apraxietest van Heugten [39].

Procedure

The framework for the procedures used in the study was determined prior to conducting the study in order to avoid bias of the interviewer for data analysis and resulting conclusions. An overview of the procedures used is given in figure 1.
A semi-structured interview was conducted, using an adapted version of Motor Activity Log (MAL), Dutch version [40, 41]. The interviewer was not involved as a caregiver to participating patients.
The original MAL measures the use of the impaired arm in daily life. The adapted version has been designed to help patients towards a decision on skill preference. The original version was condensed to 17 (out of 26) items that are relevant for technology supported skill training.
After rating the 17 skills, patients were invited to suggest 3 skills outside the given list, which they would like to practise. This procedure resulted in a 20-item list of skills per subject.
For these 20 items, the MAL scoring system was applied. For each skill a zero to ten score was thus obtained reflecting the amount of use ("How much did you use your impaired arm for this activity in the last week?") and quality of use ("How useful was your impaired arm when doing this activity in the last week?"). The sum score of 'amount of use' and 'quality of use' will further be specified as "use" of the impaired arm.
To get information on which skills patients prefer to train on, patients were asked to indicate on which 5 activities out of the 20 they would like to train most. The 20-item list with skills was offered to each of the patients in a different randomised order to minimise the influence of order of presentation on choice of skill preference.

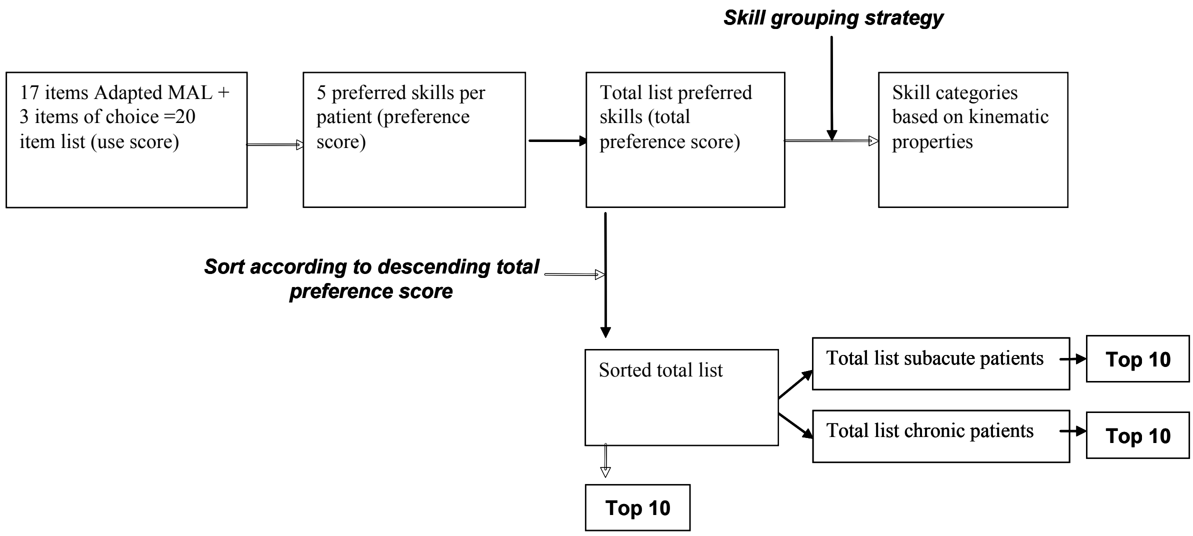

Fig. 1: Schematic presentation of procedure**.** Abbreviations: preference score = score given by a patient to the five skills that he/she prefers to train on ; Total list = list of all skills that were mentioned by the total group of patients as preferred skills to train on; total preference score = sum of all the preferences scores that were attributed by the total group to a specific skill in the total list.

Subsequently, the interviewer wrote down these five preferred skills on separate cards. The patient was then asked to rank the skills according to descending preference level. Scores 1-5 were attributed (5 for most preferred skill, 1 for least preferred skill), leading to a preference score.

The interviewer also asked the patients why they chose a certain activity to be their most preferred skill to train on (or why did they give a score of 5 to a specific skill)? This information was used to create an inventory of the reasons/motivations why skills were chosen as preferred skills to train on.

A total list was made containing all skills that were mentioned by the total group of patients as preferred skills to train on. For each skill in the total list, the preference scores attributed by patients for each skill were summed (=total preference score) and skills were ranked according to this total preference score (descending order). To identify any major differences regarding skill training preferences between persons in chronic and subacute stage after stroke, the 10 top rated skills for the two groups were compared (see also figure 1). Note that the total preference score for a skill can outnumber the number of participants from the study, as each skill can be given a score of 1-5 by each of the participants (or 0 if it was not mentioned as a preferred skill to train on).

Next, a skill grouping strategy downsized the total list of preferred training skills by clustering items, based on kinematic similarity. This procedure was initiated, in order to detect where patients mentioned similar skills in different wording. The categories also give additional information about the skills that are mentioned by patients. It was not the purpose of this procedure to replace the skill information by its kinematic components.

Two independent movement scientists made an *a-priori* grouping strategy. This resulted in the following skill categories: positioning the upper extremity, pointing to/indicate, grasp, manipulate, carry/tilt, push/pull, ‘other’. The movement scientists then evaluated the total list and mentioned for each skill the category name(s) that

was/were applicable for that skill. Skills with similar movement components could now be clustered into categories. As skills could also contain components of several categories at the same time, combination categories were constructed.
There was 70% agreement between the experts. In the case of disagreement, a third expert evaluated the skill (not having seen the analysis of the other experts) to facilitate agreement on the differences between the coders.
It was analysed how skills from the total list were distributed across the categories (or combinations of categories) mentioned above. This was done in order to ascertain how frequent all categories of upper extremity activity were represented and whether categories of upper extremity skills were over- or underrepresented.

Data analysis

A statistical analysis has been performed for following patient characteristics: age, MMSE and post-stroke time (SPSS).
The answers of the patients to the motivation question: "What was the reason for you to choose this skill as the most preferred skill to train on?" were analysed qualitatively through open coding (1 observer). To decide if motives where driven by a need to improve impairment level, activity level or participation level, the motives were matched to the following definitions. Impairment can be defined as "problems in body functions or structure" [42]. Activity can be defined as "the execution of a task by an individual"[42]. Participation can be defined as "involvement of an individual in a life situation" [42].
Use scores and total preference scores were imported into Matlab 7.14 (Mathworks Inc). A Spearman correlation coefficient was calculated as a measure of association [43] between the total preference scores and the total use score (sum of use scores from all patients for a specific skill) related to the corresponding skill. This was done for total preference scores and use scores of the total list skills and of the categorised skills. As

Table 1: Overview of patient characteristics

		Subacute (n=20)	Chronic (n=20)	Total (n=40)
Gender	Male	11	13	24
	Female	9	7	16
Post-stroke time average months (SD)		3.12 (1.21) *	24.22 (19.65) *	13.67 (17.4)
Age average years (SD) total range		61.9 (12.2) (NS) 28-79	59.71 (10.1) (NS) 41-77	60.78 (11.1) 28-79
Dominant Side	Left	3	1	4
	Right	17	19	36
Imapaired Side	Left	11	10	21
	Right	9	10	19
MMSE average score (SD)		28.35 (1.38) (NS)	28.05(1.31)(NS)	28.2 (1.34)

Abbreviations: (NS): Non-significant, *: $p < 0.001$

there were 10 participants with muscle power in the proximal upper extremity, but with a-functional hand function, it was interesting to see in how far 0 scores on the level of use influenced the association that was found. Therefore a Spearman correlation coefficient was calculated between arm use scores that are not equal to zero and their corresponding total skill preference scores.

Results

Patient characteristics

Forty persons after stroke participated in this study. Patient characteristics are displayed in table 1. No statistically significant differences can be found between subacute and chronic patients after stroke for age and MMSE. Only post-stroke time is significantly different for both groups ($p<0.001$). No racial/ethnic-based differences were present.

Skill training preferences

A list of the 10 most preferred skills, i.e. with the highest total preference scores is presented in table 2. In the list of the 10 most preferred training skills, 7 out of 10 skills chosen were the same for subacute and chronic patients after stroke (table 2). These skills encompassed: 'eating with knife and fork', 'holding an object while walking', 'keyboard use', 'taking money from purse', 'opening/closing clothing', 'grooming' and 'handling broom, rake or spade'. Both in the subacute and chronic stroke group 'holding an object while walking' and 'eating with knife and fork' rated highest. In the subacute group, also the following skills were mentioned in the top 10 skill preferences: 'bringing cup to mouth', 'using telephone' and 'using a car's steering wheel'. In the chronic group, participants mentioned 'writing', 'washing/drying body' and 'sewing'.

The sum of total preference scores of the 10 most preferred skills were comparable for the subacute and chronic patient group, i.e. 184 and 189 respectively. This indicates that both groups give equal importance to these skills.

After the skills had been clustered skills in skill categories, the categories were examined to establish whether preferred skills were spread equally over the categories. The number of skills that were attributed per skill category was calculated. Almost all categories contained multiple skills.

Table 2: Ranking of skills according to the ten highest total preference scores from the total patient group (n=40), the patients in subacute stage after stroke (n=20) and the patients in chronic stage after stroke (n=20).

Skills as named by patient	Total group R (tps)	Subacute Stroke Patients R (tps)	Chronic Stroke Patients R (tps)
Eating with knife/fork	1 (61)	1 (35)	2 (26)
Holding object while walking	2 (52)	2 (25)	1 (27)
Keyboard work	3 (42)	3 (22)	4 (20)
Taking money from purse	4 (37)	4 (21)	7 (16)
Open/Close clothing	5 (36)	5 (19)	6 (17)
Grooming	6 (33)	7 (14)	5 (19)
Writing	7 (28)		3 (25)
Holding rake/broom/spade	8 (26)	8 (13)	9 (13)
Cup to mouth	9 (18)	6 (15)	
Arm in sleeve/reach high/sewing	10 (17)		10 (x/x/(12))
Wash and dry body			8 (14)
Handling telephone and steering wheel car		9&10 (10/10)	

Abbreviations: R= ranking of skills ; tps=total preference score

Skill preference scores per category were calculated by adding up all the total preference scores of the skills belonging to a specific skill category (figure 2).
Skills that patients preferred to train on are spread along the skill categories. Most skills belonged to combination categories (‘position-grasp’, ‘position-manipulate’, ‘grasp-carry/lift’). It can be concluded that ‘manipulation in combination with positioning’ and ‘manipulation’ per se were the skills that are most preferred by patients to train on (fig. 2). This is followed by ‘grasp in combination with positioning’ and by ‘carry/lift’ (fig. 2). The above mentioned categories were all represented by multiple skills.

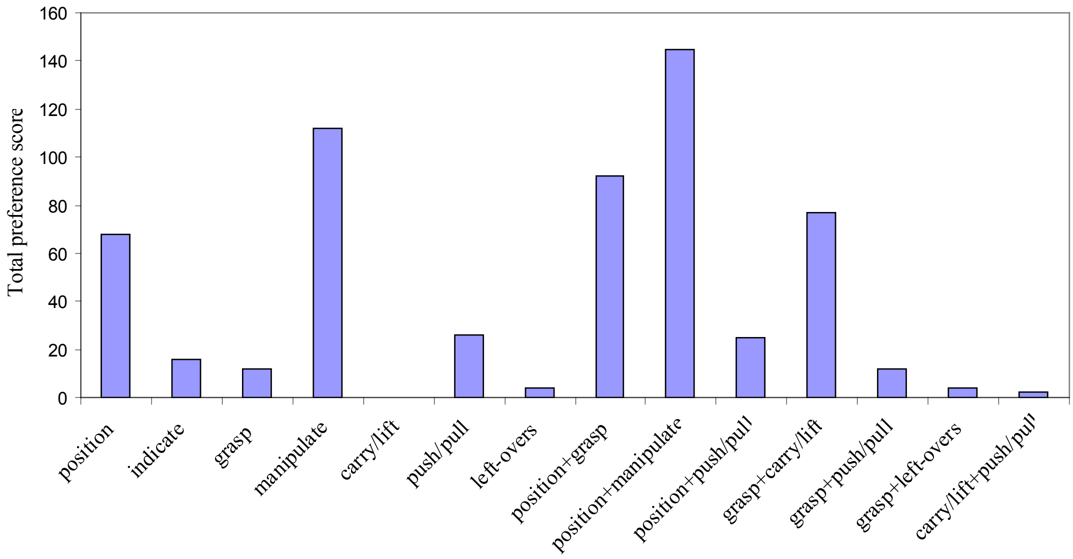

Fig. 2: Total preference scores per skill category

Motives for choosing preferred training skills

From the total inventory of motives that patients mentioned for choosing certain skills as their most preferred skill to train on; 8 motives could be identified. The motives were: hope on transfer to other activities, avoid frustration, avoid embarrassment in public, independence, not to be a burden to others, pride, joy, back to work. It seemed that patients were mostly driven to improve their participation level, rather than their impairment and activity levels.

Motives that relate to participation are: avoiding embarrassment in public ("I want to be able to hold a cup/glass or use cutlery properly when eating with friends", "I don't want to spill food/drinks when eating with others"), avoiding frustration ("It is frustrating when I have a queue of people waiting behind me while I try to take money out of my purse"), independence ("I don't want home-care to help with washing/dressing", "I don't want to ask help for taking money out of my purse"), not to be a burden to others ("I want to do my share in the household, otherwise I feel a burden to spouse/children"), pride ("I want to look good when I go out of the house"), joy ("I really enjoy cycling", "I want to caress my grandchildren"), back to work ("I have my own company and I want to fulfil my role"). Improving the activity level is related to the motive: hope on transfer to other activities ("If I can drink from a cup, I will be able to do many more activities"). Improving impairment was never mentioned by patients as a motive for choosing a skill as a preferred skill to train on.

All skills from the total list were chosen to improve participation level. Bringing cup to mouth, hold fish line and operating a PC-keyboard were also chosen for improving activity level (hope on transfer to other activities).

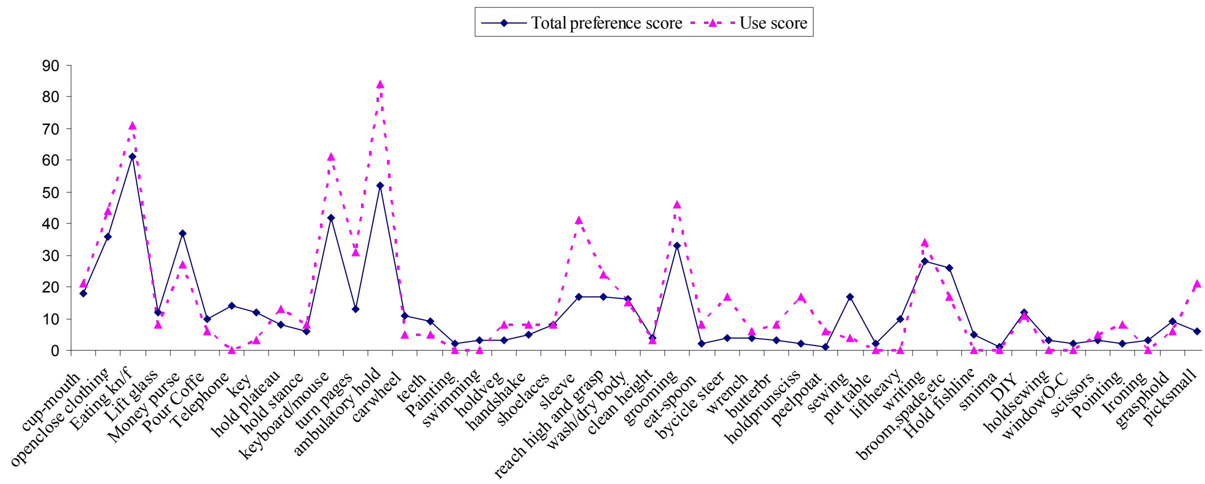

Fig. 3: Association between total preference and total arm use scores for total stroke group

Relationship between actual arm use and arm skill training preferences as perceived by persons after subacute and chronic stroke

The use score (MAL score) reflected the frequency of use; as well as the quality of involvement of the affected extremity for a certain skill. The higher the use scores for a skill, the less the upper limb was impaired for that skill.

Figure 3 presents the relationship between arm use scores for a certain skill and the corresponding total skill preference score. A positive Spearman Correlation Coefficient between skill preference totals and use totals was found ($r=0.64$, $p<0.001$).

The correlation between arm use totals that are not = 0 and their corresponding skill

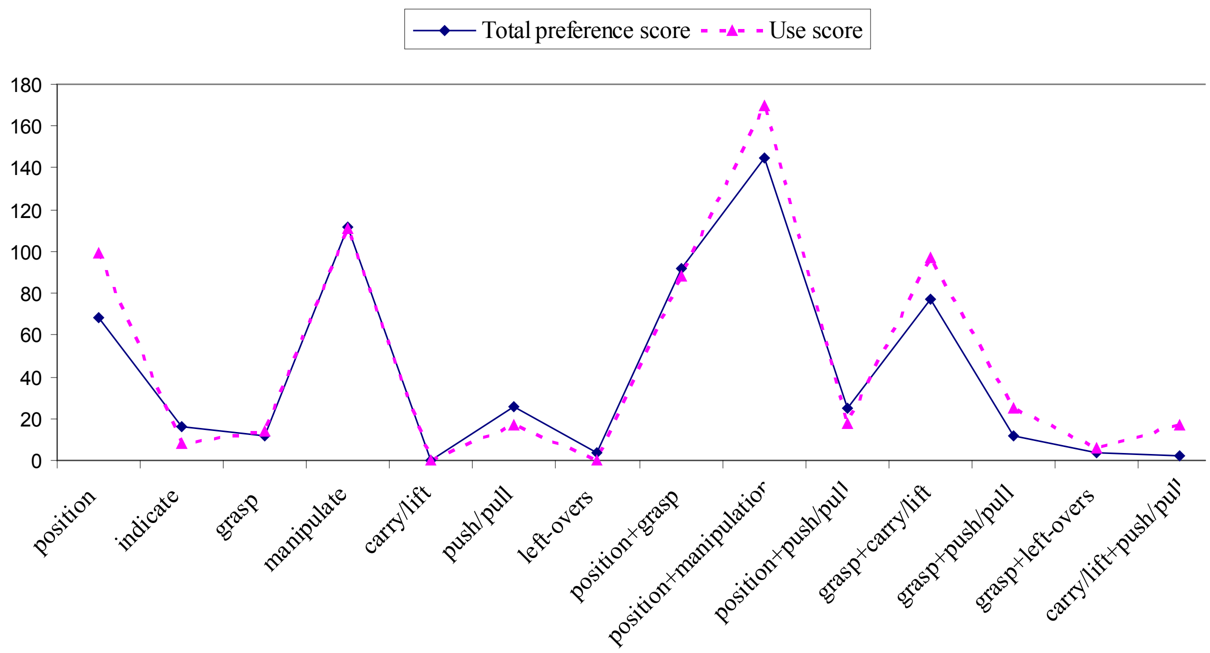

Fig. 4: Association between skill preference score and arm use score per cluster (total stroke group).

preference totals was also positive (Spearman r = 0.62, p<0.001).
This relationship is even more pronounced when total skill preference sore and use scores are summed per category (fig 4). The correlation between categorised skill preferences and categorised skill level of use equals 0.8664 (p<0.001).

Discussion

As the awareness is growing in the field of rehabilitation technology, that training of real-world activities is to be included in future technological developments [13, 16], the question remains for which functional tasks to offer upper extremity training. This is an important issue, as training opportunities should be personally meaningful and challenging in order to support motor learning processes and brain plasticity [44-46].
The first aim of this study was to identify skill training preferences of persons in a subacute and chronic phase after stroke. The skills that patients prefer to train on are very much related to fine motor skills: manipulation and grasp. This was to be expected as arm movement is to a large extent in function of the hand. Gross motor arm function was also mentioned in the category 'positioning'.
No major differences were found between skill preferences of subacute and chronic patients after stroke, as seven out of the top 10 mentioned skills were the same for both patient groups. The two most preferred skills to train on were the same for subacute and chronic patients, namely: 'hold an object while walking' and 'eating with knife and fork'. This indicates that for technology development, no separate applications are needed for subacute and chronic patients after stroke. To our knowledge, no similar studies exist that provide this information.
The second aim for this study was to find out which are motives for skill training preferences. Motives were found not to be driven by impairment and activity levels, but more by the need of patients to participate in society.
A third aim of this study was to study the relationship between use of the impaired arm for a certain skill and the level of preference that patients showed for training the same skill. The results of this study indicate that patients prefer to train on skills for which they have already achieved a certain level of use and proficiency, rather than to train on their most impaired skills. A positive correlation between use and skill preference scores was found (r= 0.64, p<0.001), which was higher if skills are considered in categories that reflect functional entities (r=0.86, p<0.001). This implies that patient training preferences are unlikely to match therapist-defined treatment goal priorities after outcome assessment. It is known that therapists tend to influence goal setting towards physical independence and mobility, and that therapist set goals are driven by economic factors [47]. It has already been indicated by spinal cord patients that rehabilitation is often not sufficiently patient-centred and is not always perceived to address enough the individual needs [48]. The result of the present paper suggests that the same might hold for persons after stroke. Currently, therapists tend to set evidence based treatment goals that are mostly based on the outcome of non client-centred assessment tools [42 49, 50]. These tools identify the body structures/functions and activities that are at risk, as well as quality of life of the person that is assessed. The results of the present study urge therapists, who are not limited in the treatment intervention they can

offer, to set treatment goals not only for, but also with the patients. Client-centred instruments should be seen as a necessary part of patient assessment.
It has been indicated that the use of a client-centred instrument, as e.g. the Canadian Occupational Performance Measure (COPM), leads to patients having an active role in the rehabilitation process and a meaningful treatment outcome in terms of self-management [21].

Limitation of the study and future research

It was not within the scope of this article to assess the use of the impaired arm for all skills that were assessed per patient. It would have been interesting to compare the average impaired arm use for skills that were not chosen as preference skills to the average use for the preference skills. This would give a more complete picture of the association between skill preference and arm use.
This study has investigated the association between skill training preferences and total use scores of the affected upper limb for that skill. A cause-effect relationship cannot be concluded. It would be interesting to know if patients have higher levels of use for skills they prefer to train on, because motivation to try has led to less learned non-use of the affected arm for these skills. Or is the relation the other way around? Because use of the affected limb for a certain skill is higher, patients may feel they will reach more arm hand function if they can optimise function that is already there. A third explanation could be that patients face more their limitations in skills they are attempting (because they like or need to do them), and therefore mention them as preferred skills to train on.
Another limitation of the study is that ten patients (5 subacute and 5 chronic) out of the forty participating had muscle activity in their upper extremity, but had no hand function. The association between arm use for a certain skill and preference scores was analysed without the results of these patients to examine if their data affected the association. The association measure was only slightly lower ($r=0{,}621$, $p<0.001$), which can be attributed to a reduced number of data in the calculation of the correlation coefficient.
This study has not revealed any clear differences in skill training preferences between patients in subacute and chronic stage after stroke. This might be due to the fact that the post-stroke time of the subacute group (0-6 months) was not different enough from post-stroke time of the chronic group (more than 1 year after stroke) who participated in this study. Many of the persons in a subacute stage after stroke were already discharged from staying in the rehabilitation centre (outpatient treatment only) and therefore were facing similar restrictions to patients in a chronic stage after stroke. More pronounced differences between the two groups (e.g. subacute group 0-3 months post stroke versus chronic more than one year post-stroke) might have revealed more differences in skill training preferences. This must be taken into account when using the presented list of skill preferences for e.g. implementation in technology for patients in the subacute stage after stroke that are still staying in rehabilitation centres. Another weakness of this study is the absence of arm-hand function assessment on impairment level and participation level as well as activity level that is measured by MAL. Results

on the different outcome measures might have been stronger predictors for the choice of skill training preferences than the post-stroke time.
Finally, it must be kept in mind that the results of this study fit a very specific group of persons after stroke. Inclusion criteria for the study were set to target that part of the stroke population, which could benefit from a therapist independent technology-supported task-oriented training program.
It would be interesting to also study skill preferences of patients after stroke with a lower functional level than the ones included in this study.

Conclusion

Patients in subacute and chronic stages after stroke share their interest in training arm-hand function skills relating to manipulation of objects and grasp. An inventory of skills that patients after stroke prefer to train on is presented. Although this list is limited in its number, the inventory is a useful starting point for implementing exercises in technology supported training systems.
A positive correlation was found between the use of the arm for a certain skill and the preference score that is attributed to the skill. Motivation for skill training preferences seems to be associated with optimising participation level, rather than function or activity level. This information supports the use of client-centred instruments in arm and hand function assessment in order to formulate therapy goals that match the motivations of persons after stroke.

Acknowledgements

We want to thank Philips Research Europe (Media Interaction Department, Eindhoven) for providing funding support for this research.
We also thank the patients of Adelante in Hoensbroek for participating in this study; J. Verbunt (MD, PhD) for her help in coding skills; M. Moennekens (MD) and the physiotherapy team of SRL for their help with patient recruitment, P. van de Sande (neuropsychologist) and H. Franck (OT) for their expert advice in the choice of test batteries.
Thank you to P. Saini (MSc) and V. van Acht (PhD) for their useful comments on reviewing this paper.

References

1. Andersen HE, Eriksen K, Brown A, Schultz-Larsen K, Forchhammer BH. Follow-up services for stroke survivors after hospital discharge--a randomized control study. *Clin Rehabil*. 2002;16:593-603
2. Broeks JG, Lankhorst GJ, Rumping K, Prevo AJ. The long-term outcome of arm function after stroke: Results of a follow-up study. *Disabil Rehabil*. 1999;21:357-364
3. Feys HM, De Weerdt WJ, Selz BE, Cox Steck GA, Spichiger R, Vereeck LE, Putman KD, Van Hoydonck GA. Effect of a therapeutic intervention for the hemiplegic upper limb in the acute phase after stroke: A single-blind, randomized, controlled multicenter trial. *Stroke*. 1998;29:785-792
4. Duncan P, Richards L, Wallace D, Stoker-Yates J, Pohl P, Luchies C, Ogle A, Studenski S. A randomized, controlled pilot study of a home-based exercise program for individuals with mild and moderate stroke. *Stroke*. 1998;29:2055-2060
5. Duncan P, Studenski S, Richards L, Gollub S, Lai SM, Reker D, Perera S, Yates J, Koch V, Rigler S, Johnson D. Randomized clinical trial of therapeutic exercise in subacute stroke. *Stroke*. 2003;34:2173-2180
6. van der Lee JH, Wagenaar RC, Lankhorst GJ, Vogelaar TW, Deville WL, Bouter LM. Forced use of the upper extremity in chronic stroke patients: Results from a single-blind randomized clinical trial. *Stroke*. 1999;30:2369-2375
7. Dobkin BH. Strategies for stroke rehabilitation. *Lancet Neurol*. 2004;3:528-536
8. Page SJ, Sisto SA, Levine P. Modified constraint-induced therapy in chronic stroke. *Am J Phys Med Rehabil*. 2002;81:870-875
9. Luft AR, McCombe-Waller S, Whitall J, Forrester LW, Macko R, Sorkin JD, Schulz JB, Goldberg AP, Hanley DF. Repetitive bilateral arm training and motor cortex activation in chronic stroke: A randomized controlled trial. *Jama*. 2004;292:1853-1861
10. Fasoli SE, Krebs HI, Stein J, Frontera WR, Hughes R, Hogan N. Robotic therapy for chronic motor impairments after stroke: Follow-up results. *Arch Phys Med Rehabil*. 2004;85:1106-1111
11. Gilbertson L, Langhorne P, Walker A, Allen A, Murray GD. Domiciliary occupational therapy for patients with stroke discharged from hospital: Randomised controlled trial. *Bmj*. 2000;320:603-606
12. Truelsen T, Piechowski-Jozwiak B, Bonita R, Mathers C, Bogousslavsky J, Boysen G. Stroke incidence and prevalence in europe: A review of available data. *Eur J Neurol*. 2006;13:581-598
13. Carignan CR, Krebs HI. Telerehabilitation robotics: Bright lights, big future? *J Rehabil Res Dev*. 2006;43:695-710
14. Riener R, Nef T, Colombo G. Robot-aided neurorehabilitation of the upper extremities. *Med Biol Eng Comput*. 2005;43:2-10
15. Mountain GW, PM ; Hammerton, J ; Mawson,S.J ; Zheng,H ; Davies, R ; Black,N ; Zhou.H. ; Hu,H ; Harris,N; Eccleston,C. The smart project: A user led approach to developing and testing technological applications for domiciliary stroke rehabilitation. In: Robinson P, ed. *Designing accessible technology*. London: Springer; 2006.
16. Johnson MJ. Recent trends in robot-assisted therapy environments to improve real-life functional performance after stroke. *J Neuroengineering Rehabil*. 2006;3:29
17. Kwakkel G, Kollen BJ, Krebs HI. Effects of robot-assisted therapy on upper limb recovery after stroke: A systematic review. *Neurorehabil Neural Repair*. 2008;22:111-121
18. Wisneski KJ, Johnson MJ. Quantifying kinematics of purposeful movements to real, imagined, or absent functional objects: Implications for modelling trajectories for robot-assisted adl tasks. *J Neuroeng Rehabil*. 2007;4:7
19. Richards LG, Latham NK, Jette DU, Rosenberg L, Smout RJ, DeJong G. Characterizing occupational therapy practice in stroke rehabilitation. *Arch Phys Med Rehabil*. 2005;86:S51-S60

20. Van Peppen RP, Kwakkel G, Wood-Dauphinee S, Hendriks HJ, Van der Wees PJ, Dekker J. The impact of physical therapy on functional outcomes after stroke: What's the evidence? *Clin Rehabil*. 2004;18:833-862
21. Wressle E, Eeg-Olofsson AM, Marcusson J, Henriksson C. Improved client participation in the rehabilitation process using a client-centred goal formulation structure. *J Rehabil Med*. 2002;34:5-11
22. Krebs HI, Mernoff S, Fasoli SE, Hughes R, Stein J, Hogan N. A comparison of functional and impairment-based robotic training in severe to moderate chronic stroke: A pilot study. *NeuroRehabilitation*. 2008;23:81-87
23. Johnson MW, KJ. ; Anderson,J. ; Nathan,D. ; Smith,RO. Development of adler: The activities of daily living exercise robot. *BioRob2006. The first IEEE/RAS-EMBS International Conference on Biomedical Robotics and Biomechatronics*. 2006:881-886
24. Sanchez RJ, Liu J, Rao S, Shah P, Smith R, Rahman T, Cramer SC, Bobrow JE, Reinkensmeyer DJ. Automating arm movement training following severe stroke: Functional exercises with quantitative feedback in a gravity-reduced environment. *IEEE Trans Neural Syst Rehabil Eng*. 2006;14:378-389
25. Johnson MJ, Ramachandran B, Paranjape RP, Kosasih JB. Feasibility study of theradrive: A low-cost game-based environment for the delivery of upper arm stroke therapy. *Conf Proc IEEE Eng Med Biol Soc*. 2006;1:695-698
26. Lum PS, Uswatte G, Taub E, Hardin P, Mark VW. A telerehabilitation approach to delivery of constraint-induced movement therapy. *J Rehabil Res Dev*. 2006;43:391-400
27. Kahn LE, Zygman ML, Rymer WZ, Reinkensmeyer DJ. Robot-assisted reaching exercise promotes arm movement recovery in chronic hemiparetic stroke: A randomized controlled pilot study. *J Neuroengineering Rehabil*. 2006;3:12
28. Morrissey MC, Harman EA, Johnson MJ. Resistance training modes: Specificity and effectiveness. *Med Sci Sports Exerc*. 1995;27:648-660
29. Pomeroy V. Facilitating independence, motivation and motor learning. *Physiotherapy*. 2007
30. Levack WM, Taylor K, Siegert RJ, Dean SG, McPherson KM, Weatherall M. Is goal planning in rehabilitation effective? A systematic review. *Clin Rehabil*. 2006;20:739-755
31. Mastos M, Miller K, Eliasson AC, Imms C. Goal-directed training: Linking theories of treatment to clinical practice for improved functional activities in daily life. *Clin Rehabil*. 2007;21:47-55
32. Siegert RJ, McPherson KM, Taylor WJ. Toward a cognitive-affective model of goal-setting in rehabilitation: Is self-regulation theory a key step? *Disabil Rehabil*. 2004;26:1175-1183
33. Crum RM, Anthony JC, Bassett SS, Folstein MF. Population-based norms for the mini-mental state examination by age and educational level. *Jama*. 1993;269:2386-2391
34. Menon A, Korner-Bitensky N. Evaluating unilateral spatial neglect post stroke: Working your way through the maze of assessment choices. *Top Stroke Rehabil*. 2004;11:41-66
35. Uttl B, Pilkenton-Taylor C. Letter cancellation performance across the adult life span. *Clin Neuropsychol*. 2001;15:521-530
36. Gauthier LD, F ; Joanette,Y. The bells test: A quantitative and qualitatitive test for visual neglect. *International Journal of Clinical Neuropsychology*. 1989;XI:49-54
37. Ferber S, Karnath HO. How to assess spatial neglect--line bisection or cancellation tasks? *J Clin Exp Neuropsychol*. 2001;23:599-607
38. Graetz PdB, A ; Willmes,K. *De akense afasie test - handleiding*. Harcourt Test Publishers; 1987.
39. Heugten C. Apraxia in stroke patients: Assessment and treatment. Dissertatie. Rijksuniversiteit groningen. 1998
40. van der Lee JH, Beckerman H, Knol DL, de Vet HC, Bouter LM. Clinimetric properties of the motor activity log for the assessment of arm use in hemiparetic patients. *Stroke*. 2004;35:1410-1414
41. Uswatte G, Taub E, Morris D, Vignolo M, McCulloch K. Reliability and validity of the upper-extremity motor activity log-14 for measuring real-world arm use. *Stroke*. 2005;36:2493-2496
42. Salter K, Jutai JW, Teasell R, Foley NC, Bitensky J. Issues for selection of outcome measures in stroke rehabilitation: Icf body functions. *Disabil Rehabil*. 2005;27:191-207
43. Siegel S CN. *Nonparametric statistics*. New York: McGraw-Hill International Editions; 1988.
44. Wade DT. Personal context as a focus for rehabilitation. *Clin Rehabil*. 2000;14:115-118

45. Woldag H, Hummelsheim H. Evidence-based physiotherapeutic concepts for improving arm and hand function in stroke patients: A review. *J Neurol*. 2002;249:518-528
46. Fisher BE, Sullivan KJ. Activity-dependent factors affecting poststroke functional outcomes. *Top Stroke Rehabil*. 2001;8:31-44
47. Wressle E, Oberg B, Henriksson C. The rehabilitation process for the geriatric stroke patient--an exploratory study of goal setting and interventions. *Disabil Rehabil*. 1999;21:80-87
48. Boschen KA, Tonack M, Gargaro J. Long-term adjustment and community reintegration following spinal cord injury. *Int J Rehabil Res*. 2003;26:157-164
49. Salter K, Jutai JW, Teasell R, Foley NC, Bitensky J, Bayley M. Issues for selection of outcome measures in stroke rehabilitation: Icf activity. *Disabil Rehabil*. 2005;27:315-340
50. Salter K, Jutai JW, Teasell R, Foley NC, Bitensky J, Bayley M. Issues for selection of outcome measures in stroke rehabilitation: Icf participation. *Disabil Rehabil*. 2005;27:507-528

Chapter 6

T-TOAT: A method of task-oriented arm training for stroke patients suitable for implementation of exercises in rehabilitation technology

Timmermans A., Geers, R., Franck J., Dobbelsteijn P., Spooren A., Kingma H., Seelen H. T-TOAT: A method of task-oriented arm training for stroke patients suitable for implementation of exercises in rehabilitation technology. *Conference proceedings of the IEEE 11th International Conference on Rehabilitation Robotics (ICORR)*. Kyoto International Conference Center. Japan, June 23-26, 2009: 98-102

Abstract

Task-oriented training improves skilled arm-hand performance after stroke. Exercises for skill training are however not easy to implement in rehabilitation technology, especially for complex skills that involve object manipulation. In this paper, a skill training method, suitable for technology-supported training of arm-hand performance after stroke is presented. A sensor-based and robotic system in which the training method is used, are described.

Introduction

About 50% of persons who suffered a stroke still have disabled arm-hand function after hospital discharge which may last for the rest of their lives [1]. Training after hospital or rehabilitation care can further improve arm-hand function [2]. However, training arm-hand function should be meaningful to the patient in order to support functional recovery [3] and in order to match patient training motives [4]. This is even more important in case of system-supported rehabilitation, where user motivation is a key issue for the success of training [5]. Task-oriented training has been found to benefit arm-hand treatment outcome [6] as well as match patient training motives [4], so its implementation in rehabilitation technology is a worthwhile endeavour.
Exercises for skills that have a low level of complexity as e.g. ‘to reach for a target’ are relatively easy to implement in technology. Implementation of exercises for skills with a high level of complexity where a large number of components and a large amount of information-processing demands are present [7] is much harder. In Rehabilitation Foundation Limburg (SRL, Hoensbroek, the Netherlands), a method has been developed, based on the analysis of skills in kinematic components (task-analysis method [7]) that keep a strong relationship with the skill itself (figure 1).
It is the combination of use of the task-analysis concept for training, features from neurodevelopmental treatment, principles from training physiology and principles from sensory motor learning in combination with technology-use, that define the T-

TOAT (Technology supported Task-Oriented Arm Training) method that is described in this paper. Also a description is given of one sensor-based training system and one robotic training system, in which the T-TOAT method has been implemented.

The T-TOAT method

To facilitate the implementation of skill training exercises in rehabilitation technology, the T-TOAT method (see table 1) is based on 'part practice'.

Table 1: The components of T-TOAT

T-TOAT: Technology-supported task-oriented arm training
Part practice based on task segmentation
Progressive part method (chaining) towards whole skill practice
Gradual increase of difficulty level: adaptation training load/frequency, influence of gravity, movement selectivity and postural control, increase degrees of freedom to be controlled, gradually out of spastic movement pattern
Feedback (on correct and erroneous movement, shaping): fading frequency, empty time slot before and after feedback delivery, guided self-control on timing of feedback delivery
Training load: dependent on the goal (e.g. training of muscle force, endurance, coordination) & according to the "overload principle"
Over-learning strategy
Exercise variability
Real object manipulation in a realistic ADL context
Distributed and random practice

The training skill is, after task-analysis, separated into parts (segmentation) that can be practiced first isolated and later in combination with subsequent parts (progressive part method or chaining method) [7]. Shaping principles (gradual increase of exercise difficulty and immediate reinforcement of successive approximations) [8] are applied. For each of the components, exercise progression is offered based on principles of training physiology (e.g. a training load that is goal-dependent and exceeding the patient's metabolic muscle capacity ('overload principle' [9, 10])), neuro-developmental treatment and on motor learning principles. Examples of motor learning principles used are a) the 'over-learning strategy' (practice that continues after achievement of the minimum performance level) [7, 11], b) inclusion of 'exercise variability' to improve retention of training effects [12] and to keep the subject engaged in cognitive processes required by the task [7, 12] and c) training in a "realistic environmental context" to provide correct sensory information for brain reorganization processes [13] and relevant (cognitive) problem solving issues [7, 14]. Distributed practice (exercises are spread over time) avoids fatigue, optimizes cognitive effort and supports memory consolidation processes [7]. Random practice (practicing different tasks in random order) leads to better performance in transfer tasks relative to conditions in which each of the different tasks would be practiced in a blocked trial. This is especially the case if skills that use

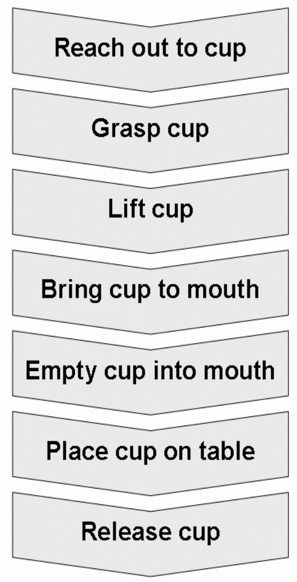

Fig. 1: Break-down of skill “drinking from cup” in functional components

different patterns of coordination are combined [15, 16]. Exercise difficulty increases gradually. Principles that are used to increase exercise difficulty are e.g. ‘influence of gravity from being facilitatory to movement through neutral to antagonistic to movement’. From the neurodevelopmental treatment approach [17] the following components are used: ‘gradual movement out of the stroke related spastic movement pattern’, ‘increase of movement selectivity’ as well as ‘increase of postural and proximal control during movement’. From the Carr and Shepherd Approach the gradual ‘increase of degrees of freedom that are to be controlled’ is used [18].
Also high importance is attributed to providing feedback to the patient that is motivating (e.g. giving feedback about correct performance) and supporting the process of motor (re)learning (e.g. decreasing frequency of feedback when performance improves, providing an empty time slot for performance evaluation before and after feedback, providing guided self-control on timing of feedback delivery) [7]. For more information on the rationale behind the choice of the training characteristics, the authors refer to a review article by Timmermans et al. on therapist guidelines for rehabilitation technology design [19].

Implementation of T-TOAT in rehabilitation technology

Sensor- based T-TOAT

The T-TOAT method was first implemented in a sensor based training system, named Philips Stroke Rehabilitation Exerciser [20, 21](figure 2).
The system comprises of 3 matchbox-sized wireless inertial sensors (π-nodes, Philips Research), a receiver module for the wireless sensors, an exercise board and a touch screen operated PC. The sensor nodes can be worn in garments (torso, upper arm and

forearm) and contain a combination of accelerometers, magnetometers and gyroscopes, as well as a rechargeable battery, microprocessor and low-power radio-unit. The exercise board uses ESP hardware and software (Serious Toys BV, Den Bosch, NL) and supports training of skilled hand performance. Each position on the interactive 8x8 checkerboard provides output through colored LED lights and supports input through presence or absence of metal coils. The Philips Stroke Rehabilitation Exerciser consists of a therapist station in which exercises and individual target movements can be programmed and reviewed as well as a patient station that guides patients through exercise performance (video-instruction of target motion) and provides feedback of exercise performance (real-time and/or after exercise termination). Feedback is provided based on the sensor recordings that are analyzed and compared to the individual patient target movements that are set by the therapist. A pilot trial (approved by medical ethical committee SRL, Hoensbroek, The Netherlands) was conducted in 2008, in which 9 chronic stroke patients performed T-TOAT for 8 weeks (4 days per week, 2 x 30 minutes/day) with the Philips Stroke Rehabilitation Exerciser. Results indicated a significant and clinically important improvement of arm-hand performance that lasted until at least 6 months after the end of the training period [22].

Robotic T-TOAT

A third study is ongoing, aiming for implementation of T-TOAT training exercises in a robotic haptic device, namely the Haptic Master. The Haptic Master is a commercially available 3 degrees of freedom (DOF) haptic robot (MOOG-FCS, the Netherlands). Compared to impedance controlled haptic devices, this admittance controlled system is suitable for larger workspaces. Also high forces can be exerted and complex end-effectors can be added to extend degrees of freedom. These features make the Haptic Master suitable for task-oriented training.

Several other studies make use of the Haptic Master in a rehabilitation setting as e.g. the studies by Johnson et al using ADLER [23, 24], the Gentle/s project [25] and the study by Seelen et al. [26]. In the latter the effect of Haptic Master training on arm-hand kinaesthetics is studied. ADLER is the first robotic system that allows for training of real-life functional tasks with 'real' object manipulation.

ADLER and Gentle/s make use of the minimum jerk theory for modulation of the movement trajectory [23]. This model has been found not to be fully adequate for generating every day life movement trajectories [27]. A software tool, named "Haptic-TOAT" was developed in SRL aiming to overcome this problem. This tool enables Haptic Master training with the T-TOAT method. Before training, a movement trajectory can be recorded, using the Haptic Master as a recording device. In this recording state, given the task constraints and patient capabilities, the end effector can be moved along the optimal path. During this recording the patient's arm may or may not be attached to the system. The Haptic Master logs 3D positions (x,y,z-coordinates) with a sample rate of 100Hz. Once recorded correctly, the movement can be saved and, when necessary, filtered and edited using the Haptic-TOAT graphical user interface (GUI).

The recorded movement trajectory can be used in two ways. First, the trajectory can be covered by the Haptic Master, taking the patient's arm along the path (passive

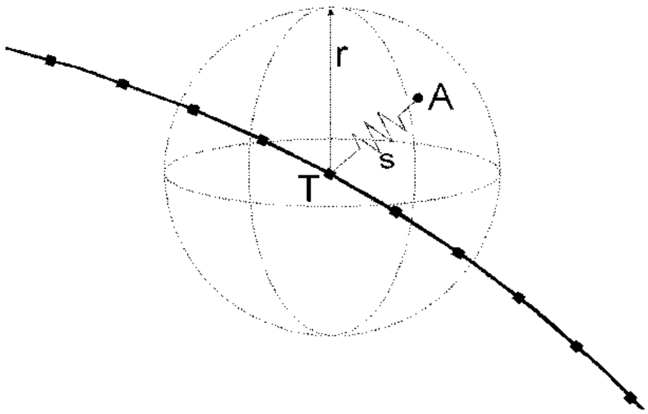

Fig. 2: Concept of real-time trajectory guidance

mode). The movement trajectory can be played in reverse and/or repetitively if needed. This passive mode is suitable for patients with little muscle strength or for ‘learning’ the movement trajectory.

Second, the patient can move through the trajectory using his own muscle strength (active mode). Deviation from the initial movement trajectory is corrected. During the movement a solid object with a radius (r), set by the therapist, is created in real time around the point on the path (T) nearest to the point of the end effector (A) (see figure 3). This will cause a sensation of bouncing into a wall when deviation from the trajectory exceeds the initially set range. For optimization of processing speed in finding the nearest point on the trajectory (T), the distance is calculated from the actual end effector position (A) to ten consecutive data points (coordinates) on the trajectory, ahead of the actual position. The smallest distance determines the current point (T). Guidance can be offered by means of a spring (s) originating from the same point on the trajectory (T) and pulling the end effector back to the trajectory. The spring force may be varied throughout the trajectory allowing adjustable guidance on different positions by means of a GUI within Haptic-TOAT. In addition to the spring-force, damping and force in vertical direction may be set at each point of the trajectory with the same GUI. Adding damping allows for strength training. Adding force in the upward vertical direction will create support against gravity, or, in the opposite direction, will be adding extra load.

The strength of the Haptic-TOAT method used for trajectory definition is that it can be programmed according to a) the patient’s physical abilities (assisting normal movement or facilitating compensatory movement) and b) patients’ motivational training needs (e.g. specific daily activity skills the patients want to train on can potentially be programmed).

A gimbal attachment, specifically designed for task-oriented training, adds 3 additional degrees of freedom providing a full 6 DOF movement of the Haptic Master with the forearm attached to it. An advantage of using a gimbal in task-oriented training is that the hand of the patient is free to grasp real objects. Traditional gimbals consist of a solid bearing that has to be large enough for the hand to fit through easily. The size of it, however, may hamper the tasks that are performed on a table. E.g., for normal conditions, while putting down a cup, the wrist nearly touches the table. The concept

design gimbal in the current study consists of a partially open bearing. Aligning both inner ring and outer ring of the bearing creates an opening through which the wrist can enter. Rotating the inner bearing 180 degrees will result in a closed bearing with the same functionality but a smaller height and diameter, making the gimbal more suitable for performing tasks on a table. The gimbal is shown in figure 4.
Two gimbal sizes will be available for the pilot study. One that will fit extra large wrist diameters or that allows fixation at elbow level. And a smaller one that will fit regular wrist sizes.
The exercise board as described in the previous section can be used in combination with Haptic Master also, providing actual visual feedback on the start and end position of object transport on the table top.
The entire system set-up is currently being prepared for patient testing. This involves adding adequate safety precautions like panic switches and brake-loose possibilities. Also a weight compensation for the upper arm or shoulder joint will be added when necessary.
A pilot study to evaluate the feasibility of robotic T-TOAT and to obtain a first indication of possible training effects has started in the autumn of 2010.

Fig. 3: Gimbal attachment for task-oriented training.

Conclusion

T-TOAT is novel method of task-oriented arm training that supports motor skill re-learning and is suitable for implementation of exercises in stroke rehabilitation technology. The training method has so far been implemented in one sensor-based training system and one robotic training system. Initial results of 8-weeks sensor-based training with T-TOAT indicate that the training method is feasible and that the method improves skilled arm-hand function in chronic stroke patients. Further clinical studies in 2009-2010 are set up to test the clinical effectiveness of the T-TOAT method, administered by robot therapy (pilot study) and sensor-based therapy (randomized clinical trial). Further implementation of the method in a variety of rehabilitation systems (e.g. Scribeo – system for training writing skills [28]) is ongoing.

Acknowledgement

The authors wish to express many thanks to the HOST/ULTRA project for providing the sensor technology and to J. te Vrugt and S. Winter for programming T-TOAT exercises in Philips Stroke Rehabilitation Exerciser (Philips Research Europe, dept Medical Signal Processing).
The authors also gratefully acknowledge W. Fontijn (Serious Toys BV, Den Bosch, NL) for providing the ESP exercise board.
We are grateful to Chi Wai Lam for programming haptic-TOAT and to M. Soede and colleagues (Centre of Research Technology in Care of Zuyd University, the Netherlands) for their input on haptic-TOAT.

References

1. Andersen HE, Eriksen K, Brown A, Schultz-Larsen K, Forchhammer BH. Follow-up services for stroke survivors after hospital discharge--a randomized control study. Clin Rehabil. 2002;16:593-603
2. Duncan P, Richards L, Wallace D, Stoker-Yates J, Pohl P, Luchies C, Ogle A, Studenski S. A randomized, controlled pilot study of a home-based exercise program for individuals with mild and moderate stroke. Stroke. 1998;29:2055-2060
3. Woldag H, Hummelsheim H. Evidence-based physiotherapeutic concepts for improving arm and hand function in stroke patients: A review. J Neurol. 2002;249:518-528
4. Timmermans AA, Seelen HA, Willmann RD, Bakx W, de Ruyter B, Lanfermann G, Kingma H. Arm and hand skills: Training preferences after stroke. Disabil Rehabil. 2009;31:1344-1352
5. Bach-y-Rita P. Theoretical and practical considerations in the restoration of function after stroke. Top Stroke Rehabil. 2001;8:1-15
6. Van Peppen RP, Kwakkel G, Wood-Dauphinee S, Hendriks HJ, Van der Wees PJ, Dekker J. The impact of physical therapy on functional outcomes after stroke: What's the evidence? Clin Rehabil. 2004;18:833-862
7. Magill R. Motor learning and control, concepts and applications. New York: The McGraw-Hill Companies; 2007.
8. Uswatte G, Taub E, Morris D, Barman J, Crago J. Contribution of the shaping and restraint components of constraint-induced movement therapy to treatment outcome. NeuroRehabilitation. 2006;21:147-156
9. McArdle WD, Katch FI, Katch VL. Essentials of exercise physiology. Philadelphia: Lippincott Williams & Wilkins; 2000.
10. Kerr K. Exercise in rehabilitation. In: Pitt-Brooke Judith HR, Lockwood Jane, Kate Kerr, ed. Rehabilitation of movement: Theoretical basis of clinical practice. London: W.B.Saunders; 1998:423-457.
11. Schendel JD, Hagman JD. On sustaining procedural skills over a prolonged retention interval. Journal of Applied Psychology. 1982;67:605-610
12. Shea CH, Kohl RM, Indermill C. Contextual interference: Contributions of practice. Acta Psychologica. 1990;73:145-157
13. Pavlides C, Miyashita E, Asanuma H. Projection from the sensory to the motor cortex is important in learning motor skills in the monkey. J Neurophysiol. 1993;70:733-741
14. Wu C, Trombly CA, Lin K, Tickle-Degnen L. Effects of object affordances on reaching performance in persons with and without cerebrovascular accident. Am J Occup Ther. 1998;52:447-456
15. Gentile AM. Skill acquisition: Action, movement, and neuromotor processes. In: Carr JS, R, ed. Movement science. Foundations for physical therapy in rehabilitation. Gaithersburg,Maryland: Aspen Publishers,Inc; 2000:111-187.
16. Shumway-Cook A WM. Motor control. Translating research into clinical practice. Wolters Kluwer/ Lippincott Williams & Wilkins; 2007.
17. Levit K. Optimizing motor behavior using the occupational therapy task-oriented approach. In: Trombly CA, Radomski MV, eds. Occupational therapy for physical dysfunction. Lippincott, Williams & Wilkins; 2002:521-541.
18. Shapero Sabari J. Optimizing motor control using the carr and shephard approach. In: Trombly CAaR, M.V., ed. Occupational therapy for physical dysfunction. Baltimore: Lippincott, Williams & Wilkins; 2002:501-519.
19. Timmermans AA, Seelen HA, Willmann RD, Kingma H. Technology-assisted training of arm-hand skills in stroke: Concepts on reacquisition of motor control and therapist guidelines for rehabilitation technology design. J Neuroeng Rehabil. 2009;6:1
20. Willmann RD, Lanfermann G, Saini P, Timmermans A, te Vrugt J, Winter S. Home stroke rehabilitation for the upper limbs. Conf Proc IEEE Eng Med Biol Soc. 2007;2007:4015-4018

21. Lanfermann GW, R ; te Vrugt,J ; Timmermans,A ; Bongers,E ; Lambert,N ; van Acht,V ;. Philips stroke rehabilitation exerciser. Technical Aids for Rehabilitation - TAR 2007. 2007
22. Timmermans A, Seelen H, Geers R, Saini PR, Winter S, Te Vrugt J, Kingma H. Sensor-based arm skill training in chronic stroke patients: Results on treatment outcome, patient motivation and system usability. IEEE Trans Neural Syst Rehabil Eng. 2010. Vol 18, 3, 284-292
23. Johnson MW, KJ. ; Anderson,J. ; Nathan,D. ; Smith,RO. Development of adler: The activities of daily living exercise robot. BioRob2006. The first IEEE/RAS-EMBS International Conference on Biomedical Robotics and Biomechatronics. 2006:881-886
24. Johnson MJ, Loureiro R, Harwin W. Collaborative tele-rehabilitation and robot-mediated therapy for stroke rehabilitation at home or clinic. Intel Serv Robotics. 2008;1:109-121
25. Coote S, Murphy B, Harwin W, Stokes E. The effect of the gentle/s robot-mediated therapy system on arm function after stroke. Clin Rehabil. 2008;22:395-405
26. Seelen HAM, Geers RPJ, Soede M, Spauwen LWL. Training of arm-hand kinaesthetics in subacute stroke patients using robotics. Journal of Biomechanics. 2007;40:S645
27. Wisneski KJ, Johnson MJ. Quantifying kinematics of purposeful movements to real, imagined, or absent functional objects: Implications for modelling trajectories for robot-assisted adl tasks. J Neuroeng Rehabil. 2007;4:7
28. Curtis J, Ruijs L, de Vries M, Winters R. Rehabilitation of handwriting skills in stroke patients using interactive games: A pilot study. CHI extended abstracts. 2009

Chapter 7

Sensor-based arm skill training in chronic stroke patients: results on treatment outcome, patient motivation and system usability

Timmermans A, Seelen H, Geers R, Saini PR, Winter S, Te Vrugt J, Kingma H. Sensor-based arm skill training in chronic stroke patients: Results on treatment outcome, patient motivation and system usability. *IEEE Trans Neural Syst Rehabil Eng*. 2010. 18, 3: 284-292.

Abstract

As stroke incidence increases, therapists' time is under pressure. Technology-supported rehabilitation may offer new opportunities. The objective of this study was to evaluate patient motivation for and the feasibility and effects of a new technology-supported task-oriented arm training regime (T-TOAT). Nine chronic stroke patients performed T-TOAT (2x30 minutes/day, 4 days/week) during 8 weeks. A system including movement tracking sensors, exercise board and software-based toolkit was used for skill training. Measures were recorded at baseline, after 4 and 8 weeks of training, and 6 months post-training. T-TOAT improved arm-hand performance significantly on Fugl-Meyer, Action-Research-Arm-Test and Motor Activity Log. Training effects lasted at least 6 months post-training. Health-related-Quality-of-Life had improved significantly after 8 weeks of T-TOAT with regard to perceived physical health, but not to perceived mental health (SF-36). None of the EuroQol-5D components showed significant differences before and after training. Participants were intrinsically motivated and felt competent to use the system. Furthermore, system usability was rated very good. However, exercise challenge as perceived by participants decreased significantly over 8 weeks of training.
The results of this study indicate that T-TOAT is feasible. Despite the small number of stroke patients tested, significant and clinically relevant improvements in skilled arm-hand performance were found.

Introduction

Recovery of arm-hand function after a stroke is associated with improved quality of life [1]. Stroke patients are generally disappointed to be discharged from physiotherapy as they feel that they could improve further by continuation treatment [2]. It is known that the majority of motor recovery occurs in the first six months after stroke after which improvement levels off[3]. At some stage during therapy, patients do not progress further. This plateau is a criterion used for discharge from therapy [4]. However, therapy approaches like constraint-induced movement therapy, but also technology-supported rehabilitation have proven to influence arm-hand function [5,6] and skilled arm-hand performance [7-9] in patients that are well beyond the motor recovery plateau

phase. Reconsideration of factors underlying any motor recovery plateau is warranted as findings suggest that patients in the chronic phase after stroke may show further motor recovery when training on new exercises, different exercise parameters and -modalities [4].
The expected increase in stroke incidence in the next 20 years [10] and the knowledge that rehabilitation in chronic stages after stroke may further improve arm-hand performance [7, 8] has enlarged the demand for rehabilitation addressing arm-hand training. An important role emerges for technology to support therapists to keep their workload manageable [11] and to enable patients to train arm-hand performance into the chronic stage after stroke.
A large spectrum of rehabilitation technology has been developed in the last decade [12]. In clinical practice nowadays, methods for stroke rehabilitation focus on the re-acquisition of meaningful movements (skills) and on improvement of functional performance [13]. Substantial evidence exists that progressive and challenging task-oriented arm training improves arm-hand performance after stroke [14, 15]. Researchers working in the field of rehabilitation technology are aware of this trend and technology offering task-oriented training [9, 16] has started to develop. Examples of such systems are AutoCITE [9], ADLER [16], MIT-Manus [17], Armeo [18], Armin [19]. Much of the current clinically tested technology implementing task-oriented training involves robotic systems. Robotic training systems have shown to improve arm-hand function of stroke patients, but to date have failed to show an improvement of skilled arm-hand performance [20, 21]. Arm-hand function refers to the ICF 'function level', whereas 'skilled arm-hand performance' refers to the level of activity in accordance with the ICF nomenclature [22].
Pavlides et al [23] found , through experiments that studied the effect of lesions in the hand area of the sensorimotor cortex in monkeys, that context-specific sensorimotor input is essential for the learning of new tasks. Timmermans et al [24] suggest, based on these findings, the use of context-specific sensorimotor input, normally associated with manipulation of natural every day life objects, in technology-supported arm-hand training that aims to (re)gain skilled performance. To date, this feature is implemented in few technological systems (e.g. in ADLER [16], AutoCITE [9]) that support training of arm-hand performance.
In this study a sensor-based and technology-supported task-oriented arm training method with real-world object manipulation, i.e. context-specific sensorimotor input, is presented and evaluated. The training method combines kinematic information, contextual information and technology-embedded training principles.
This study evaluates: a) if training skills with a sensor-based training system is feasible, especially regarding system usability and patient motivation; b) if 8 weeks of technology-supported task-oriented training can improve skilled arm-hand performance and c) if training effects last for at least 6 months after the training has stopped.

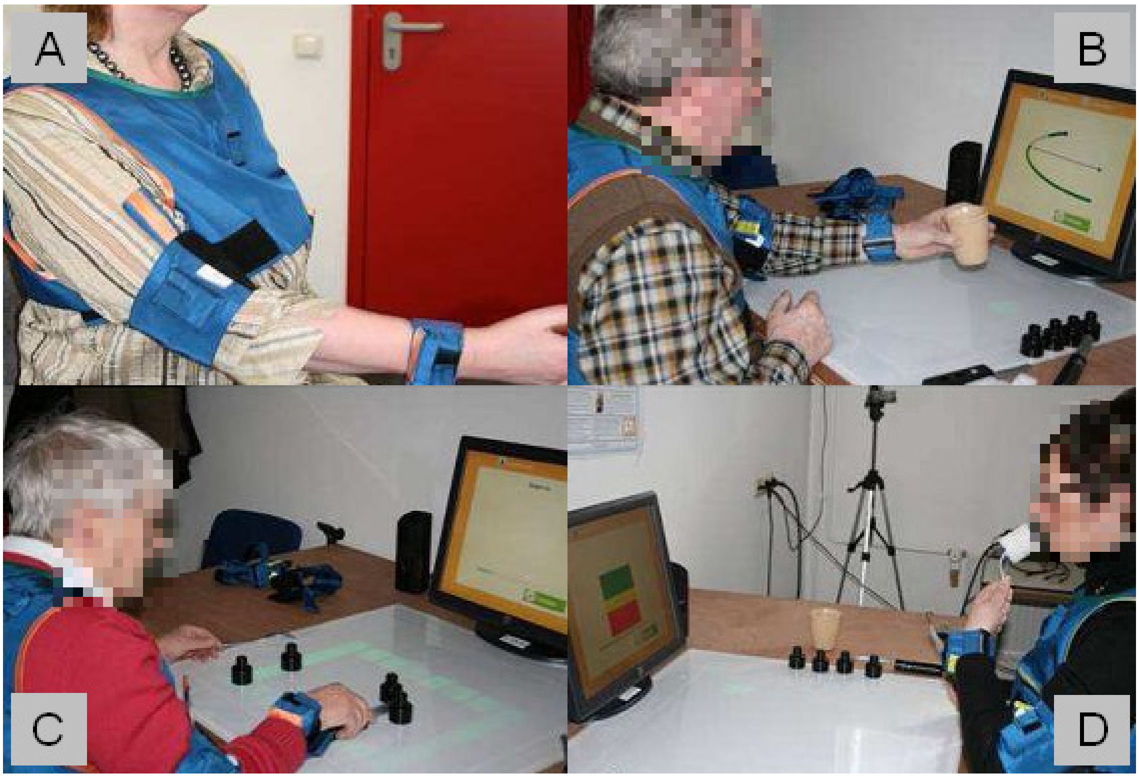

Fig. 1: Set-up of the training: A. Sensor placement and garments; B. Example of 'drinking from a cup'; C and D. Examples of 'eating with knife and fork

Methods

Apparatus

The Philips Research Stroke Rehabilitation Exerciser [25] that was used for training skilled arm-hand performance of the participants in the study, is a sensor based training system comprising of: a) a patient station, equipped with wireless inertial sensors for measuring joint kinematics, an active exercise board which is capable of interaction with real-world interactive objects and a PC with touch screen via which exercises are offered and feedback on performance is provided and b) a therapist station in which exercises can be programmed and specified to be patient-tailored. In collaboration between Philips Research Europe, Aachen (D) and Adelante Rehabilitation Centre in Hoensbroek (NL), technology-supported task-oriented arm training was implemented in this system.

Kinematic data

Exercises are offered to the patient by means of a video-instruction. Matchbox-sized wireless sensors (Philips Π-node, weight:37 gram) [26] containing accelerometers, magnetometers (3D-magnetization, earth magnetic field) and gyroscopes (3D-angular speed) (along with a microprocessor, a low-powered radio unit and a battery), are worn in garments on the thorax (corpus sterni), upper arm (proximal to epicondylus lateralis humeri) and lower arm (distal radio-ulnar joint) (figure 1A). The system is calibrated for each individual on each application. The sensors register, with an angular accuracy of 3 degrees [26], kinematic parameters during exercise such as joint range of motion, speed and jerkiness of movement. The data are compiled into orientation measurements leading, together with an underlying body model, to a series of posture representations representing the movements of the patient. This information is compared to customized target parameters that are set in advance by the therapist, allowing for real-time feedback as well as feedback of results/performance after movement completion. An example of real-time feedback is the movement of a gauge on a screen, representing the patient's actual joint angle that is automatically generated from the motion sensor data. The gauge moves in a zone, representing the target range of joint movement (i.e. angle) that is set by a therapist. Even movements like e.g. forearm pro-supination can be registered and fed back to the patient through comparison of the sensor data of the wrist to the data from the upper arm sensor. An example of feedback that is given after exercise completion is the possibility to review the movements that are done during training, played back by an avatar. The avatar is accompanied by a second avatar that plays back the target movements performed by the therapist. The patient can also review charts where the movement parameters are shown as dots in a colored zone. Depending on the color of the zone the exercises were performed very well (therapist target was comfortably achieved), moderately well (therapist target was just about achieved), or not well (therapist target was not achieved). Kinematic information is stored and can be accessed by the therapist for review at any time. Movements that have been performed by the patient can be viewed after exercise performance using an animated figure or can be reviewed as charts or graphs. For more information on the wireless kinematic data acquisition, patient user interface and exercise recognition, the authors refer to the paper by Willmann et al [27].

Contextual data

The system has a 'toolkit' with real every day life exercise materials (different kinds of cups, forks and knifes, objects to handle, etc.) that enhance exercise variability as well as context-specific sensorimotor input for the training. The toolkit is used in combination with an interactive 8x8 checkerboard (Serious Toys BV, Den Bosch, NL). On the checkerboard each position provides output through colored LED lights. Input to the software application is provided through presence or absence of metal coils that are incorporated in the real-world objects that are manipulated. The positions that light up can also be programmed in the therapist station. The exercise board helps instruct participants regarding the fine motor upper extremity movements they have to make (figure 1 B, C, D) in two ways: 1) the lighting up of the zones shows the patients the target location for object displacement (exercise instruction), and 2) the extinction of the light in a zone shows if an object has been correctly positioned (knowledge of result feedback).

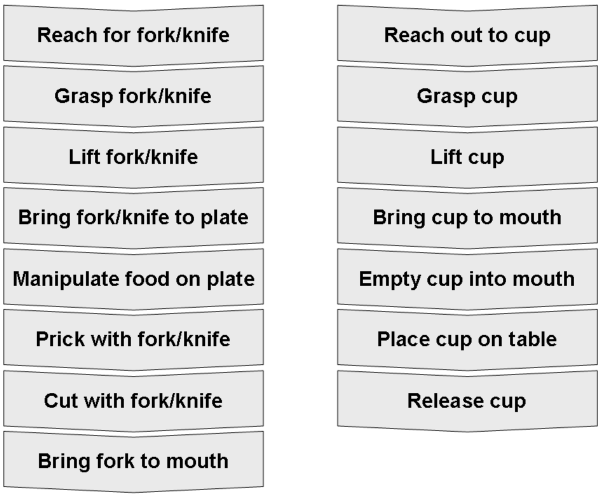

Fig. 2: Break-up of 'eating with knife and fork' and 'drinking from cup' skills

The T-TOAT training method

T-TOAT (technology-supported task-oriented arm training) is a training method that was developed at Adelante Rehabilitation Centre (formerly known as 'Rehabilitation Foundation Limburg') [28].
The training method comprises of decomposing (i.e. breaking down) skills into functional components that maintain a strong relationship with the original skill itself (figure 2). For each of these components exercises are offered at increasing levels of difficulty, based on progress criteria from the fields of exercise physiology [29] and motor learning [30] and with feedback delivered according to shaping principles [31]. The advantage of breaking down skills into subcomponents is that exercise programs can be implemented in technology-supported training, even when they concern complex skills. Participants are encouraged to first train on components of a skill, after which the complete action, sequencing all components, is trained. Participants in the study trained on 'drinking from a cup' and 'eating with knife and fork' (figure 1). The skills were chosen, based on the outcome of an earlier interview study aimed at identifying skill training preferences in stroke patients [32].

Subjects and study protocol

Nine subjects in the chronic stage (more than one year) after stroke were recruited from the Adelante rehabilitation centre (NL) over a period of 5 months to participate in a clinical intervention study. Inclusion criteria were: a) a first ever supratentorial stroke, b) age ≥18 years, c) clinically diagnosed with central paresis of the arm/hand at entry in the study (MRC grade 2-4 of the main muscles controlling the main movement directions of the shoulder, elbow and wrist), d) a post-stroke time >12 months, e) a fair cognitive level, i.e. a MMSE score≥ 26 [33], f) ability to read and understand the Dutch language. Furthermore, persons should be unable to fully perform "drinking

from a cup" and "eating with knife and fork". Exclusion criteria were: a) severe neglect in the near extra-personal space [34], established with the letter cancellation test [35] and Bell's test [36] with a minimum omission score of 15% [37], b) severe spasticity (Modified Ashworth Scale total arm score>4), c) severe additional neurological, orthopedic or rheumatoid impairments prior to stroke that might interfere with task performance, d) Aphasia as determined with Aachener Afasie Test (AAT) [38], and e) Apraxia as measured with apraxiatest of van Heugten [39]. The participating rehabilitation physicians identified potential participants based on the in- and exclusion criteria. Databases of Adelante were screened and letters to ask for participation in the study as well as information about the training study were distributed to 30 persons. On their first visit, participants were shown the training system and were informed about the training method. Subsequently, baseline measurements (T0) were performed, after which training commenced.
Participants were training 2x 30 minutes/day, 4 days/week during 8 weeks. An occupational therapist or physical therapist was present during training to help with e.g. pre-training adjustment of the chair to the patient's anthropometry, putting on garments, system initialization or answering of questions when necessary. Participants were reimbursed for transportation costs to and from the rehabilitation centre. The Medical Ethics Committee of the Rehabilitation Foundation Limburg in Hoensbroek, the Netherlands, approved all protocols used in this study.

Outcome Measures

The International Classification of Functioning, Disability and Health (ICF) [40] classifies health and disease at three levels:

1. function level (aimed at body structures and function),
2. activity level (aimed at skill execution), and
3. participation level (aimed at taking up one's role in society).

The test instruments used for assessment of arm-hand performance have been chosen in order to address and assess the influence of the training that was administered on all levels of the ICF classification.

Measurement of arm-hand function/activity

The Fugl-Meyer Motor Assessment (FM), upper extremity section was chosen for assessment of arm-hand function in stroke patients at the ICF function level [41 42]. The maximum score that can be obtained on FM, upper extremity section is 66. The Action Research Arm Test (ARA(T)) has been chosen for upper limb measurement on the ICF activity level [43-46]. The maximum score that can be obtained on ARAT is 57. The Motor Activity Log (MAL), Dutch version, is a semi-structured interview and an assessment tool of frequency and quality of use of the affected limb for skill performance [47]. It measures arm-hand performance on the ICF activity level. The maximum scores that can be obtained on MAL, amount of use/quality of use is 5. Dromerick et al [48] have shown that patients with near perfect scores on the ARA(T) show residual disability on the MAL. Assessment of how frequently participants could achieve≥3 on the MAL scale served as a meaningful outcome measure of arm-hand activity in stroke patients and was analyzed to investigate clinical relevance of changes in outcome measurement after training [15 49].

Measurement of quality of life

The EuroQol-5D (EQ-5D) is a broad generic assessment tool for quality of life [50]. It includes a VAS scale (to indicate perceived health-state) as well as scoring of 5 sub-items (mobility, self-care, usual activities, pain and anxiety).
The Medical Outcomes Study Short Form 36 (SF-36)(RAND36) is a generic survey to assess the health status in the general population [50, 51]. There is an indication that, in elderly persons, the SF-36 may be more sensitive to changes than the EuroQol [52] as it is able to detect more mild perceived health problems. The EQ-5D and SF-36 are measuring on the ICF participation level. Maximum score for EQ-5D (VAS) and for SF-36 is 100.

Measurement of usability and patient motivation

Two questionnaires for the assessment of usability were selected. The Computer-System-Usability-Questionnaire (CSUQ [53]) and the Usefulness-Satisfaction-and-Ease-of-use-questionnaire (USE [54]). The two questionnaires differ in their focus – the USE focuses more on the experience (ease of use and learning) of usage and the CSUQ more on the understanding (information and interface quality) of the system, but an overlap exists on two scales: usefulness and satisfaction. Both questionnaires use a 7-point Likert rating scale (maximum score =7). To get a quick and general impression on system usability and usefulness, also the two following questions were rated on a visual analogue scale (VAS) [55 56]:

1. How well did you manage to use the system? and
2. How challenging did you find the exercises offered?

The maximum score that could be obtained was 10.
The Health-Care-Self-Determination-Theory-Questionnaire (HCSDT) 57 is a measure to assess motivation, based on the self-determination theory 58. The self-determination theory evaluates the association between relationship-centered care and patients' motivation, behavior, family dynamics, health, and well-being 59. Three different needs are proposed by the self-determination theory: 1) the need for autonomy, 2) the need for competence and 3) the need for relatedness and support. The HCSDT is an aggregate of three questionnaires.
Questions are answered choosing the best fitting answer on a 7-point Likert rating scale (maximum score=7). The HCSDT comprises of: a) the Treatment Self-Regulation Questionnaire (TSRQ) that has three subscales that address 'autonomous regulatory style' ('autonomy'); the 'controlled regulatory style' ('control') and 'a-motivation'. An autonomous regulatory style is associated with higher internal (intrinsic) motivation, whereas a controlled regulatory style implies that individuals are driven by external rewards or forces. The a-motivation end of the continuum is associ-

ated with a complete absence of motivation (i.e. being unmotivated), b) the Perceived Competence Scale (PCS) assesses the confidence patients have in their abilities and skills to do the things they choose ('Competence'), and c) the Health Care Climate Questionnaire (HCCQ short form) addresses patients' perception of the extent to which therapists are found to be supportive ('support') [59].
The assessment protocol was as follows. Before starting the training, baseline measurements were performed. Baseline assessment of usability and exercise challenge was done slightly later, i.e. on day 3. Primary and secondary outcome measurements were repeated after 4 weeks (T1) and after 8 weeks of training (T2); and six months after the training had stopped (T3). The same therapists (one performing the Fugl-Meyer test, a second performing ARAT & MAL, and a third performing quality of life tests, usability tests and motivation questionnaire) always performed the assessments for all participants in order to avoid interrater measurement variability.

Data analysis

Data were analyzed using SPSS 16.0. (SPSS Inc, Chicago ILL).
For primary outcome measurement data, a Friedman two-way analysis of variance by ranks [60] was performed. Alpha was set at 0.05. For multiple comparison between results measured at T0, T1, T2 and T3, a Wilcoxon signed ranks test was done using a Bonferroni approach [60]. Wilcoxon signed ranks tests were also used to compare results of T0, T2 and T3 for secondary outcome measures (SF-36 and EuroQol-5D) and for the usability (VAS, USE, CSUQ) and motivation (HCSDT) questionnaires. In case of missing data in individual participants, an imputation technique [60] was used to estimate a subject's performance based on mean intra-individual progress between measurement points in time of all other participants.
The Hedges's g effect size [61] was calculated for the FM, ARAT and MAL. The difference between the means of baseline and post intervention outcome was divided by the average standard deviation. Hedges's g was bias-corrected for sample size. Cohen's classification categorizes effect sizes smaller than 0.2 as small, effect sizes between 0.2 and 0.5 as medium and larger than 0.5 as large [62].

Results

Patient characteristics

From the 30 persons that were approached, only 9 subjects (5 males and 4 females) agreed to participate. Reasons not to participate were associated with, among others, travel distance, costs and patients' willingness to participate in a training protocol lasting for 8 whole weeks. Mean age was 60.7 years. Mean post-stroke time was 2.5 years (SD=1.9). Mean MMSE score was 28.5 (SD=1.2).

Error analysis

All measurement data were collected according to the predefined protocol. The 6-month follow-up measurement (T3) values of one patient could not be used, because this patient followed constrained-induced movement therapy after finishing the 8 week training program of this study. A data-imputation technique [60] was applied to estimate this one patient's T3 values.

Arm-hand performance

Group means (and SD) of the individual results on all outcome measures are presented in table 1. Furthermore, the mean individual improvement over time (IIT) relative to the baseline values is presented (Table 1) for the primary and secondary outcome measures. To obtain this value, each individual's improvement after 8 weeks of training, normalized for baseline values, was calculated and expressed as a percentage.
Arm-hand function scores improved significantly with 8 weeks of technology-supported task-oriented training, as indicated by mean values of Fugl-Meyer (14.2% improvement) ($p<0.001$), ARAT (15.3% improvement) ($p<0.05$), MAL-AU (43.4% improvement) ($p<0.05$) and MAL-QU (34.1 % improvement) ($p<0.01$). Subsequent multiple comparison analysis showed significant improvement between the results on T0-T1, T0-T2 and T0-T3 for Fugl-Meyer and between results on T0-T2 for MAL-QU (table 1). For MAL, also the number of times that participants scored ≥ 3 ($n\geq3$) on AU or QU increased significantly between different measurement moments ($p<0.001$ for AU; $p<0.01$ for QU). Significant improvement was found between results of T0-T2 for AU (table 1). Although arm-hand performance outcome showed a trend towards decline six months after cessation of training, there were no significant differences found between T2 and T3.
Based on Cohen's classification of effect sizes, it was concluded that the effect sizes for the training with Philips Stroke Rehabilitation Exerciser are in the medium range for ARAT (i.e. between 0.2 and 0.5) and are large (i.e. > 0.5) for FM and MAL (table 1).

Functional health and quality of life

Results on the SF-36 (physical and mental health scores) and EuroQol-5D (VAS scale) are presented in table 1. There was a significant improvement (Individual improvement over time (IIT)=26.2%) between T0 and T2 for perceived physical health measured with SF-36 ($p<0.05$). There was no significant difference between T0 and T2 for perceived mental health measured with SF-36, neither on the VAS scale nor on the different sub-items of EuroQol-5D.

Table 1: Overview of arm-hand performance and health-related quality of life results at T0, T2 and T3.

	T0 Mean (SD)	T2 Mean (SD)	T3 Mean (SD)	IIT %	Significance level	Hedges's g (95%CI)
FM	53.9(10.0)	60.3(6.3)	59.6(6.5)	14.2	*** † ‡ §	0.73 (-0.22-1.68)
ARAT	41.9(11.0)	46.3(8.5)	45.4(8.2)	15.4	*	0.43 (-0.51-1.36)
MAL						
AUscore	2.6 (1.0)	3.3 (0.7)	2.9 (0.9)	43.4	*	0.77(-0.19-1.73)
QUscore	2.4 (0.7)	3.1 (0.6)	2.6 (0.8)	34.1	** ‡	1.02 (0.04-2)
AUn≥3	11.0 (5.6)	15.1(4.3)	14.6 (5.0)	103.6	*** ‡	
QUn≥3	12.4 (5.8)	17.7 (3.3)	16.3 (4.8)	70.4	**	
SF-Physical Health	65.2 (12.4)	79.9(12.7)	76.4(13.0)	26.2	*	
Mental Health	82.3 (15.0)	88.5 (6.3)	84.2(11.0)	11.5		
EQ-5D VAS	70.8 (11.0)	77.2 (11.7)	76.5 (7.4)	9.6		

Abbreviations: T0: Baseline Measurement; T2: Measurement after 8 weeks training; T3: Measurement 6 months after training stopped; IIT: Individual Improvement after 8 weeks training relative to baseline values; CI: confidence interval; AU: Amount of Use score; QU: Quality of Use score; FM: Fugl-Meyer; ARAT: Action Research Arm Test; AU and QU n≥3: How often participants could achieve a score of ≥3 on amount of use and quality of use; Friedman test significant:* p<0.05, ** p<0.01,*** p<0.001; Wilcoxon signed ranks test: †= p<0.0125 for T0-T1, ‡ p<0.0125 for T0-T2, § p<0.0125 for T0-T3.

System usability, exercise challenge and patient motivation

Group means (and SD) of the individual results on system usability tests, exercise challenge and motivation questionnaire are presented in table 2.
System usability was rated to be good (T2 values: 8.6 out of 10 on VAS scale, 5.8 out of 7 on USE, 5.2 out of 7 on CSUQ).
Exercise challenge was rated 13.6% lower after eight weeks of training (p<0.0167) (table 2). At T2, the autonomy items were rated quite high (mean = 5.8, SD=0.9), as were the perceived competence items (mean = 5.6, SD=1.4) (table 2). Only for the sub-item "support" a significant decrease was found between T0 and T2 (p<0.05).

Table 2: Overview of system usability and patient motivation results at T0 and T2.

		T0 Mean (SD)	T2 Mean (SD)	Significance level
Usability	VAS	7.0(1.4)	8.6 (1)	
	USE	5.7(0.7)	5.8(0.7)	
	CSUQ	5.6(0.8)	5.2(0.8)	
Exercise Challenge		7.3(1.8)	6.3(1.3)	‡
Motivation	Autonomy	5.7(1.3)	5.8(0.9)	
	Control	2.4(1.0)	2.9(1.1)	
	A-motivation	1.3(0.8)	1.6(0.6)	
	Competence	6.5(0.5)	5.6(1.4)	
	Support	6.8(0.3)	5.6(0.5)	‡‡

Abbreviations: T0: Baseline measurement; T2: Measurement after 8 weeks of training; Wilcoxon signed ranks test: ‡ = $p<0.05$ for T0-T2; ‡‡ = $p<0.01$ for T0-T2.

Discussion

The aim of this study was to assess: a) if training skills with a sensor-based system is feasible, especially regarding system usability and patient motivation; and b) if 8 weeks of technology-supported task-oriented training improves skilled arm-hand performance and c) if training effects last for at least 6 months after the training has stopped.

Despite the fact that only a small number of participants were included, the results of this study already clearly indicate that an 8 week (in total 32 hours) task-oriented arm training program, supported by sensor-based technology improves arm-hand skill performance for persons in the chronic phase after a stroke. The mean individual improvement in arm-hand performance exceeded 10% for all primary outcome measures after 8 weeks of training, which indicates that improvements found are clinically meaningful [7, 63]. Analogous to the results found by Wolf et al [15], the clinical relevance of our results is corroborated by the results on the MAL, where the number of skills that were given a score of 3 or higher regarding amount of use and quality of use had risen significantly within 8 weeks of training. This means that participants do use the paretic arm more and better for activities of daily living outside the clinic.

The training effect sizes of this study (table 1) are comparable (= in the same category, following Cohen's classification [62]), to the effect sizes after CIMT therapy [64] (Hedges's g for ARAT=0.48, for MAL AU=0.7 and for MAL QU=0.63) (60 hours of training vs 32 in this study). A comparison with a technology-supported task-oriented training, namely AutoCITE (25% supervision) [65] that resembles most the training offered in this study is made. Also after AutoCITE training, similar effect sizes (Hedges's g for MAL after AutoCITE = 1.09) are found than the ones from this study.

Some decline, although not proven significant, in arm-hand performance was found 6 months after the training had stopped. This indicates that patients may have to repeat (part of) the training at regular intervals in time to maintain training effects.

This study shows that technology-supported training of arm-hand performance in the chronic phase after a stroke not only may lead to benefits at the ICF function level (shown by improvement on Fugl Meyer after training), but also at activity level (shown by improvement on ARAT and MAL after training) and participation level (shown by improvements on SF-36 and EQ-5D) [40]. This finding is even more important in the field of rehabilitation technology, as 2 recent systematic reviews [20, 21] found that training with rehabilitation robotics does lead to changes on impairment level, but did not find evidence that such training might lead to improvements at the level of activities. This may be due to (one of) two factors: either no such evidence is available due to the studies focusing on function level (with regard to assessment and/or training) or previous training using robotics did not lead to improved activity levels in stroke patients. A possible cause for the latter may be that most robotic systems train only on shoulder and elbow and leave out the hand, an area that is most relevant for skilled arm-hand performance [20].
The use of technology for task-oriented training has several advantages over e.g. merely providing the same exercises without technology support:

1. technology use is motivating and invites for exercise repetition [66], which is an essential component for motor learning of skilled performance [67],
2. it guides the patient progressively through exercises that gradually increase in difficulty level [28],
3. it allows for augmented feedback that supports motor learning which can compensate for impaired intrinsic feedback mechanisms after stroke.

The system prototype used in this study did not allow for feedback on kinematics of wrist and hand. Future research should certainly aim at finding out if the addition of a hand sensor could further improve training results through feedback on hand performance during training.
The results support findings of earlier studies in which technology-supported task-oriented training has been shown to have a positive effect on arm-hand function for persons in the chronic phase after a stroke [9,68]. The findings of this study are also in line with other studies that report task-oriented training related improvement of arm-hand function for persons in the chronic phase after stroke [7, 8, 69] and support the importance of rehabilitation beyond the 'motor recovery plateau'-phase as suggested by Page et al. [4]. The motivation questionnaires focused on health behaviours related to rehabilitation. Results show that people were highly intrinsically motivated to train and thereby sustaining a high level of personal performance, and felt competent in being able to keep performing the necessary actions towards this end. The control and a-motivation scale were rated quite low, suggesting that participants did not feel external forces directing them to contribute towards recovery and performance. The perceptions relating to autonomy, control, a-motivation and perceived competence did not change significantly between the start and the end of the training, suggesting a relatively stable level of underlying motivation. The relatedness scale items were phrased to expose to what level the health professionals (physiotherapists and occupational therapists in this case) were able to create a supporting environment. It is conceivable that at the beginning of the study, in which there was more personal contact with the attending therapists, participants felt more support and encouragement to ex-

plore and work with the system. After a few sessions, where the main interactions were with the rehabilitation system and the therapist only intervened for troubleshooting, participants might have felt a lesser connection with the therapist than at the outset of the study.
System usability was rated ‘good’ by the patients (on all 3 assessment measures used), although exercise challenge should improve if the system is to be used for an 8-week training period. These results support the feasibility of technology-supported training.

Regarding this study, some methodological issues should be mentioned:

1. Given the design of the study, raters were not blinded for therapy-modality. This may have affected rating outcome. However, therapists were minimally involved in training, as it was administered by the training system.
2. Another methodological consideration is the fact that the MAL evaluates items that have been trained; and is therefore likely to show better outcome levels [70]. On the other hand, only 2 of the 26 items were trained which makes such effect less likely.
3. Motor Activity Log, SF-36 and EuroQol-5D are self-evaluation scales. Because of the work they have invested into training, high expectations of the participants for the outcome of the self-appraisal may influence the results of these scales [70]. Also the Hawthorne effect may interfere with test results of self-evaluation scales: participants may overestimate their arm-hand performance because of desire to please their examiner and/or because of mood change due to positive reinforcement of the therapist [71]. The Fugl Meyer Assessment and Action Research Arm test assessment are not influenced by these factors.
4. Only 33% of the persons that were invited to participate in the study actually were willing to take part. Participants mentioned the length of the training period as an obstacle for their participation. This might have resulted in sampling bias towards selecting persons with a high level of motivation to train. This may have had a positive influence on treatment outcome.
5. Patients included in this study had rather high functional levels. It is not known from this study if the results can be generalized to patients with more severe impairments. More research is needed for this.

Some considerations for future research are:

1. Participants in our study showed gradual improvement during 8 weeks of training. Future research needs to establish whether higher therapy intensity and/or a longer training period would have further improved arm-hand performance.
2. The authors believe that ‘refresher training courses’ would help to maintain the obtained training effects. Future research needs to establish the optimal training frequency and intensity that minimizes loss of obtained training effects.
3. To our knowledge, no clinical intervention studies are available that report outcome results across the total spectrum of stroke severity [49]. Although the participants included in this study represent only a part of the total stroke population, the training program may have a considerable benefit for arm-hand function in more persons after a stroke. Further research should investigate the benefit of task-oriented arm

training and of technology-supported task-oriented arm training on larger groups of stroke patients; also including persons with lower functional levels.
4. Although therapists were instructed to assist as little as possible during the clinical trial, they did come in to help from time to time. This was necessary as the system used was an early system prototype. In the next generation system, therapist involvement will be minimal.

Conclusions

The results of this study indicate that technology-supported task-oriented training is feasible and can lead to significant and clinically relevant improvement of skilled arm-hand performance in chronic stroke patients which may last for a prolonged time. However, a randomized controlled trial is warranted and planned (ISRCTN82787126).

Acknowledgement

The HOST/ULTRA project (Philips Research Europe, Dept. Medical Signal Processing) is gratefully acknowledged for providing the system that was used for training patients.
Dr. W. Fontijn (Serious Toys BV, Den Bosch, NL) is thanked for providing the exercise board that was used.
The rehabilitation physicians, therapists and patients from Adelante (NL) are thanked for their advice and participation in this study. Special acknowledgements go to J.A. Franck (OT) & P. Dobbelsteijn (PT) for the development of the exercise programs that are used for the training.
Dr. S. Evers (University Maastricht, NL) is thanked for her advice on data analysis of the SF-36 data.

References

1. Nichols-Larsen DS, Clark PC, Zeringue A, Greenspan A, Blanton S. Factors influencing stroke survivors' quality of life during subacute recovery. *Stroke*. 2005;36:1480-1484
2. Wiles R, Ashburn A, Payne S, Murphy C. Discharge from physiotherapy following stroke: The management of disappointment. *Soc Sci Med*. 2004;59:1263-1273
3. Demain S, Wiles R, Roberts L, McPherson K. Recovery plateau following stroke: Fact or fiction? *Disabil Rehabil*. 2006;28:815-821
4. Page SJ, Gater DR, Bach YRP. Reconsidering the motor recovery plateau in stroke rehabilitation. *Arch Phys Med Rehabil*. 2004;85:1377-1381
5. Macclellan L, Bradham D, Whitall J, Wilson P, Ohlhoff J, Meister C, Hogan N, Krebs HI, Bever C. Robotic upper extremity neurorehabilitation in chronic stroke patients. *Journal of Rehabilitation Research and Development*. 2005;42:717-722
6. Fasoli SE, Krebs HI, Stein J, Frontera WR, Hughes R, Hogan N. Robotic therapy for chronic motor impairments after stroke: Follow-up results. *Arch Phys Med Rehabil*. 2004;85:1106-1111
7. van der Lee JH, Wagenaar RC, Lankhorst GJ, Vogelaar TW, Deville WL, Bouter LM. Forced use of the upper extremity in chronic stroke patients: Results from a single-blind randomized clinical trial. *Stroke*. 1999;30:2369-2375
8. Caimmi M, Carda S, Giovanzana C, Maini ES, Sabatini AM, Smania N, Molteni F. Using kinematic analysis to evaluate constraint-induced movement therapy in chronic stroke patients. *Neurorehabil Neural Repair*. 2008;22:31-39
9. Lum PS, Uswatte G, Taub E, Hardin P, Mark VW. A telerehabilitation approach to delivery of constraint-induced movement therapy. *J Rehabil Res Dev*. 2006;43:391-400
10. Truelsen T, Piechowski-Jozwiak B, Bonita R, Mathers C, Bogousslavsky J, Boysen G. Stroke incidence and prevalence in europe: A review of available data. *Eur J Neurol*. 2006;13:581-598
11. Krebs HIP, J.J. ; Dipietro,L. ; Ferraro,M ; Volpe,B.T.; Hogan,N. Rehabilitation robotics: Performance-based progressive robot-assisted therapy. *Autonomous Robots*. 2003;15:7-20
12. Riener R, Nef T, Colombo G. Robot-aided neurorehabilitation of the upper extremities. *Med Biol Eng Comput*. 2005;43:2-10
13. Wood-Dauphinee SK, G. The impact of rehabilitation on stroke outcomes: What's the evidence? In: Barnes MPD, B H ; Bogousslavsky,J, ed. *Recovery after stroke*. Cambridge University Press; 2005:668.
14. Van Peppen RP, Kwakkel G, Wood-Dauphinee S, Hendriks HJ, Van der Wees PJ, Dekker J. The impact of physical therapy on functional outcomes after stroke: What's the evidence? *Clin Rehabil*. 2004;18:833-862
15. Wolf SL, Winstein CJ, Miller JP, Taub E, Uswatte G, Morris D, Giuliani C, Light KE, Nichols-Larsen D. Effect of constraint-induced movement therapy on upper extremity function 3 to 9 months after stroke: The excite randomized clinical trial. *Jama*. 2006;296:2095-2104
16. Johnson M, Wisneski K, Anderson J, Nathan D, Smith R. Development of adler: The activities of daily living exercise robot. *BioRob2006. The first IEEE/RAS-EMBS International Conference on Biomedical Robotics and Biomechatronics*. 2006:881-886
17. Krebs HI, Mernoff S, Fasoli SE, Hughes R, Stein J, Hogan N. A comparison of functional and impairment-based robotic training in severe to moderate chronic stroke: A pilot study. *NeuroRehabilitation*. 2008;23:81-87
18. Housman SJ, Scott KM, Reinkensmeyer DJ. A randomized controlled trial of gravity-supported, computer-enhanced arm exercise for individuals with severe hemiparesis. *Neurorehabil Neural Repair*. 2009;23:505-514
19. Nef T, Guidali M, Riener R. Armin iii - arm therapy exoskeleton with an ergonomic shoulder actuation. *Applied Bionics and Biomechanics*. 2009;6:127-142
20. Prange GB, Jannink MJ, Groothuis-Oudshoorn CG, Hermens HJ, Ijzerman MJ. Systematic review of the effect of robot-aided therapy on recovery of the hemiparetic arm after stroke. *J Rehabil Res Dev*. 2006;43:171-184

21. Kwakkel G, Kollen BJ, Krebs HI. Effects of robot-assisted therapy on upper limb recovery after stroke: A systematic review. *Neurorehabil Neural Repair*. 2008;22:111-121
22. Spooren AI, Janssen-Potten YJ, Post MW, Kerckhofs E, Nene A, Seelen HA. Measuring change in arm hand skilled performance in persons with a cervical spinal cord injury: Responsiveness of the van lieshout test. *Spinal Cord*. 2006;44:772-779
23. Pavlides C, Miyashita E, Asanuma H. Projection from the sensory to the motor cortex is important in learning motor skills in the monkey. *J Neurophysiol*. 1993;70:733-741
24. Timmermans AA, Seelen HA, Willmann RD, Kingma H. Technology-assisted training of arm-hand skills in stroke: Concepts on reacquisition of motor control and therapist guidelines for rehabilitation technology design. *J Neuroeng Rehabil*. 2009;6:1
25. Lanfermann G, Willmann R, te Vrugt J, Timmermans A, Bongers E, Lambert N, van Acht V. Philips stroke rehabilitation exerciser. *Technical Aids for Rehabilitation - TAR 2007*. 2007
26. van Acht V, Bongers E, Lambert N, Verberne R. Miniature wireless inertial sensor for measuring human motions. *Conf Proc IEEE Eng Med Biol Soc*. 2007;2007:6279-6282
27. Willmann RD, Lanfermann G, Saini P, Timmermans A, te Vrugt J, Winter S. Home stroke rehabilitation for the upper limbs. *Conf Proc IEEE Eng Med Biol Soc*. 2007;2007:4015-4018
28. Timmermans AAA, Geers RPJ, Franck JA, Dobbelsteijn P, Spooren AIF, Kingma H, Seelen HAM. T-toat: A method of task-oriented arm training for stroke patients suitable for implementation of exercises in rehabilitation technology. *IEEE 11th International Conference on Rehabilitation Robotics*. 2009:98-102
29. McArdle WD, Katch FI, Katch VL. *Essentials of exercise physiology*. Philadelphia: Lippincott Williams & Wilkins; 2000.
30. Shumway-Cook A WM. *Motor control. Translating research into clinical practice*. Wolters Kluwer/ Lippincott Williams & Wilkins; 2007.
31. Taub E, Uswatte G, King DK, Morris D, Crago JE, Chatterjee A. A placebo-controlled trial of constraint-induced movement therapy for upper extremity after stroke. *Stroke*. 2006;37:1045-1049
32. Timmermans AA, Seelen HA, Willmann RD, Bakx W, de Ruyter B, Lanfermann G, Kingma H. Arm and hand skills: Training preferences after stroke. *Disabil Rehabil*. 2009;31:1344-1352
33. Crum RM, Anthony JC, Bassett SS, Folstein MF. Population-based norms for the mini-mental state examination by age and educational level. *Jama*. 1993;269:2386-2391
34. Menon A, Korner-Bitensky N. Evaluating unilateral spatial neglect post stroke: Working your way through the maze of assessment choices. *Top Stroke Rehabil*. 2004;11:41-66
35. Uttl B, Pilkenton-Taylor C. Letter cancellation performance across the adult life span. *Clin Neuropsychol*. 2001;15:521-530
36. Gauthier LD, F ; Joanette,Y. The bells test: A quantitative and qualitatitive test for visual neglect. *International Journal of Clinical Neuropsychology*. 1989;XI:49-54
37. Ferber S, Karnath HO. How to assess spatial neglect--line bisection or cancellation tasks? *J Clin Exp Neuropsychol*. 2001;23:599-607
38. Graetz PdB, A ; Willmes,K. *De akense afasie test - handleiding*. Harcourt Test Publishers; 1987.
39. Heugten C. Apraxia in stroke patients: Assessment and treatment. Dissertatie. Rijksuniversiteit groningen. 1998
40. World Health Organization. International classification of functioning, disability and health: Icf. 2001
41. Gladstone DJ, Danells CJ, Black SE. The fugl-meyer assessment of motor recovery after stroke: A critical review of its measurement properties. *Neurorehabil Neural Repair*. 2002;16:232-240
42. Salter K, Jutai JW, Teasell R, Foley NC, Bitensky J. Issues for selection of outcome measures in stroke rehabilitation: Icf body functions. *Disabil Rehabil*. 2005;27:191-207
43. Hsieh CL, Hsueh IP, Chiang FM, Lin PH. Inter-rater reliability and validity of the action research arm test in stroke patients. *Age Ageing*. 1998;27:107-113
44. Weerdt de WHM. Measuring recovery of arm-hand function in stroke patients: A comparison of the brunnstrom-fugl-mayer test and the action research arm test. *Physiotherapy Canada*. 1985;37:65-70
45. Yozbatiran N, Der-Yeghiaian L, Cramer SC. A standardized approach to performing the action research arm test. *Neurorehabil Neural Repair*. 2008;22:78-90

46. Van der Lee JH, De Groot V, Beckerman H, Wagenaar RC, Lankhorst GJ, Bouter LM. The intra- and interrater reliability of the action research arm test: A practical test of upper extremity function in patients with stroke. *Arch Phys Med Rehabil*. 2001;82:14-19
47. van der Lee JH, Beckerman H, Knol DL, de Vet HC, Bouter LM. Clinimetric properties of the motor activity log for the assessment of arm use in hemiparetic patients. *Stroke*. 2004;35:1410-1414
48. Dromerick AW, Lang CE, Birkenmeier R, Hahn MG, Sahrmann SA, Edwards DF. Relationships between upper-limb functional limitation and self-reported disability 3 months after stroke. *J Rehabil Res Dev*. 2006;43:401-408
49. Wolf SL, Winstein CJ, Miller JP, Blanton S, Clark PC, Nichols-Larsen D. Looking in the rear view mirror when conversing with back seat drivers: The excite trial revisited. *Neurorehabil Neural Repair*. 2007;21:379-387
50. Salter K, Jutai JW, Teasell R, Foley NC, Bitensky J, Bayley M. Issues for selection of outcome measures in stroke rehabilitation: Icf participation. *Disabil Rehabil*. 2005;27:507-528
51. Dorman P, Slattery J, Farrell B, Dennis M, Sandercock P. Qualitative comparison of the reliability of health status assessments with the euroqol and sf-36 questionnaires after stroke. United kingdom collaborators in the international stroke trial. *Stroke*. 1998;29:63-68
52. Brazier JE, Walters SJ, Nicholl JP, Kohler B. Using the sf-36 and euroqol on an elderly population. *Qual Life Res*. 1996;5:195-204
53. Lewis J. Ibm computer usability satisfaction questionnaires: Psychometric evaluation and instructions for use. *International Journal of Human-Computer Interaction*. 1995;7:57-78
54. Lund AM. Measuring usability with the use questionnaire. *The Usability SIG Newsletter*. 2001
55. Parkin D, Rice N, Jacoby A, Doughty J. Use of a visual analogue scale in a daily patient diary: Modelling cross-sectional time-series data on health-related quality of life. *Soc Sci Med*. 2004;59:351-360
56. Ostelo RW, Swinkels-Meewisse IJ, Knol DL, Vlaeyen JW, de Vet HC. Assessing pain and pain-related fear in acute low back pain: What is the smallest detectable change? *Int J Behav Med*. 2007;14:242-248
57. Williams GC, Ryan RM, Deci EL. 2008
58. Deci EL, Ryan RM. The "What" And "Why" Of goal pursuits:Human needs and the self-determination of behavior. *Psychological Inquiry*. 2000;11:227-268
59. Mc Ardle WD, Katch FI, Katch FL. *Essentials of exercise physiology*. Philadelphia: Lippincott, Williams & Wilkins; 2000.
60. Rosner B. *Fundamentals of biostatistics*. Duxbury: Thomson Brooks/Cole; 2006.
61. Hedges LV, Olkin I. Nonparametric estimators of effect size in meta-analysis. *Psychological Bulletin*. 1984;96:573-580
62. Cohen J. *Statistical power analysis for the behavioral sciences*. Hillsdale, NJ: Lawrence Earlbaum Associates; 1988.
63. van der Lee JH, Beckerman H, Lankhorst GJ, Bouter LM. The responsiveness of the action research arm test and the fugl-meyer assessment scale in chronic stroke patients. *J Rehabil Med*. 2001;33:110-113
64. van der Lee JH, Beckerman H, Lankhorst GJ, Bouter LM. Constraint-induced movement therapy. *Arch Phys Med Rehabil*. 1999;80:1606-1607
65. Taub E, Lum PS, Hardin P, Mark VW, Uswatte G. Autocite: Automated delivery of ci therapy with reduced effort by therapists. *Stroke*. 2005;36:1301-1304
66. Bach-y-Rita P, Wood S, Leder R, Paredes O, Bahr D, Bach-y-Rita E, Murillo N. Rehabilitation for institutional, home, and educational late stroke programs. *Top Stroke Rehabil*. 2002;8:1-10
67. Nudo RJ. Postinfarct cortical plasticity and behavioral recovery. *Stroke*. 2007;38:840-845
68. Sanchez RJ, Liu J, Rao S, Shah P, Smith R, Rahman T, Cramer SC, Bobrow JE, Reinkensmeyer DJ. Automating arm movement training following severe stroke: Functional exercises with quantitative feedback in a gravity-reduced environment. *IEEE Trans Neural Syst Rehabil Eng*. 2006;14:378-389
69. Page SJ, Levine P, Leonard A, Szaflarski JP, Kissela BM. Modified constraint-induced therapy in chronic stroke: Results of a single-blinded randomized controlled trial. *Phys Ther*. 2008;88:333-340

70. Dobkin BH. Confounders in rehabilitation trials of task-oriented training: Lessons from the designs of the excite and scilt multicenter trials. *Neurorehabil Neural Repair*. 2007;21:3-13
71. Mark VW, Taub E. Constraint-induced movement therapy for chronic stroke hemiparesis and other disabilities. *Restor Neurol Neurosci*. 2004;22:317-336

Chapter 8

General discussion

At the start of this project in September 2006, many rehabilitation systems had been developed, several of which were supporting the training of the arm and hand in stroke patients. Most systems focussed on single-plane movements, targeting the improvement of muscle strength, of joint motion ranges and/or the alteration of kinematic properties (e.g. movement speed). The training approaches were mostly targeting the ICF function level. Only a few systems existed that were supporting environmentally contextual task training with real life objects[1, 2]. Little was formalized regarding task-oriented training characteristics in the field of stroke rehabilitation, but even less in the field of technology-supported stroke rehabilitation. With regard to the feasibility and effects of technology-supported client-centred task-oriented training, publications were almost non-existent. The main focus of the present thesis has been on studying the feasibility and effects of technology-supported client-centred task-oriented training.

The main aims of this thesis were

1. to a) provide criteria that may be used to chart the potential of existing rehabilitation technologies for arm-hand training after stroke, and b) contribute towards identifying which technological training solutions are beneficial for different patient categories through a standardized procedure for the selection of outcome measures;
2. to define and operationalize a task-oriented training approach and investigate the relative contribution of specific training characteristics to treatment effect sizes;
3. to investigate the feasibility of technology-supported client-centred task-oriented training and
4. to investigate possible effects of technology-supported task-oriented training on arm-hand skill performance in persons with chronic stroke.

In this general discussion, for each of the abovementioned aims of this thesis, the state-of-the-art as found at the start of the project will be briefly recapitulated, after which recent developments in the field of rehabilitation and rehabilitation technology are presented and results from our own research are discussed. Several unsolved issues and new research questions that need to be addressed in future research are focused upon. Finally, some methodological considerations and a statement of contribution are presented.

Potential of existing rehabilitation technology

Charting possibilities of rehabilitation technology

After the development of prosthetics and assistive technologies, technology development for rehabilitation started in the mid-nineties [3]. The first technologies to support

rehabilitation were robotic systems, MIT-Manus being the first around 1995 [4, 5]. Innovation in robotic systems for rehabilitation did, in most cases, start in university engineering departments at a time when the field of user-centred design [6, 7] had not yet become adopted by technology developers. Furthermore, before that time relatively little was known with regard to stroke guidelines for rehabilitation or evidence-based stroke therapies. As a consequence, more than a decade of work in robotic rehabilitation technologies for stroke focused on the three basic ways of supporting and/or challenging exercises that therapists use when treating patients, i.e. the passive, active-assisted and active-resisted exercise modalities [8].
Recent meta-analyses of clinical trial evidence [9-11] have shown that robot-based rehabilitation of the upper extremity after stroke is very successful for improving functions that are prerequisite for skill performance. Examples of such functions are muscle strength, correction of muscle activation patterns, speed of movement, and active range of joint motion. However, these meta-analyses have also shown that, to date, robot-based rehabilitation failed to improve the arm-hand activity level (ADL activities) [9-11]. This finding begged the question which criteria rehabilitation technology should fulfil in order to improve ‘skilled arm-hand performance’. In order to answer this question, criteria were identified based on recent evidence from the fields of rehabilitation and motor control (chapter 2). A literature search was conducted in clinical databases set up between 1997 and 2007. State-of-the-art approaches to support motor learning after stroke were studied, and criteria for rehabilitation technology design aiming to influence skilled arm performance after stroke were identified. Upper limb rehabilitation technology that had been used in clinical trials was reviewed against the suggested criteria to map strengths of different systems. This review showed that nearly all of the currently existing systems are robot systems. Very few sensor-based applications had been realised so far, despite their advantage of avoiding the complexity of actuators and mechanical parts. This is probably due to the fact that engineering efforts in prototyping were based on the active, passive, and active assisted modalities, the latter two of which can only be realized when both actuators and sensors are used. Also, when assistance to movement is provided, patients with lower functional levels can be addressed by rehabilitation technology. Most rehabilitation systems were shown to provide objective and valid feedback on exercise performance. Feedback may contribute to improving motor performance and motor learning [12], which was corroborated by the findings in the systematic review presented in chapter 3 [13]. Feedback does not only support motor learning, but it also allows the patient to strive towards a specific goal [14]. It motivates patients as even small changes in performance can be monitored and fed back to the patient. This is especially important as many times the patient has to train very hard to obtain small progress, which without feedback is hard to perceive.
In our review [15], we concluded that, in order to influence ‘skilled arm-hand performance [16]’ upper limb rehabilitation technology for stroke patients needs to align with developments in rehabilitation training approaches of the last decade. In order to also improve performance at the activity level, patient-tailored task-oriented arm-hand training in natural environments that involves a multitude of ‘real-world’ problem solving strategies is essential. Several reasons prevent this from happening in the majority of robotic solutions available:

1. the robot end-effector doesn't allow real object manipulation, thereby preventing the patient from tackling related 'real life problems';
2. the available range of motion is limited, preventing training of many tasks that are of interest to the patient and that are close to his/her personal needs (absence of so-called client-centeredness);
3. the available degrees of freedom are often limited, preventing the patient from performing natural movements and from learning to master redundant degrees of freedom which would lead to efficient motor performance;
4. the robot only supports the proximal upper extremity and doesn't involve the hand which is crucial for mastering activities of daily living (ADL) [9] (only few clinically tested upper extremity rehabilitation systems involve hand training, namely the Rutgers Master II glove [17], Cyber Glove [17], ADLER[18] and the MIT-Manus wrist module [19]); and
5. the frequent presence of a stimulus-response discrepancy, i.e. a dissociation between the (feedback) information presented to the patient and the movement (s)he is required to make, preventing the patient from learning cognitive processing that is transferable to 'real-life' activities.

Next to the technological limitations for task-oriented training, also the insensitivity of used outcome measures (especially for the ADL scales) in the evaluation of robot interventions may have contributed to the lack of demonstrated training effects on the ICF activity level [10]. Most used outcome measures on activity level were the Functional Independence Measure (FIM) and the Barthel Index, which are not specific measures of dexterity. Kwakkel et al. [10] advocate that evaluation of robot interventions should use more scales that measure specific dexterity like the Wolf Motor Function Test, the Nine Hole Peg Test, the Jebsen Test, and, if possible, kinematic movement registration.

Another reason that could explain the poor functional outcome of robot-assisted interventions was the insufficient contrast between control groups and experimental groups with regard to exercise repetitions [11]. The number of repetitions that may be done during robot therapy is far higher than in non-technology supported training and has proven to be an important factor contributing to the improvement in arm-hand function after robot training [10]. Studies that matched the number of repetitions of the control and the robot intervention [20] didn't show a differential effect [10]. The number of repetitions in training protocols for stroke patients may not be sufficient to drive optimal neural reorganisation. Lang et al., in two observational surveys, studied the number of repetitions during inpatient [21] and outpatient [21, 22] physiotherapy and occupational therapy sessions. On average, one training session included 39 active, 34 passive and 12 to 32 repetitions of purposeful movements [21, 22]. It was concluded that the amount of practice is small in comparison with animal studies in which training repetitions may amount to 400-600 repetitions. Robot-assisted training is very suitable for a large number of exercise repetitions, because of its engaging environment and its interactive properties (i.e. the adaptation of the robot assistance to the abilities of the patient). Robot-assisted training has therefore the potential to play an important role in motor learning.

For a large number of patients, robot training may be instrumental towards full task-oriented training (e.g. by means of sensor-technology) that allows for full ranges of motion, and full degrees of freedom in all upper extremity joints without any support during movement. Rehabilitation robots are of crucial value to provide learning opportunities and challenges to patients who are not at a high enough functional level to face all the challenges that are related to full environmentally contextual training. By offering support in those cases where the patient cannot perform the movement to be exercised, robots are well placed to provide continuous challenge to the patient and prompt for sustained exercise. Therefore, a variety of robotic and sensor systems, each with different levels of support, with different exercise instructions and feedback, and with different training environments are necessary to accommodate patients with different motor abilities and to offer a variety of training strategies.

It appears to be difficult, if not impossible, to implement all training opportunities in one device. Krebs [23] and Johnson [24] both have envisioned that training in rehabilitation centres in the future will happen in a gym where patients can train on different devices that complement each other. Therefore, the list of therapy-oriented criteria for rehabilitation technology that is presented in chapter 2 should be seen as a list where strengths of different systems can be indicated, rather than an overview of all features that an ideal system should incorporate.

With the large number of systems that have been developed to date, a large variety of games and exercises, supporting different training approaches, will be available for patients in the near future. These new training possibilities offer extra opportunities to patients to use their full potential for functional recovery. Currently, patients are discharged from further therapy, even though they still experience arm-hand performance problems that seriously interfere with every day life activities. The reason for discharge is typically a limited progress during therapy, which is known as the 'motor recovery plateau' [25]. It has been argued that the plateau is not because of a limited potential for further recovery, but that it is merely due to neuromuscular adaptation processes, implying that novel or different treatment approaches could lead to further improvement [26]. This argument has been corroborated by a large number of studies that reported further progress in skilled arm-hand performance after treatment of chronic stroke patients with novel techniques, like e.g. CIMT [27] , robot- technology [28-31], robot-technology in combination with virtual reality [32], functional electrical stimulation [33] or sensor-based technology [34]. The large variety of new training opportunities that have been developed in the last 15 years may facilitate a shift of the motor recovery plateau to a much later stage where patients also may achieve a much higher level of performance.

Benchmarking solutions for different patient groups

A broad spectrum of technological systems for upper extremity rehabilitation after stroke has been developed in the last 15 years. However, it remains unclear to date which system works best for which patient group. It is likely that different patient groups are served better by different technologies. For example, it may be hypothesized that patients with a lower functional level benefit more from treatment with robotic systems in which actuators compensate for low muscle power, whereas patients with a higher functional level may benefit more from sensor-based systems that enable more 'real-life' movement performance and the learning of associated problem solving strategies [35]. In order to benchmark solutions for different patients, two crucial conditions have to be fulfilled:

1. standardization of the use of valid, reliable and sensitive outcome measures, and
2. standardization of training protocols.

At this moment numerous arm-hand outcome measures exist. The choice of outcome measures is currently guided by a variety of factors (e.g. client-centeredness of the therapy provided, purpose of evaluation, psychometric properties, ICF), amongst which the ICF classification is widely used [36]. However, as to the latter, classifying existing outcome measures in only 3 categories (i.e. function, activity, participation) does not seem to provide enough guidance to choose the most appropriate measurement instrument to evaluate an intervention. To obtain more standardized use of outcome measures, it is desirable that interventions following a similar approach are evaluated with similar measures. Therefore, a concept for guiding the choice of outcome measures was proposed, consisting of the following 8 measurement components: arm-hand function, complex arm-hand activities, basic arm activities, basic hand activities, bilateral arm-hand activities, participation, real-life measurement and exact measurement (chapter 4). To make a first operational version of the concept, 28 clinical tests, that were used in 16 task-oriented training interventions included in a systematic review, were labelled (i.e. marked when the component was measured by the test). Once the specific characteristics of an intervention are determined, one can search in the concept containing the marked test instruments, which measurement instruments evaluate the characteristics that are apparent in the training. Besides the measurement of training-specific effects, one can also add measurement instruments that allow for evaluation of generalized training effects by choosing measurement instruments that evaluate different characteristics than the ones comprising the intervention. A choice of measurement instruments, based on this concept, allows for a comparison of the strengths (training-specific and general effects) of similar interventions.
Although a substantial start towards the guidance of outcome measure choice, the above mentioned model needs to be further elaborated. First of all, a weighing (i.e. to which extent does the test measure the component) needs to be defined for all its components. Secondly, more tests need to be added to the model, as more arm-hand tests exist than the 28 tests that were included in the 16 interventions of the systematic review. Thirdly, additional tests may necessitate additional components (e.g. 'quality of life measurement' and ' reflection of a patient's personal needs [37]'), a subdivision of existing components (subdivision of function into 'arm function' and 'hand function') or refinement of other components (e.g. 'exact measure' may be subdivided into time, strength and kinematic measurement). Furthermore, findings of the interview study of stroke patients, presented in chapter 5 of this thesis, underlined the need for evaluation of a patient's personal needs [38]. For example, the study revealed that patients rather optimize skills for which they have some proficiency level, rather than train on the most impaired functions and activities. And finally, the user of the concept should be able to choose an outcome measure on the basis of the psychometric quality of the tests (regarding e.g. validity, reliability, sensitivity) and based on the target population (to avoid e.g. ceiling or floor effects).

Several technological systems have appeared to support kinematic outcome assessment [39, 40]. Bosecker et al [40] identified a set of kinematic metrics that can be used to predict outcome on function level (Fugl Meyer and Motor Status Score) by means of MIT-Manus. This is an important first step towards automated objective outcome measurement and outcome assessment standardization. Technology-supported outcome measurement may become very important in the process of understanding motor learning, as it has potential to differentiate between true recovery (the same muscle coalitions as before the injury are recruited) and compensatory strategies (alternative muscle coalitions are used for skill performance). Most current clinical outcome measures cannot be used to detect if improvements are due to motor recovery or to compensation, as they neither specify how the task is performed nor which compensatory movements were used [41, 42].
Finally, in order to enable benchmarking of solutions, outcome measures need to be standardized. Similarly, experimental procedures and training protocols need to be standardized in order to enable comparisons of similar interventions across systems.

Evidence-based training approaches and motor learning

In a systematic review, including 151 studies (123 randomized controlled trials and 28 controlled clinical trials), it was shown that strong evidence exists for task-oriented exercise training influencing functional outcome, in particular when applied intensively [43]. These findings were corroborated by the results of another systematic review by French et al [44]. Other training approaches that have proven to improve functional outcome after stroke are constraint induced movement therapy and bilateral training [43].
Motor learning can be defined as a long lasting behavioural change after repetitive motor action [45] that enables the use of the correct movement in a proper context [41]. Although to date the differential central nervous system adaptations behind true recovery and compensation are still poorly understood, it is generally accepted that motor learning is a necessary condition for both to occur [41].
Below we discuss which features of task-oriented training may effectively influence motor learning.
First of all, during task-oriented training patients *learn to solve task-specific problems* pertaining to anticipatory locomotor adjustments, cognitive processing, and finding efficient goal-oriented movement strategies. For successful performance of daily life activities, the capacity to adapt to environmental challenges, often by learning associations between external events and behavioural motor acts, is essential [46]. Furthermore, through task-oriented training, patients learn to control redundant degrees of freedom during voluntary movement so that movement occurs in a way that is as economic as possible for the human body, given the fact that the activity result needs to be achieved to the best of the patient's ability [15]. It is important that, in the initial stage of the training, the practice situation resembles as much as possible the real-life situation, in order to enable learning of skill-related cognitive and problem solving strategies. Such learning leads to cortical changes that make the learned strategies available for future behaviour [46, 47]. Examples of such changes are the strengthening of pre-existing

neural connections, changes in task-related cortico-cortical and cortico-subcortical connections, and modifications of the mapping between behaviour and neural activity that take place in response to changes in afferent input or efferent demand [47]. It is also important to include variability of movement and context characteristics in the training, as these have been shown to increase engagement and attention during learning [48], as well as the retention of learning effects. Practice variability also provides the learner with a wider range of movement experiences related to the trained skill and improves the adaptation to other motor skills [48]. Transfer, defined as the capability gain for performance in one task as a result of practice or experience on some other task, is higher when more similarity between two conditions exists[45]. The broader the variability of acquired movement experiences, the more transfer can be expected to happen as it is more likely to have learned the necessary strategies that are involved in the new task execution [41].

Second, in task-oriented training, there is most often a demonstration of the exercise to be performed through therapist demonstration or, in case of technology-supported training, through e.g. video-observation. *Observational practice* has been shown to be better than no practice and, in combination with physical practice, it has been shown to produce better transfer effects [49]. Observation enables the learner to extract important information of appropriate task coordination patterns and subtle task requirements 50. It also has been shown that during observation of movement performance, when accompanied by mental imagery, augmented blood circulation and the neural activation occurs in a set of similar brain areas to those activated during actual performance of the movement by the patient 50-52. Motor learning after mental imagery mainly occurs through improvement of movement preparation and movement anticipation [51, 52]. The active 'thinking along' of a patient during task instruction should be encouraged, especially when repetitive instructions are available, as they may enhance motor learning.

Third, it has also been found that patients are *motivated* for skill training. The following motivational reasons for improving the level of skill performance were mentioned by persons after stroke: avoiding embarrassment in public, avoiding frustration, independence, not to be a burden to others, pride, joy, going back to work [38] (see chapter 5). An optimal motivational state of the learner enhances motor learning effects [50]. Motivation leads to enhanced attention during task performance, which in turn leads to optimal storage of information in the short and long-term memory [53]. Motivation also leads to more exercise repetitions and prolonged training, which have both proven to enhance upper limb training outcome in stroke [54, 55].

In this thesis we operationalized task-oriented training with 15 components (chapter 3). 'Distributed practice' and 'feedback' were associated with the largest post-intervention effect sizes. Distributed practice has also been shown in other research to result in better motor learning than massing practice sessions [56]. Possible explanations for the better results are that less fatigue occurs than in massed practice, that the amount of cognitive effort one is prepared to put in is higher, and that there is more opportunity for memory consolidation processes [57]. Information on the efficiency of augmented feedback in motor skill learning is scarce [58]. There is evidence that, for skill learning in general [59] and also specifically for persons afters stroke [60], the use of knowledge of performance feedback results in better motor skill performance. Knowledge of performance feedback facilitates 1. declarative or explicit learning processes (prescriptive feedback), resulting in factual knowledge that can be consciously recalled from the long-term memory [61] and 2. non-declarative or implicit learning processes, such as associative learning (classical and operant conditioning) and procedural learning (skills and habits), after which information is stored in the long-term memory [53, 61].

'Random practice' and 'use of clear functional goals' were associated with the largest follow-up effect sizes. Working towards a clear functional goal encourages the patients to continue doing the training activity beyond training sessions, which may lead to better follow-up results. During random practice, high contextual interference (i.e. "the memory and performance disruption that results from performing multiple skills or variations of a skill within the context of practice" [48]) occurs. High contextual interference leads to increased cognitive processing, because simultaneous presence of related motor performance experiences in the working memory facilitate interim processing that ultimately results in retention benefits (elaboration hypothesis) [62]. Also, the learner has to generate a solution for the task-related problems on each movement execution. For previously encountered problems, solutions need to be retrieved from the long-term memory each time, which leads to better retention of learning effects. This is called the action plan reconstruction hypothesis [48].

It seems that 'distributed practice', 'feedback' and 'random practice' contribute to optimal memory consolidation processes and that 'the use of clear functional goals' allows for to the learning content to be meaningful for 'skilled' arm hand performance.

Technology-supported client-centred task-oriented training

The implementation of *task-oriented training exercises* in technology is a challenge for several reasons. First of all, it should be possible to support multiplanar movements, as this is an essential aspect of task-oriented training. Second, feedback should be patient-customized (e.g., adapted according to the proficiency level of the learner) and it should support motor learning (e.g. knowledge of performance feedback should be included and the system user should be able to decide on the delivery time of the feedback). Third, supporting exercises with clear functional goals in a task-specific environmental context and preferably with real life objects by means of technology is complex.

A training method was developed at Adelante (Hoensbroek, NL) in collaboration with a physiotherapist and occupational therapist, to enable the implementation of exercises that support task-oriented training in rehabilitation technology [63] (chapter 6). The training method can be used in almost all technological systems, e.g. robot systems, sensor-based systems, in combination with functional electrical stimulation, etc. The training method is based on task-segmentation, i.e. the break-up of skills in skill components. The latter are functional entities that keep a link with the skill itself. Exercise content, progression, as well as training schemes, are based on findings from motor control research and exercise physiology. Together with Philips Research (HOST/ULTRA project, Biomedical Sensor Systems Eindhoven & Medical Signal Processing, Aachen), this T-TOAT method (Technology-supported Task Oriented

Arm Training) has been implemented in a sensor based prototype, called Philips Stroke Rehabilitation Exerciser [64, 65]. To use the T-TOAT method with Haptic Master, specific software was developed (i.e. Haptic TOAT [63]) in Adelante in collaboration with the Centre of Research Technology in Care of Zuyd University (Heerlen, NL).
In previous research, software to model and generate functional movement trajectories within a Haptic Master-mediated therapy environment, based on the minimal jerk algorithm[2, 66] was developed. The latter predicts straight line movements and bell shaped velocity curves with zero starting and end-points. However, the minimal jerk algorithm is still under development and does not yet accommodate for trajectory dependence on variable object shapes, object orientation, plane of movement, and different velocity and straightness of movement in stroke patients[66, 67]. In Haptic TOAT[63], the patient's desired movement trajectory can be recorded by Haptic Master. The movement can be saved and replayed (in either a passive, active-assisted, active or active-resisted mode). Individual haptic feedback is provided through a pre-programmed spring that pulls the patient back to the optimal path and/or through a sensation of 'bouncing into a wall' when deviation from the trajectory exceeds the set range. Van Asseldonk et al [68] found, in healthy persons, that the more Haptic Master induced guiding forces restrict the occurrence of execution errors, the smaller the amount and rate of motor learning. The authors concluded, based on their results, that persons learn from execution errors and suggest that the amount of support should be progressively lowered in the course of rehabilitation. In Haptic TOAT, the haptic guidance can be progressively lowered when the patient progresses in the course of rehabilitation, in order to further facilitate sensorimotor learning. The Haptic TOAT software tool enables patient-customized task-oriented training with real life objects, and, within the limitations of the Haptic Master movement range, in a realistic environmental context.
Next to work on the task-oriented aspect of technology-supported training, we aimed to facilitate technology-supported training to be *client-centred*. It is important that stroke patients can choose exercises that support skills that are close to what they want/need to train on. An interview study in subacute and chronic stroke patients was performed to identify skill training preferences of stroke patients [38] (chapter 5). An inventory was made of 46 skills in descending order of preference. A training program with exercises supporting 2 and 4 out of the10 most preferred skills was implemented in the Philips Stroke Rehabilitation Exerciser and Haptic Master respectively. Allowing patients to choose the exercises (and choose which progression criteria they wanted to use, which variation in materials, etc.) enhances their active role in the rehabilitation process, and thus their motivation and compliance.
To our knowledge, the sensor-based T-TOAT training with Philips Stroke Rehabilitation Exerciser and the Haptic TOAT training (Haptic Master) currently are the only existing technology-supported client-centred task-oriented training systems allowing for individual exercises with real life objects in a realistic environmental context, supported by individualized feedback.

Effect of technology-supported task-oriented training on arm-hand skill performance

In chapter 7 we reported the results on treatment outcome, patient motivation, and system usability of sensor-based arm skill training in chronic stroke patients. Nine patients participated for 8 weeks (4 times 1 hour per week) in a T-TOAT training program. Video-based exercise instructions could be replayed when and as many times as patients wanted (thereby learning through observation). Patients received feedback during and after the exercise performance on the basis of a comparison of sensor data that registered the trunk and arm movements during exercise performance, with individualized training targets that therapists had set (knowledge of performance feedback). Real life objects were used on a sensorized exercise board that supports individualized exercise instructions and feedback on successful completion. Arm hand performance measures were recorded at baseline, after 4 weeks of training, after 8 weeks of training, and also 6 months after the training had stopped. T-TOAT improved arm-hand performance and health-related quality of life significantly. The patients improved 14.2% on Fugl-Meyer, 15.3% on ARAT, 43% on MAL-amount-of-use and 34.1% on MAL-quality-of-use after 8 weeks of training. These improvements are very important, especially for persons in the chronic phase (on average 2.5 years) after stroke. Some decline in training effects, although not statistically significant, was found 6 months after the training had stopped. This suggests that patients may benefit from refresher training courses at regular intervals to maintain training effects. Participants felt intrinsically motivated and competent to use the system.
The treatment effect sizes were comparable to those found after constraint induced movement therapy [69], a treatment method that has been extensively investigated and proven to be effective [70-73]. Also, the improvements found on all arm-hand tests after 8 weeks of sensor-based T-TOAT very clearly exceeded the limit associated with a minimal clinically important difference (MCID) as put forward by Van der Lee. Even six months after the training had stopped, the individual improvements over time exceeded the aforementioned MCID levels. These findings are important in the field of rehabilitation technology, as, apart from in the AUTOCITE [27]trial and in a randomized clinical trial with T-WREX [30], no influence of technology-supported training on specific arm-hand measures on the ICF activity level has been shown in other studies. It should be investigated further to which extent improvement in arm hand skilled performance, using the training approach presented in this thesis, might improve patients' independence in ADL, and, as a result of this, might lead to reduction in health care consumption and improvement in quality of life.

Some methodological considerations

In the interview study that investigated training preferences of stroke patients, patients with a high functional level were included. This should be taken into account when extrapolating these data to other patient categories. However, we do think it is a very important section as these patients, who do have some remaining function in their hand, are most likely to benefit from task-oriented arm training. A comparable study,

including stroke patients with a lower functional level, is warranted to have similar information on training preferences of such patients.
The trial design of the sensor-based pilot study (chapter 7) optimized intervention components and settled on outcome measure use in preparation of a larger scale randomized clinical trial (RCT). In our trial patients were their own controls. We included stroke patients that were at least 1 year post-stroke (average=2.5 years post-stroke) and that were not receiving any additional treatment. However, for future trials, it is advised to use a control group that trains with the same amount of therapist attention, and in an intervention with equal dosage and one single experimental contrast (in this case the sensor-technology training). In case of no control group, multiple baseline measurements (weekly for a few weeks before the intervention) should establish the stable situation of the baseline clinical outcome measurement results [74]. Dobkin [74] also advises to have a phase-in of arm therapy as this approach lessens the likelihood of a rapid gain in participants who have a greater latent capacity to improve than expected and simply needed some additional routine therapy, rather than a new form of treatment. The phase-in arm therapy can be a modest conventional intervention for approximately 6 sessions. If the outcome measure improves, then this serves as a new baseline and another round of 6 sessions should be provided until participants reach a plateau by conventional therapy. Like this, the chance is reduced that a few outlier participants, who improve beyond expectations, will lead to impressive but unrealistic mean group results [74]. Analysis of data collected from the sensor system during exercise performance could have given an additional objective measure for performance improvement after training. This would also have enabled us to study the relationship between kinematic data and the results from the clinical tests (primary outcome measures). However, this was not the primary goal of this thesis. This possibility will be implemented in future research.

General conclusion: statement of contribution

From a literature review (chapter 2), we identified that, in order to improve skilled arm-hand performance, technology-supported motor rehabilitation after stroke should include a task-oriented training approach. We also identified criteria for the design of rehabilitation systems which aim to influence skilled arm-hand performance, based on literature from the fields of rehabilitation and motor learning. By reviewing randomized clinical trials (chapter 3) and existing technology (chapter 2), it was found that the task-oriented training approach has, to date, been used sparsely, both in regular therapy (only 16 RCT interventions!) and in technology-supported therapy. We operationalized task-oriented training with 15 characteristics (chapter 3) and found, in a systematic review, that training, whether technology-supported or not, should include at least the 'use of clear functional goals', 'feedback', 'random practice' and 'distributed practice', as these characteristics are linked to the higher post-intervention and follow-up treatment effect sizes.
The review in chapter 2 also showed that there is a shift towards client-centred training in the field of rehabilitation. Technology-supported training can be client-centred by offering exercises that support training preferences of stroke patients. In chapter 5

of this thesis the arm training preferences of subacute and chronic stroke patients, with a high functional level, were identified. It was also found that patients prefer to train on skills for which they already have some proficiency level. The latter underlines the importance of including client-centred assessment tools to set treatment goals.
Technology-supported task-oriented training, in which the criteria that were identified in chapter 2 are taken into account, is fully possible through T-TOAT, a training method that is described in chapter 6 of this thesis. Chapter 6 also describes Haptic-TOAT, a software package that allows for the implementation of T-TOAT in Haptic Master. In chapter 7, it was described how sensor-based T-TOAT is feasible and a clinical trial is described of which results indicate that sensor-based T-TOAT may strongly improve skilled arm-hand performance and health-related quality of life in stroke patients.
The review in chapter 2 also described how technology for training has major additional strengths and opportunities that complement what therapists can offer traditionally. Rehabilitation technology can register movement performance (range of movement, smoothness of movement, velocity, etc.) and can give objective feedback, based on kinematic registration informing the patient about even small steps in progress. Also technology-supported training has a unique position to offer training that is engaging by allowing patients to control interactive game elements with body movements. These can provide a large range of feedback possibilities, various reinforcement strategies and can even engage players and make them, to a certain extent, oblivious of the hardship of training. The active role that a patient can take in his/her rehabilitation process and the fact that training is engaging are essential components that technology can target in order to enhance patient motivation for training. Amongst others, motivation has a positive influence on the attention of the patient during training, which in turn may facilitate storage of information in the long-term memory. But motivation may also encourage patients for a high number of exercise repetitions and prolonged exercise performance, which are factors known to positively influence motor learning. The task-oriented training approach (e.g. T-TOAT) can be used for implementation of exercises in robotic technology, sensor technology and in combination with other electromechanical devices such as functional electrical stimulation (FES), transcranial magnetic stimulation (TMS) and transcranial direct current stimulation (tDCS).
In chapter 4, we defined a concept to guide clinicians and researchers to choose outcome measures for the evaluation of (technology-supported) motor interventions of the upper extremity in stroke patients. As mentioned before, the concept needs further elaboration, for which suggestions were given.

Future research

A multitude of rehabilitation technology systems have been developed in the last 15 years. As it is likely that different systems may complement each other, the *further standardization of outcome measures, experimental and training protocols in clinical trials of these technologies* could help advance this field, by characterizing how to optimally combine different technologies for specific patient categories [35, 75]. The most optimal training for patients (type, modalities), the best trial designs, the best dose-response characteristics of interventions (exercise frequency, exercise load and exercise duration), the best outcome measures, and the likelihood of transfer of trained performance to untrained skills and to real-world settings need to be tested and established within and across patient pathologies. With regard to modalities, it needs to be investigated which treatment modalities work best for which patient. Modalities that are currently used in robotic rehabilitation are [9, 76]: passive, active, active-assisted, active resisted and gravity-compensated movement training. Also the benefits of more recent treatment modalities like e.g. error reduction and error augmentation[77] for specific patient categories should be studied more extensively. When addressing the standardization of the training protocol, also an investigation into the *timing of (electro-mechanical and robot-assisted) arm training* should be addressed. Standardization is first of all necessary within disease categories, but also across different neurological diseases to find common denominators in the conceptual basis and deployment of rehabilitation interventions [78]. This is important for all neuromotor training programs, but even more so for technology-supported training as the use of similar technologies for different neurological pathologies will be much more cost-effective for rehabilitation centres. Clinical acceptance of new valued techniques may also be higher if the same intervention can be applied across a spectrum of pathologies [78].

Currently it is seen that patients do not always maintain the level of improved arm-hand performance obtained after rehabilitation. Future research should focus on *establishing* the *optimal time and training dosage to be applied in so called refresher courses,* i.e. short training sessions to maintain an optimal level of performance. A study is planned where patients, more than 6 months after completion of an intensive training protocol do a refresher course of home-based task-oriented training to monitor if post-training arm-hand performance levels can be achieved again with reduced practice duration.

Bosecker et al. [40] have made linear regression models to estimate clinical scores on Fugl-Meyer, Motor Status Score and Motor Power for the upper extremity from robot-based metrics. They identified a set of kinetic and kinematic macro-metrics that may be used for fast outcome evaluations. Future research is needed to study the relationship between kinematic data that are collected during skilled task-performance and clinical outcome test data. Therefore, a model needs to be developed that can predict the outcome on clinical test batteries on activity level from kinematic data that are registered during task-oriented exercise-performance.

There is a need for assessment of the quality of arm-hand performance in the patient's real life situation, as transfer effects of any intervention, whether technology-supported or not, are critical to any proof of concept of efficacy trial [78]. But also possibilities for training in the home situation should be explored, as training in a natural environmental context gives optimal training effects. We envision and hope to be able to contribute to a future where rehabilitation will be implemented in ubiquitous training systems in rehabilitation centres as well as at the patient's home. Multi-level tele-rehabilitation where therapists communicate with patients, where health care professionals communicate between each other and where patients communicate and train together may enable high level guided treatment. Patients should be encouraged to have an active role in their rehabilitation process and will be motivated and persuaded

to optimally challenge their motor learning processes. To contribute towards this vision, our future research will be aiming to give clinical input into technology-development of our technological partners, as well as to test the potential of developed technologies through clinical and randomized clinical trials.
Future research should map the costs of purchasing rehabilitation technology versus the benefits and the implications for the total utilization cost of the health care system. In these studies, also reimbursement issues need to be addressed, as well as the potential negative consequences of less personal contact with therapists or health care providers [79].

References

1. Lum PS, Taub E, Schwandt D, Postman M, Hardin P, Uswatte G. Automated constraint-induced therapy extension (autocite) for movement deficits after stroke. *J Rehabil Res Dev*. 2004;41:249-258
2. Johnson M, Wisneski K, Anderson J, Nathan D, Smith R. Development of ADLER: The activities of daily living exercise robot. *BioRob2006. The first IEEE/RAS-EMBS International Conference on Biomedical Robotics and Biomechatronics*. 2006:881-886
3. Krebs HI, Carrozza MC. Guest editorial: Special issue on rehabilitation robotics: From bench to bedside to community care. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*. 2007;15:325-326
4. Aisen ML, Krebs HI, Hogan N, McDowell F, Volpe BT. The effect of robot-assisted therapy and rehabilitative training on motor recovery following stroke. *Arch Neurol*. 1997;54:443-446
5. Krebs HI, Hogan N. Therapeutic robotics: A technology push: Stroke rehabilitation is being aided by robots that guide movement of shoulders and elbows, wrists, hands, arms and ankles to significantly improve recovery of patients. *Proc IEEE Inst Electr Electron Eng*. 2006;94:1727-1738
6. Gould JD, Lewis C. Design for usability: Key principles and what designers think. *Commun ACM*. 1985;28:300-311
7. Norman DA. *The psychology of everyday things*. New York: Basic Books; 1988.
8. Lum P, Reinkensmeyer D, Mahoney R, Rymer WZ, Burgar C. Robotic devices for movement therapy after stroke: Current status and challenges to clinical acceptance. *Top Stroke Rehabil*. 2002;8:40-53
9. Prange GB, Jannink MJ, Groothuis-Oudshoorn CG, Hermens HJ, Ijzerman MJ. Systematic review of the effect of robot-aided therapy on recovery of the hemiparetic arm after stroke. *J Rehabil Res Dev*. 2006;43:171-184
10. Kwakkel G, Kollen BJ, Krebs HI. Effects of robot-assisted therapy on upper limb recovery after stroke: A systematic review. *Neurorehabil Neural Repair*. 2008;22:111-121
11. Mehrholz J, Platz T, Kugler J, Pohl M. Electromechanical and robot-assisted arm training for improving arm function and activities of daily living after stroke. *Stroke*. 2009
12. Cirstea MC, Levin MF. Improvement of arm movement patterns and endpoint control depends on type of feedback during practice in stroke survivors. *Neurorehabil Neural Repair*. 2007;21:398-411
13. Timmermans AAA, Spooren AIF, Kingma H, Seelen HAM. Influence of task-oriented training content on skilled arm-hand performance in stroke: A systematic review. *Neurorehabil Neural Repair*. 2010; In press.
14. Magill R. Augmented feedback. *Motor learning and control*. Boston: Mc Graw Hill; 2007:331-366.
15. Timmermans AA, Seelen HA, Willmann RD, Kingma H. Technology-assisted training of arm-hand skills in stroke: Concepts on reacquisition of motor control and therapist guidelines for rehabilitation technology design. *J Neuroeng Rehabil*. 2009;6:1
16. Spooren AI, Janssen-Potten YJ, Post MW, Kerckhofs E, Nene A, Seelen HA. Measuring change in arm hand skilled performance in persons with a cervical spinal cord injury: Responsiveness of the van lieshout test. *Spinal Cord*. 2006;44:772-779
17. Boian R, Sharma A, Han C, Merians A, Burdea C, Adamovich D, Recce M, Tremaine M, Poizner H. Virtual reality-based post-stroke hand rehabilitation. *Medicine Meets Virtual Reality 2002 Conference*. 2002:64-70
18. Johnson MJ, Loureiro RCV, Harwin WS. Collaborative tele-rehabilitation and robot-mediated therapy for stroke rehabilitation at home or clinic. *Intel Serv Robotics*. 2008;1:109-121
19. Krebs HI, Volpe BT, Williams D, Celestino J, Charles SK, Lynch D, Hogan N. Robot-aided neurorehabilitation: A robot for wrist rehabilitation. *IEEE Trans Neural Syst Rehabil Eng*. 2007;15:327-335

20. Kahn LE, Zygman ML, Rymer WZ, Reinkensmeyer DJ. Robot-assisted reaching exercise promotes arm movement recovery in chronic hemiparetic stroke: A randomized controlled pilot study. *J Neuroengineering Rehabil*. 2006;3:12
21. Lang CE, Macdonald JR, Reisman DS, Boyd L, Jacobson Kimberley T, Schindler-Ivens SM, Hornby TG, Ross SA, Scheets PL. Observation of amounts of movement practice provided during stroke rehabilitation. *Arch Phys Med Rehabil*. 2009;90:1692-1698
22. Lang CE, MacDonald JR, Gnip C. Counting repetitions: An observational study of outpatient therapy for people with hemiparesis post-stroke. *J Neurol Phys Ther*. 2007;31:3-10
23. Krebs HI. Robot-mediated movement therapy: A tool for training and evaluation. *European Symposium Technical Aids for Rehabilitation – TAR 2007*. 2007
24. Johnson MJ, Feng X, Johnson LM, Winters JM. Potential of a suite of robot/computer-assisted motivating systems for personalized, home-based, stroke rehabilitation. *J Neuroengineering Rehabil*. 2007;4:6
25. Demain S, Wiles R, Roberts L, McPherson K. Recovery plateau following stroke: Fact or fiction? *Disabil Rehabil*. 2006;28:815-821
26. Page SJ, Gater DR, Bach YRP. Reconsidering the motor recovery plateau in stroke rehabilitation. *Arch Phys Med Rehabil*. 2004;85:1377-1381
27. Lum PS, Uswatte G, Taub E, Hardin P, Mark VW. A telerehabilitation approach to delivery of constraint-induced movement therapy. *J Rehabil Res Dev*. 2006;43:391-400
28. Dipietro L, Krebs HI, Fasoli SE, Volpe BT, Stein J, Bever C, Hogan N. Changing motor synergies in chronic stroke. *J Neurophysiol*. 2007;98:757-768
29. Fasoli SE, Krebs HI, Stein J, Frontera WR, Hughes R, Hogan N. Robotic therapy for chronic motor impairments after stroke: Follow-up results. *Arch Phys Med Rehabil*. 2004;85:1106-1111
30. Housman SJ, Scott KM, Reinkensmeyer DJ. A randomized controlled trial of gravity-supported, computer-enhanced arm exercise for individuals with severe hemiparesis. *Neurorehabil Neural Repair*. 2009;23:505-514
31. Staubli P, Nef T, Klamroth-Marganska V, Riener R. Effects of intensive arm training with the rehabilitation robot armin ii in chronic stroke patients: Four single-cases. *J Neuroeng Rehabil*. 2009;6:46
32. Broeren J, Claesson L, Goude D, Rydmark M, Sunnerhagen KS. Virtual rehabilitation in an activity centre for community-dwelling persons with stroke. The possibilities of 3-dimensional computer games. *Cerebrovasc Dis*. 2008;26:289-296
33. Hughes AM, Freeman CT, Burridge JH, Chappell PH, Lewin PL, Rogers E. Feasibility of iterative learning control mediated by functional electrical stimulation for reaching after stroke. *Neurorehabil Neural Repair*. 2009;23:559-568
34. Timmermans AAA, Seelen HAM, Geers RPJ, Saini PK, Winter S, Te Vrugt J, Kingma H. Sensor-based skill training in chronic stroke patients: Results on treatment outcome, patient motivation and system usability. *IEEE Trans. Neural Syst. Rehabil. Eng*. 2010; 18 (3):284-292
35. Timmermans A, Seelen H, Kingma H. Task-oriented training: An essential element in technology-supported rehabilitation of skilled arm-hand performance after stroke. *IEEE-EMBS Benelux Chapter Symposium*. 2009:63-66
36. Salter K, Jutai JW, Teasell R, Foley NC, Bitensky J, Bayley M. Issues for selection of outcome measures in stroke rehabilitation: Icf activity. *Disabil Rehabil*. 2005;27:315-340
37. Hurn J, Kneebone I, Cropley M. Goal setting as an outcome measure: A systematic review. *Clin Rehabil*. 2006;20:756-772
38. Timmermans AA, Seelen HA, Willmann RD, Bakx W, de Ruyter B, Lanfermann G, Kingma H. Arm and hand skills: Training preferences after stroke. *Disabil Rehabil*. 2009;31:1344-1352
39. Feng X, Winters JM. A pilot study evaluating use of a computer-assisted neurorehabilitation platform for upper-extremity stroke assessment. *J Neuroeng Rehabil*. 2009;6:15
40. Bosecker C, Dipietro L, Volpe B, Krebs HI. Kinematic robot-based evaluation scales and clinical counterparts to measure upper limb motor performance in patients with chronic stroke. *Neurorehabil Neural Repair*. 2010;24:62-69
41. Krakauer JW. Motor learning: Its relevance to stroke recovery and neurorehabilitation. *Curr Opin Neurol*. 2006;19:84-90

42. Levin MF, Kleim JA, Wolf SL. What do motor "Recovery" And "Compensation" Mean in patients following stroke? *Neurorehabil Neural Repair*. 2009;23:313-319
43. Van Peppen RP, Kwakkel G, Wood-Dauphinee S, Hendriks HJ, Van der Wees PJ, Dekker J. The impact of physical therapy on functional outcomes after stroke: What's the evidence? *Clin Rehabil*. 2004;18:833-862
44. French B, Thomas LH, Leathley MJ, Sutton CJ, McAdam J, Forster A, Langhorne P, Price CI, Walker A, Watkins CL. Repetitive task training for improving functional ability after stroke. *Stroke*. 2009
45. Schmidt RA, Lee TD. *Motor control and learning. A behavioral emphasis*. Champaign, Ilinois: Human Kinetics; 2005.
46. Hummel JM, Snoek GJ, van Til JA, van Rossum W, Ijzerman MJ. A multicriteria decision analysis of augmentative treatment of upper limbs in persons with tetraplegia. *J Rehabil Res Dev*. 2005;42:635-644
47. Pascual-Leone A, Amedi A, Fregni F, Merabet LB. The plastic human brain cortex. *Annu Rev Neurosci*. 2005;28:377-401
48. Magill R. Practice variability and specificity. *In: Motor learning and control*. Boston: Mc Graw Hill; 2007:368-389.
49. Shea CH, Wright DL, Wulf G, Whitacre C. Physical and observational practice afford unique learning opportunities. *J Mot Behav*. 2000;32:27-36
50. Wulf G, Shea C, Lewthwaite R. Motor skill learning and performance: A review of influential factors. *Med Educ*. 2010;44:75-84
51. Jackson PL, Lafleur MF, Malouin F, Richards C, Doyon J. Potential role of mental practice using motor imagery in neurologic rehabilitation. *Arch Phys Med Rehabil*. 2001;82:1133-1141
52. Jackson PL, Lafleur MF, Malouin F, Richards CL, Doyon J. Functional cerebral reorganization following motor sequence learning through mental practice with motor imagery. *Neuroimage*. 2003;20:1171-1180
53. Kandel E, Kupfermann I, Iversen S. Learning and memory. In: Kandel ER SJ, Jessell TM, ed. *Principles of neural science*. New York: McGraw-Hill; 2000:1227-1246.
54. Kwakkel G, Wagenaar RC, Twisk JW, Lankhorst GJ, Koetsier JC. Intensity of leg and arm training after primary middle-cerebral-artery stroke: A randomised trial. *Lancet*. 1999;354:191-196
55. Kwakkel G, van Peppen R, Wagenaar RC, Wood Dauphinee S, Richards C, Ashburn A, Miller K, Lincoln N, Partridge C, Wellwood I, Langhorne P. Effects of augmented exercise therapy time after stroke: A meta-analysis. *Stroke*. 2004;35:2529-2539
56. Shea CH, Lai Q, Black C, Park J. Spacing practice sessions across across days benefits the learning of motor skills. *Human Movement Science*. 2000;19:737-760
57. Magill R. The amount and distribution of practice. *Motor learning and control. Concepts and applications*. Boston: Mc Graw Hill; 2007:390-404.
58. van Vliet PM, Wulf G. Extrinsic feedback for motor learning after stroke: What is the evidence? *Disabil Rehabil*. 2006;28:831-840
59. Kernodle MW, Carlton LG. Information feedback and the learning multiple-degree-of-freedom activities. *J Mot Behav*. 1992;24:187-196
60. Cirstea CM, Ptito A, Levin MF. Feedback and cognition in arm motor skill reacquisition after stroke. *Stroke*. 2006;37:1237-1242
61. Shumway-Cook A WM. *Motor control. Translating research into clinical practice*. Wolters Kluwer/ Lippincott Williams & Wilkins; 2007.
62. Shea CH, Kohl RM. Composition of practice: Influence on the retention of motor skills. *Res Q Exerc Sport*. 1991;62:187-195
63. Timmermans AAA, Geers RPJ, Franck JA, Dobbelsteijn P, Spooren AIF, Kingma H, Seelen HAM. T-toat: A method of task-oriented arm training for stroke patients suitable for implementation of exercises in rehabilitation technology. *IEEE 11th International Conference on Rehabilitation Robotics*. 2009:98-102
64. Lanfermann G, Willmann R, te Vrugt J, Timmermans A, Bongers E, Lambert N, van Acht V. Philips stroke rehabilitation exerciser. *Technical Aids for Rehabilitation - TAR 2007*. 2007
65. Willmann RD, Lanfermann G, Saini P, Timmermans A, te Vrugt J, Winter S. Home stroke rehabilitation for the upper limbs. *Conf Proc IEEE Eng Med Biol Soc*. 2007;2007:4015-4018

66. Wisneski KJ, Johnson MJ. Quantifying kinematics of purposeful movements to real, imagined, or absent functional objects: Implications for modelling trajectories for robot-assisted adl tasks. *J Neuroeng Rehabil*. 2007;4:7
67. Ruparel R, Johnson M. A task-oriented trajectory planner: Could it train stroke survivors to move normally on adls. *2nd Biennal IEEE/RAS-EMBS International Conference on Biomedical Robotics and Biomechatronics*. 2008
68. van Asseldonk EH, Wessels M, Stienen AH, van der Helm FC, van der Kooij H. Influence of haptic guidance in learning a novel visuomotor task. *J Physiol Paris*. 2009;103:276-285
69. van der Lee JH, Wagenaar RC, Lankhorst GJ, Vogelaar TW, Deville WL, Bouter LM. Forced use of the upper extremity in chronic stroke patients: Results from a single-blind randomized clinical trial. *Stroke*. 1999;30:2369-2375
70. van der Lee JH, Beckerman H, Lankhorst GJ, Bouter LM. Constraint-induced movement therapy. *Arch Phys Med Rehabil*. 1999;80:1606-1607
71. Taub E, Uswatte G, King DK, Morris D, Crago JE, Chatterjee A. A placebo-controlled trial of constraint-induced movement therapy for upper extremity after stroke. *Stroke*. 2006;37:1045-1049
72. Wolf SL, Winstein CJ, Miller JP, Taub E, Uswatte G, Morris D, Giuliani C, Light KE, Nichols-Larsen D. Effect of constraint-induced movement therapy on upper extremity function 3 to 9 months after stroke: The excite randomized clinical trial. *JAMA*. 2006;296:2095-2104
73. Wolf SL, Winstein CJ, Miller JP, Thompson PA, Taub E, Uswatte G, Morris D, Blanton S, Nichols-Larsen D, Clark PC. Retention of upper limb function in stroke survivors who have received constraint-induced movement therapy: The excite randomised trial. *Lancet Neurol*. 2008;7:33-40
74. Dobkin BH. Progressive staging of pilot studies to improve phase iii trials for motor interventions. *Neurorehabil Neural Repair*. 2009;23:197-206
75. Butter M, Rensma A, van Boxtel J, Kalisingh S, Schoone M, Leis M, Gelderblom G, Cremer G, de Wilt M, Kortekaas W, Thielmann A, Cuhls K, Sachinopoulou A, Korhonen I. Robotics for healthcare: Final report. Edited by european commission, dg information society. *5.0*. 2008:1-179
76. Riener R, Nef T, Colombo G. Robot-aided neurorehabilitation of the upper extremities. *Med Biol Eng Comput*. 2005;43:2-10
77. Reinkensmeyer DJ, Patton JL. Can robots help the learning of skilled actions? *Exerc Sport Sci-Rev*. 2009;37:43-51
78. Dobkin BH. Motor rehabilitation after stroke, traumatic brain, and spinal cord injury: Common denominators within recent clinical trials. *Curr Opin Neurol*. 2009
79. Gelderblom GJ. Onderzoek naar effecten en doelmatigheid [in dutch]. In: Kort H, Cordia A, de Witte L, eds. *Langdurige zorg en technology*. den Haag: Lemma; 2008:373-379.

Summary

Technology-supported training of arm-hand skills in stroke

Impaired arm-hand performance is a serious consequence of stroke that is associated with reduced self-efficacy and poor quality of life. Task-oriented arm training is a therapy approach that is known to improve skilled arm-hand performance, even in chronic stages after stroke. At the start of this project, little knowledge had been consolidated regarding task-oriented arm training characteristics, especially in the field of technology-supported rehabilitation. The feasibility and effects of technology-supported client-centred task-oriented training on skilled arm-hand performance had not been investigated but to a very limited degree.

Reviewing literature on rehabilitation and motor learning in stroke led to the identification of therapy oriented criteria for rehabilitation technology aiming to influence skilled arm-hand performance (chapter 2). Most rehabilitation systems reported in literature to date are robotic systems that are aimed at providing an engaging exercise environment and feedback on motor performance. Both, feedback and engaging exercises are important for motivating patients to perform a high number of exercise repetitions and prolonged training, which are important factors for motor learning. The review also found that current rehabilitation technology is focussed mainly on providing treatment at a function level, thereby improving joint range of motion, muscle strength and parameters such as movement speed and smoothness of movement during analytical movements. However, related research has found no effects of robot-supported training at the activity level. The review concluded that a challenge exists for upper extremity rehabilitation technology in stroke patients to also provide more patient-tailored task-oriented arm-hand training in natural environments to support the learning of skilled arm-hand performance.

Besides mapping the strengths of different technological solutions, the use of outcome measures and training protocols needs to become more standardized across similar interventions, in order to help determine which training solutions are most suitable for specific patient categories. Chapter 4 contributes towards such a standardization of outcome measurement. A concept is introduced which may guide the clinician/researcher to choose outcome measures for evaluating specific and generalized training effects. As an initial operationalization of this concept, 28 test batteries that have been used in 16 task-oriented training interventions were rated as to whether measurement components were measured by the test. Future research is suggested that elaborates the concept with information on the relative weighing of components in each test, with more test batteries (which may lead to additional components) and by adding more test properties into the concept (e.g. psychometric properties of the tests, possible floor- or ceiling effects).

Task-oriented training is one of the training approaches that has been shown to be beneficial for skilled arm-hand performance after stroke. Important mechanisms for motor learning that are identified are patient motivation for such training, and the learning of efficient goal-oriented movement strategies and task-specific problem solving. In this thesis we operationalize task-oriented training in terms of 15 compo-

nents (chapter 3). A systematic review that included 16 randomized controlled trials using task-oriented training in stroke patients, evaluated the effects of these training components on skilled arm-hand performance. The number of training components used in an intervention aimed at improving arm-hand performance after stroke was not associated with the post-treatment effect size. Distributed practice and feedback were associated with the largest post-intervention effect sizes. Random practice and use of clear functional training goals were associated with the largest follow-up effect sizes. It may be that training components that optimize the storage of learned motor performance in the long-term memory are associated with larger treatment effects. Unfortunately, feedback, random practice and distributed practice were reported in very few of the included randomized controlled trials (in only 6,3 and 1 out of the 17 studies respectively).

Client-centred training, i.e. training on exercises that support goals that are selected by the patients themselves, improves patient motivation for training. Motivation in turn has proven to positively influence motor learning in stroke patients, as attention during training is heightened and storage of information in the long-term memory improves. Chapter 5 reports on an interview of 40 stroke patients, investigating into training preferences. A list of 46 skills, ranked according to descending training preference scores, was provided that can be used for implementation of exercises in rehabilitation technology, in order for technology-supported training to be client-centred.

Chapter 6 introduces T-TOAT, a technology supported task-oriented arm training method that was developed together with colleagues at Adelante (Hoensbroek, NL). T-TOAT enables the implementation of exercises that support task-oriented training in rehabilitation technology. The training method is applicable for different technological systems, e.g. robot and sensor systems, or in combination with functional electrical stimulation, etc. To enable the use of T-TOAT for training with the Haptic Master Robot (MOOG-FCS, NL), special software named Haptic TOAT was developed in Adelante together with colleagues at the Centre of Technology in Care of Zuyd University (chapter 6). The software enables the recording of the patient's movement trajectories, given task constraints and patient possibilities, using the Haptic Master as a recording device. A purpose-made gimbal was attached to the end-effector, leaving the hand free for the use and manipulating objects. The recorded movement can be replayed in a passive mode or in an active mode (active, active-assisted or active-resisted). Haptic feedback is provided when the patient deviates from the recorded movement trajectory, as the patient receives the sensation of bouncing into a wall, as well as feeling a spring that pulls him/her back to the recorded path. The diameter of the tunnel around the recorded trajectory (distance to the wall), and the spring force can be adjusted for each patient. An ongoing clinical trial in which chronic stroke patients train with Haptic-TOAT examines whether Haptic Master provides additional value compared to supporting the same exercises by video-instruction only. Together with Philips Research Europe (Eindhoven, Aachen), the T-TOAT method has been implemented in a sensor based prototype, called Philips Stroke Rehabilitation Exerciser. This system included movement tracking sensors and an exercise board interacting with real life objects. A very strong feature of the system is that feedback is provided to patients (real-time and after exercise performance), based on a comparison of the patient's exercise performance to individual targets set by the therapist.

Chapter 7 reports on a clinical trial investigating arm-hand treatment outcome and patient motivation for technology-supported task-oriented training in chronic stroke patients. It was found that 8 weeks of T-TOAT training improved arm-hand performance in chronic stroke patients significantly on Fugl-Meyer, Action Research Arm Test, and Motor Activity Log. An improvement was found in health-related quality of life. Training effects lasted at least 6 months post-training. Participants reported feeling intrinsically motivated and competent to use the system. The results of this study showed that T-TOAT is feasible. Despite the small number of stroke patients tested (n=9), significant and clinically relevant improvements in skilled arm-hand performance were found.

In conclusion, this thesis has made several contributions. It motivated the need for client-centred task-oriented training, which it has operationalized in terms of 15 components. Four of these 15 components were identified as most beneficial for the patient. A prioritized inventory of arm-hand training preferences of stroke patients was compiled by means of an interview study of 40 subacute and chronic stroke patients. T-TOAT, a method for technology-supported, client-centred, task-oriented training, was conceived and implemented in two target technologies (Haptic Master and Philips Stroke Rehabilitation Exerciser). Its feasibility was demonstrated in a clinical trial showing substantial and durable benefits for the stroke patients. Finally, the thesis contributes towards the standardization of outcome measures which is necessary for charting progress and guiding future developments of technology-supported stroke rehabilitation. Methodological considerations were discussed and several suggestions for future research were presented.

The variety of treatment approaches and the various ways of support and challenge that are offered by existing rehabilitation technologies hold a large potential for offering a variety of extra training opportunities to stroke patients that may improve their arm-hand performance. Such solutions will be of increasing importance, to alleviate therapists and reduce economic pressure on the health care system, as the stroke incidence is increasing rapidly over the coming decades.

Samenvatting

Technologie-ondersteunde training van arm-handvaardigheden na een CVA

Arm- en handvaardigheidsproblematiek is een ernstig gevolg van CVA en is geassocieerd met verminderde zelfredzaamheid en lagere levenskwaliteit. Taakgerichte training is een therapiebenadering waarvan bekend is dat ze armhandvaardigheid verbetert, zelfs in de chronische fase na een CVA. Bij de start van dit project was weinig bekend over de karakteristieken van taakgericht trainen, vooral in het veld van technologie-ondersteunde revalidatie. De haalbaarheid en de effecten van cliëntgerichte technologie-ondersteunde training op armhandvaardigheid waren slechts beperkt onderzocht.
Een literatuuronderzoek met betrekking tot revalidatie en motorisch leren heeft geleid tot de identificatie van therapiegeoriënteerde criteria voor de ontwikkeling van revalidatietechnologie die arm-handvaardigheidstraining bij personen met een CVA ondersteunt (hoofdstuk 2). De meeste revalidatiesystemen die gerapporteerd werden in de literatuur zijn robot systemen die als doel hebben een aantrekkelijke oefenomgeving aan te bieden en feedback te geven op de oefenprestatie. Dit motiveert patiënten om een hoger aantal oefeningen uit te voeren en langer te trainen. Dit zijn belangrijke factoren voor motorisch leren. Het literatuuronderzoek heeft ook aangetoond dat de huidige revalidatietechnologie zich hoofdzakelijk richt op het aanbieden van behandeling op functieniveau, waarbij vooral geoefend wordt op het verbeteren van gewrichtsbeweeglijkheid, spierkracht en parameters zoals bewegingssnelheid en vloeiendheid van bewegen. Er wordt geconcludeerd dat een uitdaging bestaat om met behulp van armhand gerichte revalidatietechnologie meer patiëntgericht en taakgericht training aan te bieden in natuurlijke omgevingen ter ondersteuning van het leren van armhandvaardigheden.
Naast het in kaart brengen van de sterkte van verschillende technologische toepassingen, dient het gebruik van uitkomstmaten en trainingprotocols gestandaardiseerd te worden voor gelijkaardige interventies. Dit kan helpen bij het bepalen van welke trainingsystemen het meest geschikt zijn voor verschillende patiëntencategorieën. Hoofdstuk 4 draagt bij tot dergelijke standaardisatie van het gebruik van uitkomstmaten. Een concept wordt geïntroduceerd dat de onderzoeker/clinicus kan leiden in zijn keuze van testbatterijen voor de evaluatie van specifieke en generieke trainingseffecten. Bij achtentwintig testbatterijen, die gebruikt werden in zestien taakgerichte interventies, werd onderzocht welke componenten gemeten werden door de test. Suggesties voor het verder uitwerken van het concept worden voorgesteld. Er wordt ondermeer voorgesteld om aan te geven in welke mate een bepaalde component gemeten wordt in een test. Ook dienen meer testbatterijen toegevoegd te worden aan het concept, dat kan leiden tot additionele componenten. Ook kunnen meer eigenschappen worden toegevoegd aan het concept, zoals psychometrische eigenschappen.
Belangrijke mechanismen waardoor taakgerichte training kan bijdragen aan motorisch leren zijn het leren van efficiënte doelgerichte bewegingsstrategieën, het aanleren van een taakgericht probleemoplossend vermogen en de motivatie van de patiënt om deze

trainingsvorm te (blijven) gebruiken. In dit proefschrift hebben we taakgericht trainen gekarakteriseerd door middel van 15 componenten (hoofdstuk 3). In een systematische review werden 16 gerandomiseerde onderzoeken met daarin een controlegroep en waarbij minstens 1 groep taakgericht trainde, geïncludeerd. Onderzocht werd welke de effecten zijn van taakgerichte trainingscomponenten op de trainingseffecten met betrekking tot armhandvaardigheid. Een associatie tussen het aantal componenten dat gebruikt wordt in een taakgerichte trainingsinterventie en de behandeluitkomst werd niet gevonden. 'Feedback' en 'distributed practice' waren geassocieerd met de hoogste postinterventie behandeleffecten. Random practice en duidelijke functionele doelstellingen waren geassocieerd met de hoogste follow-up behandeleffecten. Het lijkt dat trainingcomponenten, die het opslaan van de tijdens training opgedane ervaring in het lange termijn geheugen bevorderen, geassocieerd zijn met de grootste behandeleffecten. De componenten 'feedback', 'distributed practice', 'random practice' werden spijtig genoeg slechts in respectievelijk 6, 1 en 3 van de 17 studies gebruikt.

Patiëntgecentreerde training, dit is training waarvan de oefeningen behandeldoelen ondersteunen die door de patiënt zelf gesteld worden, verbetert motivatie voor training. Motivatie heeft op haar beurt bewezen bij te dragen aan motorisch leren in patiënten met een CVA, omdat het via toename van aandacht zorgt voor een verbeterde opslag van informatie in het lange termijn geheugen. Hoofdstuk 5 rapporteert een interviewstudie van 40 patiënten met een CVA waarbij onderzocht is welke vaardigheden deze patiënten verkiezen om te trainen. Een lijst van 46 vaardigheden, geordend volgens dalende trainingsvoorkeur, is opgesteld. Deze informatie kan gebruikt worden voor de implementatie van oefeningen in revalidatietechnologie, zodat ook technologie-ondersteund trainen patiëntgericht kan zijn.

Hoofdstuk 6 introduceert T-TOAT (Technology-supported Task-Oriented Arm Training), een methode voor technologie-ondersteunde patiëntgerichte armhandvaardigheidstraining, die ontwikkeld is in samenwerking met collega's in Adelante (Hoensbroek, NL). Deze methode is toepasbaar voor verschillende technologische systemen, zoals robot- en sensorsystemen, of in combinatie met functionele elektrostimulatie, enzovoorts. Om T-TOAT training met een Haptic Master robot (MOOG-FCS, NL) toe te laten, werd speciale software, Haptic TOAT genaamd, ontwikkeld. De software laat toe om bewegingstrajecten van de patiënt te registreren, rekening houdend met de beperkingen van de taak en/of van de patiënt. Een voor deze training ontwikkelde arm orthese werd aan het grijper mechanisme vastgemaakt, waarbij de hand werd vrijgelaten voor het vastpakken van objecten. De opgenomen beweging kan opnieuw worden afgespeeld in een passieve of actieve (actief, actief ondersteund of actief tegen weerstand) modus. Haptische feedback wordt verschaft wanneer de patiënt afwijkt van het opgenomen bewegingspad. De patiënt voelt de sensatie om 'tegen een muur te botsen met de hand', of voelt een veer die hem/haar terug naar het vooraf geregistreerde bewegingspad trekt. De diameter van de tunnel rond het geregistreerde bewegingspad (afstand tot de 'muur') en de sterkte van de veer kunnen aangepast worden per patiënt en per oefening. In een klinische studie die momenteel uitgevoerd wordt, wordt de meerwaarde van Haptic Master bij het taakgericht trainen met de T-TOAT methode (ten opzichte van trainen van dezelfde oefeningen door middel van enkel een video-instructie) beoordeeld. In samenwerking met Philips Research Europe (Eindhoven, Aken), is de T-TOAT methode geïmplementeerd in een sensorgebaseerd trainingsprototype, Philips Stroke Rehabilitation Exerciser genaamd. Dit systeem bevat sensoren die beweging registreren en een oefenbord dat interageert met objecten uit het alledaagse leven. Een zeer waardevol kenmerk van dit systeem is dat feedback wordt teruggekoppeld aan de patiënt over zijn/haar bewegingsuitvoering, gebaseerd op een vergelijking van de bewegingsprestatie van de patiënt met de door de therapeut voor deze patiënt ingestelde doelstellingen.

Hoofdstuk 7 rapporteert een klinisch onderzoek dat de effecten van T-TOAT op armhandvaardigheid onderzocht, evenals de patiëntenmotivatie voor deze training. Uit het onderzoek kwam naar voren dat na 8 weken T-TOAT training de armhandvaardigheid van chronische CVA patiënten significant verbeterde (op Fugl Meyer Test, Action Research Arm Test en Motor Activity Log). Ook werd een verbetering gevonden ten aanzien van kwaliteit van leven. De trainingseffecten bleven aanwezig tot minstens 6 maanden na het stopzetten van de training. Deelnemers waren intrinsiek gemotiveerd voor deze training en voelden zich competent om het systeem te gebruiken. De resultaten van deze studie toonden aan dat T-TOAT haalbaar is. Ondanks het kleine patiëntenaantal in deze test werden significante en klinisch relevante verbeteringen in armhandvaardigheid gevonden.

Concluderend kan gesteld worden dat het onderzoek dat in dit proefschrift gerapporteerd wordt verschillende bijdrages heeft geleverd. Het nut van patiëntgerichte taakgerichte training wordt gemotiveerd. Taakgerichte training wordt gekarakteriseerd door 15 componenten. Vier van deze componenten zijn geïdentificeerd als karakteristieken van taakgericht trainen die een grotere bijdrage leveren aan het tot stand komen van grote behandeleffecten. Een lijst van trainingsvoorkeuren met betrekking tot 46 taken wordt weergegeven in dalende volgorde van patiëntenvoorkeur. Deze lijst is gebaseerd op resultaten van een interview van 40 CVA patiënten. T-TOAT, een methode voor patiëntgerichte technologie-ondersteunde taakgerichte training, is ontwikkeld en geïmplementeerd in twee technologische systemen: Haptic Master en Philips Stroke Rehabilitation Exerciser. De haalbaarheid van deze trainingsmethode is aangetoond in een klinisch onderzoek dat goede en duurzame effecten met betrekking tot armhandvaardigheid kon aantonen. Tenslotte heeft dit proefschrift bijgedragen tot een concept van standaardisatie van het keuzeproces voor selectie van uitkomstmaten. Een dergelijke standaardisatie is noodzakelijk bij het systematisch vergelijken van vooruitgang bij diverse therapievormen en trainingsvormen. Het concept kan toekomstige ontwikkelingen in het domein van technologie-ondersteunde revalidatie van de arm en hand na een CVA verder leiden. Enkele methodologische beschouwingen zijn besproken en suggesties voor toekomstig onderzoek zijn uitgewerkt.

De variëteit van behandelbenaderingen en de verscheidenheid in ondersteuning en uitdaging die geboden kan worden door bestaande revalidatietechnologieën hebben een grote potentie voor verbreding van het trainingsaanbod aan patiënten met een CVA, dat wederom armhandvaardigheid bij deze patiënten ten goede kan komen. Aangezien in de volgende decennia een snelle toename van de CVA incidentie en prevalentie verwacht wordt, zal het gebruik van revalidatietechnologie aan belang winnen om therapeuten te ondersteunen en de economische druk op de gezondheidszorg te verlichten.

Dankwoord

Ik wil heel graag een aantal mensen bedanken die een onmisbare bijdrage hebben geleverd aan het tot stand komen van dit werk.

Eerst en vooral heel erg veel dank aan jou Boris de Ruyter. Zonder jou zou er vandaag geen boekje zijn. Dank voor je vertrouwen, dat me de kans heeft gegeven om via Philips Research dit promotieonderzoek uit te voeren. Dank ook voor je vriendschap en je steun, je waardevolle inbreng in het begin van dit project en voor de vele nuttige adviezen deze jaren! Het is een eer dat je ook bij mijn promotie aan mijn zijde wil staan als paranimf.

Het was voor mij zeer leerrijk om te mogen samenwerken met een aantal Philips medewerkers. Ik dacht dat ik de ingenieurswereld wel wat kende (van jou Panos), maar het samenwerken met ingenieurs, wis- en natuurkundigen en psychologen (he Shalu!) voor beroepsdoeleinden was een uitdaging en sublieme leerervaring. Ook een beetje kunnen meepikken van de dynamiek die heerst in een bedrijf als Philips was opwindend en leerrijk. Ik wil dan ook de mensen van Philips Research in Eindhoven en Aken bedanken voor de samenwerking en de gekregen kansen.

Ook wil ik graag de medewerkers van de Technische Universiteit Eindhoven bedanken. Ook al was ik niet zo vaak bij jullie, alles werd altijd op de meest efficiënte manier voor me geregeld op alle niveaus. Hartelijk dank daarvoor! Bedankt Professor Hilbers, voor uw steun tijdens dit promotietraject.

Professor Herman Kingma. Bedankt voor je enthousiaste steun en goede raad tijdens deze jaren. Bedankt ook voor de pittige discussies die steeds vriendelijk, maar duidelijk peilden of ik wel wist waar ik mee bezig was. Toen het even moeilijk ging, zorgden jij en Henk er kordaat voor dat ik nooit hoefde te twijfelen en dat ik met voldoende wind in de zeilen verder kon. Dank je wel!

Dr. Henk Seelen, beste Henk. Ik vind het een zeer groot voorrecht om je leerling te zijn en ook om je te kennen als persoon. Zonder jou zou er vandaag ook geen boekje zijn. Ik heb enorm veel van je geleerd en erg genoten van al onze discussies. Je bent een onbaatzuchtige leermeester. Zelfs als jij allang wist hoe het allemaal in elkaar zat, liet je me ‘met de nodige ondersteuning en op eigen tempo’ zelf ontdekken, zodat ik continu kon genieten van creativiteit en zelfontplooiing. Weet dat ik me zeer bewust ben van de unieke kansen die ik heb gekregen door met jou te mogen werken. Je faciliteert op de aan jou eigen rustige manier het uitvoeren van moeilijke onderzoeksonderdelen (e.g. technologieontwikkeling), als het maar gaat om degelijk onderzoek dat patiënten en/of therapeuten ten goede komt! Ik hoop dat we in de toekomst nog met evenveel enthousiasme goed onderzoek kunnen doen samen. Bedankt voor je vertrouwen, je grote inspanningen om een optimale begeleiding te geven, je medeleven en zorg tijdens de moeilijke momenten. Bedankt voor de enorm mooie onderzoeksjaren!

Ik wil ook graag het personeel van Adelante in Hoensbroek enorm hard bedanken! Dank aan Jos Penders, de mensen van de planning en PSB, Ben Eisermann en Christian Rocks voor al de extra inspanningen die jullie leverden voor onze onderzoeken, en hartelijk dank aan revalidatieartsen Wip Bakx en Martine Moennekens voor het meedenken bij het opzetten van onderzoeken en het faciliteren ervan. Martine, ik zal nooit vergeten hoe je me een hart onder de riem kwam steken in Brazilië voor mijn allereerste congrespresentatie! Beste patiënten, fysio- en ergotherapeuten van Adelante (in het bijzonder Mieke Velders, Melanie Kleynen, Huub Olijve, Veerle Baeten, Rebecca Frederix en Christiane Stens), dank jullie wel voor de flexibiliteit en medewerking. Zonder jullie zouden de klinische onderzoeken absoluut onmogelijk zijn geweest. Speciale dank aan Han Franck en Paul Dobbelsteijn, ik heb zeer veel van jullie mogen leren. Ontzettend bedankt ook voor jullie gedrevenheid, al het extra werk, de waardevolle taakanalyses en enthousiaste medewerking aan de onderzoeken! Beste collega's van kenniscentrum, ik wil jullie ook allemaal bedanken voor jullie goed gezelschap deze jaren. Rob Smeets en Nicole de Rouw, hartelijk dank voor jullie steun en voor de gekregen kansen. Richard, dank je wel voor de fijne samenwerking, al je ondersteuning bij de technologieontwikkeling en experimenten, en ook voor je eindeloze geduld bij het opnemen van al die video's! Yvonne, dank je wel voor het kritisch nalezen van verschillende stukken! John, bedankt voor je hulp bij het opzoeken van literatuur en voor je steun! Jeanine, bedankt om mee te helpen aan de analyse voor de interviewstudie. Ryanne, bedankt voor het overnemen van testen in de laatste fase van het schrijven. En speciale dank ook aan mijn kamergenootjes Patrick, Ivan, Ananda, Rachma, Veronique en Annemie. We hebben veel zitten zuchten en hebben hard gewerkt, maar hebben toch ook goed gelachen! Patrick, dank je wel om steeds klaar te staan als er iets niet lukte. En liefste Annemie, voor jou een speciale dikke dank je wel! Het betekent veel voor me dat jij ook paranimf bent bij mijn promotie. Tijdens onze autoritten naar en van Hoensbroek konden we mooie en moeilijke momenten bespreken en analyseren. Bedankt voor het meevoelen en meedenken deze jaren. We hebben verschillende belangrijke mijlpalen samen genomen, waaronder een eerste wereldcongres (met een onvergetelijke ervaring in Iguazu!). En nu het inleveren van ons proefschrift! Ik vond het ook verrijkend om een stuk onderzoek samen met jou te kunnen doen en ik verheug me op meer onderzoek samen in de toekomst.

Lieve zus en schoonbroer, lieve vrienden en vriendinnen, bedankt voor jullie steun en leuke verhalen. Bedankt om te begrijpen ook, dat ik minder sociaal was het laatste jaar (of jaren…). Vooral bedankt omdat het, als we elkaar zien altijd weer even gezellig is! Liliane, Irene en Jaak, dank jullie voor de onmisbare hulp en steun deze jaren!

Allerliefste mama en papa, jullie wil ik ook graag heel bijzonder bedanken. Jullie zorgen elke week met de grootste zorg voor ons. Jullie deden dat jaar in jaar uit. Ook toen het heel erg moeilijk was na jullie accident. Bedankt voor jullie liefde en jullie begrip deze jaren. Jullie hebben me altijd alle kansen gegeven en zijn steeds een groot voorbeeld geweest. Papa, van jou heb ik ondermeer gezien en geleerd dat je alles kan leren wat je wilt, op welke leeftijd ook. En mama, jij hebt me zelf laten ervaren hoe het naast een voltijdse baan toch mogelijk is om aan je kinderen te laten voelen dat je er onvoorwaardelijk voor hen bent om hen met alle liefde en goede zorgen te laten opgroeien. Ik zou dit project nooit hebben durven beginnen indien je me dat vertrouwen niet had meegegeven. Mama en papa, jullie liefde en goede zorgen geven mij tot vandaag veel kracht, vrijheid en geluk.

Lieve Josephine en Emiel. Jullie hebben meermaals gevoeld, bij beide ouders, hoe meeslepend onderzoek doen is en hoe het vaak een groot deel van ons denken inneemt, ook in onze 'vrije tijd'. Jullie konden mij echter steeds tonen waar het echte zwaartepunt van mijn leven ligt. Bij jullie thuiskomen en samen met jullie en Panos genieten is altijd de geluksbasis geweest van waaruit ik ook hard heb kunnen werken.

Bedankt voor al het meevoelen met deze studie, het samen aftellen en voor de vele duwtjes in de rug. Ik zal nooit vergeten Josephine hoe jij me, terwijl ik zuchtend naar mijn discussie zat te staren, met een dikke knuffel zei: jij kan het wel mama, het komt wel in orde. Het gaf me zoveel moed. Ook bedankt voor je vele mooie gezellige pianomomenten terwijl ik zat te werken. Emiel, bedankt om zoveel leuke grappen, zoveel heerlijke kusjes, om altijd zo blij gezind te zijn en voor het heerlijke gezelschap als je op de grond naast me zat te spelen terwijl ik zat te werken. Jullie zijn echt fantastische kinderen.

Allerliefste Panos, jij bent echt mijn zielemaatje. Dank je wel dat je het me ten volle gunde om deze studie te doen, ook al wist je goed op voorhand dat ik er minder zou zijn voor jou en dat de combinatie van mijn studie met jouw werk niet altijd gemakkelijk zou zijn. Het was soms koorddansen om werk en gezinsleven in evenwicht te houden, maar het is ons toch gelukt. Dank je wel voor al je steun tijdens dit project, en voor je medeleven met de mooie en met de moeilijke momenten. Bedankt om steeds in mij te geloven. Ik heb me voor jou nooit hoeven te bewijzen en dat heeft me ook in dit traject veel vertrouwen en kracht gegeven. Ik ben ontzettend dankbaar en gelukkig om met jou te leven.

Ithaka

Konstantinos Kavafis (1863-1933)
Translated by E. Keely and P. Sherrard

As you set out for Ithaka
hope your road is a long one,
full of adventure, full of discovery.
Laistrygonians, Cyclops,
angry Poseidon-don't be afraid of them:
you'll never find things like that on your way
as long as you keep your thoughts raised high,
as long as rare excitement
stirs your spirit and your body.
Laistrygonians, Cyclops,
wild Poseidon-you won't encounter them
unless you bring them along inside your soul,
unless your soul sets them up in front of you.

Hope your road is a long one.
May there be many summer mornings when,
with what pleasure, what joy,
you enter harbors you're seeing for the first time;
may you stop at Phoenician trading stations
to buy fine things,
mother of pearl and coral, amber and ebony,
sensual perfume of every kind-
as many sensual perfumes as you can;
and may you visit many Egyptian cities
to learn and go on learning from their scholars.

Keep Ithaka always in your mind.
Arriving there is what you're destined for.
But don't hurry the journey at all.
Better if it lasts for years,
So you're old by the time you reach the island,
wealthy with all you've gained on the way,
not expecting Ithaka to make you rich.

Ithaka gave you the marvellous journey.
Without her you wouldn't have set out.'
She has nothing left to give you now.

And if you find her poor, Ithaka won't have fooled you.
Wise as you will have become, so full of experience,
you'll have understood by then what these Ithakas mean.

Curriculum Vitae

Annick Timmermans was born in 1966 in Hasselt (Belgium). She graduated in Latin-Mathematics/Sciences at Virga Jesse College (Hasselt, Belgium) in 1984. After obtaining a bachelor degree in Physiotherapy (cum laude) from the Institute of Physical Education and Physioterapy 'Parnas' (Dilbeek, Belgium) in 1987, she started a special program at the Katholieke Universiteit Leuven (Belgium) to obtain a Master degree in Physiotherapy and Rehabilitation Sciences where she graduated cum laude in 1989. She also obtained a degree for teaching sciences in higher education from Katholieke Universiteit Leuven in 1990 (cum laude).

From 1989 until 1994, the author was a full time lecturer, first at the Parnas Institute in Dilbeek and afterwards at PHL University College, Department of Health Sciences (Hasselt, Belgium).

In September 1994, she went to study at University College London (Dept Physiology, UK), to graduate in 1995 for an additional Master in Musculoskeletal Physiotherapy. From 1995 until 1998, she was a senior physiotherapist at Greenwich District Hospital in London (UK) (outpatient department).

In 1999, she returned to PHL University College (Department of Health Sciences), where she was involved in reshaping the curriculum from a Bachelor to a Master level and was lecturing theoretical as well as practical courses on musculoskeletal physiotherapy and human movement kinematics.

In September 2006, she was appointed at Eindhoven University of Technology for a four year PhD trajectory, funded by Philips Research Europe (User Experiences, Biomedical Sensor Systems)(Eindhoven, The Netherlands). Most of the work was carried out at Adelante Rehabilitation Centre in Hoensbroek (The Netherlands).

The author is involved in several research projects that are related to technology-supported task-oriented training and outcome measurement in real life settings in neurological patients.

Annick is married to Panos Markopoulos and mother of 2 children: Josephine (11) and Emiel (9).

List of publications

Journal publications

Timmermans AA, Seelen HA, Willmann RD, Kingma H. Technology-assisted training of arm-hand skills in stroke: Concepts on reacquisition of motor control and therapist guidelines for rehabilitation technology design. *J Neuroeng Rehabil*. 2009;6:1

Timmermans AA, Seelen HA, Willmann RD, Bakx W, de Ruyter B, Lanfermann G, Kingma H. Arm and hand skills: Training preferences after stroke. *Disabil Rehabil*. 2009;31:1344-1352

Timmermans A, Seelen H, Geers R, Saini PR, Winter S, Te Vrugt J, Kingma H. Sensor-based arm skill training in chronic stroke patients: Results on treatment outcome, patient motivation and system usability. *IEEE Trans Neural Syst Rehabil Eng*. 2010, 18:3: 284-292

Timmermans AAA, Spooren AIF, Kingma H, Seelen HAM. Influence of task-oriented training content on skilled arm-hand performance in stroke: A systematic review. *Neurorehabil Neural Repair*. 2010. In press

Book chapters

Timmermans AAA, Spaepen AJ, van den Bergh O. Belang van onderzoek naar en behandeling van stress bij werkgerelateerde overbelastingsproblematiek van het spierskeletsysteem. In: Danneels L, Isselee H, Staes F, Vaes P, Weymans m, eds. *Jaarboek voor kinesitherapeuten 2005-2006*. Antwerpen: Standaard Uitgeverij; 2005:37-45

Peer reviewed conference publications

Willmann RD, Lanfermann G, Saini P, Timmermans A, te Vrugt J, Winter S. Home stroke rehabilitation for the upper limbs. *Conf Proc IEEE Eng Med Biol Soc*. 2007;Lyon, France 23-26 August 2007:4015-4018

Lanfermann G, Willmann R, te Vrugt J, Timmermans A, Bongers E, Lambert N, van Acht V. Philips stroke rehabilitation exerciser. *Technical Aids for Rehabilitation - TAR 2007*. Berlin, Jan 25-26, 2007

Timmermans AAA, Seelen HAM, Willmann RD, Franck JA, Dobbelsteijn P, Saini PK, Kingma H. Technology-supported task-oriented arm training in chronic stroke patients. *5th World Congress for Neurorehabilitation*. Brasilia, Brazil, 24-27 September 2008; *Neurorehabil Neural Repair* 22:582-583

Timmermans A, Seelen H, Willmann RD, Bakx W, De Ruyter B, Lanfermann G, Kingma H. Technology-supported task oriented arm training in stroke: Which skills do stroke patients prefer to train on? *5th World Congress of Neurorehabilitation.* Brasilia, Brazil, 24-27 September 2008; *Neurorehabil Neural Repair* 2008;22:541-542

Timmermans AAA, Geers RPJ, Franck JA, Dobbelsteijn P, Spooren AIF, Kingma H, Seelen HAM. T-toat: A method of task-oriented arm training for stroke patients suitable for implementation of exercises in rehabilitation technology. *IEEE 11th International Conference on Rehabilitation Robotics*. Kyoto, Japan. 23-26 June 2009:98-102

Timmermans A, Seelen H, Kingma H. Task-oriented training: An essential element in technology-supported rehabilitation of skilled arm-hand performance after stroke. *IEEE-EMBS Benelux Chapter Symposium*. Twente, The Netherlands, 9-10 November 2009:63-66

Timmermans AAA, Spooren AIF, Kingma H, Seelen HAM. A concept to guide the choice of measurement instruments for evaluation of technology-supported task-oriented training interventions. *6th World Congress on Neurorehabilitation*. Vienna, Austria, 21-25 March 2010:122

Patents related to this thesis

Saini P., Timmermans A.., Willmann R., te Vrugt J., Winter S. Patient Monitoring System. WO/2010/015968

Willmann R., Lanfermann G., Timmermans A., Winter S., te Vrugt J. System and Method for training motion tasks of a person. WO/2009/136319

te Vrugt J., Willmann R., Lanfermann G., Winter S.., Saini P., Timmermans A. Method and system for selecting the viewing configuration of a rendered figure. WO/2009/053901

Wilmann R., Lanfermann G., te Vrugt J., Winter S., Saini P., Timmermans A. Apparatus, Method and computer program of time alignment. WO/2009/083831