Influence of augmented feedback

on learning upper extremity tasks after stroke

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Contents

1

General Introduction

Parts of this chapter have been published as book chapter
Upper extremity rehabilitation systems and augmented feedback
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1.1 Motor learning

In literature motor skill learning is defined as: *'a set of processes associated with practice or experience leading to relatively permanent changes in the capability of movement'*. [1] Motor skill learning generally progresses from conscious knowledge in the early stages of learning to a more automatic control when well learned. In literature motor learning is subdivided in three phases; the cognitive, associative and autonomous phase. [2]

In the cognitive phase different strategies are tested to perform the movement. The cognitive load is very high in this phase of learning. Therefore availability of instructions and feedback are essential in to determine the best movement strategy. The performance gains are often large, whereas performance level is rather inconsistent and movement speed is generally low.

The associative phase of learning starts when the most effective way of performing is determined. Fine tuning of the motor skill occurs. Performance gains are moderate, performance level is more consistent, and movement speed is higher than in the cognitive phase.

The autonomous phase is reached after intensive practice. The practiced motor skill has become more or less automatic. The task can be performed without conscious thinking, and with less or no interference from simultaneous activities. There are only subtle performance gains, performance is consistent, and movement speed is high. [1,2]

Although these phases of learning seem to be distinct phases, they mostly run (partly) parallel and merge into one another. The speed of learning, and the time needed in the particular stages of learning differ per person. The speed of learning depends strongly on the complexity of the task, the neuromuscular control of the person, and the availability of information about the performance of the task. [1]

1.2 Stroke

Around sixty percent of the stroke survivors experience disturbed motor control six month after stroke due to sensorimotor problems resulting in difficulties in daily living. [8] Muscle weakness of the upper extremity is a common impairment directly after stroke in 77 percent of the stroke survivors. [3, 4] This is followed by hyperactive reflexes and increased muscle tone, eventually often resulting in abnormal muscle synergies. This is expressed in the limitation to selectively activate muscles, resulting in coupled activation of muscles such as shoulder abduction and elbow flexion, which is called a flexion synergy and shoulder adduction and elbow extension, which is called an extension synergy. [6, 7] These problems limit the manipulation of the surrounding environment and thus the functional use of the hemiparetic arm.

1.3 Augmented feedback

The functional recovery of the arm can be stimulated by higher frequency or longer duration of exercises in rehabilitation therapy. [9-11] Also the active participation and active performance of movements in exercise therapy are associated with improved motor performance of the affected arm. [12, 13] There are indications that addition of augmented feedback to exercises can stimulate the learning process in rehabilitation therapy by making patients more aware of their performance. [14, 15]

Research is mainly performed about the influence of augmented feedback in healthy young subject. Van Dijk et al. [16, 17] studied the effect of augmented feedback in healthy elderly, and observed that young and elderly subjects learned in similar ways with augmented feedback. Whether stroke survivors make use of augmented feedback in a comparable way as healthy subjects to learn a motor task is hardly studied. [18] Augmented feedback can be provided about the movement performance or results of the movement (nature of feedback), during the movement execution or when the movement is completed (timing of the feedback). [1] Another element of augmented feedback reflects the source of the feedback, which originates from an external source (auditory, sensory, or visually) providing extra information to the internal sensors of the body (ears, skin, and eyes), also called the type of feedback. [15]

1.4 Objective

In this thesis the influence of nature, timing, and type of augmented feedback on motor skill relearning of arm movements in stroke rehabilitation therapy is studied.

1.5 Thesis outline

In chapter 2 a systematic review of the scientific literature is described. This review provides an overview of research incorporating training environments using augmented feedback for stroke survivors. Insight is provided about current knowledge of use and effect of augmented feedback.

In chapter 3 a training experiment is described, in which stroke survivors performed repetitive reaching movements by using position feedback. The focus in this chapter is on the amount of use of the available position feedback and the overall effect on arm motor function after six weeks of training.

For chapter 4, an experiment is performed in which we tested the influence of three augmented visual feedback conditions on motor learning: concurrent knowledge performance, terminal knowledge of performance, and terminal knowledge of results. Learning and consolidation of a visual distortion reaching task with different augmented visual feedback conditions in both healthy elderly and stroke survivors is studied.

In chapter 5 an explorative experiment to the possible existence of differences in amount of learning in different areas of the reaching workspace in healthy young subjects is conducted. Since in stroke rehabilitation therapy reaching movements are practiced in different areas of the workspace, possible differences in amount of learning in this workspace are of essence for rehabilitation therapy.

From chapter 5 we observed a difference in amount of learning into reaching movements across the midline of the body. Therefore in chapter 6 we performed an visual distortion experiment in which healthy elderly and stroke survivors performed repetitive movements into different directions of the workspace. We tested whether reaching directions influence start level, end level, and amount of learning.

This thesis is completed in chapter 7 with discussing the results from preceding chapters. The observed results on nature, timing, and type of the augmented feedback are discussed in the light of current knowledge and the influence of attentional demands on the patient. Remarkable findings concerning low-capacity learners are addressed.

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2

Nature, timing, frequency, and type of augmented feedback; does it influence motor relearning of the hemiparetic arm after stroke? A systematic review.

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Abstract

To investigate the effect of different aspects and types of augmented feedback on motor functions and motor activities of the hemiparetic arm after stroke.

Systematic search of the scientific literature was performed in the Pubmed and Cochrane database from 1975 to March 2009. The augmented feedback used in the intervention was classified with respect to aspects (nature, timing, frequency) and types (auditory, sensory, visual).

The systematic literature search resulted in 299 citations. Based on in- and exclusion criteria 23 full-text articles were included for analysis. There are some trends in favour of providing augmented knowledge of performance feedback, augmented auditory and combined sensory and visual feedback. No consistent effects on motor relearning were observed for summary or faded, terminal or concurrent, solely visual or solely sensory augmented feedback.

Based on current literature it was not possible to determine which combinations of aspects and types of augmented feedback are most essential for a beneficial effect on motor activities and motor functions of the hemiparetic arm after stroke. This was due to the combination of multiple aspects and types of augmented feedback in the included studies. This systematic review indicates that augmented feedback in general has an added value for stroke rehabilitation.

2.1 Introduction

2.1.1 Background

Stroke is one of the main causes of disability in the USA and Europe. In the USA, the prevalence of stroke was 5.5 million (2.6 percent of the total population) in 2003 [1], and in Europe 1.13 million in 2003. In the same year 700,000 people experienced a new stroke in the USA [1], in Europe the estimated amount of people experiencing a new stroke every year varies between 460 thousand and 1.1 million people. Six months after stroke, 30 - 66 percent of the patients have no proper arm-hand function [2], which limits their activities of daily life. To improve their independence optimal restoration of arm and hand function is crucial.

Rehabilitation therapy contributes to motor relearning and as a consequence improvement of lost functions. Literature indicates that motor relearning is influenced by several key elements; intensity [3], task-specificity [4,5] active-initiation [6-8], motivation and feedback [9]. In past decades different innovative technologies have emerged that enlarge the possibilities to integrate these key elements in rehabilitation therapy, such as robotics and virtual reality (VR).

2.1.2 Robotics

The overall effectiveness of robot-aided therapy on the upper extremity in stroke survivors is promising. In two reviews, by Prange et al. [10] and Kwakkel et al. [11], it is concluded that robot-aided therapy of the upper extremity improves both short and long-term motor functions of the paretic shoulder and elbow for stroke survivors. [10,11] However, no consistent influence on motor activities was observed. [10] Therapeutic robots can implement different modalities (passive, active-assisted, and active-resisted) in rehabilitation therapy. Prange et al. [10] stated that most therapies implement different modalities in one robotic treatment protocol. Therefore it is unclear what the contribution of the different modalities is with respect to motor relearning. [12]

Robots are generally equipped with many sensors measuring joint angles, grip strength, or forces generated by the patient. These sensors can be used in rehabilitation training to provide objective augmented feedback to stroke survivors about their performance. The usage of different sensors enhances the possibilities of providing various modalities of augmented feedback. However, it is unclear what the essential features of augmented feedback are.

2.1.3 Feedback

As in robotic training the same trend in research can be observed in VR training. The effect on motor relearning by means of VR training is studied in three reviews, by Holden [9], Henderson [13], and Crosbie [14]. All reviews carefully concluded that VR seems to have a beneficial effect on motor relearning [9]. However, it is unclear which modality of VR works best or which stroke survivors (subacute or chronic) will benefit most from VR training. [9]

In order to clarify the role of different augmented feedback principles, it is important to have a clear categorization. Augmented feedback is given in addition to intrinsic feedback. Intrinsic feedback is the sensory-perceptual information from internal sensory processes that is available as a result of the execution of a movement, such as vision, proprioception, and audition [15]. In stroke survivors the intrinsic feedback is often disturbed.

By providing extrinsic (or augmented) feedback from an outside source in therapy, the functionality might be increased [15,16]. Regarding augmented feedback roughly two main categories exist, aspects and types. An aspect of augmented feedback is defined as the more fundamental way of providing feedback (nature, timing, frequency). The type of augmented feedback reflects the source of feedback, which originates from an external source (auditory, sensory, and visual) providing extra information to the internal sensors of the body (ears, skin, and eyes).

2.1.4 Objective

Multiple aspects and types of augmented feedback are combined in past and recent research. However, it is unclear how augmented feedback results in a beneficial or detrimental effect on motor functions and motor activities of the upper extremity in stroke survivors. The objective of this systematic review is to investigate the effect of different aspects and types of augmented feedback on motor functions and motor activities of the hemiparetic arm after stroke.

2.2 Method

2.2.1 Literature search

An extensive systematic search of the scientific literature was performed in the Pubmed and Cochrane database from 1975 till March 2009. The goal was to identify published experimental and observational studies (including randomized controlled trials (RCTs), controlled trials (CTs), single case studies, case series, and pre-post study designs) that focused on the use of augmented feedback in rehabilitation therapy of the hemiparetic arm in stroke survivors.

The following keywords were used in this search: upper extremity, upper extremities, upper limb, upper limbs, arm, arms, hand, hands, shoulder, wrist, finger, elbow, fingers, myography, virtual, visual, sensory, sensor*, augmented, augment*, force, biofeedback, quantitative, qualitative, tactile, audition, auditory, audit*, performance, knowledge, KR, KP, knowledge of results, haptic, haptic*, olfactory, vibration, proprioception, vibratory, proprioceptive, enhanced, cerebrovascular disorders, cerebrovascular trauma, stroke, CVA, cerebrovascular accident, hemiplegia, hemipleg*, hemiparesis, hemipare*, paralysis, feedback, environment, motor learning.
The search strategy that was used for PubMed is presented in the appendix 1.

2.2.2 Study selection

Three reviewers (BM, EA, MJ) independently screened the titles and abstracts. Articles that met the following criteria were included in the review:

- therapeutic intervention using augmented feedback,
- involve stroke survivors,
- full-length journal publication.

Studies with usage of augmented feedback for purposes other than therapeutic (e.g. design studies or validation studies) were excluded. Studies providing electromyography feedback were excluded, because of the extended research done on this type of feedback and a recent Cochrane review by Woodford (2008). [17]

Table 2.1: Classification in levels of evidence based on the type of the study design (as described in Jovell and Navarro [18]).

Level	Strength of evidence	Type of study design
I	Good	Meta-analysis of randomized controlled trials (RCTs)
II	-	Large-sample RCTs
III	Good to fair	Small-sample RCTs
IV	-	Non-randomized controlled prospective trials
V	-	Non-randomized controlled retrospective trials
VI	Fair	Cohort studies
VII	-	Case-control studies
VIII	Poor	Non-controlled clinical series; descriptive studies
IX	-	Anecdotes or case reports

To enable the most complete view of current literature, no limitations in the search by language were made. The publications that appeared to meet the inclusion criteria were retrieved, and full-length articles were reviewed in more detail. Reference tracking was performed manually on all included articles.

2.2.3 Classification of study design

Studies with a variety of designs rather than only randomized controlled trials (RCTs) were selected. The rationale for this is the relatively young research area resulting in a limited amount of clinical studies about the use of augmented feedback for the training of the affected upper extremity in stroke survivors.

In rating the strength of the evidence from each selected article, the 9-level classification of Jovell and Navarro-Rubio was used [18] (table 2.1).

2.2.4 Data extraction

The three reviewers (BM, EA, MJ) independently extracted data (patient characteristics, aspects and types of augmented feedback, effect on motor functions and motor activities, and rating of the strength of the evidence) using a structured form. The reviewers met regularly to discuss their findings and decisions, and to find a consensus through debate on instances of disagreement.

Concerning the therapeutic intervention, different aspects and types of feedback were categorized. The aspects of feedback are:

- nature; which concerns information about the movement itself, knowledge of performance (KP), or about the outcome of the movement, knowledge of results (KR), [15, 16]

- timing; which can be either concurrent or terminal. Concurrent feedback is delivered during the movement, while terminal feedback is postponed until after the movement has been completed, [15]

- frequency; which can be either summary or faded. An example of summary feedback is after every 10th trial, whereas faded feedback follows a certain schedule, first after the 5th trial, then after the 15th, and so on.

The types of augmented feedback can be categorized as:

- auditory feedback, which can include verbal encouragements and sound beeps,
- sensory feedback, including force, tactile and position feedback,
- visual feedback, which can include vision of own body, virtual reality, or a score on a screen.

The effect of the intervention on the outcome measures (motor functions and motor activities) was summarized, according to the results presented in the original publications. If all outcome measures described a beneficial effect, a '+' effect was assigned. If the used outcome measures reported a varied effect, e.g. some outcome measures beneficial and some outcome measures no effect, an inconclusive effect '~' was assigned. When adverse effects were reported a negative effect '-' was assigned. A none effect '0' was assigned if no beneficial or detrimental effect was measured.

Motor functions are in the context of this paper defined as an objective measure that describes the performance of executing a specific motor function via kinematics and/or kinetics, such as grip strength and joint angles. Motor activities are in the context of this paper defined as a measure of quality of motor activities, scored by means of questionnaires/lists of scoring forms, such as Fugl-Meyer, Action Research Arm Test and Motricity Index.

2.3 Results

2.3.1 Study selection

From the systematic literature search 299 citations were found. After title, abstract and full-text screening, 23 studies were enrolled that focused on the use of augmented feedback to improve the arm and/or hand function after stroke. These were included for data subtraction (see also table 2.2). Articles which were conference papers or design studies were excluded.

Four publications [19-22] included several consecutive clinical trials and often used the same subjects. Of these four studies only the most recent article [22] was included in the analysis. Subtracted data, including subject characteristics, feedback aspects and types used, motor functions and motor activities measures and effect, and rating of the strength of the evidence, are presented in table 2.3. The different studies were categorized to the main aspects or types of augmented feedback used in their intervention.

Table 2.2: Overview of the amount of included studies, based on the first search result, title, abstract and full-text screening.

Search result:	299 citations
Based on title:	105 studies
Based on abstract:	47 studies
Based on full-text:	23 studies

Table 2.3: Overview of procedure, augmented feedback, study design and research population used in the included studies. + beneficial effect, 0 no effect, ˜ inconclusive effect. KP= Knowledge of Performance, KR= Knowledge of Results, CONC= concurrent, TERM=terminal, SUM= summary, FAD= faded, AUD= auditory, SENS= sensory, VIS= visual, n= amount, E= experimental group, C= control group.

Reference	**Procedure**	**Feedback**	**Study design**	**Research population**
		KP versus KR feedback		
Cirstea 2006 [24]	Movement reaching repetitions (n=75), 1h per day for 10 sessions (in 2 weeks). Movements as quickly and precise as possible. KP info about joint motion.KR about precision.	E1: AUD, KR, TER, SUM (no vision) E2: AUD, KP, CON, FAD (no vision)	Level III double blind RCT n=2x14	Chronic stroke Age E1:55.7±15.4yrs E2:59.1±7.9yrs Time post stroke E1:12.1 ± 4.9mns E2:11.4±6.3mns
Cirstea 2007 [27]	Repetition (n=75) of pointing movements to a target on contra lateral workspace. 10 sessions of 1h for 2 weeks.	E1: VIS, KR, TERM, SUM, (no vision) E2: AUD, KP, CON, FAD (no vision)	Level III RCT n=2x14	Chronic stroke Age E1:55.7±15.4yrs E2:59.1±17.9yrs Time post stroke E1:12.1±4.9mns E2:11.4± 6.3mns
		Summary versus faded feedback		
Winstein 1999 [31]	Discrete coordination movements (sinus path), elbow extension-flexion in horizontal plane. Total 198 trials in 2 days.	E1: VIS, KP & KR TER, SUM E2: VIS, KP & KR TER, FAD	Level IV matched-pair design E1:n=20 E2:n=20	Chronic stroke Age 57.1±11.1yrs Time post stroke (7-255)mns
		Visual feedback		
Bourbonnais 2002 [34]	Force production exercises: combinations of moments of force production in 1 or 2 joints. 6-8 repetitions per movements. For 6 weeks 3x pw.	VIS, KP, CONC	Level VI pre-post test n=13	Chronic stroke Age 47.2±13.9yrs Time post stroke 37.3±14.3mns

Colombo 2008 [40]	Point-to-point reaching movements in horizontal plane, circles as goals on display. Twice a day, 5 days a week for 3 weeks.	E1&E2: VIS, KP, CONC & VIS, KR, CONC	Level VI pre-post test E1:n=9 E2:n=13	E1 : Subacute stroke E2:Chronic stroke Age E1:57.4±14.4yrs E2:54.5±12.5yrs Time post stroke E1:2.1±1.3mns E2:20.9±12.6mns
Carey 2007 [26]	Tracking waveforms with (index) finger, 180 tracking trials per day for 10 days.	E:VIS, KP, CONC & VIS, KP, TERM, FAD & VIS, KR, TERM, SUM C: no feedback.	Level III RCT n=2x10	Chronic stroke Age E:65.9±7.4yrs C:67.4±11.8yrs Time post stroke E:42.5±24.3mns C:35.6±26.1mns
Auditory and visual feedback				
Eckhouse 1990[30]	Reaching movements toward targets, 20 trials x3 tasks per sessions. For 4 weeks 3x per week	E: AUD & VIS, KR, TER, SUM C: no feedback	Level IV matched-pair design E:n=6 C:n=6	Chronic stroke Age 45-70yrs Time post stroke 6-24mns
Maulucci 2001 [32]	Reaching movements towards a goal over reference trajectories, total 42 trials per session, for 6 weeks 3x per week.	E1:VIS, KR, TERM, SUM & AUD, KP, CONC E2:VIS, KR, TERM, SUM	Level IV no randomization E1:n=8 E2:n=8	Chronic stroke Age between 50-70yrs
Piron 2004 [42]	Performance of simple movements in VR, e.g. pouring water. 1h daily VR tele-therapy for 4 weeks 5x per week.	VIS, KP, CONC & AUD, KP & KR TERM & CONC (from therapist)	Level VIII experimental observational study n=5	Chronic stroke Age 53±15.4yrs Time post stroke 12.8±1.9mns
Ellis 2005 [35]	Three sets of each 3 multi-DOF isometric tasks were performed. 12 repetitions per set. Joint torque combinations away form abnormal pattern. For 8 weeks, 3x per week for 1.5 hours.	VIS, KP, CONC & AUD, KP, CONC (by therapist)	Level VI pre-post test n=8	Chronic stroke Age 41-80yrs Time post stroke 14-66mns

Sanchez 2006 [36]	7 VR games (horizontal or vertical plane movements) arm and hand movements, for 45 minutes, 3x per week for 8 weeks.	VIS, KR, TERM, SUM; VIS & AUD, KP, CONC	Level VI pre-post test n=5	Chronic stroke Age 60.2±15.2yrs Time post stroke 6.6±3.4yrs
Merians 2006 [22]	Four hand VR exercises for flexion, extension, velocity, fractionation and force, for 2-2.5 hours per day for 13 days.	AUD & VIS, KR, TER, SUM & KP, CONC	Level VI pre-post test n=8	Chronic stroke Age 64±11yrs Time post stroke 1-4yrs
Fischer 2007 [25]	30 Functional grasp-release tasks per session. For 6 weeks, 3x per week for 1 hours.	E1 & E2: AUD, KR, CONC & VIS, KP, CONC C: AUD, KR, CONC	Level III RCT n=3x5	Chronic stroke Age: E1:53±12.2yrs E2:71.6±13.9yrs C: 55.6±9.9yrs Time post stroke E1:6.4±4.4yrs E2:4.5±2.9yrs C:9.2±10.8yrs
Holden 2007 [38]	Reaching, hand to body, repeated reciprocal movements and control of hand. Telerehabilitation training for 2 blocks of 3 weeks, 1 hour sessions 5x per week	VIS & AUD, KP & KR, CONC & TERM	Level VI pre-post test n=11	Chronic stroke Age 56.7±15.6yrs Time post stroke 3.8±3.1yrs
Housman 2009 [29]	E: VR games, repetitive task-specific practice: grocery shopping, cleaning stovetop, playing basketball. Gravity reduced. 24 sessions of 1 hour during 8 weeks. C: similar movements without T-WREX and games.	E: AUD & VIS, KP, CONC & VIS, KR, TERM C: no feedback	Level III RCT n=2x14	Chronic stroke Age E:54.2±11.9yrs C:56.4±12.8yrs Time post stroke E:84.5±96.3mns C:112.4±128.5mns
Broeren 2008 [33]	E:conventional therapy with additional VR therapy 3x per week for 45 minutes for 4 weeks. Unsupported arm. C: only conventional therapy.	E: AUD, KP, CONC & VIS, KP, CONC & VIS, KR, TERM C: no feedback	Level IV pre-post test with control group n=2x11	Chronic stroke Age E:67.0±12.5yrs C:68.0±12.5yrs Time post stroke: E:62.3±28.4mns C:72.0±35.9mns

Sensory and visual feedback				
Broeren 2004 [43]	VR game 3D bricks, elbow and shoulder movements For 4 weeks, 12x 90 minutes sessions.	VIS & SENS, KP, CONC	Level VIII Single case study	Subacute in the late fifties 12 weeks post stroke
Jang 2005 [23]	Reaching, lifting and grasping motor skills by arm and trunk movement for 4 weeks, 5x per week, for 60 minutes.	E: VIS & SEN, KR & KP, CON & TERM, FAD C: no intervention	Level III RCT E:n=5 C:n=5	Chronic stroke Age E:59.8±3.4yrs C:54.4±5.3yrs Time post stroke E:13.8±3.6mns C:13.4±2.2mns
Kahn 2006 [12]	E:robot-guided active assist training, linear reaching movements C: Unconstrained unassisted repetitive voluntary reaching Both for 8 weeks, 24 45-minutes sessions.	E: VIS, KR, TERM, SUM & VIS, KP, CONC & SENS, KP, CONC C:VIS, KR & KP, TERM, SUM	Level III double blind RCT E:n=10 C:n=9	Chronic stroke Age E:55.6±12.2yrs C:55.9±12.3yrs Time post stroke E:75.8±45.5mns C:103±48.2mns
Broeren 2007 [39]	3D bricks game for hand an arm movements, 15 sessions of 45 minutes for 5 weeks.	SEN, KP, CONC & VIS, KP, CONC & VIS, KR, TERM	Level VI pre-post test n=5	Chronic stroke Age 59±5yrs Time post stroke 33.5±22.5mns
Coote 2008 [28]	2 groups (E1:BC or E2:CB), robot-mediated (B) and Sling suspension training (C), arm de-weighted, hand-to-mouth, reaching table height, reaching shoulder height. 3x pw 30 mins.	B: VIS, KP & KR, CONC & SENS, KP, CONC C: no feedback	Level III blinded randomization n=2x10	Subacute & chronic stroke Age E1:66±7.8yrs E2:70.1±11.1yrs Time post stroke E1:15.9±9.4mns E2:25.6±25.1mns
Casadio 2009 [41]	Active execution of reaching movements to targets in horizontal plane, with force field, some blocks with and some blocks without vision. 10 sessions of 1 hour.	SENS, KP, CONC & VIS, KP, CONC	Level VI pre-post test n=10	Chronic stroke Age 52.8±13.4yrs Time post stroke 46.2±41.5mns

Auditory & **sensory** & **visual feedback**				
Stewart 2007 [37]	Reaching, ball shooting, rotation and pinch VR games (arm and hand movements), for 3 weeks 1-2 hours per day 4x per week	VIS, KR, TERM, SUM AUD & SENS & VIS, KP, CONC	Level VI pre-post test n=2	Chronic stroke Age 73 and 88yrs Time post stroke 29 and 30mns

2.3.2 Level of evidence

Eight studies were RCTs (level of evidence of III) [12,23-29] see table 2.3. Four studies were non-randomized controlled studies (level of evidence of IV) [30-33]. Nine studies had a pre-post treatment measurement design (level of evidence of VI) [22,34-41]. And two studies had a level of evidence of VIII, of which one study was an experimental observational study [42] and the other a single case study [43].

2.3.3 Patients

Of the 23 enrolled studies, 20 studies focused fully on chronic stroke survivors (more than 6 months post-stroke [44]), see table 2.3. The case study focused on non-chronic stroke survivors (less than 6 months post-stroke [44]) [43]. Colombo et al. [40] and Coote et al. [28] focused on both chronic and non-chronic stroke survivors in their pre- and post- treatment design study and RCT study, respectively.

2.3.4 Outcome measures

Motor functions

On average three motor function outcome measures were used per study with a range of one to six motor function outcome measures, see table 2.4. Main motor function outcome measures were grip strength, range of motion, velocity, precision and finger fractionation. Thirteen [22-24, 27, 28, 30, 34, 35, 38, 39, 41-43] out of 23 studies found a beneficial effect on motor functions, five studies [26, 32, 33, 36, 40] found an inconclusive effect, and four studies found no effect [12, 25, 29, 31]. No adverse effects were reported on motor function outcome measures. One study did not use any motor function outcome measures [37].

Motor activities

On average three motor activities tests were used per study with a range of one to four motor activities tests, see table 2.4. Main motor activities tests are the Fugl-Meyer (FM) and Box and Blocks Test (BBT), eight and thirteen studies, respectively. On motor activities a beneficial effect was observed in seven studies [23, 27, 28, 38, 40, 42, 43], eleven studies [22, 24-26, 29, 33, 34, 36, 37, 39, 41] found an inconclusive effect and one study reported no effect [12]. No adverse effects were reported on motor activities outcome measures. Four studies [30-32, 35] did not use any motor activities tests, see table 2.4.

2.3.5 Intervention

Two studies focused solely on hand exercises [22, 26]. Six studies [9, 23, 25, 36, 37, 39] focused on both hand and arm movements in their exercises, of which two studies [23, 25] used virtual reality and three studies [36, 37, 39] virtual reality and robotics.
Twelve studies [12, 24, 27-29, 31-33, 40-43] only performed arm (elbow and shoulder)

movements in their movement therapy, of which three studies [33, 42, 43] used virtual reality, two studies used both robotics and virtual reality [12, 29], and one study only used robotics [28].
Two studies used force production (isometric) exercises in their training [34, 35].

2.3.6 Effect of the intervention

Different combinations of aspects of augmented feedback (nature, timing and frequency) are used in therapy. Also different combinations of aspects with types (sensory, auditory and visual) of augmented feedback are used. An overview of the effect of different combinations of aspects and types of augmented feedback in therapy is given in table 2.4.

Nature

All studies used a form of Knowledge of Results (KR) or Knowledge of Performance (KP) to provide augmented feedback. Four studies used solely KP feedback in their training [34, 35, 41, 43], and all studies found a beneficial effect on motor functions. On motor activities one study found a beneficial effect [43] and two studies found an inconclusive effect [34, 41].
One study used solely KR feedback in their training [30] and found a beneficial effect on motor functions.
One study compared KP and KR feedback versus only KR feedback [32], and found an inconclusive effect on motor functions; no motor activities tests were used.
Two studies compared KR feedback versus KP feedback [24, 27], see table 2.3. Both found a beneficial effect for the KP feedback group on motor functions [24, 27]. On motor activities one of these studies found an inconclusive effect [24], and one a beneficial effect [27] for the KP feedback group.

Timing

In the present review no studies were found which investigate the specific effect of concurrent or terminal augmented feedback on motor relearning of the hemiparetic arm.

Frequency

Most studies did not mention their frequency of providing feedback. From the description of the experiment it could be derived that most studies provided summary feedback. Only one study focused on the effect of providing summary versus faded feedback [31] and found similar results for the summary and the faded training group.

Visual

Different types of augmented feedback were used solely or combined, see table 2.3. Solely visual feedback is used in four studies [26, 31, 34, 40]. Of these studies, one study found a beneficial effect on motor functions [34], one study no effect [31], and two studies found an inconclusive effect [26, 40]. On motor activities two studies found an inconclusive effect [26, 34] and one study a beneficial effect [40].

Auditory and visual

The combination of auditory and visual feedback was used in ten studies [22, 25, 29, 30, 32, 33, 35, 36, 38, 42], of which one study tested the effect of auditory and visual feedback versus only visual feedback (the added effect of auditory feedback) [32]. They found an inconclusive effect on motor functions for the additional auditory feedback group.

One study tested the effect of visual versus auditory feedback [27] and found a beneficial effect on both motor functions and motor activities for the auditory-group (in this study no vision was used in the auditory group). [27]

Sensory and visual

Five studies used sensory and visual augmented feedback in their studies [23, 28, 39, 41, 43]. All studies reported a beneficial effect on motor functions. On motor activities thee studies [23, 28, 43] reported a beneficial effect and two studies [39, 41] found an inconclusive effect.
One study tested the effect of sensory and visual feedback versus only visual feedback [12]. This study found no favourable effect for sensory and visual or only visual feedback for both motor functions and motor activities.

Auditory, sensory and visual

One study used a combination of all three types (auditory, sensory, and visual) of augmented feedback in their training [37] and found an inconclusive effect on motor activities, they did not use any motor function outcome measures.

Table 2.4: Overview of the effect of the used augmented feedback on Motor Function and Motor Activities outcomes measures in stroke survivors of the included studies. + beneficial effect, 0 no effect, ˜ inconclusive effect. BBT= Box and Blocks Test, FIMS= Functional Independence Measure Scale, FM= Fugl-Meyer scale, FTHUE= Functional Test of the Hemiparetic Upper Extremity, RLA= Rancho Los Amigos Functional Test, TEMPA= Test Evaluant la Performance des Membres Superieurs des Personnes Agees.

Reference	Effect on Motor Function		Effect on Motor Activities	
		KP versus KR feedback		
Cirstea 2006 [24]	movement time (+ E2), precision (+ E1), segmentation (+E2), variability of velocity (+E2), precision (+E2)	0	FM (˜), Composite Spasticity Index (˜), TEMPA (˜)	˜ E2 0 E1
Cirstea 2007 [27]	angular motions (+), inter-joint coordination (+), trunk recruitment (+)	+ KP	FM (+), Composite Spasticity Index (+), TEMPA (+)	+ KP
		Summary versus faded feedback		
Winstein 1999 [31]	Root Mean Square error and variable error of reaching trajectory (0)	0	—-	—-
		Visual feedback		
Bourbonnais 2002 [34]	handgrip force (+)	+	BBT (+), FM(+), finger to nose test (+), TEMPA (0)	˜
Colombo 2008 [40]	movement efficacy (+), velocity (+), accuracy (0 sas + cs), efficiency (+ sas 0 cs), smoothness (+), force control (0)	˜ sas ˜ cs	FM (+), Motor Power Score (+), Motor Status Score (+)	+ sas + cs

Carey 2007 [26]	finger range of motion (+), accuracy (+), finger movement tracking test with fMRI (˜) (more effect for E group)	˜	BBT (˜), Jebsen Taylor Hand Test (0)	˜
	Auditory and visual feedback			
Eckhouse 1990[30]	average point score of performance (+), reaching position and time (+)	+	—-	—-
Maulucci 2001 [32]	orientation (+), error (+), linearity (0), oscillations (+), timing (0), elbow and upper arm path (+)	˜	—-	—-
Piron 2004 [42]	velocity (+) and duration (+)	+	FIMS (+), FM (+)	+
Ellis 2005 [35]	maximum voluntary torque for joint torque coupling (+)	+	—-	—-
Sanchez 2006 [36]	grip strength (˜), supported and unsupported range of motion (˜)	˜	BBT (0), FM (+), RLA (0)	˜
Merians 2006 [22]	fractionation (+), range of motion (+), velocity (+)	+	Jebsen Taylor Hand Test (+), reach to grasp test (˜)	˜
Fischer 2007 [25]	grip strength (0), isometric extension (0), peak extension velocity (0), extension range of motion (0), spasticity (0)	0	BBT (˜), FM (˜), RLA (0), WMFT (+)	˜
Holden 2007 [38]	shoulder strength (+), grip strength (+)	+	FM (+), WMFT (+)	+
Housman 2009 [29]	active range of motion (0), grip strength (0)	0	FM (+), RFTPUE (0), Motor Activity Log (0)	˜
Broeren 2008 [33]	time (+), hand path ratio (+), velocity (0)	˜	BBT (+) , ABILHAND (0)	˜
	Sensory and visual feedback			
Broeren 2004 [43]	hand grip strength (+), upper-extremity test (+)	+	Purdue pegboard test (+), interview(+)	+
Jang 2005 [23]	cortical activation by means of fMRI (+)	+	BBT (+), FM (+), Motor Activity Log (+), Manual Function Test (+)	+
Kahn 2006 [12]	limb stiffness (0), supported and unsupported range of motion (0), velocity (0), straightness (0), smoothness (˜).	0	Chedoke-MCMaster (0), RLA (0)	0
Broeren 2007 [39]	velocity (+), time (+), hand path ratio (+)	+	assessment of motor and process skills (˜), BBT (+)	˜
Coote 2008 [28]	active shoulder range (+), elbow flexion (+)	+ B	Ashworth scale (+), FM (+), Motor Assessment Scale (+)	+ B
Casadio 2009 [41]	mean speed (+), number sub movements (+), endpoints error (+), T-ratio (sub movement time / total time) (+)	+	FM (+), Ashworth scale (0)	˜

Auditory and sensory and visual feedback				
Stewart 2007 [37]	—-	—-	BBT (˜), FM (˜), FTHUE (˜), Stroke Impact Scale (˜)	˜

2.4 Discussion

By providing augmented feedback, successes or errors during training are more emphasized. The internal system might be more activated than it would be by own observation. A beneficial effect on motor relearning may be expected.

In this systematic review a qualitative analysis of 23 studies was performed to assess the effect of different aspects (nature, timing, and frequency) and types (sensory, visual and auditory) of augmented feedback on motor relearning of the hemiparetic arm after stroke. Most of the included studies in the present review used a combination of different aspects and types of augmented feedback in their therapy sessions. Only a few studies specifically looked into the separate effects. Especially these studies provide crucial insight in optimizing augmented feedback in rehabilitation therapy.

2.4.1 Aspects of augmented feedback

Two major classes of the nature of feedback can be distinguished: knowledge of performance (KP) and knowledge of results (KR). Most studies used a combination of both KP and KR in their training sessions and it became evident that very little research has been done to the separate effect of KP and KR. Research in healthy subjects only give inconclusive results about whether to provide KP or KR feedback. [16] Studies investigating the effect of KP and KR feedback on motor learning for stroke survivors are scarce.

The timing, concurrent or terminal, of providing augmented feedback, is closely related to the nature (KP or KR) of augmented feedback. In the present review no studies were found which investigate the specific effect of concurrent or terminal augmented feedback on motor relearning of the hemiparetic arm. In healthy subjects some research into the effectiveness of providing either concurrent or terminal feedback has been provided. When concurrent feedback was provided during practice in healthy subjects, it enhanced the performance at that moment, but in transfer tests (post measurements) without concurrent feedback, it resulted in performance decrements. [45]

A plausible explanation for this finding might be that concurrent feedback conflicts with the internal feedback system in healthy subjects. This finding might be valid for stroke survivors to a lesser extent, because their internal feedback system is disturbed. Therefore, concurrent information about their performance might be a supplement to their affected internal feedback system, instead of conflicting with the system. Insight in the influence of the timing of augmented feedback on motor learning for stroke survivors is necessary.

The frequency of providing augmented feedback can be implemented in different schemes, summary or faded. Several studies in healthy subjects demonstrate that learning improved more when augmented feedback on a reduced frequency (faded) scheme was provided, than when feedback after every trial (summary) was provided. [46-48] But based on a study by Winstein et al. [31] no favourable effect of either summary or faded feedback in motor learning for stroke survivors was observed.

2.4.2 Types of augmented feedback

In the present review, most studies used multiple types of augmented feedback in their therapies, which makes it rather complex to define what the contribution of different types of augmented feedback is on motor relearning of stroke survivors.

All studies in the present review used some form of augmented visual feedback (solely, or combined with augmented auditory or sensory feedback).

Mostly auditory feedback is provided by means of verbal encouragements by physiotherapists in therapy, as is found in this review. Not much is known about the effect of the different ways of providing augmented auditory feedback. Only one study by Maulucci et al. [32] found a favourable effect of adding auditory feedback to visual feedback. [32]

Sensory feedback is widely used since the introduction of rehabilitation robotics. Mostly sensory feedback is provided combined with different kinds of augmented feedback, such as augmented visual feedback.

Adding augmented visual feedback to the rehabilitation exercises stimulates the learning process, of patients by making patients more aware of their performance. Combinations of auditory and visual feedback, sensory and visual feedback, and all types of augmented feedback have found no clear beneficial effect on rehabilitation training. Therefore more insight in the different aspects and types of augmented feedback is essential to optimally induce motor relearning of stroke survivors.

2.5 Conclusions

Based on current literature, it was not possible to determine which combinations of aspects and types of augmented feedback are most essential for a beneficial effect on motor activities and motor functions of the hemiparetic arm after stroke.

This was due to the combination of multiple aspects and types of augmented feedback in the included studies.

This systematic review indicates that augmented feedback in general has an added value for rehabilitation therapy for stroke survivors. There are some trends in favour of providing augmented knowledge of performance feedback, augmented auditory and combined sensory and visual feedback. No consistent effects on motor relearning were observed for summary or faded, terminal or concurrent, solely visual or solely sensory augmented feedback.

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2.7 Appendix

List of keywords used in pubmed systematic literature search.

(upper extremity OR upper extremities OR upper limb OR upper limbs OR arm OR arms OR hand OR hands OR shoulder OR wrist OR finger OR elbow OR fingers)

AND (myography OR virtual OR visual OR sensory OR sensor* OR augmented OR augment* OR force OR biofeedback OR quantitative OR qualitative OR tactile OR audition OR auditory OR audit* OR performance OR knowledge OR KR OR KP OR knowledge of results OR haptic OR haptic* OR olfactory OR vibration OR proprioception OR vibratory OR proprioceptive OR enhanced)

AND (cerebrovascular disorders OR cerebrovascular trauma OR stroke OR CVA OR cerebrovascular accident OR hemiplegia OR hemipleg* OR hemiparesis OR hemipare* OR paralysis)

AND (feedback OR environment[TW] OR (learning[TW] AND motor[TW]))

NOT ((functional[TW] AND electrical[TW] AND stimulation[TW]) OR parkinson OR child OR children OR neurosurgery OR (neuromuscular[TW] AND stimulation[TW]) OR surgery OR prostheses OR FES OR prosthetic OR (transcranial[TW] AND magnetic[TW]) OR TMS OR foot)

3

Effect of position feedback during task-oriented upper-limb training after stroke: Five-case pilot study.

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Abstract

Feedback is an important element in motor learning during rehabilitation therapy following stroke. The objective of this pilot study was to better understand the effect of position feedback during task-oriented reach training of the upper limb in people with chronic stroke.

Five subjects participated in the training for 30 minutes three times a week for 6 weeks. During training, subjects performed reaching movements over a predefined path. When deviation from this path occurred, shoulder and elbow joints received position feedback using restraining forces. We recorded the amount of position feedback used by each subject. During pre- and posttraining assessments, we collected data from clinical scales, isometric strength, and workspace of the arm.

All subjects showed improvement on one or several kinematic variables during a circular motion task after training. One subject showed improvement on all clinical scales. Subjects required position feedback between 7.4 and 14.7 percent of training time.

Although augmented feedback use was limited, kinematic outcome measures and movement performance during training increased in all subjects, which was comparable with other studies. Emphasis on movement errors at the moment they occur may possibly stimulate motor learning when movement tasks with sufficiently high levels of difficulty are applied.

3.1 Introduction

Restoring upper-limb function is a major aim in stroke rehabilitation. Of the people who experienced a stroke, 30 to 66 percent do not have proper arm-hand function after six months [1]. Restoration of arm-hand function is crucial to improving independence. Improving lost function is stimulated through motor relearning during stroke rehabilitation. The literature shows that several elements of training contribute to motor relearning [2]. Repetitive, active training of functional tasks in a meaningful environment is known to improve motor control, functional recovery, and strength in upper-limb stroke rehabilitation [2-8]. Using appropriate feedback to enhance motor learning and motivate the patient is an essential part of the training [9-10].

Feedback refers to a person's sensory-perceptual awareness regarding their interaction with the environment. This information can be available as sound, vision, or sensation during or after the movement is performed. Since intrinsic feedback mechanisms are often impaired after stroke, providing augmented feedback is thought to be beneficial. Augmented feedback by sound, vision, or touch may be provided to enhance task performance or goal achievement [11-12]. Using forces applied to the upper limb during movement as augmented feedback might activate the internal proprioceptive system more than during normal movement. Using a robotic device, augmented feedback regarding the position of the arm during movement can be provided by resistance forces when the patient deviates from a predefined path [13].

The goal of this pilot study is to better understand the effect of position feedback use during task-oriented reach training of the upper limb in people with chronic stroke. We expect to find improvements in arm movement ability on both kinematic outcome measures and clinical scales. We also expect more position feedback use when the difficulty level of training increases.

3.2 Methods

This pilot study comprised a 6-week training period. Prior to training, we performed two measurement sessions (spaced 1 week apart) on subjects to identify a possible baseline trend. After the training period, we performed a posttraining evaluation measurement session.

Table 3.1: Subject characteristics.

Subject	**Sex**	**Age (yr)**	**Hand Dominance**	**Time Post-stroke (mo)**
1	Female	50.8	Right	30
2	Male	53.4	Right	44
3	Female	68.7	Right	51
4	Male	59.8	Right	20
5	Male	57.5	Left	32

Note: Right affected side in all subjects.

3.2.1 Subjects

This study included five people with chronic stroke. Inclusion criteria were left hemispheric stroke and the ability to move the upper limb slightly against gravity. We excluded subjects if they had shoulder pain or were <6 months poststroke. Table 3.1 presents the subjects' ages, affected sides, hand dominance, and time poststroke.

3.2.2 Training

Training sessions took place three times a week for 30 minutes supervised by a trained physical therapist. The training program consisted of three active reaching tasks: task 1, sliding the hand over the table; task 2, lifting and moving the hand above the table; and task 3, lifting and moving the hand to a shelf. Figure 3.1 illustrates the different tasks. Subjects performed these reaching exercises on a tabletop divided into nine squares (three in each row) of 15 by 15 cm. For task 3, subjects used two additional shelves, each with three squares of 15 x 15 cm, at 25 and 45 cm above the table.

The physical therapist determined the succession of the tasks, difficulty level (ascending from tasks 1 to 3), and diameter of the predefined path (as represented by a virtual tunnel). Subjects started the reaching task with their hand in front of the midline and as close as possible to their trunk. This position corresponded with placing the hand on the front row in the middle square.

3.2.3 Feedback

A virtual tunnel, a zone in which the subject is free to move, represented the predefined path. Each time subjects moved outside the virtual tunnel, they received position feedback. Position feedback provided resistance on the shoulder and elbow joints, preventing movements, to make subjects aware that they deviated from the predefined path. To have the feedback forces removed, subjects needed to actively correct their path by moving back toward the virtual tunnel. At this point, the reach movement could continue within the virtual tunnel toward the target. During the exercises, subjects could see their own arm and the table with its movement goals. The virtual tunnel was visible on a computer monitor only to the therapist. Subjects experienced the feedback solely as resistance on their arm without any additional visual or auditory cues.

3.2.4 Exoskeleton

A robotic exoskeleton device (Dampace [Figure 3.2]) provided the resistive forces. It has been used in previous experiments [14-15]. This device has three degrees of freedom at the shoulder: shoulder plane of elevation (EP, corresponding with clinical terms of shoulder horizontal abduction and/or adduction), shoulder elevation angle (EA, corresponding with shoulder anteflexion or shoulder abduction), and axial rotation (AR, corresponding with endorotation and/or exorotation). It also has two degrees of freedom at the elbow: elbow flexion (EF) and elbow extension. These joint angles (Figure 3.3) are defined according to the recommendations of Wu et al. and the International Society of Biomechanics [16]. The device applied resistive forces to each of these four axes individually [14].

We attached the device to the subject's upper arm and forearm using soft straps. A flexible wrist attachment allowed pronation and supination of the forearm without force control. The device was attached to a rigid frame, situated behind the subject, in such a way that the shoulder could move freely. To minimize the effect of compensating trunk movements, we strapped the subject to the seat with a four-point safety belt.

Integrated potentiometers measured shoulder rotation, and linear optical encoders measured shoulder translations. A rotational optical encoder measured the EE. The digital values were sampled with a rate of 1 kHz, low-pass filtered with a first-order Butterworth filter with a cutoff frequency of 40 Hz, and stored on a computer with a sample frequency of 20 Hz. Before analysis, all measured signals were off-line filtered with a first-order, zero phase-shift, low-pass Butterworth filter with a cutoff frequency of 5 Hz.

3.2.5 Data Collection

During pre- and posttraining evaluations, we measured arm-movement ability changes using the Fugl-Meyer Assessment Upper-Limb (FMA-UL) subscale, the Motricity Index (MI), the Action Research Arm Test (ARAT), circular arm movements, and isometric strength.

Clinical Assessments

For the FMA-UL (maximum score: 66 points), subjects perform upper-limb movements ranging from gross movements of the shoulder and elbow to detailed finger movements. The upper-limb portion of the MI (maximum score: 100 points) measures maximal isometric muscular strength. During the ARAT (maximum score: 57 points), subjects manipulate various objects. Higher scores on all scales represent better performance. The same investigator performed all tests during each evaluation.

Circular Arm Movements

Subjects made two sets of five consecutive circular motions above a tabletop: one set clockwise (CW) and one set counterclockwise (CCW). Subjects started the circular motion task with their hand in front of the midline and as close as possible to their trunk. They performed movements at a self-selected speed. The tabletop showed templates of circles of different radii to motivate subjects to make the circles as large and round as possible. We randomized the order of direction of the circular motion task (CW or CCW) across subjects and sessions.

The device recorded joint excursions of shoulder and elbow in 'free mode' without applying any forces during circular arm movements. To calculate the hand position, we transformed joint angles into joint positions using segment lengths of the upper arm (defined as the distance between the acromion and the lateral epicondyle of the humerus) and forearm (defined as the distance between the lateral epicondyle of the humerus and the third metacarpophalangeal joint). Joint positions were expressed relative to the shoulder position by defining the position of the shoulder joint as the origin to exclude contributions of compensatory trunk movements.

From the hand position data, we deduced the circular movement made by the subject. We extracted individual circles from the data between two minima of the Euclidian distance in the horizontal plane between the hand and the shoulder joint. We connected start and end positions of the circle to ensure a closed curve. We selected the three largest circles for each subject after a visual inspection for completeness and correctness.

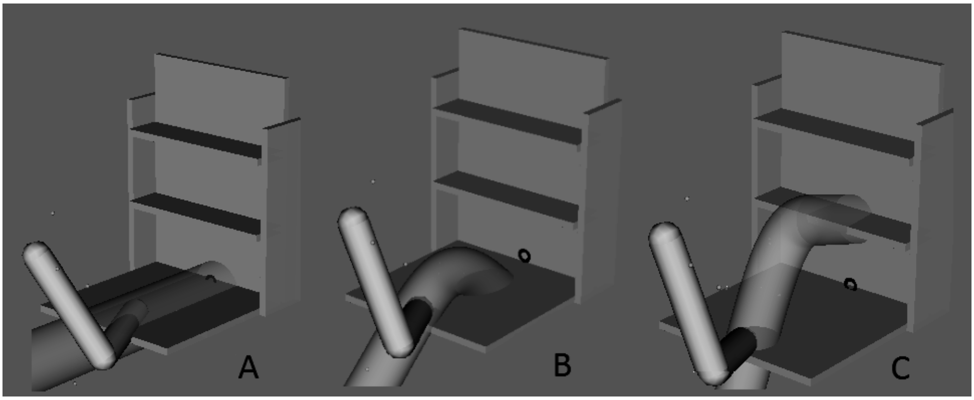

Figure 3.1: Virtual representation of movement exercises and corresponding virtual tabletop in three-dimensional views. Starting point of task is close to body and in front of trunk. Hand is then moved farther from body in same column. (a) Moving hand (task 1). (b) Moving hand to another field by making curve (task 2). (c) Lifting hand to shelf (task 3).

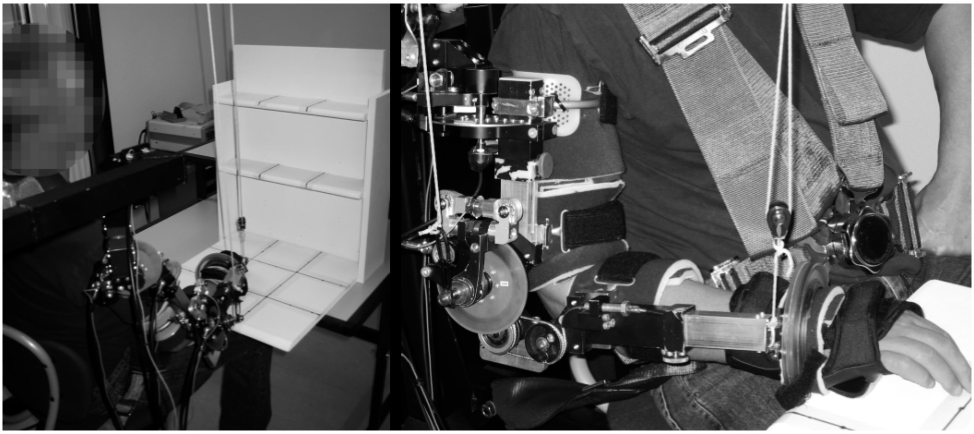

Figure 3.2: (a) Subject in exoskeleton* performing reaching movements on tabletop. (b) Close-up of exoskeleton arm, with upper arm and forearm in soft straps. *Stienen AH, Hekman EE, Prange GB, Jannink MJ, Aalsma AM, Van der Helm FC, Van der Kooij H. Dampace: Design of an exoskeleton for force-coordination training in upper-extremity rehabilitation. ASME J Med Dev. 2009;3(3):1-10.

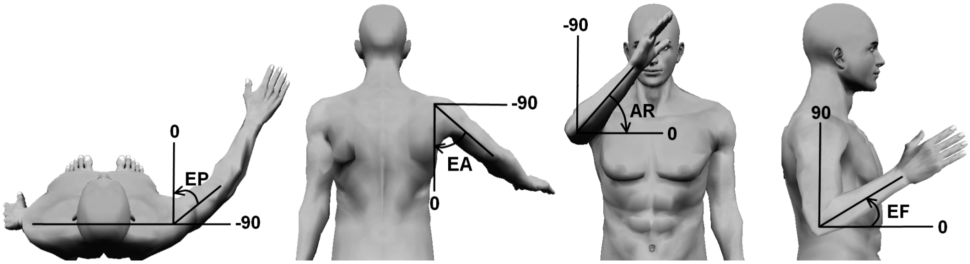

Figure 3.3: Graphical representation of joint angles: (a) shoulder plane of elevation (EP), (b) shoulder elevation angle (EA), (c) axial rotation (AR), and (d) elbow excursion (EE).

To represent workspace, we calculated the active range of motion as the area enclosed by the projection of the hand path onto the tabletop. Corresponding joint excursions (EP, EA, AR, and EE) during each circular movement represented movement coordination. We averaged these parameters over the three selected circles. We pooled data from the CW and CCW circular motions using a paired-samples Student t-test ($p>0.05$) after confirming that no significant differences existed.

Isometric Strength

Subjects performed three maximal contractions of isometric elbow extensions. The contractions were spaced 1 min apart to minimize fatigue. We used the maximum value sustained for 0.25 s of the three performed extensions as the maximal voluntary torque (MVT). The subjects started with their upper limb in 80 degrees of shoulder abduction and 90 degrees of elbow flexion. The investigator provided verbal encouragement during elbow extensions.

A custom-built six degrees of freedom force-torque sensor based on strain gauges measured the MVT. These sensors measured forces and torques simultaneously in three directions and were real-time filtered with a fourth order Butterworth low-pass filter with a cutoff frequency of 10 Hz. We stored the data with a sample rate of 100 Hz on a computer.

Feedback

In addition to these evaluations, we collected data during training about the frequency of position feedback (as described in the earlier Feedback section) to study the actual contribution of position feedback to the training. We recorded the total number of collisions with the virtual wall within each training session along with the total number of movements in that session. We calculated the average use of position feedback during the entire training period as the percentage of collisions with respect to the total number of movements for each session, averaged over all training sessions. To indicate changes in difficulty level during the training, we recorded additional information about the height and diameter of the virtual tunnel.

3.2.6 Data Analysis

Initial analysis of the data obtained during baseline measurements revealed some variations in motor performance (in clinical tests, circular motion, and strength tasks), but we saw no clear trend in one direction. Therefore, we averaged the data

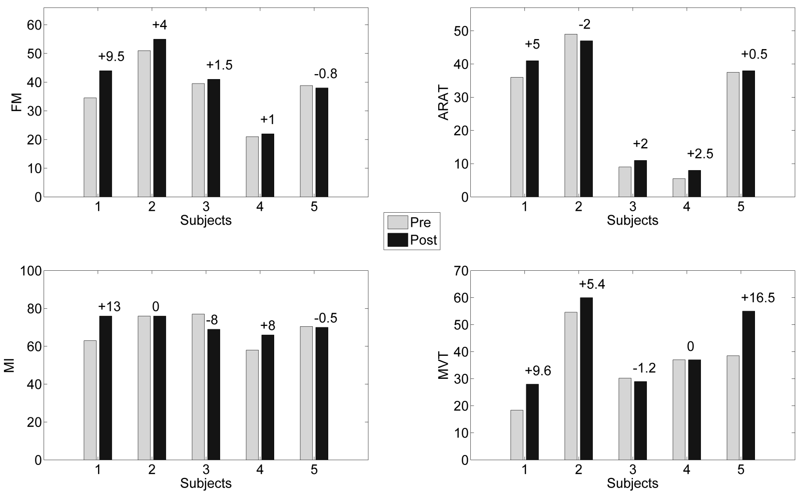

Figure 3.4: (a) Fugl-Meyer Assessment upper-limb subscale (FMA-UL), (b) Action Research Arm Test (ARAT), (c) Motricity Index (MI), and (d) maximal voluntary torque (MVT) values with absolute values before (pre) and after (post) training.

of the baseline measurements and compared them per subject with the data obtained during the posttraining evaluation measurements. We calculated the differences between pre-and posttraining evaluations. In addition, we used scatter plots for each subject to study the relationship between changes in different outcome measures.

3.3 Results

3.3.1 Clinical Assessment

Figure 3.4 presents individual baseline scores of the FMA-UL, ARAT, and MI together with the absolute differences of the scores posttraining. Four subjects improved on the FMA-UL by between 1.0 and 9.5 points. On the MI, two subjects improved by 8 and 13 points each. Four subjects improved on the ARAT by between 0.5 and 5.0 points.

3.3.2 Circular Arm Movements

Three subjects showed improvement on increasing their workspace by between 20.2 and 63.4 percent. Three subjects improved their range of EP by between 5.2 and 10.6 degrees (8.0 - 12.6 percent). Two subjects decreased their range of EP with 3.5 degrees and 18.2 degrees (4.8 and 23.8 percent) each. All subjects showed shoulder EA improvement by between 0.9 degrees and 6.5 degrees (9.5 - 97.0 percent). The EE range improved for all subjects by between 1.5 degrees and 17.3 degrees (2.7 - 57.5 percent).

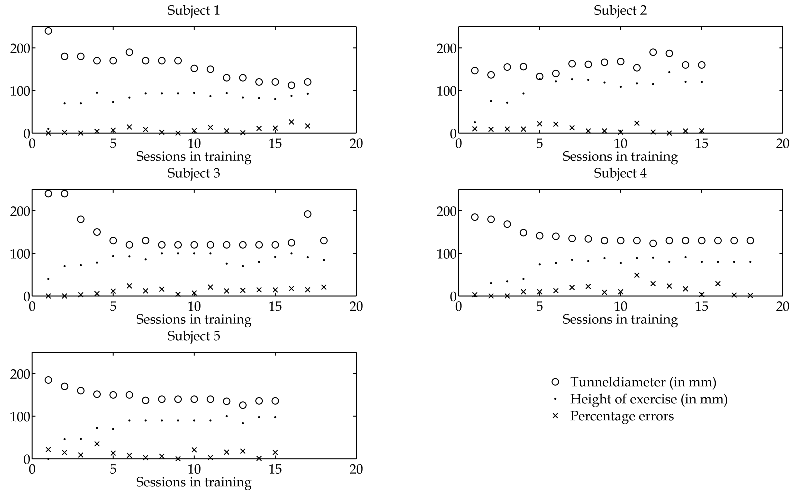

Figure 3.5: Percentage error, tunnel diameter, and height of movement per session for entire training period for all five subjects.

3.3.3 Isometric Strength

Figure 3.4 displays the MVT of all subjects together with the absolute difference of the score posttraining. Three subjects showed improvement on their MVT by between 5.4 and 16.5 Nm (9.9 - 52.2 percent).

3.3.4 Feedback

In general, subjects performed around 100 movements per training session. Every subject participated in at least 15 sessions. Figure 3.5 displays the percentage errors, tunnel diameter, and movement height per session for all five subjects for the entire training period. The difficulty of the exercises increased during training, characterized by the increased height of the movement and decreased tunnel diameter (Figure 3.5). This indicates improved movement performance during the training period for all subjects.

Table 3.2: Average use of position feedback (percentage errors) per subject over all sessions.

Subject	**Average percentage Error**
1	7.4
2	9.3
3	12.8
4	14.7
5	12.2

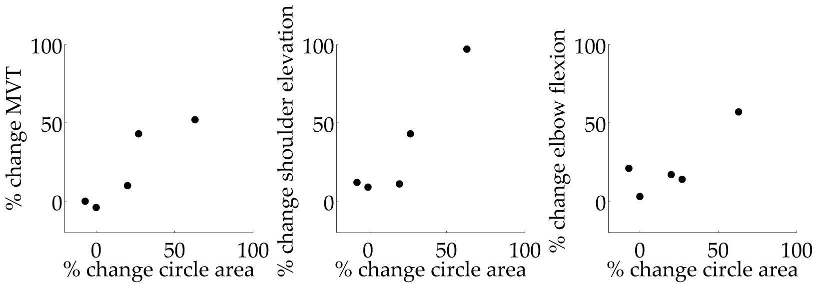

Figure 3.6: Relative improvement in percentage of baseline score per subject. (a) Circle area versus maximal voluntary torque (MVT). (b) Circle area versus shoulder elevation angle. (c) Circle area versus elbow flexion.

Average use of position feedback during the training period was between 7.4 percent and 14.7 percent (Table 3.2). During training, position feedback use changed independent of changes in difficulty of the exercises.

3.3.5 Overall Effect

Subject 1 showed improvement on all outcomes measures. Subjects 2 and 5 showed improvement on both MVT and kinematic outcome measures. Subjects 3 and 4 showed varying results over all outcome measures. Improvement in workspace seems to coincide with improved MVT and improved shoulder EA excursions and elbow joint excursions. This is illustrated in scatter plots of the relative improvement percentage with respect to the baseline score per subject of circle area versus MVT, circle area versus shoulder EA, and circle area versus elbow excursion (Figure 6).

3.4 Discussion

Our objective was to better understand the effect of position feedback during task-oriented reach training of the upper limb in people with chronic stroke. We observed improvement in kinematic outcome measures for all subjects, but only one subject showed improvement on clinical scales. Other studies using forces for emphasizing errors during reach training found similar improvement on kinematic outcome measures [17-19].

In our study, feedback made subjects aware of their errors at the moment the error was made. Subjects needed to actively correct their movement before the feedback forces were removed and the movement could be continued. Several studies have suggested that this type of augmented feedback, provided by placing emphasis on errors during rehabilitation therapy, is potentially beneficial for motor learning [20-21]. Also, the direct response of the movement error by means of augmented feedback is thought to contain components that stimulate motor learning. Shabbott and Sainburg tested the timing effect of augmented feedback in nondisabled subjects during a visuomotor task [22]. The group receiving feedback after the completed movement showed less improvement on the learned task than the group receiving feedback during movement execution. In the same study, Shabbott and Sainburg tested whether this observed difference in learning could be caused by the (in)ability to correct for movements during reaching. They observed no difference in reaching performance between the group that corrected their errors during the movement and the group that did not [22]. This might indicate that availability of knowledge of movement errors at the moment they occur seems to be more important for motor learning than the ability to correct movement errors.

In the present study, we provided augmented feedback in addition to the available intrinsic feedback. This resulted in the actual use of augmented feedback in 7.4 to 14.7 percent of movements. Despite this limited use of augmented feedback, subjects showed improved movement ability during and after training, which was also reflected in the increasing difficulty level during training. Other studies that showed similar improvement used augmented feedback 20 percent or more of the time during training, but provided no data on how many subjects actually used it [23-25]. A possible explanation for improvement in training results, together with limited augmented feedback use, could be that this augmented feedback does not substantially activate the internal proprioceptive system. The tasks used in this study may not have been that demanding, so they could have largely been executed solely using the present intrinsic feedback mechanisms. More complex movement tasks could contribute to a higher use of augmented feedback. This could be achieved by applying a visual distortion task, creating a mismatch between the intrinsic and augmented feedback systems. This would enable specific testing of the effect of augmented feedback on motor learning in both nondisabled subjects and people with stroke. In all, we observed improvement on kinematic outcome measures and movement performance during training for all subjects and improvement on clinical scales for one subject, even though augmented feedback use was limited. Since these changes are in line with comparable studies, it seems that the available augmented feedback may have contributed to this, although direct comparison with a control group is needed for confirmation. Findings from the present study and available literature further suggest that emphasis on movement errors at the moment they occur can potentially stimulate motor learning, but applying sufficiently high difficulty levels during movement tasks is important.

3.5 Conclusions

Although the augmented feedback was used in a limited amount of movements, kinematic outcome measures and movement performance during training increased in all subjects. These changes are comparable with other studies applying error feedback. We suggest that emphasis on errors at the moment they occur may possibly stimulate motor learning when patients perform movement tasks with sufficiently high difficulty levels.

3.6 References

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4

Influence of augmented visual feedback on motor skill learning and consolidation in healthy elderly and stroke survivors.

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Abstract

Stroke is a frequent cause of limited function that leads to permanent disability. Augmented feedback is an essential element contributing to improved motor learning. The objective of this study is to explore the influence of different feedback conditions on motor learning in healthy elderly and stroke survivors.

Nineteen healthy elderly and 19 stroke survivors performed repetitive reaching movements with a visual distortion of hand movements. Three conditions of feedback were provided in three distinctive sessions: concurrent (cKP) and terminal knowledge of performance (tKP) and terminal knowledge of results (tKR). Main outcome measures were amount of learning and remembering (consolidation).

In both groups, cKP feedback resulted in a higher amount of learning than either tKR or tKP. The amount of consolidation was poorest with tKP, between cKP and tKR consolidation was comparable. Two healthy subjects and six stroke survivors showed limited amounts of learning, independent of the provided feedback.

The highest potential for learning and consolidation was achieved with cKP in both groups, suggesting benefit for motor learning with cKP feedback. However, attention should be paid to a lower capability of some patients to learn a specific task regardless of the provided feedback.

4.1 Introduction

Regaining arm function is a major concern in stroke rehabilitation to improve independence of the patient. Improvement of lost functionality is stimulated through motor skill learning during stroke rehabilitation therapy. Appropriate augmented feedback about achievements during training is essential to enhance motor skill learning. [1, 2] Augmented feedback is increasingly used and applied in virtual reality (VR) environments. Therefore innovative exercises can be created to stimulate the patient's senses by means of visual (score on a screen, blinking colours), touch (vibrations), or sound (music, clapping) cues. From a literature study of Molier et al. [5] it is known that several augmented feedback conditions are used for arm motor skill learning in stroke survivors. Research of the scientific literature into the separate effect of augmented feedback conditions however is scarce and therefore it is inconclusive which way of providing feedback works best. [5]

More specifically little is known about the influence of knowledge of performance (KP) feedback during movement execution (cKP), KP after the movement has been performed (tKP), and terminal knowledge of results (tKR) feedback on motor skill learning. Schmidt and Wulf [6] studied in healthy subjects the effect of concurrent feedback during practice and how well the practiced task was remembered. It was shown that learning with concurrent feedback enhanced performance at that moment, but in retention tests (repeating the learned task after a certain time interval) without the concurrent feedback it resulted in performance decrements. The task was not well remembered with the provided concurrent feedback, while consolidation of a task is of importance for rehabilitation therapy to be able to execute the learned task outside the rehabilitation setting. The influence of augmented feedback in stroke survivors is tested only in one study; Cirstea et al. [7] observed better movement performance after 10 days training of a repetitive pointing task with KP compared to KR feedback. [7]

More specific information about the potential of different feedback conditions to improve arm function during rehabilitation can be obtained through visuomotor adaptation experiments, where learning of a new movement during a single session is assessed. Motor adaptation experiments use a perturbed spatial relationship between vision and action to study motor skill learning, by altering the visually perceived location of a target in such a way that it appears to be at a point in space different from its actual location. This results in a discrepancy between the observed and perceived location of a target. When subjects reach toward a target without being able to see their hand, they will initially reach toward the visual location of the target and will not be able to reach the target. [8] From experiments performed by Shabott and Sainburg [9] and Sober and Sabes [10] it became evident that by providing feedback healthy subjects are able to learn to anticipate to the visual distortion. Applying different feedback conditions will provide information about their differential contribution to motor learning. In this way, Shabott and Sainburg [9] tested in healthy young subjects the effect of cKP versus tKP feedback and found increased motor skill learning for cKP feedback. Sober and Sabes [10] observed in healthy young subjects comparable movement performance when a visumotor task was practiced in a virtual environment with either fingertip (KR) or visual arm representation (KP) feedback. Visuomotor experiments with stroke survivors indicate that stroke survivors are able to learn a visuomotor task with a visual and/or haptic rotation. [11-13] However, no information is available about the influence of different feedback conditions on motor skill learning in stroke survivors.

The objective of this study was to explore the influence of different visual feedback conditions on learning and consolidation of an arm motor task in healthy elderly and stroke survivors. We test whether subjects are able to learn the visuomotor task, and whether there are differences in learning and consolidation between the different feedback conditions and the two groups.

4.2 Methods

4.2.1 Subjects

Nineteen healthy elderly and 19 stroke survivors were included. They all gave their written informed consent prior to the experiment. The protocol was approved by the local ethics committee. All subjects were able to understand and follow instructions and were in the age between 40 and 75 years. For all stroke survivors the time post stroke was more than six months. All subjects were able to repetitively perform reaching movements without shoulder or upper limb pain.

4.2.2 Experimental apparatus

Subjects were seated on a chair. Their trunk was strapped with two crossed seat belts to prevent trunk movement. A wrist splint was attached to the hand used for the test, to stimulate arm movements instead of wrist movements. The table was placed as close to the subject as possible. The table height was adjusted to the height of the hand when the elbow was 90 degrees in flexion with the upper arm along the trunk. The vision of the subject's arm and hand was obstructed by a shelf, see figure 4.1. The subject held a hand grip through which hand position data was measured by means of four encoders (Wachendorff SZG65-1250-N-UpH05-05).

A representation of the hand was visualized as a 20 mm red sphere on the shelf above the arm, projected by a beamer (Optoma EX 525ST). The provided KP feedback was represented by the travelled movement path and projected as a line. The KR feedback was represented by the endpoint of the movement and was projected as a red dot, see figure 4.1. Subjects made centre-out reaching movements, starting from the midpoint of the circle, with their dominant (healthy elderly) or affected arm (stroke survivors) to one of five targets. The targets were represented as sheep with a 20 mm diameter. The targets are equally spaced (72 degrees) about the perimeter of a circle, see figure 1. The diameter of the circle equals 95 percent of the maximal active range of motion (aROM) of the subject which was determined prior to the start of the experiment by performing three circular reaching movements.

4.2.3 Experimental protocol

The experiment consisted of three separate sessions in which subjects learned the same arm movement task with one of the feedback conditions: cKP, tKP, or tKR. In the successive measurement session minimal interference of the learning of the previous measurement session should be present to be able to test the influence of the feedback conditions on motor skill learning. Therefore we took two precautions to prevent these carry over effects; a two week interval between the sessions and an unlearning stage at the end of every session, as suggested by literature [14-16] and confirmed by pilot tests prior to the start of the experiment.

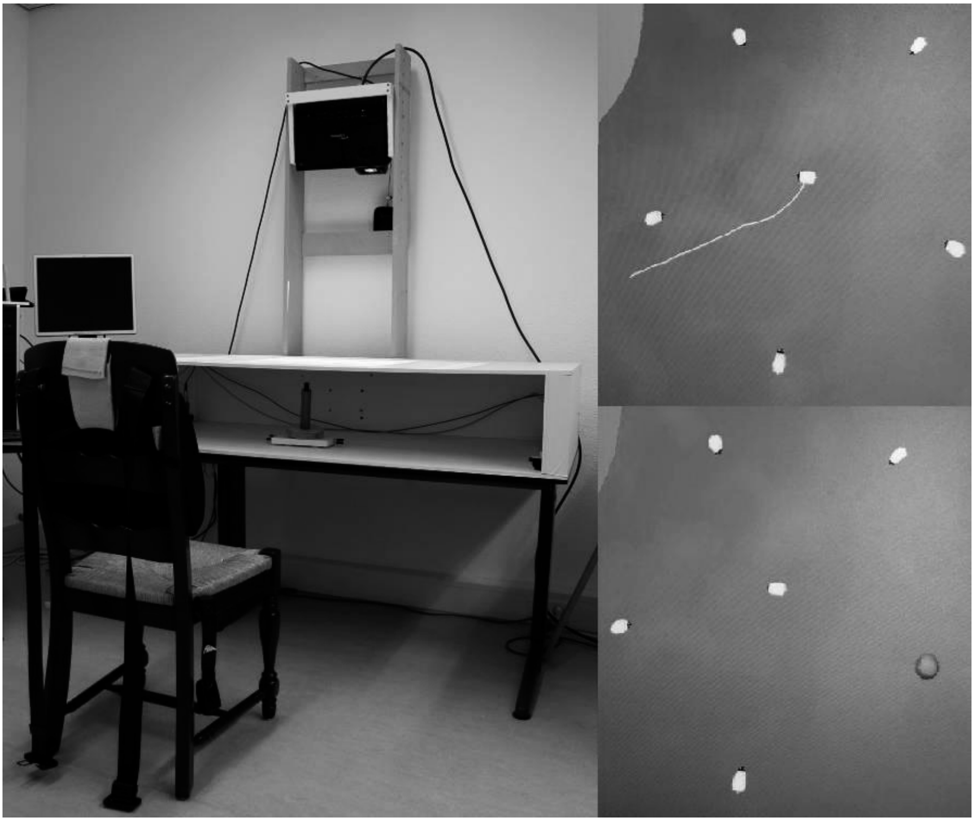

Figure 4.1: Overview of experimental setup. Subjects sat behind the in height adjustable table. They held a hand grip through which hand position was measured. The vision of the arm and hand is obstructed, and a representation of the hand is visualized on the shelf above the arm, projected by a beamer. A representation of the KP and KR feedback, with the five targets and the midpoint of the circle are visualized.

Each session consisted of repetitive movements towards the five targets, with or without perturbation or feedback. The order of the targets was randomized in each cycle, where a cycle consisted of one movement to each target (five movements), and each block consisted of 11 cycles (=55 movements), with 30-second time intervals between the blocks. All subjects performed a total of 93 cycles of five movements per session broken down into the following phases:

- The baseline phase consisted of two blocks of reaching movements, with a total of (2 x 5 x 11 =) 110 repetitions. The cursor was projected constantly during the movements. No rotation and additional feedback were given. The baseline stage was only applied in the first session so subjects became familiar with the task and apparatus.
- The learning phase consisted of three blocks of reaching movements (3 x 5 x 11= 165 repetitions). A 30 degrees counter clockwise (CCW) visual distortion of hand position about the starting location of the movements was applied, with one of the feedback conditions (cKP, tKP, or tKR).
- The retention phase was performed after a 10-minute rest period. Subjects performed five cycles of movements (=25 repetitions), with 30 degrees CCW rotation. There was no visibility of the cursor during these movements. Of interest in this test was to find out how well subjects can reproduce the learned deviation after a rest period. The difference between the learned deviation in the learning phase and the deviation in the retention stage is the amount consolidated (remembered).
- In the unlearning phase subjects performed three blocks of reaching movements (3x5x11=165 repetitions). The cursor was counter-rotated compared to the learning phase; a 30 degrees clockwise (CW) visual distortion was applied. The cursor was projected constantly during the movements. No additional feedback was given.

For the stroke survivors, clinical tests of arm function and capacity were performed after the second session, the Fugl-Meyer assessment [17] and the Stroke Upper Limb Capacity Scale (SULCS) [18]. The SULCS is a hierarchical scale that assessed upper limb capacity with a maximal score of 10 points.

4.2.4 Data analysis

The position data of the hand was used to assess the reaching performance of the subjects in the different stages and conditions. Of main interest was the difference in amount of learning between the different feedback conditions in the learning stage. To determine the amount of learning we calculated the difference between the start (first cycle) and end (last cycle) directional error. The directional error was calculated as the angle between the vector from the starting position to the cursor position at 200 ms and the vector from the starting position to the target. We used 200 ms because we were primarily interested in the first part of the movement, when no error corrections have been made. [11, 19]

Outliers were removed when the movement deviation exceeded 90 or − 90 degrees from the target direction. We regarded these outliers as non-interpretable movements.

In the learning phase the trials were averaged per cycle (5 trials). The first (C1) and last (C33) cycles were used to calculate the amount of learning, defined as the difference in deviation between the first cycle of learning (C1) and the last cycle (C33). The higher the positive values the more is learned (less deviation). Retention was defined as the average of all 25 movements of the retention stage. The difference between the last learning cycle (C33) and the averaged retention value represented the amount of consolidation. Positive values indicate consolidation of the learned 30 degrees CCW rotation. The baseline and unlearning phase data were not analyzed.

4.2.5 Statistical Analysis

Statistical analysis in this study consisted of comparison of data between different feedback conditions and between the healthy elderly and stroke survivors groups using a repeated measure ANOVA (rmANOVA). For all significant main and/or interaction effects post-hoc tests with Sidak adjustments for multiple comparisons were performed to deduce which feedback conditions differed significantly from each other. The level of significance was defined as $\alpha<0.05$. All analyses were performed using the software package PASW (SPSS) 18.0.

The three feedback conditions were applied in six test orders (cKP-tKP-tKR, cKP-tKR-tKP, tKP-cKP-tKR, tKP-tKR-cKP, tKR-cKP-tKP, tKR-tKP-cKP). An interference of the preceding session would be present in the next sessions when differences between the first cycles of the different feedback orders were present. To investigate this possible interference we performed rmANOVA with the start samples (C1) of the learning phase as dependent variable, and the different orders of feedback conditions (6-levels) and group (2-levels) as between-subjects factors.

To test whether the amount of learning was significantly different among the feedback conditions and groups, a rmANOVA was performed with deviation as dependent variable and group (2-levels) as between-subjects factor and feedback (3-levels) and cycle (2-levels: C1 and C33) as within-subjects factors. Subsequently, to take individual differences in start and end values into account, the influence of feedback was tested using a rmANOVA with amount of learning as dependent variable and group (2 levels) as between-subjects factor and feedback (3-levels) as within-subjects factor. A similar rmANOVA was used to evaluate differences in amount of consolidation between groups and feedback conditions.

4.3 Results

Nineteen healthy elderly subjects and 19 stroke survivors participated in this study. Information about the age, hand dominance, time post stroke, FM and SULCS scores, and circle diameter for the healthy elderly and stroke survivors groups are shown in table 4.1.

4.3.1 Outliers and interference

For the healthy group a total of 72 trials with a deviation over 90 degrees were removed and 69 trials with a deviation less than -90 degrees. The percentage of outliers varied among the healthy group between 0.20 and 4.65 percent. A total of 141 outliers over (3x165x19=) 9405 movements were removed, resulting in 1.50 percent data reduction.

For the stroke group 237 trials with a deviation over 90 degrees were removed and

232 trials with a deviation of less than -90 degrees. The percentage of outliers varied among subjects between 0.40 and 11.3 percent, with one outlier of 18.6 percent. A total of 469 outliers over 9405 movements were removed, resulting in 5.0 percent data reduction.

No interference was present between the different measurement sessions for the different feedback orders for both the healthy elderly (p=0.755) and stroke survivors groups (p=0.347). This indicates that the learned task in the preceding measurement sessions did not interfere with the following measurement sessions.

Table 4.1: Information about the age, hand dominance, time post stroke, FM and SULCS scores, and circle diameter for the healthy elderly and stroke survivors group.

Characteristics	**Healthy Elderly**	**Stroke Survivors**
Age (yrs ± sd)	59.8±7.7	61.2±9.6
Hand dominance (R/L)	19 / 0	19 / 0
Sexe (M/F)	11 / 8	14 / 5
Time post stroke (yrs ± sd)	-	3.7±5.3
Affected side (R/L)	-	9 / 10
Fugl-Meyer (median (range))	-	61 (48-65)
SULCS (median (range))	-	10 (7-10)
BMI (kg/m2 ± sd)	25.8±2.3	25.7±2.8
Circle diameter (cm ± sd)	10.5±1.4	9.6±1.5

4.3.2 Learning

The rmANOVA showed that healthy elderly and stroke survivors were able to learn a visuomotor adaptation task, which is expressed in the significantly ($p<0.001$) lower deviation in the last cycle compared to the deviation in the first cycle of the learning phase. A typical example of the learning curve of a stroke survivor with the three feedback conditions is shown in figure 4.2. No significant difference in learning between healthy elderly and stroke survivors groups was present.

At the start of the exposure to the visual rotation both the healthy elderly and stroke survivors group experienced a higher deviation with the cKP feedback compared to tKP and tKR feedback ($p<0.001$), see table 4.2 and figure 4.3. At the end of the exposure, after 33 repetitions, there was a significantly higher last cycle deviation for tKR feedback compared to cKP and tKP feedback ($p<0.001$). The stroke survivors group showed significant higher last cycle deviations compared to the healthy elderly for the cKP and tKR feedback ($p\leq0.027$). Healthy elderly had comparable end levels of deviation for all three feedback conditions, see table 4.2 and figure 4.3.

The amount of learning is highest for both healthy elderly and stroke survivors with cKP feedback compared to both tKP and tKR ($p\leq0.026$), but there was no significant difference in amount of learning between the groups. A trend can be observed that stroke survivors learned less than healthy elderly with all feedback conditions, see table 4.2, although this trend was non-significant.

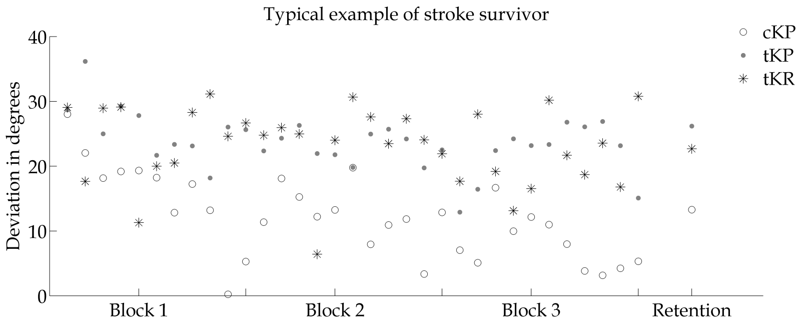

Figure 4.2: Typical example of the learning curves of a stroke survivor for the three different feedback conditions and the averaged retention value.

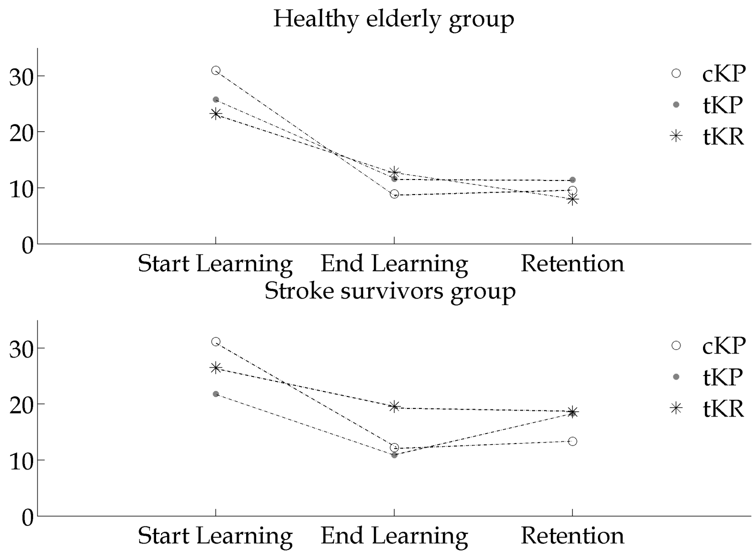

Figure 4.3: The averaged first and last cycle of learning and the retention are displayed for the different feedback conditions for the healthy elderly group and the stroke survivors group.

Table 4.2: Averaged start deviation (cycle 1), end deviation (cycle 33), amount learned, averaged retention, and amount consolidated*. *Amount consolidated is a positive value if it is consolidated; negative value is when the visual distortion is forgotten.

Feedback condition	Start (C1)	End(C33)	Amount learned	Averaged retention	Amount consolidated
			Healthy Elderly		
cKP	31.0±7.8	9.0±6.6	22.0±8.8	9.5±8.9	-0.6±10.4
tKP	25.8±10.6	11.6±7.5	14.2±13.7	11.4±12.7	0.1±11.4
tKR	23.2±11.7	12.8±9.7	10.5±11.4	8.0±12.3	4.8±9.0
			Stroke survivors		
cKP	31.2±12.3	12.2±8.8	18.9±16.8	13.4±5.7	-1.1±9.4
tKP	21.8±11.8	10.9±11.9	10.9±9.4	18.3±8.6	-7.4±9.0
tKR	26.5±10.3	19.6±11.8	6.9±12.1	18.6±9.2	1.0±10.8

To get more insight into the number of subjects and their amount of learning we analyzed the amount of learning for all subjects and presented the results in a histogram, grouped for all three feedback conditions for both groups, see figure 4. Most healthy elderly (17) were able to learn the task with more than 10 degrees by means of cKP feedback, 13 with tKP feedback, and 10 subjects with tKR feedback. Twelve stroke survivors were able to learn the task with more than 10 degrees with cKP feedback, eight with tKP and six subjects with tKR. More detailed inspection of the data revealed that two healthy elderly and six stroke survivors were not able to learn the task by more than 10 degrees independent of the feedback condition available.

4.3.3 Consolidation

No statistical significant difference between the retention values of the different feedback conditions was present; also healthy elderly and stroke survivors did not differ significantly in their retention values. The amount of consolidation, the difference between deviation in the last cycle of learning and the retention value, of the learned visual distortion after a 10-minute rest period was poorest after learning with tKP feedback compared to tKR feedback (p=0.005), but not to cKP feedback (p=0.495) for both healthy elderly and stroke survivors groups, see figure 4.3 and table 4.2.

4.4 Discussion

The objective of this study was to gain insight in the influence of nature and timing of augmented visual feedback on learning an arm motor task. We observed no differences in the influence of different feedback conditions on learning and consolidation between the healthy elderly and stroke survivors groups. Subjects learned best with cKP feedback, compared to tKP and tKR feedback. The amount of consolidation was poorest for tKP feedback. Highest last cycle deviation was observed with tKR feedback. Interestingly, two healthy elderly and six stroke survivors were not able to learn the task independent of the available feedback condition. Our findings are in line with other studies looking into the influence of augmented feedback on learning an arm motor task in stroke survivors. Cirstea et al. [7] observed

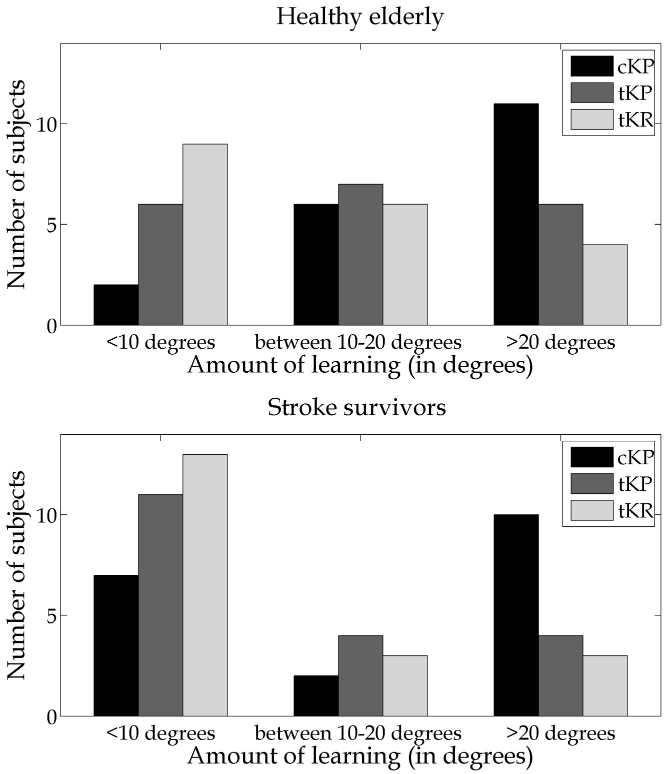

Figure 4.4: Histograms of categories of amount of learning (in degrees) over the three different feedback conditions for the healthy elderly and stroke survivors.

that most optimal learning of an arm motor task is achieved with the availability of concurrent feedback about the performance during movement execution and not with tKP or tKR feedback. A recent study of Acosta et al. [19] into the application of augmented feedback in virtual environments for stroke survivors observed that reaching abilities increased more when reaching was practiced with a visual arm representation (upper and lower arm orientation) than with a virtual gaming environment with only cursor feedback.

The lower amount of learning for tKP compared to cKP feedback can be explained by the mismatch between the availability of the performance error and the moment of error, as suggested in research [9, 20] from healthy subjects that observed poorer learning with tKP feedback compared to cKP feedback. Studies [21–23] looking into the influence of the timing of the feedback, either terminal or concurrent, observed higher cognitive load necessary for learning with terminal compared to concurrent feedback. This is confirmed when looking at the after-effects of learning a visuomotor task. When after-effects are present this means that the task is learned and remembered well. In a study of Hinder et al. [22] after-effects were only observed when the task was learned with cKP feedback and not with tKP and tKR feedback (in healthy subjects). This means that learning with cKP feedback was more consistent. In our experiment we observed similar results, which could mean that due to the higher attentional demands necessary to learn with tKP and tKR feedback compared to cKP feedback, the visual distortion task was not learned optimally with these feedback conditions.

The amount of consolidation is lowest after learning with tKP feedback, which may be related to a mismatch in the timing of the occurrence of the error and the information about the error with tKP. [9, 20] The amount of consolidation was not different between learning with cKP and tKR feedback, whereas cKP feedback did result in a higher amount of learning than either tKR or tKP feedback. This indicates that with cKP feedback the highest potential for learning and consolidation is achieved in this study.

Besides the lower amount of learning for tKP and tKR feedback compared to cKP feedback, we also observed that stroke survivors showed less complete learning of the adaptation task compared to healthy elderly subjects, demonstrated by the significant higher end deviations, as was also observed by Patton et al. [11]. Stroke survivors seem to need more repetitions than healthy subjects to achieve a more persistent adaptation, which was not reached after the applied 33 repetitions in our experiment. Research from Trempe and Proteau [24] in healthy subjects observed that more persistent after-effects (meaning anticipation of the perturbation, thus indicating learning) are present when a certain level of performance is reached. If stroke survivors would practice with more repetitions, at least with visual feedback, they might reach more complete learning, and if this is occurs better consolidation might be achieved.

The observed poor consolidation, especially for stroke survivors, could also be related to the limited amount of learning for some subjects. We observed that not all participants were able to learn the visuomotor task, independent of the provided feedback conditions. This could imply some subjects are not able to learn this type of task. Most subjects (29 of 38 subjects) learned the task with cKP feedback and least with tKR feedback (16 of 38 subjects). Besides this, a considerable larger amount of stroke survivors (six) than healthy elderly (two) were not able to learn the task with any of the feedback conditions. All patients were able to understand the instructions, execute the task, had a FM score greater than 48 points, and had no remarkable scores on the finger to nose FM subtest investigating propriocepsis. We looked into possible correlations between these factors and the amount of learning, but no relations were observed. It could be that other cognitive processes than were measured are responsible for the lower capability of learning the specific task by some participants in our study.

Based on our results it cannot be assumed these subjects are not able to learn at all. Therefore it is of interest to find out whether these low-capacity learners are able to learn other types of tasks and whether their lower capability to learn a certain task is reflected in limited arm motor function changes. It should also be studied whether the application of other types than visual feedback, such as (additional) touch or auditory feedback, would be more suitable for the learning strategies of this group.

All in all, the present study indicates that application of specific visual feedback has additional value on learning an arm motor task; whether cKP feedback has a beneficial effect on arm motor function in rehabilitation therapy should be examined in future research.

4.5 Conclusions

The visuomotor adaptation experiment as performed in this study provided insight into the influence of feedback conditions on motor learning and consolidation. The amount of consolidation was not different between learning with cKP and tKR feedback, whereas cKP feedback did result in a higher amount of learning than either tKR or tKP feedback. This indicates that with cKP the highest potential for learning and consolidation is achieved in this study. The higher attentional demand for learning with terminal versus concurrent feedback could explain why we observed little learning with terminal feedback. Also, attention should be paid to the capability of subjects to learn a specific task in therapy since we observed that two healthy elderly and six stroke survivors were not able to learn the visuomotor task.

4.6 References

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5

Influence of reaching direction on visuomotor adaptation: an explorative study.

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Abstract

Robotics is increasingly used in rehabilitation therapy of the hemiparetic arm after stroke. Several studies performed adaptation experiments to gain more insight in the underlying learning processes. In these studies adaptation during reaching movements in different directions is assessed. No information about influence of direction on the amount of learning to these separate directions is present. In this paper we assessed the effect of reaching direction on visuomotor learning.

Forty healthy subjects performed 48 movements to five different directions during adaptation to a 30 degrees visuomotor rotation. The execution error was defined as the initial direction error at peak velocity and after 100 ms after onset of the movement. The amount of learning was defined as the difference between the start value and the end value of the execution error.

A significant higher amount of adaptation in the movement towards the contralateral part of the body compared to reaching towards other directions was observed. When possible feedback and corrections mechanisms are taken into account; results indicate that subjects adapt most towards direction 2 and least towards direction 3.

Data of healthy elderly and stroke survivors would be essential to test whether observed results are present in these populations as well, which could have implications for motor relearning in rehabilitation therapy.

5.1 Introduction

Robotics is increasingly used in rehabilitation therapy of the hemiparetic arm after stroke. From several studies it is known that robot aided therapy can contribute to enhanced motor learning in stroke survivors. [1,2] Robotics can also be used to gain more insight into underlying learning processes by means of visuomotor adaptation experiments. It is known that stroke survivors have the ability to adapt to changing environments, which is the basis for their ability to learn. [3] Insight from adaptation experiments of healthy subjects [4,5] could also contribute to a better understanding of motor learning in stroke survivors. These studies could demonstrate the potential use of robotic error-enhanced therapy for motor learning in rehabilitation settings for stroke survivors.

Visuomotor adaptation experiments use a perturbed spatial relationship between vision and action to study motor (re)learning. This can be achieved by altering the visually perceived location of a target in such a way that it appears to be at a point in space different from its actual location. This results in a discrepancy between the observed and perceived location of a target. When subjects reach toward a target without being able to see their hand, they will initially reach toward the visual location of the target and will not be able to reach the target. Due to the provided error-feedback subjects are able to learn to anticipate to the applied misalignment, after repetitive movements, this can result in a decreased error. [6]

Generally in these experiments reaching movements are made in different directions. Data from different movement directions is gathered to constitute a learning curve. [3,7] Earlier research has been performed into the amount of trials necessary to learn to one or more directions. [8] They found slower total rate of learning of the applied rotation with multiple directions, compared to one direction. But the rate of adaptation was equal for the different directions when plotted as a function of the number of repetitions to the specific direction. This would indicate that a similar adaptation occurs to each direction independently and there is no difference between adaptation rates into different directions. However, recent results from our pilot study gave indications that differences in amount of motor adaptations might exist between different directions. Therefore, in this explorative study we further explore the influence of movement direction on visuomotor adaptation in healthy subjects.

5.2 Methods

5.2.1 Subjects

Forty healthy subjects between the ages of 18 and 26 were included in the experiment. They all had normal or to normal corrected vision, were right handed and had no motor or cognitive impairments. All subjects gave their written informed consent prior to the experiment.

5.2.2 Set-up and apparatus

Subjects were seated and made reaching movements in the horizontal plane with their right arm holding the end effector of a 3D haptic robot, the HapticMASTER (Moog FCS, Nieuw-Vennep, the Netherlands). The arm robot was placed in a closet-like box. The combination of a mirror and projection screen gave the illusion that

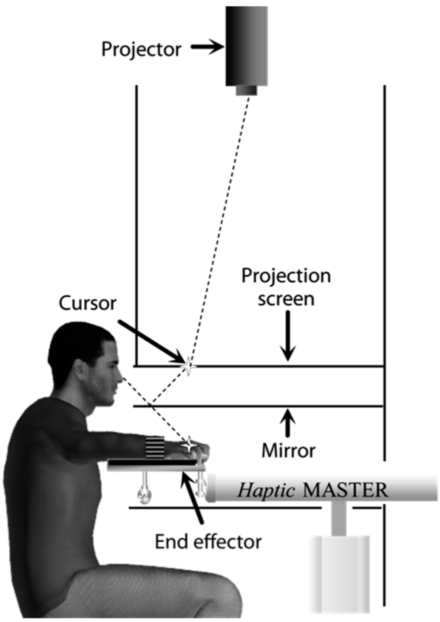

Figure 5.1: A schematic view of how the projection of the cursor is viewed by the subject. The subject is holding the end effector of the HapticMaster.

the projected image was in the same horizontal plane as the hand. The subjects were instructed to look into the mirror to see a projection of their right-hand position on a screen located parallel and just above the mirror. The mirror also prevented direct sight of the arm. The arm was supported against gravity by a support mechanism that allowed low-friction movements over the underlying surface; see figure 5.1. The visual scene was updated with a frequency of 100 Hz.

5.2.3 Reaching task and procedure

Subjects performed centre-out reaching movements with their right hand to one of five different targets equally spaced (72 degrees apart) about the perimeter of a circle of 10 cm radius (figure 5.2). The hand position was indicated with a 8 mm blue sphere, in the following referred to as “cursor”. The targets were presented as yellow spheres with a 17 mm diameter.

The starting posture was obtained by a shoulder plane of elevation of 45 degrees, shoulder elevation angle of 90 degrees, and elbow flexion of 90 degrees [7]. At the start of each trial, a target was presented and a short beep triggered the initiation of the movement. A cycle consisted of one trial to each direction (five movements). The order of the directions was randomized per cycle to prevent sequence learning. Between movements, the cursor was made invisible while the arm was returned to the initial position by the robot.

Visual distortion of hand position was a 30 degrees counterclockwise rotation about the starting location of movements. The experiment consisted of two phases. In the familiarization phase subjects became familiar with the robot, performing

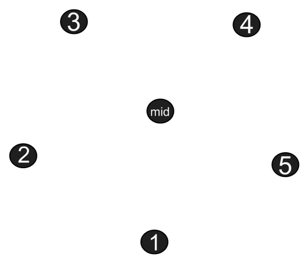

Figure 5.2: Localization of the five targets and the midpoint of the circle.

normal movements without rotation. In the learning phase subjects performed 60 movements to each different direction within the visual-rotated field (total of 60 x 5 = 300 movements). Every fifth trial was a catch trial; no feedback was visible for the subjects. These trials were not used in the analysis, resulting in a total of 48 movements to each direction available for data analysis.

5.2.4 Data analysis

Movement position of the hand was used to assess the execution error of the subjects during the learning phase. The direction error at peak velocity was used as a measure of the execution error. The direction error was defined as the angle between the vector from the starting point to the cursor position at maximum velocity and the vector from the starting position to the target. A positive value meant that the movement path was on the counterclockwise side of the ideal path, and a negative value meant a movement path on the clockwise side of the ideal path.

A total of 48 repeated movements to all five targets is obtained. From this, five learning curves of all the different targets can be plotted. The amount of learning is calculated as the difference between the start (first sample) and end (last sample) value of the execution error per subject and per direction. This results in a positive value if the end execution error is lower than the start execution error. This was calculated for all forty subjects per direction, for all five directions.

The execution error at peak velocity averaged over all subjects, per direction, at start and end of the learning phase, and the average amount of learning ± standard deviation.

The movement speed was varied over the subjects. No interaction effects were observed over the movement directions. But to exclude possible effects of perceived feedback and movement corrections due to the different movement speeds, we also performed analysis at 100 ms after onset of the movement. Subjects will not have been able to generate any feedback corrections in the first 100 ms after movement onset.

5.2.5 Statistics

The amount of learning is compared between the five different movement directions using a five levels (different directions) repeated measures ANOVA. If any differences were found, post hoc comparisons were made and Sidak adjustments were used to correct for multiple tests. If missing values were present for one of the directions, data of that subject could not be used in the statistical analysis.

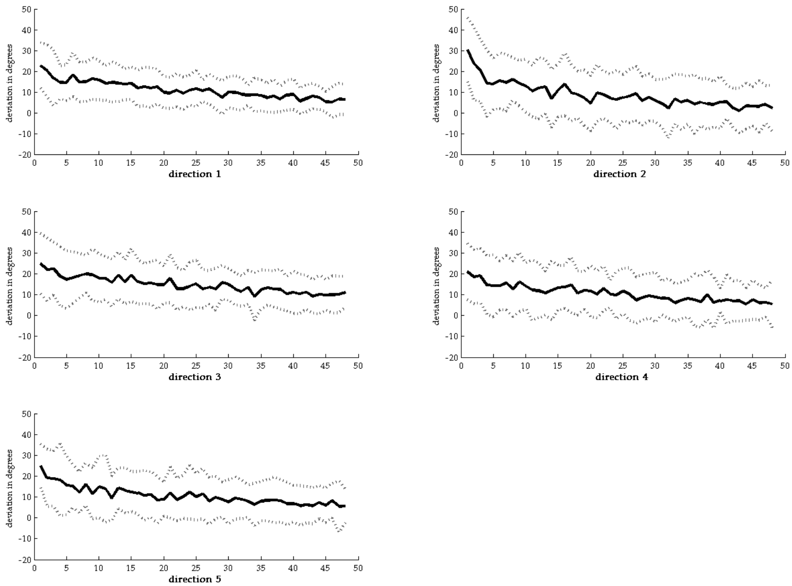

Figure 5.3: The learning curves of the execution error for the five directions. The lines represent averages across all subjects, plus and minus the standard deviation.

5.3 Results

5.3.1 Direction error at maximum velocity

In figure 5.3 the averaged learning curves plus and minus their standard deviation are shown for the different directions. From the learning curves it can be observed that direction 2 seems to have a larger execution error at the start and a smaller execution error at the end of the learning phase, compared to the other four directions. Per direction the execution errors at the start of the movement (the first sample) and at the end of the movement (last sample) were averaged over the subjects (table 5.1).

These observations were supported by a statistical repeated measures ANOVA analysis. Near significant different start values were observed between direction 2 and 1 ($p=0.059$), and direction 2 and 4 ($p=0.052$). A significant different end value was observed between directions 3 and 2 ($p=0.00$), 3 and 1 ($p=0.005$), and 3 and 5 ($p=0.043$).

A significant difference in amount of learning between the different directions was found ($p<0.05$). Post hoc analysis revealed significantly larger amount of learning towards direction 2, compared to three other targets (1, 3, 4), respectively, $p=0.007$, $p=0.014$, $p=0.041$. A near significant effect was observed between directions 2 and 5 ($p=0.064$). No other statistical significant differences were revealed by this analysis.

Table 5.1: The execution error at peak velocity averaged over all subjects, per direction, at start and end of the learning phase, and the average amount of learning ± standard deviation.

	Execution error ± standard deviation		
Direction	**Start (n=40)**	**End (n=40)**	**Amount of learning (n=40)**
1	22.13±11.01	6.31±7.10	15.82±12.30
2	30.54±15.37	1.72±11.11	28.83±20.63
3	25.07±13.88	11.18±7.53	13.89±16.76
4	20.55±13.12	5.37±11.22	15.18±15.11
5	23.42±11.72	6.26±9.48	17.16±13.42

5.3.2 Direction error after 100 ms

From the start and end values and the amount of learning it can be observed that direction 2 seems to have a larger execution error at the start and a smaller execution error at the end of the learning phase, compared to the other four directions. Per direction the execution errors at the start of the movement (the first sample) and at the end of the movement (last sample) were averaged over the subjects (table 5.2).

These observations were supported by a statistical repeated measures ANOVA analysis. A significant different end value was observed between direction 3 and 2 ($p=0.004$), and 3 and 1 ($p=0.021$). No further statistical significant differences were revealed (amount of learning $p>0.65$, start value $p>0.87$).

We also tested whether the observed higher initial value towards direction 2 was due to the order of movement directions. No order effect between the directions was found.

Table 5.2: The execution error after 100 ms averaged over all subjects, per direction, at start and end of the learning phase, and the average amount of learning ± standard deviation.

	Execution error ± standard deviation		
Direction	**Start (n=33)**	**End (n=37)**	**Amount of learning (n=30)**
1	28.82±25.32	5.89±8.91	22.65±25.02
2	33.89±25.02	2.33±13.62	31.87±31.38
3	30.68±21.52	11.37±9.74	19.43±23.69
4	30.75±17.02	9.85±16.87	23.70±20.76
5	36.60±23.14	5.82±10.15	29.07±20.21

5.4 Discussion

In this study we explored the influence of movement direction on amount of visuomotor adaptation in healthy subjects. Analysis at peak velocity show larger adaptation to direction 2 compared to other directions. When possible feedback and corrections mechanisms are taken into account; results indicate that subjects adapt most towards direction 2, and least towards direction 3.

The difference in observed directional errors at peak velocity and after 100 ms of the onset of the movement can be related to feedback and corrections mechanisms. The movement time from onset till peak velocity is typically around half of the movement (>250 ms). [8] Therefore subjects had more time, compared to the directional error at 100 ms, to execute corrections for the calculated directional error at peak velocity. Observed differences in the end values of direction 3 and 2 directions are also present after 100 ms. This could indicate that, in line with a study of Krakauer et al. [9] who found that different adaptation rates are present for different directions, updating of the internal model occurs in different ways for different directions, independent of the amount of feedback available. It is of interest to notice that main results are observed in the directions across the midline.

The observed differences of adaptation into different directions may also be related to the contribution of multi- or single joint movements. From literature is suggested that movements across the body usually have a more curved path and are accounted for by more single joint movements. [10] During the performed task in the present study, both multi- and single -joint movements were necessary to execute movement towards the different directions. Although no kinematic data from joint angles was available, it could be there is a different use of elbow and shoulder muscles for the different directions. [11-13] This information would be of interest for understanding motor learning and movement control in neurological patients. It is known that stroke survivors have a limited amount of degrees of freedom (DOF) of the hemiparetic arm due to synergistic movement patterns. [14,15] Stroke survivors generally experience difficulties of single or multi-joint movements requiring extension of the elbow, due to the flexion synergy consisting of a combination of elbow flexion and shoulder abduction. If motor adaptation is influenced by movement direction in stroke survivors as well could have implications for future stroke rehabilitation.

In this explorative study we did observe a difference in amount of adaptation between different directions, which should be studied in more detail in future research. Examples are calculating the rate of adaptation by means of curve fitting instead of the amount of adaptation. Also data of healthy elderly and stroke survivors would be essential to test whether observed results are present in these populations as well, which could have implications for motor relearning in rehabilitation therapy.

5.5 Conclusion

Subjects show larger adaptation towards direction 2 at peak velocity compared to other directions. When possible feedback and corrections mechanisms are taken into account; results indicate that subjects adapt most towards direction 2, and least towards direction 3. Data consisting of the constitution of different movement directions in one learning curve should be analyzed with care while movements into different directions seemed to be learned differently.

5.6 References

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6

Learning a visual distortion task is not influenced by movement direction for healthy elderly and mildly-affected stroke survivors.

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Abstract

In stroke rehabilitation reaching movements are practiced within different parts of the workspace. Little information is available about differences in learning between separate reaching directions in stroke survivors. Therefore, we assessed the influence of reaching direction on visuomotor learning in 19 healthy elderly and 19 mildly-affected stroke survivors. Subjects performed a visual distortion task into five different directions. There were no significant differences in learning between directions, except for higher deviation at the start of the learning phase for stroke survivors in one direction. Learning a visual distortion didn't vary between movement directions for healthy elderly and stroke survivors, suggesting that this doesn't have to be taken into account when practicing reaching in different areas of the workspace during rehabilitation.

6.1 Introduction

Six months after stroke, 30 - 66 percent of the stroke survivors have no proper arm-hand function. [1] This limits their ability to manipulate objects and thus the functional use of the hemiparetic arm. When looking specifically at reach performance, one of the commonly observed changes after stroke is a reduction in reaching distance. [2, 3] Reaching movements with the hemiparetic arm are further characterized by decreased movement speed, reduced smoothness, altered coordination, and abnormal muscle synergies. [2]

Restoration of arm and hand function is crucial to improve independence in activities of daily life. Improvement of lost functionality can be stimulated through motor relearning in stroke rehabilitation. In rehabilitation reaching movements are practiced within different parts throughout the workspace to improve arm function. [4] Since stroke survivors show difficulties in simultaneously extending the elbow and flexing the shoulder, especially reaching towards the lateral and distal part of the workspace is limited. [5] Therefore it is important to include all areas of the workspace during practice to induce functional use in activities in daily life.

Learning of reaching movements towards different targets involves updating of the internal models for motor planning to induce increased ability to move. [6] Research has shown that stroke survivors are able to learn a new movement task. [7] Nevertheless, the amount of learning of stroke survivors is less than of healthy subjects. [7] For motor skill acquisition it is important to understand whether motor learning ability of reaching varies across different directions of the workspace. Results from a previous study [8] indicate that differences in motor learning seem to exist between different movement directions in right-handed young healthy subjects. More specifically we observed a higher amount of learning into the reaching movement towards the body across the midline. [8]

The influence of movement direction on motor learning can be tested by inducing a visual distortion during a reaching task. In these visuomotor adaptation experiments perturbed spatial relationships between vision and action are used to study motor learning. Generally, reaching movements towards different directions are pooled to constitute one learning curve in such experiments. [7, 9] However, the question arises if this averaging across different movements directions is valid if learning differs between these directions. Moreover, the differences observed in healthy subjects may be even more pronounced in stroke survivors considering their less selective control of multi-joint arm movements. [2] If learning differs across areas of the workspace, different numbers of repetitions or strategies could be necessary for stroke survivors to improve at a reaching task in a certain part of the workspace. Different exercises may then be necessary to induce functional recovery.

In this study we explored the influence of different movement directions on learning a visual distortion reaching task in stroke survivors. We also included a healthy elderly group to provide a reference frame for interpretation of the findings in stroke survivors. Although information about adaptation in healthy young subjects is available from several motor adaptation experiments [9, 10], this is not the case for healthy elderly, who likely have lower adaptation capabilities compared to young subjects. [11, 12]

6.2 Methods

6.2.1 Subjects

Nineteen healthy elderly and 19 stroke survivors were included in this study. Prior to the experiment all subjects gave their written informed consent. Inclusion criteria for both healthy subjects and stroke survivors were: ability to understand and follow instructions, age between 40 and 75 years, ability to repetitively perform reaching movements without shoulder or upper limb pain, and for stroke survivors the time post-stroke had to be more than six months.

The protocol was approved by the local ethics committee.

6.2.2 Experimental set-up

Subjects were seated on a chair. Their trunk was strapped with two crossed seat belts to prevent trunk movement. A wrist splint was attached to the hand, to stimulate arm movements instead of wrist movements. The table was placed as close to the subject as possible. The table height was adjusted to the height of the hand when the elbow was flexed 90 degrees and the upper arm was aligned with the trunk. The vision of the subject's arm and hand was obstructed by a shelf, see figure 6.1. The subject held a hand grip through which hand position data was measured by means of four encoders (Wachendorff SZG65-1250-N-UpH05-05). A representation of the hand was visualized as a 20 mm red sphere on the shelf above the arm, projected by a beamer (Optoma EX 525ST). Subjects were provided with concurrent feedback about their movement performance.

Subjects made centre-out reaching movements, starting from the midpoint of the circle, with their dominant (healthy elderly) or affected arm (stroke survivors) to one of five targets. The targets had a diameter of 20 mm. The targets are equally spaced (72 degrees) about the perimeter of a circle, see figure 6.2. The diameter of the circle equals 95 percent of the maximal active range of motion of the subject, which was determined prior to the start of the experiment by performing three circular reaching movements.

6.2.3 Experimental protocol

Each session consisted of repetitive movements towards the five targets, with or without the visual distortion. The order of the targets was randomized in each cycle. A cycle consisted of one movement to each target (five movements), and each block consisted of 11 cycles (=55 movements), with 30-second time intervals between the blocks. All subjects performed a total of 55 cycles of five movements per session, broken down into the following phases:

- The baseline phase consisted of two blocks of reaching movement, with a total of (2x5x11=) 110 repetitions. Subjects became familiar with the task and apparatus. The cursor was projected constantly during the movements. No rotation and additional feedback were provided.

- The learning phase consisted of three blocks of reaching movements (3 x 5 x 11= 165). A 30 degrees counter clockwise (CCW) visual distortion of the hand position about the starting location of the movements was applied. A line representing the actual movement path was displayed as feedback during movement execution.

Figure 6.1: Overview of the experimental set-up. Subjects sat behind the in height adjustable table. They held a hand grip through which hand position was measured. The vision of the arm and hand is obstructed, and a representation of the hand is visualized on the shelf above the arm, projected by a beamer.

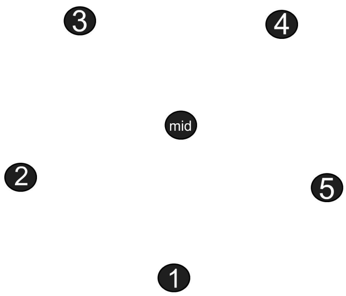

Figure 6.2: Orientation of the five targets and the midpoint of the circle.

For the stroke survivors the Fugl-Meyer assessment [13] and the Stroke Upper Limb Capacity Scale (SULCS) [14] were scored. The SULCS is a hierarchical scale that assesses upper limb capacity on the activity level with a maximal score of 10 points.

6.2.4 Data analysis

The position data of the hand was used to assess the reaching performance of the subjects between the different directions in the learning phase.

To calculate the amount of learning we used the initial direction error at 200 ms after onset of the movement, in the following referred to as deviation. The directional error was calculated as the angle between the vector from the starting position to the cursor position at 200 ms and the vector from the starting position to the target. We used 200 ms because we were primarily interested in the first part of the movement, when no error corrections have been made. [7, 15]

Outliers were removed when the movement deviation exceeded 90 or -90 degrees from the target direction.

A total of 22 repeated movements to every five targets were performed in the baseline phase and 33 in the learning phase. For the baseline phase the last five movements per direction were averaged. For the learning phase the start and end deviation per direction were used to calculate the amount of learning; this is the difference between the start and end value of the execution error per subject and per direction. This results in a positive value if the end value is lower than the start value.

6.2.5 Statistical Analysis

To test whether differences between directions exist in the baseline and learning phase separate repeated measure ANOVA's (rmANOVA) were performed with baseline, start, and end value, and amount of learning as dependent variables and direction (5-levels) as within-subjects factor for the healthy elderly. For the stroke survivors we performed similar rmANOVAs, with arm tested as additional between-subjects factor.

For all significant effects post-hoc tests with Sidak adjustments for multiple comparisons were performed to deduce which directions differed significantly from each other in the case of a significant effect of direction. The level of significance was defined as $\alpha<0.05$. All analyses were performed using the software package PASW (SPSS) 18.0.

6.3 Results

6.3.1 Healthy elderly

All healthy elderly were right handed and performed the test with their right arm. Mean age was 59.8 years, see table 6.1 for other characteristics.

In the baseline phase a total of 52 outliers over (22x5x19=) 2090 movements were removed, resulting in 2.5 percent (0 - 6.2 percent) data reduction. In the learning phase a total of 43 outliers over (33x5x19=) 3135 movements were removed, resulting in 1.4 percent (0 - 3.0 percent, one outlier of 10.9 percent) data reduction.

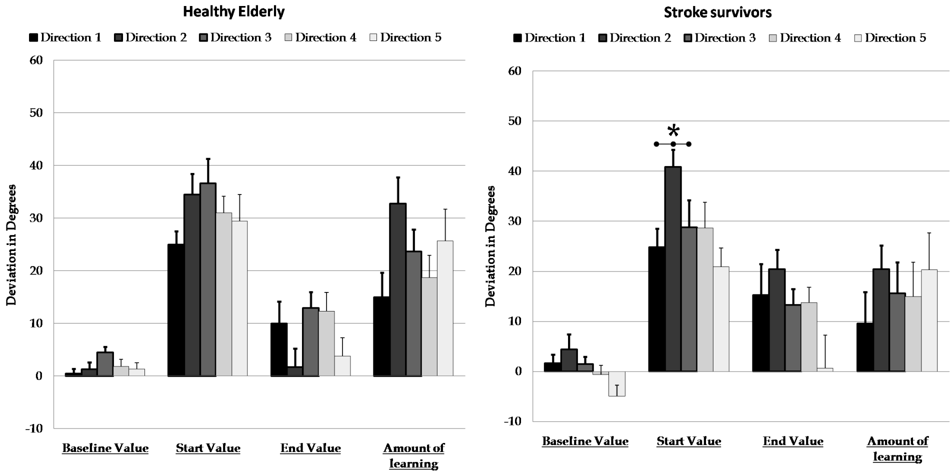

Figure 6.3: The mean baseline, start and end values, and amount of learning for the healthy elderly and stroke survivors for the five movement directions plus the standard error of the mean (SEM) (* indicates significant differences).

Table 6.1: Information about the age, hand dominance, time post stroke, FM and SULCS scores, and circle diameter for the healthy elderly and stroke survivors.

Characteristics	Healthy subjects	Stroke Survivors
Age (yrs ± sd)	59.8±7.7	61.2±9.6
Gender (M/F)	11 / 8	14 / 5
Time post stroke (yrs ± sd)	-	3.7±5.3
Affected side (R/L)	-	9 / 10
Fugl-Meyer (median (range))	-	61 (48-65)
SULCS (median (range))	-	10 (7-10)
Circle diameter (cm ± sd)	10.5±1.4	9.6±1.5

All healthy elderly were able to move to all directions without any initial deviations in the baseline phase ($p=0.129$). In the learning phase no significant ($p\geq0.098$) differences between the different directions were observed for the start and end levels, and amount of learning, see also figure 6.3.

6.3.2 Stroke Survivors

All stroke survivors were right-handed, of which nine subjects performed the test with their right-affected arm and ten subjects with their left-affected arm. Mean age was 61.2 years, see table 6.1 for other characteristics.

In the baseline phase a total of 91 outliers over 2090 movements were removed, resulting in 4.4 percent (0 - 7.6 percent) data reduction. In the learning phase a total of 105 outliers over 3135 movements were removed, resulting in 3.4 percent (0 - 9.7 percent) data reduction.

In the baseline phase a significant ($p=0.043$) effect of arm was observed. The deviation was on average 2.2 degrees in counterclockwise direction for the right-affected arm and -1.2 degrees in clockwise direction for the left-affected arm.

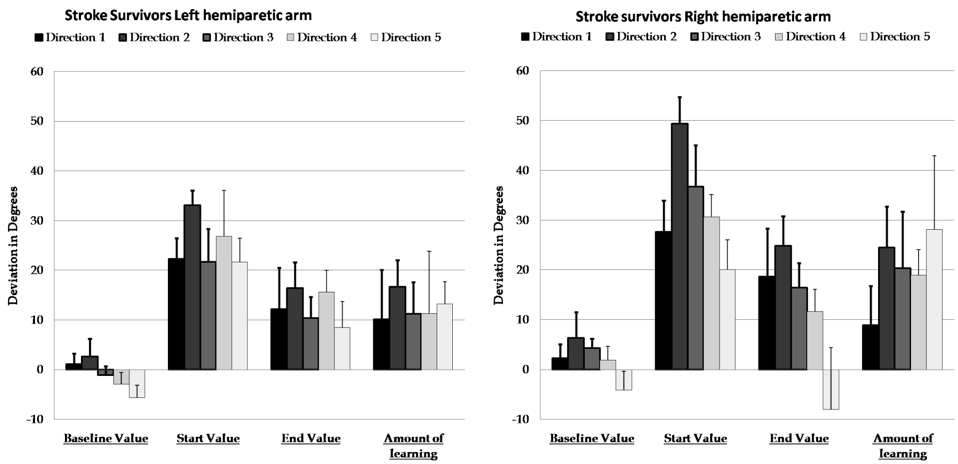

Figure 6.4: The mean baseline, start and end values, and amount of learning for the left and right hemiparetic arm of stroke survivors for the five movement directions plus the SEM.

In the learning phase, a higher start value for direction 2 compared to direction 1 (p=0.011) and 3 (p=0.037) was the only significant direction effect (p=0.027), see also figure 6.3. Despite the observed lower end levels for direction 5 (see figure 6.3), this did not reach significance (p=0.050). More importantly, looking at the amount of learning from start to end deviation per individual, no significant differences between movement directions were observed (p=0.252). It was examined whether higher initial deviations could be due to reaching towards certain directions for the very first time during the learning phase. As can be observed in table 6.2, there are no indications that there were more initial exposures to direction 2 compared to the movements towards other directions.

Table 6.2: Information about the amount of times directions 1 to 5 were practiced at initial exposure to the rotation for healthy elderly and stroke survivors.

Direction	**1**	**2**	**3**	**4**	**5**
Healthy elderly	7x	2x	4x	2x	4x
Stroke survivors	2x	5x	4x	2x	6x

In order to test whether differences between the left- and right-affected arms were present, we looked at the separate data of the left- and right-affected arm, see figure 6.4. We noticed that the higher start value in direction 2 is mainly present in the right-, and not in the left-affected arm data. It can also be seen that in the right-affected arm data the end levels of direction 5 is lower compared to the other directions, see figure 6.4. However, differences between left- and right-affected arm were not significant (p=0.258).

So, despite a difference in start value of direction 2, amount of learning was not influenced by movement directions or affected arm.

6.4 Discussion

In this study we explored the influence of movement direction on learning a visual distortion reaching task in healthy elderly and stroke survivors. We observed that for healthy elderly and stroke survivors learning a visual distortion is not different between movement directions. For the stroke survivors the only statistically significant difference was a higher start value towards movement direction 2. The finding that the amount of learning was not different between movement directions is not in line with our expectations based on previous research [8]. Those differences in amount of learning in young healthy subjects were mainly due to a higher start value in that specific contralateral direction. [8] Remarkably, this specific difference was also observed in the present study in predominantly the right-affected stroke survivors, although not in healthy elderly.

This higher start value in the contralateral direction for right-affected arms might be explained by the observation made in the study of Gabbard and Rabb [16], where healthy subjects performed reaching movements towards targets in the entire range of the workspace. Subjects selected themselves whether they used their left or right arm to reach towards the targets. It was observed that subjects preferred to execute reaching movements towards the midline and same side (ipsilateral) of the body with the ipsilateral arm, whereas movements towards the contralateral part of the workspace were performed using the arm on that side of the workspace (ipsilateral), irrespective of hand dominance. [16] Thus, since the right-affected stroke survivors would probably have reached to the contralateral target with the other arm in a different setting, this may contribute to the initial higher start value of the right arm towards the target across the midline of the body compared to the other directions. This could imply for rehabilitation therapy that practicing contralateral reaching movements with the hemiparetic arm may not be essential to enhance use of the arm in daily life activities in stroke survivors.

On the other hand, the ten stroke survivors that performed the reaching task with their left-affected arm did not show similar deviations for movements towards their contralateral targets. This might be explained by differences in motor control between left and right hemispheres. In a study of Schaefer et al. [17] stroke survivors with either left or right hemisphere damage performed a visual distortion task with their ipsilesional arm. They observed that stroke survivors with left hemisphere damage had problems with adaptation of the initial direction but not with the final position control, while stroke survivors with right hemisphere damage displayed problems with online corrections to the final position but not with initial direction control. [17] Therefore it may be that the stroke survivors with the left-affected arms (right hemisphere damage) in our study seem to be better able to control the start of the movement, and might therefore lack the initial deviation towards the contralateral target, as was observed in the right-affected arms in the present study. Although no conclusive results can be observed regarding differences between left and right hemiparetic arm control, these findings suggest that overall learning performance for the left and right hemiparetic arm does not seem to be consistently different in the present study.

In terms of reaching performance, limitations in reaching distance account for most problems for stroke survivors several months after stroke. [2, 3, 5] Nevertheless, when looking into the control of reaching movements, in terms of smoothness and directional control, towards various proximal, distal, ipsilateral, and contralateral targets, no differences between movement directions were present [3]. This is confirmed by a study where directional control of reaching movements was preserved in mildly-affected stroke survivors. [18] However, severely-affected stroke survivors did display constraints in directional control during reaching. [18]

This indicates that movement execution of reaching is similar across the workspace in mildly-affected stroke survivors when assessed several months after stroke. Together with the findings in the present study concerning learning a new task, this suggests that improvement of reaching after stroke isn't different across a variety of movement directions; irrespective of potential limitations in reaching performance.

All in all, the findings from this study showed that the individual amount of learning did not vary between movement directions. This indicates that first of all, in visuomotor experiments reaching movements towards different directions can be represented by one learning curve for both healthy elderly and stroke survivors. Furthermore, these findings imply that it may not be essential to take differences in learning across different parts of the workspace into account when practicing reaching movements in stroke rehabilitation. However, whether these findings are also valid for the more severely affected stroke survivors should be studied in future research.

6.5 Conclusions

No differences in learning a visual distortion task were observed between movement directions for healthy elderly and mildly-affected stroke survivors. Thus, visuomotor experiments performing reaching movements towards different directions can be represented by one learning curve. For clinical practice, these findings imply that no difference in motor learning is expected for practicing reaching in different areas of the workspace for mildly-affected stroke survivors.

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7

General Discussion

Restoration of upper limb function is a major aim in stroke rehabilitation as a good arm/hand function is crucial in regaining an independent living. The fact that six months after stroke, 30 - 66 percent of the stroke survivors still have no proper arm-hand function [1] underlines the importance of an adequate treatment. Improvement of lost functionality is stimulated through motor relearning during stroke rehabilitation. Functional recovery of the arm, after stroke, can be stimulated by a high frequency and/or a longer duration of the exercises. [2-4] Also the active participation in exercise therapy is associated with improved motor performance of the affected arm. [5, 6] There are indications that the use of augmented feedback during exercises can stimulate the learning process by making patients more aware of their performance. [7, 8] With the upcoming innovative technologies, such as robotics and virtual reality, more and more possibilities arise to apply augmented feedback in rehabilitation therapy. In the systematic review [9] we conducted, 23 studies were included describing the different modalities of augmented feedback, such as music, touch, scores, and movement paths which are applied to the patient groups in different virtual rehabilitation environments. However, in most studies several modalities were applied simultaneously and only few authors [10, 11] studied the effect of the separate components (nature, timing, and type) of augmented feedback on motor learning.

The aim of this thesis was to study the influence of nature, timing, and type of augmented feedback on motor skill relearning of arm movements during reaching tasks in stroke rehabilitation therapy.

Type of feedback

With the upcoming availability of robotics [12, 13] and virtual reality [7, 14] in rehabilitation therapy new opportunities arise for using augmented feedback. Due to the integrated sensors in rehabilitation robotics, the quality of the movements can be measured simultaneously. Depending on the type of robotic device, different modalities of sensory feedback can be applied, i.e. assistive-forces, guidance, or resistive-forces. [12] In combination with a virtual environment different kinds of visual feedback, i.e. score on a screen, or movement path, can be added during the training. Within such virtual environments additional auditory feedback, i.e. background music, or beeps, is extensively applied.

Auditory feedback

From the literature review it became clear that the auditory feedback provided during therapy consists mainly of verbal comments provided by the therapist. [9] In case of virtual environments music and beeps were reported as additional feedback. So far, only one study [15] specifically studied the separate effect of auditory feedback in stroke survivors. In this study subjects trained to minimize trunk movement during reaching exercises by touch (a strap) or by sound (beeps). It was observed that stroke survivors learned faster and better during the auditory condition. [15] As far as we know, no other research has been described in scientific literature focusing on the effect of auditory feedback during rehabilitation therapy. Therefore it can be concluded that the specific influence of auditory feedback on motor learning is still unclear.

Sensory feedback

With the application of sensory feedback by using forces applied to the upper extremity during movement execution, the internal proprioceptive system might be activated more than during normal movement for stroke survivors. Findings from the literature review in chapter 2 indicate potential beneficial effects of sensory feedback. All five studies, using a kind of sensory feedback in their training, reported a beneficial effect on motor performance. In our experimental training study described in chapter 3 five stroke survivors participated in a 6-weeks training. During the training active reaching movements through a virtual tunnel were performed. When the reaching movement deviated from the applied tunnel, sensory feedback was provided as resistance on shoulder and elbow joints, by the robotic device. It was observed that the amount of use of the feedback varied over the subjects between 7.4 and 14.7 percent during the entire training. Despite this low amount of use of the available feedback, improvements on kinematics were observed, but not on Fugl-Meyer score. [16]

The limited use of sensory position feedback by stroke survivors during reaching exercises suggests that this type of feedback is not a crucial component for motor relearning after stroke. This was confirmed by the additional research we performed to gain insight in the use of sensory feedback in current clinical practice. [17] In this observational study a total of 14 recorded physical and occupational therapy sessions were systematically analyzed using auditory, visual, and sensory feedback as categories. The majority of the feedback provided during a 30–minutes therapy session by a therapist was verbal (55 percent), while sensory (or assistive force) feedback (5 percent) was hardly provided. [17]

This finding is in line with the results from research on assistive forces provided by robotic devices. Kahn et al. [18] showed in his study on robot assisted movement training that exercise therapy focusing on active initiation and execution of movements is associated with improved arm function. The study of Wolbrecht et al. [19] showed that assistive forces induce ‘slacking’ behavior of the human motor control system. This suggests that when the subject is given the opportunity he will reduce his efforts and let the robotic device do the work. Lotze et al. [20] demonstrated that active training led to significant improvements in motor performance (range, duration and velocity) whereas passive training did not. The importance of active movement execution is also underlined in brain studies in which cortical activity [21] and motor cortex excitability [6] are larger during active execution of movements, than during passive movements. These results suggest that application of sensory feedback by means of robotic devices should focus on the active component of learning.

Visual feedback

Alongside the developments in the field of robotics is the increasing use of virtual reality environments in rehabilitation therapy. Display of exercises on screens creates opportunities to use a wide scale of visual information, and thus enable visual feedback, to stimulate motor relearning.

Although it is known that healthy subjects are able to learn to integrate information from different feedback modalities [22], visual information seems to be dominant over other modalities when several information sources are available. [23, 24] In stroke survivors this visual reliance during movement execution is believed to be present to an even higher extent. [25, 26] This visual dominance or dependency is underlined by a remark of one of the stroke survivors participating in our study 'If I don't look at the cup of coffee while I'm walking across the room, it will slip out of my hands.'

The high potential of visual feedback became also evident in the literature review (chapter 2). In this review we observed that all studies made use of visual feedback, either alone or in combination with auditory and/or sensory feedback. Thirty-five percent of the studies using visual feedback reported beneficial effects on motor activities (such as Fugl-Meyer score) and 58 percent on kinematic outcome measures. [9] This indicates that the application of visual feedback in rehabilitation technologies may be an essential factor for the highly visually dependent stroke survivors.

Nature and timing of feedback

As described in the introduction of this thesis, motor learning is often subdivided in three phases; the cognitive, associative and autonomous phase. In the cognitive phase different strategies are tested to perform the movement. The performance gains are often large, whereas performance level is rather inconsistent. The associative phase of learning starts when the most effective way of performing the movement has been determined. Fine tuning of the motor skill occurs. The autonomous phase is reached after intensive practice. The practiced motor skill has become more or less automatic. [27]

In this thesis we focused on the effect of augmented feedback in the cognitive phase of learning. In the experimental study in chapter 4, we studied the effect of concurrent and terminal knowledge of performance (cKP and tKP) and terminal knowledge of results (tKR) feedback on learning a visual distortion task. We observed that both healthy elderly and stroke survivors learned best with cKP feedback, compared to tKP and tKR feedback. This observation might be explained by the fact that during the cognitive phase of learning a high attentional demand is necessary for the specific motor task. This leaves little space for additional attentional demands for the available feedback. Since concurrent feedback is known to require less cognitive demands compared to terminal feedback [28], the application of cKP feedback in the cognitive phase seems to be most optimal. In later phases of learning (associative and automaticity phase) lower attentional demands are necessary for the execution of the movement [27], leaving more room for other learning strategies.

Influence of movement direction on motor learning

In large parts of the stroke population reaching movements with the hemiparetic arm are characterized by decreased movement speed, reduced smoothness, altered coordination, and abnormal muscle synergies. [29] The reaching movements can be stimulated through motor relearning in stroke rehabilitation by practicing these reaching movements in different directions of the individual workspace. [30] Whether different directions have influence on motor learning is not known from literature.

To examine the possible influence of movement direction on motor skill learning, we performed visual distortion experiments. From literature it becomes clear that generally, reaching movements towards different directions are pooled to compose one learning curve. [31] However, the question arises whether this averaging across different movements directions is valid or not, since learning and the amount of learning in different directions might differ. Indications for this hypothesis were found in our experiment with right-handed young healthy subjects, described in chapter 5; a higher deviation at the start of learning, and higher amount of learning in reaching towards the body across the midline was found [32]. In chapter 6 we studied the influence of movement direction on motor learning in healthy elderly and mildly affected stroke survivors. We observed that despite the higher start deviations for one direction for the stroke survivors, no influence on learning a visual distortion task was observed for different movement directions for both healthy elderly and mildly affected stroke survivors. Based on these findings no influence on motor learning is expected for practicing in different areas of the workspace for mildly affected stroke survivors during rehabilitation.

Lower capacity learners

A remarkable finding arises from the results of chapter 4 about motor learning; 10 percent of the healthy elderly and 30 percent of the stroke survivors were not able to learn the 30 degrees visual distortion task by more than 10 degrees, independent from the provided feedback. In a different research area comparable observations were reported. In the study of Bouwsema et al. [33] healthy subjects practiced a complex arm task. Subjects learned to activate specific muscles to control a prosthetic hand. It was observed that 44 percent of the subjects were not able to learn to control the prosthetic hand as demanded. To our knowledge no other study described these so called lower capacity learners (LCL), while this might have substantial consequences for rehabilitation therapy.

Rehabilitation therapy could possibly stimulate functional recovery in a more efficient way by introducing other learning strategies. Introducing a different learning approach for LCL could potentially stimulate their learning ability, for example the learning by means of smaller steps. This strategy showed in young healthy subjects that learning a visual distortion task with the gradual introduction of the distortion results in more complete learning than the sudden introduction of a distortion. [34] On the other hand the application of visual distortion measurements (as performed in chapter 4) could be of help in the detection of potential LCL at the onset of therapy. Although more research to this field of application is necessary. Consequently, with the potential detection of LCL, the participation in therapy for certain patients could possibly be refrained.

Automaticity of movements

Automaticity is generally defined as when the task can be performed without conscious thinking, and with less or no interference from simultaneous activities. [27] A considerable amount of research has been performed into the attentional load during walking by means of dual tasks [35, 36], such as walking while simultaneously having a conversation. These studies have shown that gait is not as automated in stroke survivors as in healthy controls.

Only one study [36] so far has looked into the automaticity aspect of learning in reaching movements in mildly affected stroke survivors. Subjects performed reaching movements with the affected-arm while simultaneously performing a triangular movement with the other arm. The authors suggested that these mildly-affected stroke survivors did not experience altered attentional demands, and thus reach comparable levels of automaticity as healthy subjects. [36] In this experiment the execution of two motor tasks simultaneously was used as a dual task. Combining motor tasks with a cognitive task generally is thought to be more suitable for this kind of research. [27] Within the VIRTUROB consortium the group from the St. Radboud University in Nijmegen studied the attentional load of using the affected-arm in moderately and mildly affected stroke survivors. Subjects performed a dual-task experiment that consisted of simultaneous performing a circle drawing task and an auditive Stroop task. [37] Results of this submitted paper [37] suggest that moderately affected stroke survivors suffer from a lack of automaticity of motor control when performing movements with their affected arm.

According to this paper of Houwink et al. [37] no research has been performed which uses dual-tasks in their training environment. While, performing a dual-task is a more accurate representation of daily life than a controlled therapy setting without any concurrent cognitive tasks. Incorporating dual tasks into rehabilitation therapy may therefore provide a more realistic training environment to stimulate reaching ability for activities in daily life. More research should be performed to (train and to) assess the gained automaticity of movement execution in stroke survivors.

Implications for therapy and future developments

This thesis has shed some light on the influence of nature, timing, and type of augmented feedback on motor skill learning. The obtained results from the experimental studies suggest that the application of concurrent visual feedback is more effective compared to tKP and tKR feedback. Especially during the cognitive phase of the rehabilitation process continuous visual feedback should be applied, for instance an avatar of the subjects arm together with the travelled movement path.

Although, this thesis did not explicitly focus on the assessment of learning capacity of stroke survivors, results from chapter 4 suggest that the applied visual distortion during the reaching task is difficult to learn for 30 percent of the participating stroke survivors.

This remarkable finding should be investigated in more detail and alongside to what extend the visual distortion task can be used as an assessment tool for the detection of possible LCL and the consequences for therapy.

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8

Summary

With the upcoming innovative technologies more and more possibilities arise in the application of augmented feedback in rehabilitation therapy of the hemiparetic arm of stroke survivors.

This thesis provides insight into the current knowledge of augmented feedback in stroke rehabilitation in **chapter 2**. The effect of different aspects and types of augmented feedback on motor functions and motor activities of the hemiparetic arm after stroke are studied. A systematic search of the scientific literature was performed in the Pubmed and Cochrane database from 1975 to March 2009 which resulted in 299 citations. The augmented feedback used in the intervention was classified with respect to aspects (nature, timing, frequency) and types (auditory, sensory, visual). Based on in- and exclusion criteria 23 full-text articles were included for analysis. There are some trends in favour of providing augmented knowledge of performance feedback, augmented auditory and combined sensory and visual feedback. No consistent effects on motor relearning were observed for summary or faded, terminal or concurrent, solely visual or solely sensory augmented feedback. Based on current literature it was not possible to determine which combinations of aspects and types of augmented feedback are most essential for a beneficial effect on motor activities and motor functions of the hemiparetic arm after stroke. This was due to the combination of multiple aspects and types of augmented feedback in the included studies. This systematic review indicates that augmented feedback in general has an added value for stroke rehabilitation.

Knowledge about the actual use of position feedback during practice in reaching training after stroke is obtained in **chapter 3**. Five subjects participated in the training for 30 minutes three times a week for 6 weeks. During training, subjects performed reaching movements over a predefined path. When deviation from this path occurred, shoulder and elbow joints received position feedback using restraining forces. We recorded the amount of position feedback used by each subject. During pre- and posttraining assessments, we collected data from clinical scales, isometric strength, and workspace of the arm. All subjects showed improvement on one or several kinematic variables during a circular motion task after training. One subject showed improvement on all clinical scales. Subjects required position feedback between 7.4 and 14.7 percent of training time. Although augmented feedback use was limited, kinematic outcome measures and movement performance during training increased in all subjects, which was comparable with other studies. Emphasis on movement errors at the moment they occur may possibly stimulate motor learning when movement tasks with sufficiently high levels of difficulty are applied.

In **chapter 4** an experimental study was performed to explore the influence of different feedback conditions on motor learning in healthy elderly and stroke survivors. Nineteen healthy elderly and 19 stroke survivors performed repetitive reaching movements with a visual distortion of hand movements. Three conditions of feedback were provided in three distinctive sessions: concurrent (cKP) and terminal knowledge of performance (tKP) and terminal knowledge of results (tKR). Main outcome measures were amount of learning and remembering (consolidation). In both groups, cKP feedback resulted in a higher amount of learning than either tKR or tKP. The amount of consolidation was poorest with tKP, between cKP and tKR consolidation was comparable. Two healthy subjects and six stroke survivors showed limited amounts of learning, independent of the provided feedback. The highest potential for learning and consolidation was achieved with cKP in both groups, suggesting benefit for motor learning with cKP feedback. However, attention should be paid to a lower capability of some patients to learn a specific task regardless of the provided feedback.

The differential effect of movement direction on motor learning in healthy subjects and stroke survivors is studied in chapter 5 and 6. In **chapter 5** the effect of reaching direction on visuomotor learning by means of a visual distortion experiment was studied. Forty healthy subjects performed 48 movements to five different directions during adaptation to a 30 degrees visuomotor rotation. The execution error was defined as the initial direction error at peak velocity and after 100 ms after onset of the movement. The amount of learning was defined as the difference between the start value and the end value of the execution error. A significant higher amount of adaptation in the movement towards the contralateral part of the body compared to reaching towards other directions was observed. When possible feedback and corrections mechanisms are taken into account; results indicate that subjects adapt most towards direction 2 and least towards direction 3. Data of healthy elderly and stroke survivors would be essential to test whether observed results are present in these populations as well, which could have implications for motor relearning in rehabilitation therapy.

In **chapter 6** the influence of reaching direction on visuomotor learning in 19 healthy elderly and 19 mildly-affected stroke survivors was studied. Subjects performed a visual distortion task into five different directions. There were no significant differences in learning between directions, except for higher deviation at the start of the learning phase for stroke survivors in one direction. Learning a visual distortion didn't vary between movement directions for healthy elderly and stroke survivors, suggesting that this doesn't have to be taken into account when practicing reaching in different areas of the workspace during rehabilitation.

9

Samenvatting

Met het ontstaan van innovatieve technologieën komen er steeds meer mogelijkheden voor de toepassing van augmented feedback in de revalidatie therapie van de aangedane arm voor mensen die een beroerte (CVA) hebben gehad.

Dit proefschrift geeft inzicht in de huidige kennis over augmented feedback in de CVA revalidatie **hoofdstuk 2**. In hoofdstuk 2 wordt het effect van verschillende aspecten en typen van augmented feedback onderzocht met betrekking tot motor functies en activiteiten van de aangedane arm na een CVA. De wetenschappelijke literatuur is systematisch onderzocht in de Pubmed en Cochrane database tussen 1975 en 2009, dit leverde 299 citaties op. De augmented feedback die in de interventie gebruikt werd is geclassificeerd naar aspecten (nature, timing, frequentie) en typen (auditief, senorisch, visueel). Op basis van een aantal in- en exclusie criteria zijn er 23 artikelen geïncludeerd voor analyse. Een aantal trends zijn gevonden m.b.t. de nature van augmented feedback, auditieve feedback en gecombineerde sensorische en visuele feedback. Er zijn geen consistente effecten waargenomen m.b.t de timing, frequentie, alleen visuele of sensorische augmented feedback. Gebaseerd op de huidige literatuur is het niet mogelijk om te bepalen welke combinaties van aspecten en typen van augmented feedback het meest essentieel zijn voor het positieve effect op motorische activiteiten en functies van de aangedane arm na een CVA. Dit komt door de aanwezigheid van een combinatie van meerdere aspecten en typen in de geïncludeerde studies. Uit deze systematische review kan afgeleid worden dat augmented feedback in het algemeen een toegevoegde waarde heeft voor de revalidatie van de aangedane arm na een beroerte.

In **hoofdstuk 3** wordt kennis verkregen over het werkelijke gebruik van positie feedback gedurende training van reikbewegingen van mensen na een beroerte. Vijf patiënten namen deel aan de training van 30 minuten, 3 x per week gedurende 6 weken. In deze training werden reikoefeningen over een vastgesteld pad uitgevoerd. Wanneer een beweging van dit pad afweek, werd er positie feedback op het schouder en elleboog gewricht uitgeoefend d.m.v. limiterende krachten. De hoeveelheid gebruikte positie feedback werd voor iedere patiënt opgeslagen. Gedurende de voor- en nametingen werd data van klinische testen, isometrische kracht en het bereik van de arm verzameld. Alle proefpersonen lieten verbeteringen zien na de training op één of meerdere kinematische variabelen welke gemeten zijn gedurende een cirkelbeweging van de arm. Eén proefpersoon liet een verbetering zien op alle klinische testen. De proefpersonen gebruikten de positie feedback tussen de 7.4 en 14.7 procent van de trainingstijd. Ondanks dat het feedback gebruik gematigd was, zijn verbeteringen voor alle proefpersonen waargenomen gedurende de training op kinematische uitkomstmaten en bewegingsuitvoering. Deze verbeteringen zijn vergelijkbaar met andere studies. De nadruk die op de bewegingsfouten gelegd wordt op het moment dat de fout voorkomt kunnen mogelijk het motorisch leren stimuleren wanneer de moeilijkheidsgraad van de bewegingstaken hoog genoeg is.

In **hoofdstuk 4** is een experimentele studie gedaan om de invloed van verschillende feedback condities op motorisch leren in gezonde ouderen en CVA patiënten te onderzoeken. Negentien gezonde ouderen en 19 CVA patiënten hebben herhaalde reikbewegingen uitgevoerd met een aangebrachte visuele verstoring. Drie feedback condities zijn aangeboden in 3 verschillende sessies: feedback gedurende (cKP) en na (tKP) de beweging over de uitvoering van de beweging, en feedback over het eindresultaat van de beweging na de beweging (tKR). Hoofduitkomstmaten waren de hoevelheid leren en onthouden. Voor zowel gezonde ouderen als CVA patiënten resulteerde cKP feedback in een grotere hoeveelheid leren dan tKR en tKP feedback. De hoeveelheid die onthouden werd, was het laagst met tKP feedback en vergelijkbaar tussen cKP en tKR feedback. Twee gezonde ouderen en 6 patiënten lieten een beperkte hoeveelheid leren zien, welke onafhankelijk was van de feedback condities. Het hoogste potentieel voor leren en onthouden werd behaald met cKP feedback in beide groepen. Echter, aandacht moet worden besteed aan de proefpersonen die een verminderd leervermogen lijken te hebben om deze specifieke taak te leren ongeacht de aangeboden feedback.

Het effect van bewegingsrichting op motorisch leren in gezonde proefpersonen en CVA patiënten is onderzocht in de hoofdstukken 5 en 6. In **hoofdstuk 5** is het effect van bewegingsrichting op leren met een aangebrachte visuele verstoring onderzocht. Veertig gezonde proefpersonen hebben 48 reikbewegingen uitgevoerd naar vijf verschillende richtingen terwijl ze adapteerden aan een 30 graden rotatie. De gemaakte fout is gedefinieerd als de beginfout op pieksnelheid en na 100 ms vanaf de start van de beweging. De hoeveelheid die geleerd was is gedefinieerd als het verschil tussen de start- en eindfout. Een significante hogere hoeveelheid adaptatie van de bewegingsrichting naar de andere kant van het lichaam, vergeleken met bewegen naar andere richtingen, is geobserveerd. Het lijkt erop dat proefpersonen het meest naar richting 2 en het minst naar richting 3 adapteren in deze studie. De data van gezonde ouderen en CVA patiënten zou essentieel zijn om te testen of de gevonden resultaten in deze groepen ook gelden, dit zou namelijk implicaties voor motorisch leren in de revalidatie therapie tot gevolg kunnen hebben.

In **hoofdstuk 6** is de invloed van bewegingsrichting op leren met een aangebrachte visuele verstoring onderzocht in 19 gezonde ouderen en 19 CVA patiënten. De proefpersonen hebben een visuele verstoringstaak uitgevoerd in 5 verschillende richtingen. Er waren geen significante verschillen in het leren van een visuele verstoring naar verschillende richtingen voor gezonde ouderen en CVA patiënten, behalve de hogere start afwijking in één richting voor CVA patiënten. Dit suggereert dat er geen rekening gehouden hoeft te worden met bewegingsrichting bij het oefenen van reikbewegingen tijdens de revalidatie.

10

Dankwoord

Na vier jaren van hard wachten, werken en eigen deadlines verplaatsen is dit boekje uiteindelijk toch een feit geworden. Zoals velen zullen beamen, met name collega's, bevatte ook mijn onderzoek een boel karakteristieken van hoe het een echt onderzoek betaamt om te verlopen. Niks gaat zoals je verwacht, en alles gaat zoals je het niet had bedacht. Soms vind je ineens resultaten uit je onderzoek waarvan je niet kan geloven dat het erin zit, dus ga je op zoek naar die ene meetfout of onoverkomenlijkheid die je over het hoofd hebt gezien. Na heel veel statistiek bedrijven kun je jezelf een statisticus noemen, maar je hebt geen fouten in je analyse gevonden. Dus zit je ineens met een paar interessante resultaten, waar je dan een super artikel van gaat schrijven. Andersom gebeurd natuurlijk ook regelmatig, maar dan is er nog altijd de troostende uitspraak: geen resultaat is ook een resultaat.

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Dat promoveren niet alleen maar om onderzoek doen draait, is natuurlijk wel duidelijk geworden. Maar dat de aspecten van maatschappelijk werk soms zo prominent naar voren zouden komen, had ik van te voren niet aan zien komen. Meerdere werk situaties zijn onderwerp van gesprek geweest wanneer ik in mijn ouderlijk nest bivakkeerde, en daarna vol inspirerende woorden terug naar huis keerde. Het heeft mij doen beseffen dat iedereen een wijze in zijn midden nodig heeft bij wie je altijd om raad en advies kan vragen. Zelfs en misschien wel juist op de momenten wanneer de wijze geen ervaring heeft in dat specifieke werkgebied. Deze leidende wijze is zich hier waarschijnlijk niet altijd bewust van geweest, maar de verhelderende adviezen hebben bijgedragen aan het afronden van mijn promotie en het doorgroeien van mij als persoon. Bedankt, en ik zal je blijven weten te vinden!

Als promovendus vergeet je soms dat er nog meer op de wereld gebeurd, dan je eigen eilandje. De woorden: *'ik zou echt niet een hele dag in zo'n hokje achter een computer kunnen zitten'* zullen me altijd bijblijven. Ook al was (en ben) ik nog zo blij met een flexibele baan, het doet me wel realiseren dat je inderdaad eigenlijk de hele dag in je kamertje zit, die zomers te warm is , en 's winters te koud. Maar er zijn ook banen waar ik niet aan zou moeten denken, maar waar ik wel heel veel waardering voor heb. Hopelijk ben ik er in de loop der jaren dan ook in geslaagd om van dat eilandje af te komen en de rest van de aarde te ontdekken.

Door de vele congressen heb ik in ieder geval fysiek de wereldbol mogen ontdekken, en mijn horizon flink mogen verbreden. Mijn (bijna) nimmer ontbrekende reismetgezel zorgde er voor dat alles tot in de puntjes verzorgd was. De essentiële vaardigheden van navigeren en restaurantjes zoeken kwamen altijd goed te pas. Onder ander Berlijn, Japan, Zürich en Wenen hebben we samen, en met menig andere collega's, onveilig mogen maken. Hierbij werd de waardering van de congressen, naast natuurlijk de wetenschappelijk vernieuwingen, gerelateerd aan de aanwezigheid van koffie, koekjes en de lunch. Hoewel de lokatie hier toch ook zeker invloed op had. Het was meestal leerzaam en altijd erg gezellig, bedankt!

Dan heb je natuurlijk ook nog dat je je werk niet mee naar huis mag nemen. Maar wie is dat eigenlijk ooit gelukt? Een collega zij laatst: *'op weg naar huis moet je het eigenlijk kwijtraken'*. Ja inderdaad eigenlijk wel, maar helaas lukt dat niet altijd. Soms heb je gewoon even een boksbal, knuffeldier(en) of praatmuur nodig. Gelukkig kon ik deze allemaal thuis vinden, wat tot inspirerende en ontspannende gesprekken leidde! Dit soms zelfs tot in de vroege uurtjes buiten in de tuin onder de sterrenhemel. Ik realiseer me ook dat het voor mijn praatmaatje soms nog zwaarder is geweest dan voor mij. Als ik weer met mijn handen in m'n haar zat als ik het allemaal niet meer wist of niet meer zag zitten. Hoe kon jij het dan weten? Maar je bent goed in relativeren, ook al wil ik het niet altijd zien. Je hebt me ertoe gezet om verder te kijken en te handelen dan mijn veilige omgeving en mijn dromen waar te maken. Hopelijk ben ik voor jou op z'n tijd ook een bron van inspiratie en rust. Jij in ieder geval wel heel erg voor mij. En daar ben ik je heel erg intens dankbaar voor!

Het laatste half jaar bij RRD was een tijd van keihard doorzetten en keuzes maken. Mijn kamergenoot was dan ook regelmatig de pineut en de gelukkige omdat we eigenlijk soort van in hetzelfde schuitje zaten. Dit heeft tot veel inzichtgevende en ontspannende gesprekken geleid, bedankt! Uiteindelijk hebben we allebei gekozen voor de niet makkelijke weg. Of zoals sommigen zouden zeggen: de weg met de minste zekerheid. Ik kan alleen maar zeggen dat de minste zekerheid voor mij absoluut tot meer voldoening heeft geleid.

De aller-aller laatste loodjes hebben voor mij zeker het zwaarst gewogen, en ik ben dan ook zeer verheugd met mijn beide paranimfen die aan mijn zijden willen staan tijdens de aller-aller-aller laatste fase. In de afgelopen vier jaren kon ik altijd bij jullie terecht, of het nu uit kwam of niet, sorry en bedankt! Jullie hebben me scherp gehouden, qua statistiek, matlab en persoonlijk. Ik hoop in de nabije toekomst dat jullie promotie er ook aan komt. Succes met de bijna laatste loodjes. Zie deze maar alvast als een oefening.

Wat mij rest is om iedereen die het vertrouwen in het volbrengen van deze promotie hebben te bedanken. Leden van de commissie bedankt voor het zitting nemen in mijn commissie. Een ieder van jullie heeft ervoor gezorgd dat ik met deze mijlpaal verder kan blijven groeien.

'Be like a duck. Remain calm on the surface and paddle like hell underneath.' - Michael Caine

11

Over de Auteur

Birgit Molier werd geboren op 5 maart 1984 te Meppel. De middelbare school volgde zij in Hardenberg aan het Vechtdal College, waar zij in 2002 haar Gymnasium diploma haalde. Aansluitend begon zij aan de Universiteit Twente met de opleiding Biomedische Technologie.

Tijdens haar Bachelor heeft ze een studiereis naar Canada gemaakt, waarbij meedere bedrijven, universiteiten en ziekenhuizen bezocht zijn. De Bachelor Biomedische Technologie heeft zij in 2005 afgerond met een onderzoek bij het Medisch Spectrum Twente te Enschede naar de invloed van elektrische stimulatie van de Nervus Vagus bij epilepsie patiënten.

Haar Master stage heeft zij aan de University of Auckland, Nieuw-Zeeland voltooid met een onderzoek naar een voetmodel. De Master Biomedical Engineering heeft zij in September 2007 afgerond met een onderzoek naar lichaamspositionering op een in houding verstelbare stoel bij de Universiteit Twente.

In November 2007 kwam zij bij Roessingh Research and Development in dienst op het VirtuRob project als junior onderzoeker. Dit proefschrift is het resultaat van dit vier-jarige promotie onderzoek.

Momenteel is zij werkzaam als Projectleider Medische Techniek en Onderhoud bij Logic Medical BV te Almelo.

12

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13

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Progress in rehabilitation science 28

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