# Tele-Rehabilitation of Upper Limb Function in Stroke Patients using Microsoft Kinect

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BY
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AALBORG UNIVERSITY
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# CV

Daniel Simonsen received his Bachelor and Master degree in Biomedical Engineering and Informatics from Aalborg University in 2010 and 2012, respectively. In 2013, Daniel Simonsen was enrolled in the doctoral school at the Faculty of Medicine at Aalborg University under the supervision of Professor Ole Kæseler Andersen and Associate Professor Erika G. Spaich.

# ENGLISH SUMMARY


Stroke is a major cause of death and disability worldwide. The damage or death of brain cells caused by a stroke affects brain function and leads to deficits in sensory and/or motor function. As a consequence, a stroke can have a significantly negative impact on the patient's ability to perform activities of daily living and therefore also affect the patient's quality of life. Stroke patients may regain function through intensive physical rehabilitation, but often they do not recover their original functional level. The incomplete recovery in some patients might be related to e.g. stroke severity, lack of motivation for training, or insufficient and/or non-optimal training in the initial weeks following the stroke.

A threefold increase in the number of people living past the age of 80 in 2050, combined with the increasing number of surviving stroke patients, will very likely lead to a significant increase in the number of stroke patients in need of rehabilitation. This will put further pressure on healthcare systems that are already short on resources. As a result of this, the amount of therapeutic supervision and support per stroke patient will most likely decrease, thereby affecting negatively the quality of rehabilitation.

Technology-based rehabilitation systems could very likely offer a way of maintaining the current quality of rehabilitation services by supporting therapists. Repetition of routine exercises may be performed automatically by these systems with only limited or even no need for human supervision. The requirements to such systems are highly dependent on the training environment and the physical and mental abilities of the stroke patient. Therefore, the ideal rehabilitation system should be highly versatile, but also low-cost. These systems may even be used to support patients at remote sites, e.g. in the patient's own home, thus serving as tele-rehabilitation systems.

In this Ph.D. project the low-cost and commercially available Microsoft Kinect sensor was used as a key component in three studies performed to investigate the feasibility of supporting and assessing upper limb function and training in stroke patients by use of a Microsoft Kinect sensor based tele-rehabilitation system. The outcome of the three studies showed that the Microsoft Kinect sensor can successfully be used for closed-loop control of functional electrical stimulation for supporting hand function training in stroke patients (Study I), delivering visual feedback to stroke patients during upper limb training (Study II), and automatization of a validated motor function test (Study III).

The systems described in the three studies could be developed further in many possible ways, e.g. new studies could investigate adaptive regulation of the intensity used by the closed-loop FES system described in Study I, different types of feedback

to target a larger group of stroke patients (Study II), and implementation of more sensors to allow a more detailed kinematic analysis of the stroke patients (Study III). New studies could also test a combined version of the systems described in this thesis and test the system in the patients' own homes as part of a clinical trial investigating the effect of long-term training on motor function and/or non-physical parameters, e.g. motivational level and quality of life.

# DANSK RESUME

Apopleksi er en væsentlig årsag til død og invaliditet verden over. Skade og død af hjerneceller forårsaget af apopleksi påvirker hjernefunktionen og forårsager ofte mangler i sensorisk og/eller motorisk funktion. Som følge heraf, kan apopleksi have væsentlig negativ indvirkning på patientens evne til at udføre dagligdags aktiviteter og kan derfor også påvirke patientens livskvalitet. Apopleksipatienter kan genvinde funktionsevne gennem intensive fysisk rehabilitering, men ofte genvindes den fulde funktionsevne ikke. Den ufuldstændige bedring hos nogle patienter kan være relateret til f.eks. alvorlighedsgraden af apopleksitilfældet, mangel på motivation for at træne, eller utilstrækkelig og/eller sub-optimal træning i den første tid efter slagtilfældet.

Antallet af mennesker, der forventes at leve længere end 80 år, ventes at tredobles i 2050. Kombineret med det stigende antal patienter der overlever et slagtilfælde, vil dette sandsynligvis lede til en betydelig forøgning af antallet af apopleksipatienter, der har behov for rehabilitering. Dette vil sætte sundhedssystemerne, som i forvejen er knappe på ressourcer, under yderligere pres. Som resultat heraf, vil mængden af terapeutisk supervision og støtte per apopleksipatient falde, hvilket vil påvirke kvaliteten af rehabilitering negativt.

Teknologi-baserede rehabiliteringssystemer kan sandsynligvis være med til at opretholde den nuværende kvalitet af rehabiliteringsservices ved at understøtte terapeuter. Repetitive rutine-baserede opgaver kan muligvis udføres automatisk af disse systemer, med brug for begrænset eller ingen menneskelige ressourcer. Kravene til sådanne systemer er stærkt afhængige af træningsomgivelserne og apopleksipatientens fysiske og mentale evner. Derfor, bør det ideelle rehabiliteringssystem være alsidigt, men også omkostningslet.

I dette Ph.D. projekt blev den omkostningslette og kommercielt tilgængelige Microsoft Kinect sensor brugt som en central komponent i tre gennemførlighedsstudier om understøttelse apopleksipatienters armtræning ved brug af et Microsoft Kinect sensor baseret tele-rehabiliteringssystem. Udfaldet af de tre studier vist at Microsoft Kinect sensoren kan anvendes succesfuldt til closed-loop kontrol af funktionel elektrisk stimulation til understøttelse af træning af håndfunktion hos apopleksipatienter (Studie I), levering af visuelt feedback til apopleksipatienter under armtræning (Studie II) og automatisering af en valideret motorfunktionstest (Studie III).

Systemerne beskrevet i de tre studier kan videreudvikles på mange tænkelige måder, f.eks. kan nye studier undersøge adaptive regulering af intensiteten som anvendes i systemet beskrevet i Studie I, andre typer af feedback for at rette systemet mod andre/flere typer af apopleksipatienter (Studie II) og implementering af multiple

sensorer for at muliggøre mere detaljeret kinematisk analyse af apopleksipatienter (Studie III). Nye studier kunne også teste en kombineret udgave af de tre systemer beskrevet i denne afhandling i patienternes eget hjem som del af et klinisk studie, der undersøger effekten af længerevarende træning med systemet på motorisk funktion og ikke-fysiske parametre, f.eks. movitationsniveau og livskvalitet.

# ACKNOWLEDGEMENTS

I would like to thank my supervisors Professor Ole K. Andersen, Associate Professor Erika G. Spaich, and John Hansen for their support and guidance throughout the Ph.D. project.

I would also like to thank Gitte H. Knudsen, and Ingrid Hugaas from Træningsenheden, Aalborg Kommune, and Helle R. M. Jørgensen from Neuroenhed Nord for their great help during subject recruitment and conduction of the experiments.

Lastly, I would like to thank my family, my lovely girlfriend and our precious daughter Agnethe for their love, support, and patience.

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# CHAPTER 1. INTRODUCTION

Stroke is a major cause of death and disablity worldwide (1). A cerebral stroke can be either ischaemic or haemorrhagic (2), i.e. caused by occlusion or rupture of a bloodvessel, respectively. Following the onset of a stroke, blood flow is interrupted, leading eventually to brain cell damage or death in the absence of medical intervention. The damage or death of brain cells affects brain function and often causes deficits in sensory and/or motor function, dependent on the location of the stroke in the brain (3). The consequences of stroke have a negative impact on the patient's ability to perform activities of daily living (ADL) and also affect quality of life.

## 1.1. REHABILITATION OF STROKE PATIENTS

Following a stroke, patients receive acute medical treatment (Figure 1-1). After the acute treatment and stabilization patients who have suffered from a minor stroke may be able to return to their own home. Other patients may be more affected by the stroke and thus require more care. In that case, one of the next steps is functional assessment of the patient. Based on the assessments, a specialized rehabilitation strategy can be made. The rate of recovery of function is greatest during the initial weeks following stroke (acute and sub-acute phase) (4), where patients may experience spontaneous recovery of function caused by e.g. reactivation of penumbreal brain areas initially affected by the stroke (5). Therefore, it is considered important that rehabilitation is initiated early, within a few days, following a stroke (6). Even though surviving stroke patients are capable of regaining function through intensive physical rehabilitation, 5% to 20% of stroke patients never recover their original functional level (7), (8). Several different training-related causes might explain the incomplete recovery in some patients, e.g. lack of motivation for training, insufficient amount of training or non-optimal training in the initial weeks following the stroke or stroke severity.

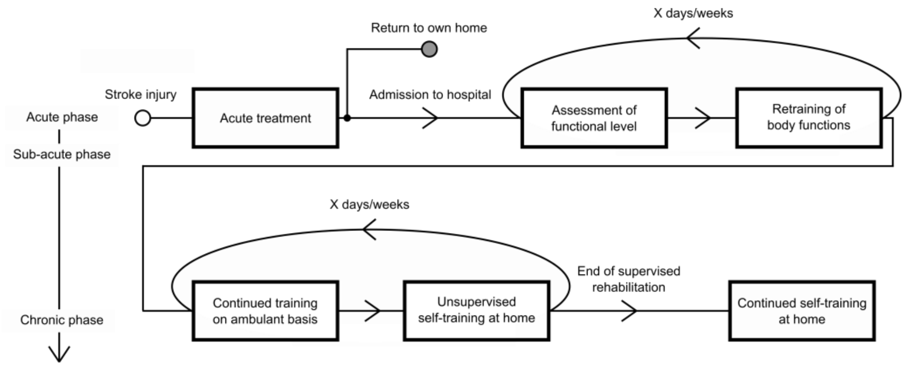


*Figure 1-1 Simplified overview of the phases of treatment and rehabilitation following stroke (for patients in need of motor rehabilitation).*

When a patient has been discharged from the hospital, training may continue on an ambulant basis combined with unsupervised self-training often in the patients own home. Supervision during training is an important factor in rehabilitation, since e.g. verbal feedback from a therapist (extrinsic feedback) and physical assistance can help to ensure that patients will not develop inappropriate compensatory movement strategies. Even though compensatory movement strategies may help the patient complete certain movement goals, the movements might be inappropriate on a long term, causing pain and thus inhibiting further motor recovery (9). Therefore, stroke patients should regularly be supervised during training, but this may not always be feasible due to resource limitations. Considering the expected threefold increase in the number of people living past the age of 80 in 2050 (10), along with the increasing number of stroke survivors (84% increase from 1990 to 2010 (1)), more stroke patients will have to share the same limited resources, inevitably leading to less therapeutical supervision per stroke patient.

The use of technology-based rehabilitation systems could very likely offer a way of maintaining the current quality of rehabilitation services. The introduction of technology based rehabilitation systems could potentially mean that trivial tasks may be performed automatically by these systems with only limited or even no need for human resources. Previous studies have shown that technology based systems based on electro-mechanical sensors and/or computer vision can be used to provide physical assistance to stroke patients (11), (12), provide extrinsic feedback (13)–(16), and perform automatic assessment of motor function (17), (18).

## 1.2. REHABILITATION SYSTEMS FOR UNSUPERVISED TRAINING OF MOTOR FUNCTION IN STROKE PATIENTS

The usability of support/technological systems for unsupervised stroke rehabilitation is highly dependent on the training environment and the physical and mental abilities, and thereby the needs, of the stroke patient. A stroke patient undergoing active motor rehabilitation needs regular motor function assessments, some stroke patients may require physical assistance in order to be able to perform training exercises, and others may be highly dependent on extrinsic feedback, e.g. visual feedback displayed on a monitor (19). Due to the heterogeneity of stroke patients and the great economical cost of stroke rehabilitation, rehabilitation systems for unsupervised training should ideally be both highly versatile, but also low-cost if the current level of rehabilitation is to be maintained (19), (20).

### 1.2.1. STATIONARY ELECTRO-MECHANICAL SYSTEMS

Previous studies have shown that stationary workstations equipped with electro-mechanical or pneumatic robotic systems are capable of providing stroke patients with physical support during training, e.g. by weight unloading, mechanical support, and/or by reducing movement friction, leading to improvements in motor function (21)–(23). Takahashi et al. (2008) used a 3 degrees-of-freedom pneumatic robotic system for assisting hand grasping and releasing in stroke patients. Similar to other robotic systems/workstations, the user has to be secured to the mechanical system using straps/belts and the comfortable or maximum passive range of motion of the limb attached to the robotic system must be determined (for each degree-of-freedom) and set in the system to ensure patient safety (21). A workstation based robotic system for training of upper limb function, e.g hand function (21), may be ideal for training of a specific body function, but it is also limited to this specific body function.

### 1.2.2. COMPUTER VISION AND WEARABLE SYSTEMS

Rehabilitations systems based on wearable motion sensors or computer vision can in principle be used for training of any motor function, and in the case of computer vision based systems the user does not even need to be physically in contact with the system (Study II-III), (24). There are multiple examples of wearable sensor based rehabilitation systems designed to improve motor function in stroke patients, e.g. a glove instrumented with bend sensors, that was used for control of functional electrical stimulation (FES) of the most affected hand in hemiplegic stroke patients (25). Another study, showed that a system based on kinematic sensors (magnetic, angular rate, and gravity sensors) allowed automatization of selected parts of the Wolf Motor Function Test (17). Rehabilitation systems based on wearable sensors, e.g. Cruz et al. (2014) and Yang et al. (2013), and especially computer vision based systems, e.g. González-Ortega et al. (2014) and Chang et al. (2013), provide the stroke patient with a workspace larger than that provided by stationary workstations, enabling them to train functional exercises requiring full body movements, e.g. walking (Da Gama et al. (2015) (24) and Clark et al. (2012) (26)). Systems based on wearable sensors and computer vision do not offer physical support to the patient like stationary workstations do, but they can be combined with functional electrical stimulation and/or mechanical systems to form a system offering physical support

(Study I), (12), (25), (27), (28). The preparation required before using systems based on wearable sensors and computer vision sensors includes both calibration and careful positioning of the sensors. However, computer vision based systems have an advantage over wearable sensors, if they are used in a fixed setup, e.g. the camera is mounted on a fixed position in a training room, as this setup does not necessarily require calibration prior to use. A disadvantage of the computer vision based systems is their dependency on light settings in the environment in which they are used, e.g. computer vision systems using infrared light (e.g. the Microsoft Kinect sensor (29) and the Leap Motion Controller (30)) for kinematic measurements may be sensitive to disturbances by sunlight (29). However, commercial computer vision based systems like the Microsoft Kinect and the Leap Motion Controller are lowcost. The Microsoft Kinect sensor offers a workspace larger than the Leap Motion controller and can be used for video recording along with kinematic recording, thereby offering the therapist a possibility for performing a qualitative assessment of the patient by visual inspection of the video recordings (31). Computer vision based rehabilitation systems can be combined with FES to support stroke patients physically, can be used for video recording and kinematic analysis, provide a workspace large enough to perform whole body training, and require minimal effort to calibrate and set up. Thus, this type of system seems to be the most ideal for use in an unsupervised training setup. Therefore, the Microsoft Kinect sensor was selected as a key component in the three studies of this Ph.D. project.

## 1.3. AIMS OF THE PH.D. PROJECT

The overall aim of the Ph.D. project was to investigate the feasibility of supporting upper limb training in stroke patients by use of a Microsoft Kinect sensor based tele-rehabilitation system. Based on the overall aim, three specific research questions were formulated:

1. How can stroke patients be supported during hand function training by a FES system controlled in a closed loop manner using a Microsoft Kinect sensor?

2. How does adaptive visual feedback delivered by a system based on the Microsoft Kinect sensor affect upper limb movement in stroke patients?

3. How can the Microsoft Kinect sensor be used for automatization of a validated motor function test?

Each of the research questions was addressed in individual studies (Study I, II and III).

The three studies are:

**Study I**

Simonsen D., Spaich E. G., Hansen J., & Andersen O. K. (2016). Design and Test of a Closed-Loop FES System for Supporting Function of the Hemiparetic Hand Based on Automatic Detection using the Microsoft Kinect sensor. IEEE Transactions on Neural Systems and Rehabilitation Engineering, DOI: 10.1109/TNSRE.2016.2622160 (accepted for publication).

**Study II**

Simonsen D., Popovic M. B., Spaich E. G., & Andersen O. K. (2017). Design and Test of a Microsoft Kinect-based System for Delivering Adaptive Visual Feedback to Stroke Patients during Training of Upper Limb Movement. Medical and Biological Engineering and Computing (accepted for publication).

**Study III**

Simonsen D., Spaich E. G., Nielsen I. F., & Andersen O. K. (2016). Design and Test of an Automated Version of the Modified Jebsen Test of Hand Function using Microsoft Kinect. Journal of NeuroEngineering and Rehabilitation (under revision).

## 1.4. DISSERTATION OVERVIEW

This thesis describes the implementation of three core functionalities in a framework for a tele-rehabilitation system for supporting upper limb training in stroke patients based on the Microsoft Kinect sensor. Although, the three functionalities are considered to be important for successful upper limb rehabilitation in the absence of therapeutical supervision, they do not represent a complete framework for a tele-rehabilitation system for supporting of upper limb training in stroke patients.

The system should be able to provide physical support (research question 1, study I, chapter 2) and feedback to the patient (research question 2, study II, chapter 3). The system should also be able to monitor the progress of the patient (research question 3, study III, chapter 4). Finally, the three research questions are synthesized in chapter 5.

# CHAPTER 2. FES FOR UPPER LIMB REHABILITATION

FES is the application of electrical stimulation to fully provide (acting as an assistive device or tool for early rehabilitation of patients with complete paralysis) or partially assist (acting as a rehabilitation tool) voluntary functional movements to individuals with limited mobility (11). FES is often delivered transcutaneously through electrodes mounted on the surface of the skin on top of a muscle, but may also be delivered via intramuscular or implanted electrodes (11), (32). When FES is applied with a sufficiently high amplitude, through electrodes placed on top of a muscle (close to or on top of the motor endplate), electric activation of the underlying motor neurons occurs (33). Thereby, FES may act as a rehabilitation tool that can help the patient complete training exercises and increase training intensity (number of repetitions) which would not have been possible without FES.

## 2.1. FES SYSTEMS – OPEN-LOOP VS CLOSED-LOOP

Generally, FES systems may be divided into two main categories based on their control methods: open-loop and closed-loop controlled systems. FES systems based on preprogammable time schemes, which offer the user to set up a sequence of stimulations, are examples of open-loop controlled systems. In this type of system, the output depends only on the input specified by the user and does not change once the stimulation sequence has been started (unless it is terminated by the user) (34), (35), (36). In other open-loop controlled systems where FES is triggered by pressing a button or similar, the user can control the timing of the stimulation (36). However, FES systems based on trigger buttons may not be appropriate for stroke patients with cognitive deficits, as these types of systems force the users to divide their attention between operating the system and performing movements during training. This reduced amount of focus of attention towards the execution of the movements may eventually compromise the effect of training (37).

In contrast to open-loop controlled FES systems, closed-loop controlled systems adjust their output based on the user's input and performance and the effect of the stimulation. Thus, closed-loop controlled FES systems can be used for control of both the timing of stimulation and all other parameters of the stimulation (Study I), (12). Examples of closed-loop controlled FES systems include systems controlled by kinematic sensors, e.g. accelerometers or goniometers mounted on the subject's arm (38), (39), electromyographic (EMG) signals (34), (40), (28) and computer vision (Study I), (41) (Figure 2-1).

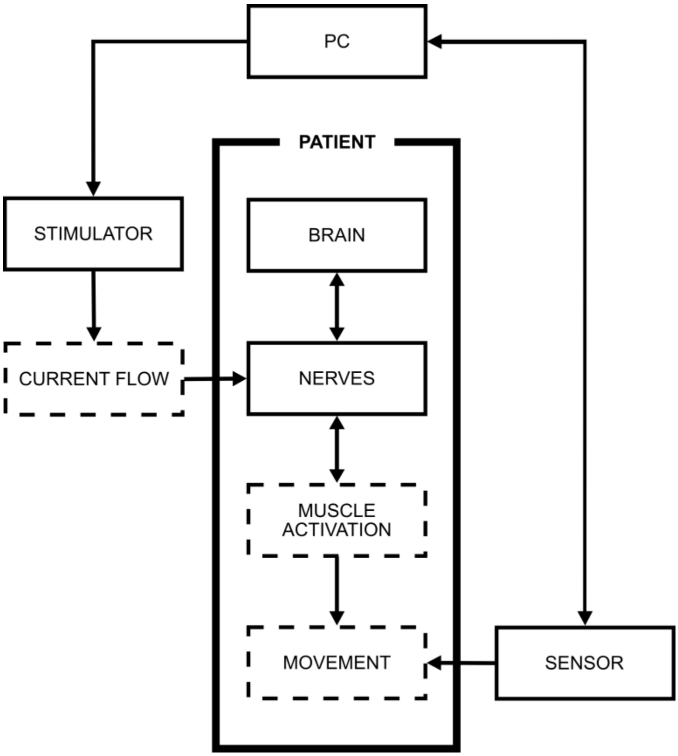


*Figure 2-1 Schematic illustration of a closed-loop FES system connected to a patient (solid boxes: physical entities, dashed boxes: actions).*

Compared to preprogrammable timescheme based FES systems, closed-loop controlled FES systems require the user to perform voluntary movements in order to trigger the stimulation, likely leading to a higher training intensity. At the same time, closed-loop FES systems do not force the user to divide his/her attention, since the system automatically controls the stimulation timing and parameters, meaning that the user can focus his/her attention entirely on the execution of the movements. This type of active support, where FES reinforces the user's voluntary movements, enabling the user to perform successful movement repetitions and thereby increasing training effectivity, have likely a positive impact on motor control (42)–(44). These systems do however require accurate positioning of additional sensors besides the stimulation electrodes, e.g. electrodes used for EMG recording, goniometers, accelerometers etc. (34), (12), (38), (45). This preparation process can be tedious and may therefore compromise the usability of these systems in a telerehabilitation setup. Contrary to FES systems based on body mounted sensors, systems based on computer vision do not require accurate positioning of additional sensors or electrodes besides the stimulation electrodes (Study I), (28), (41).

## 2.2. CONTROL OF FES PARAMETERS

When FES is applied, the electric activation of the underlying motor neurons occurs in an order of recruitment which is reversed, compared to what is observed during voluntary muscle activation (where activation of smaller motor units occurs prior to activation of larger motor units) (33). As a result of the reversed recruitment order during FES, muscle fatigue occurs faster compared to when the recruitment order is normal (46), but this may be reduced by modulation of the stimulation parameters (47). Adjustable FES parameters include the stimulation duration, pulse amplitude, shape, duration, and frequency.

Generally, the duration of FES is determined by the type of movement it aims to assist. The amplitude of FES may be up to 60 mA, but may likely be lower when FES is not acting as a functional substitute, i.e. no voluntary effort is required by the user to induce a movement (44). Increasing the pulse amplitude or pulse duration (typically set to 200-300 µs) will increase the number of motor neurons recruited by FES (44). Thus, the amplitude of the stimulation can be adjusted to change the level of difficulty for a stroke patient during training, e.g. as the patient starts to regain motor function, the amplitude may be gradually lowered in order to decrease the level of physical assistance provided by FES. Similarly, the amplitude of FES may be increased, when the difficulty of a training exercise becomes too high for the patient to comply with it or during a training session to compensate for muscle fatigue. However, stroke patients requiring high intensity FES (produced from high pulse amplitude or long pulse durations) may not be able to tolerate the stimulation, if it becomes painful due to activation of nociceptors fibers (33).

Previous studies reported that a pulse duration of 300 µs was associated with higher comfortability and the least amount of pain when compared to longer pulse durations (48), (49). Also the pulse frequency can compromise comfortability if set too high and will cause additionally the stimulated muscles to fatigue faster compared to stimulation with lower pulse frequencies. Typically, the pulse frequency is set between 20-50 Hz (44). When the pulse frequency is lower than 12 Hz the resulting response to the stimulation is a series of twitches, which often is not functionally appropriate during a training session (33). Therefore, the recommended pulse frequency is typically 30 Hz (50). The parameters of FES used in Study I (individual intensity for each patient, pulse frequency of 30 Hz, and pulse duration of 200 µs), was based on these previous findings.

## 2.3. EFFECT OF FES ON MOTOR RECOVERY

In a recent meta-analysis by Howlett et al.(2015), investigating the effect of FES, it was concluded that FES, when combined with training, has a positive effect on activity levels (e.g. walking, grasping objects and moving them), compared to training alone (51). However, another recent meta-analysis by Vafadar et al. (2015)

(52) did not find any evidence for a positive effect of FES on motor function in stroke patients, though FES had a positive effect on shoulder subluxation. A possible explanation for the different findings of the effect of FES on motor function could be the level of patient participation during the application of FES. In the studies included in the meta-analysis by Vafadar et al. (2015), patients received FES in a cyclic manner (open loop preprogrammed sequences of stimulations), where no active participation was required. On the contrary, the patients in the studies included in the meta-analysis by Howlett et al. (2015), were required to train actively during the application of FES. Thus, it seems likely that patients experience a positive effect of FES on their activity level, when FES is combined with physical training.

Considering that FES can improve the activity level of stroke patients (51), it could be used to increase training repetition and intensity, and thereby exploit experience-dependent plasticity, which is believed to be a central factor in motor relearning following stroke (43). This is in line with the results of previous studies, suggesting that the effect of FES on motor function is better in closed-loop FES systems that require the user to be physically active and cognitively involved during the use of the system (25), (44), (53). Stroke patients performing training while being assisted by a closed-loop FES system will experience that their intention to perform a movement will be time locked to the stimulation resulting in a successful movement (44). Matching the patient’s cognitive intent to move with the timing of stimulation onset could possibly affect corticospinal plasticity and thus also skill acquisition (54).

Another mechanism behind the positive effect of FES, combined with physical training, on motor function may likely be the increased training specificity. With the aid of FES, stroke patients with hand function deficits, having poor compliance in grasping exercises, can become able to perform this type of training exercises successfully (Study I). The results from Study I showed that patients using the closed-loop controlled Kinect based FES system were able to improve their number of successful grasps by 29 % compared to when not being assisted by the FES system. This improvement was accompanied by a decrease in the average time taken to establish a grasp. Thus, the results from Study I showed that the closed-loop controlled Kinect based FES system supported the stroke patients’ grasping function positively, which likely will have an impact on the patients’ motivation for training. Though, it cannot be concluded from Study I whether the effect of the FES system on the stroke patients’ performance translates into long-term motor relearning. Generally, stroke patients performing skilled movement training while being assisted by a closed-loop FES system are able to increase their percentage of successful repetitions (Study I), (36),(12).

Considering the positive effect of FES, combined with physical training, on motor function, it is important to continuously graduate the level of difficulty of training for the stroke patient, in order to maximize the effect of FES and maintain the patient's motivation. Maintaining the stroke patient's level of motivation at a high level affects the potential outcome of rehabilitation as it affects experience-dependent plasticity (55). If the level of assistance from FES is too low for the administered training exercises, the patient will be unable to comply with the exercises, thereby compromising the effect of training and likely also the patient's motivation towards training, which would further lower the outcome of training (56). Likewise, the patient's training motivation may likely be compromised if the level of assistance from FES becomes too high, as the physical effort required of the patient to comply with training exercises ends up being minimal. The issue of adjusting the level of assistance from FES was not addressed in Study I, but the kinematic data that can be obtained from the Kinect based FES system could be used to implement continuous regulation of the intensity of FES.

# CHAPTER 3. ROLE OF FEEDBACK IN UPPER LIMB REHABILITATION

Feedback on training performance, e.g. a therapist providing the patient with verbal instructions or physical guidance during or following a movement task, is an essential part of stroke rehabilitation. Compared to healthy individuals, stroke patients often rely more on this type of feedback, which is known as extrinsic feedback, due to sensory deficits making them unable to make proper use of the somatic information from their own body (intrinsic feedback) (57) (Figure 3-1).

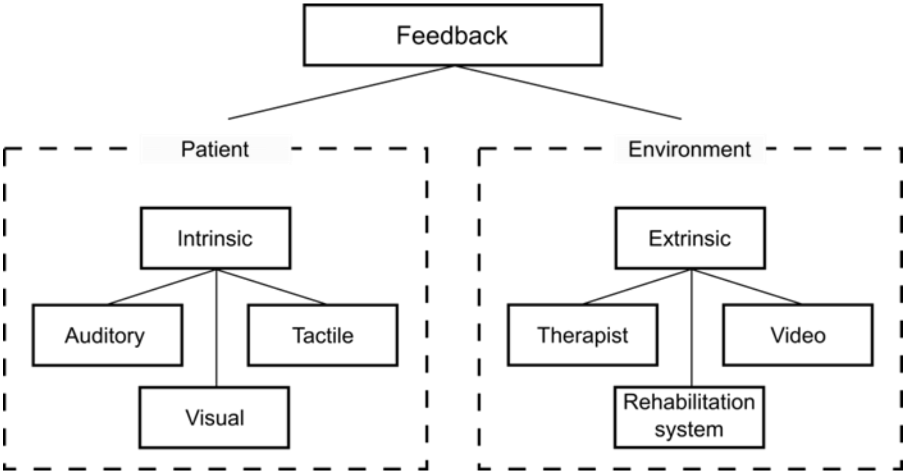


*Figure 3-1 Patient feedback can be categorized as intrinsic or extrinsic. Intrinsic feedback refers to somatic information from a stroke patient's own sensory system, e.g. proprioceptive, tactile, and/or visual information, whereas extrinsic feedback refers to information originating from the environment.*

As stated in the introduction of this thesis, stroke patients will at some point during their rehabilitation program be asked to perform training exercises on their own, which means that they have to rely solely on intrinsic feedback. This might lead to a non-optimal outcome of self-training, since stroke patients have sensory deficits, meaning that this type of information may be distorted or incomplete and therefore not optimal to use (57). Technology based rehabilitation systems may be used as a substitute for a therapist to enhance the quality of unsupervised training by providing the patient with extrinsic feedback based on continuous analysis of the patient's movements (13)–(16). Rehabilitation systems for unsupervised training could also be used to carry out automatic assessments of motor function in stroke patients.

## 3.1. EXTRINSIC FEEDBACK TYPES AND SCHEDULING

In a rehabilitation context, extrinsic feedback can be characterized as information provided to the patient by an external source. Extrinsic feedback may be of different types, i.e. consisting of different modalities of sensory information. The optimal type of feedback depends on the individual stroke patient, e.g. stroke patients with tactile deficits may be better suited with extrinsic feedback based on visual information rather than tactile information provided by a robotic system (58).

Extrinsic feedback may further be subcategorized based on the information it provides to the patient. When extrinsic feedback is delivered following a goal-related movement, in order to let the patient know whether the movement was successful, it is categorized as *knowledge of results* (59), whereas extrinsic feedback providing information about the quality of the movement is categorized as *knowledge of performance* (60).

Besides the content, another key aspect of extrinsic feedback is the scheduling of delivery (59), (60). With regards to the time aspect of extrinsic feedback, the delivery of feedback may be varied by timing, e.g during a movement (concurrent feedback) or following a movement (terminal feedback), and/or frequency, e.g. after each n'th movement trial or after a specified number of movement trials (summary feedback).

In Study II, the stroke patients were provided with visual feedback (provided on a monitor embedded in a table) on an upper limb movement exercise. Based on the findings of previous studies showing that both *knowledge of performance* and *knowledge of results* improve outcome of motor function training in stroke patients, the feedback in Study II was chosen to be a combination of both types (13), (61), (62).

## 3.2. EFFECT OF SENSOR-BASED FEEDBACK ON MOTOR RECOVERY AFTER STROKE

Several studies have shown that stroke patients can improve their outcome of training by using systems based on motion sensor technology and/or virtual environments providing them with extrinsic feedback during training (13)–(16). Stroke patients included in these studies showed greater improvements and/or higher rates of recovery on several different outcome measures, including movement duration, movement variability, cortical activation, and clinically validated rating scales including Fugl-Meyer Assessment scale, Motor Assessment Scale (63), and Functional Independence Measure scale. The types of extrinsic feedback used in these studies include combinations of haptic, visual, and auditory stimuli in response to movements performed by the patients (13)–(16).

A key factor that could explain the positive effect of extrinsic feedback on motor function could be that stroke patients are capable of utilizing the information of extrinsic feedback for modifying and thereby adapting their movement strategies (64).This suggestion is supported by the findings of Maulucci and Eckhouse (15), demonstrating that although stroke patients can modify their reach trajectory by practice alone, the path performance was improved only when auditory feedback was provided during training. In the study by Maulucci and Eckhouse (15), auditory feedback was provided to the patients during movement execution and a light located at the target was exstinguished upon completion of each reaching movement task, thus providing the patients with both *knowledge performance* and *knowledge of results*. When comparing the two delivery types, the effect of *knowledge of performance* is better and longer lasting than that of *knowledge of results*, measured on several different outcome scores based on e.g. Fugl-Meyer Assessment, movement variability (reduced variability), and cortical activation measured by (fMRI) (13), (61), (62). The greater effect of *knowledge of performance* provided to stroke patients may be related to the partial or complete inability of stroke patients to rely on their own intrinsic feedback, contrary to healthy people (57).

The effect of *knowledge of performance* may likely have been an important factor in Study II, where the participating stroke patients were provided with concurrent adaptive visual feedback during a movement task, leading to significantly smoother movement patterns and longer movement durations, when compared to the control session where no feedback was provided. If the movements performed by the stroke patients in Study II, during the feedback session are considered as more skilled or more purposeful movements than the movements performed during the control session, a tentative explanation of the positive effect of feedback on movement smoothness could be related to changes in excitability of the involved upper limb cortical area (65). The extended movement durations in the experimental group of stroke patients participating in Study II could be considered both as a positive and a negative outcome. The extended movement durations could possibly be a result of a higher cognitive load on the stroke patients making their movements slower, which could be either voluntary or involuntary. If the cognitive load is too high the patient may not be able to comprehend the feedback given and thus it could disturb the movement execution, whereas if it is too low the feedback would not have any impact. In any case the extended movement durations mean that the stroke patients perform the exercises at a lower frequency and thus the physical intensity of training is lowered, which could have a negative impact on the outcome of training (55).

Common for Study II and other studies investigating the effect of extrinsic feedback on motor function is that the feedback likely draws the stroke patient's focus of attention towards the effect of the movements performed. Instructing subjects to focus on the effect of their movements instead of the body parts involved in the movement has been shown to enhance the effect of movement training on motor learning, likely because the external focus of attention interferes less with intrinsic automatic control processes that are responsible for movement adaptation (37), (66), (67). Though, not all stroke patients may be eligible for training where they are required to focus their attention towards their movements, e.g. stroke patients with spatial neglect or other attentional deficits (68), (69).

# CHAPTER 4. ASSESSMENT OF UPPER LIMB MOTOR FUNCTION IN STROKE PATIENTS

Assessment of a stroke patient's functional level is a key aspect of any rehabilitation programme. Comparing results from repeated motor function tests administered to a stroke patient provides the therapist with valuable information about the efficacy of the chosen training scheme. Thereby, the results from motor function tests can be used as a tool for planning the future the rehabilitation program and for assessing the effects of training of stroke patients. A therapist may assess changes in a stroke patient's motor function by repeated use of a standardized motor function test, e.g. Wolf Motor Function Test (WMFT) (16), Fugl-Meyer Assessment (FMA) (17), Jebsen Test of Hand Function (JTHF) (18) or similar motor tests. Standardized motor function tests are comprised of a number of movement exercises which are performed by the stroke patient using the most affected limb and in some tests also the less affected limb. The performance of the stroke patient is then graded by the therapist, e.g. by measuring the time taken to complete each exercise (using a stopwatch) and/or by rating the quality of the movement on a fixed point ordinal scale (16)–(18). Several studies have shown that kinematic and timing measures from electro-mechanical sensors (workstations and/or wearable devices), and/or computer vision based sensors are in close agreement with the results from standardized motor function tests (Study III), (19)–(23). By using sensor-based approaches for measurement of motor function in stroke patients, measurement objectivity is likely increased and these systems could possibly be used in an unsupervised setting, e.g. as part of a tele-rehabilitation system.

## 4.1. VALIDITY OF MOTOR FUNCTION TESTS

There are numerous methods for assessing the functional level of the upper limb of stroke patients based on quantitative and/or qualitative measures. Tests like the Jebsen Test of Hand Function (70), Nine Hole Peg Test (71), and Box and Blocks Test (72) measure the performance of the subject in functional tasks on a quantitative scale only. For example, in the Box and Block Test, the subject is seated on a chair in front of a box with two equally sized compartments divided by a center partition, and instructed to move as many onesquare inch plywood blocks (one at a time) as possible from one side of the box to the other during a one minute period using one hand (both hands are tested) (72). The measured outcome of the test is the number of blocks successfully transferred between the two compartments of the box regardless of how the movements are performed (72). Therefore, the difference between outcomes from repeated tests measuring performance only on a quantitative scale may not provide information about the quality of the movements performed during the tests and how this may have changed. Assessing the quality of the movement makes it possible to discover early signs of development of inappropriate compensatory movement strategies that could lead to pain, negatively affecting further functional improvement (9), (73). Examples of motor function tests including assessment of the quality of movements are the Fugl-Meyer Assessment (FMA) (74) and the Wolf Motor Function Test (WMFT) (75). In both of these tests, the therapist assesses the quality of the movements by rating them on a 3-point (FMA) or 6-point (WMFT) ordinal scale. The movement quality rating scale in the WMFT ranges from 0-5, where a rating of 0 corresponds to no attempt made to use the more affected upper extremity and 5 corresponds to a movement that appears to be normal (75). Although, the FMA and WMFT assesses the patient in more detail than tests like the Box and Block Test, they may not necessarily provide more valid results, since the test results may be affected by human factors as e.g. differences between therapists opinions about the quality of the movements performed by patients (some therapists may have higher requirements to the patients than others) and/or the reaction time of the therapist administering the test (76), (77). In timed motor function tests, as the WMFT and the Jebsen Test of Hand Function, also the reaction time of the patient may introduce an unwanted bias or variability to the measured test outcome, as indicated by the results found in Study III. Changes in the bias due to an altered reaction time of the patient over the time period of a rehabilitation programme could potentially make a motor function test show a significant outcome change that is not related to changes in the motor function itself. Similarly, if different therapists administer motor function tests to the same patient it could potentially introduce unwanted variability, affecting the sensitivity of the test. Therefore, these sources of variability should be minimized, e.g. by using sensor-based systems to assist therapists in the assessment of motor function in stroke patients (Study III is an example of how this could be implemented, proving the concept with one therapist and one Kinect based system). Furthermore, the high complexity of tests like the FMA compared to e.g. the Box and Block Test makes these tests far more time consuming and useful only to therapists with expert skills, meaning that they are less likely to be used in healthcare systems with limited resources.

## 4.2. SENSOR-BASED AUTOMATIZATION OF MOTOR FUNCTION TESTING IN STROKE PATIENTS

Multiple studies have shown that sensor-based systems can be used to automatize validated motor function tests (17), (18), (Study III). Automatization of motor function tests using kinematic sensors and/or computer vision is an emerging field; however the number of published studies is still limited. Therefore, in Study III, the modified version of the Jebsen Test of Hand Function (3 subtests) (70), (78), which is a validated motor function test, was selected for automatization, in order to establish a proof-of-concept that a standardized hand function test can be automatized successfully. The results from Study III showed 95 % limits of agreement (Bland-Altman analysis) ranging from 0.5 s to 2.7 s for the differences between the times recorded by the Kinect system and the therapist. The results from Study III also showed that the agreement between actual times (ground truth) and times recorded by the Kinect system was better than the agreement between the actual times and the therapist. Other studies have have used different approaches for automatizing motor function tests, e.g. Cruz et al. (2014) showed that selected subtests of the WMFT, along with ratings of the quality of the movements, can be automated by analyzing three-dimensional kinematics data from a wearable sensor system based on magnetic, angular rate, and gravity sensors mounted on the more affected upper limb (wrist, arm, and shoulder) of stroke patients (17). The algorithms used for automating the selected WMFT subtests included comparing the kinematic data from the stroke patients' affected limb to quality metrics based on clinical prescriptions, kinematic data from the less affected upper limb and population based kinematic data (17). The average difference between the WMFT times recorded by the system and the times recorded by a clinician were found to be 0.17 s (clinician times were systematically longer) (17). In another study, by Huang et al. (2012), a computer vision based system for automated evaluation of selected subtests of the WMFT was tested in healthy participants and results were compared to results obtained manually using a stopwatch (18). Also in this study, the comparison of the manual times and automatic times revealed that stopwatch times were systematically longer than the times recorded by the computer vision based system (18). These systematic manual overtimes differ from the results found in Study III, where the manually recorded times in the modified version of the JFHT were systematically shorter than the times recorded by the Kinect based system. However, the results from Study III showed that the times recorded by the Kinect based system were in better agreement with the ground truth times. This suggests that the discrepancy in the results from Study III and previous studies could be explained by human factors related to the individual style of the examiner in each study, e.g. some examiners may for example consistently start time too early or end time too late. The differences in the results may also be explained by human factors related to the participants, e.g. some stroke patients may have longer reaction times than others or may start a test before time recording has been initiated. The variability related to human factors would most likely be minimized by using sensor-based systems for evaluation of motor function tests, leading to increased objectivity and reliability. On top of this, the use of sensor-based systems may also allow to administrate motor function tests to stroke patients at remote sites, without direct supervision, as part of a tele-rehabilitation service.

# CHAPTER 5. OVERALL CONCLUSION

The aim of the present Ph.D. project was to investigate the feasibility of supporting upper limb training in stroke patients by use of a Microsoft Kinect sensor based tele-rehabilitation system. The Ph.D. project focused on three core components of upper limb rehabilitation: physical support, extrinsic feedback, and functional assessment. Based on these three core components, three studies were completed.

The first core component considered in the present thesis was the use of FES for upper limb rehabilitation. FES can be used to assist stroke patients with motor function deficits during physical training. Study I described how the Microsoft Kinect sensor can be used for closed-loop control of FES for supporting hand opening and closing training in stroke patients. According to the results from Study I, patients using the FES system increased their percentage of successful grasps and decreased the time spent on establishing a succesful grasp and release of a cylindric object. In Study I, only the onset and offset (thereby also the duration) of FES was controlled by the Microsoft Kinect sensor, whereas the intensity, pulse frequency, and pulse duration was preset. Thus, the closed-loop FES system could be further developed by adding continuous adaptive regulation of the stimulation intensity. This would make possible to adapt the level of physical assistance to the minimum needed by the individual patient at all times. For example, the intensity could be decreased along with the stroke patient’s motor improvement, which could in fact also be measured using a Microsoft Kinect sensor (Study III), thereby always encouraging the patient to put in a maximum of rehabilitation effort. The Microsoft Kinect sensor based FES system could also be used for analyzing quality of movement patterns. The information from this type of kinematic analysis could then possibly be used to correct inappropriate movement patterns, e.g. by providing the stroke patient with physical feedback/guidance from FES or another type of extrinsic feedback (Study II).

The second core component considered in the Ph.D. project was the role of feedback in upper limb rehabilitation. Feedback is a significant factor for the outcome of motor rehabilitation of stroke patients. Hence, the provision of feedback from an extrinsic source is known to have a positive effect on the outcome of motor function training. Study II showed that by tracking and analyzing movements in stroke patients, the Microsoft Kinect sensor can be used as a control source for extrinsic adaptive visual feedback provided to stroke patients. Furthermore, the results from Study II showed that the movement smoothness of the stroke patients was increased, when providing adaptive visual feedback controlled by the Microsoft Kinect sensor, compared to when no feedback was provided. This outcome clearly indicated that adaptive visual feedback provided to stroke patients increased their motor control. However, the results from Study II also showed that the time needed to complete a specific movement increased when adaptive visual feedback was provided. This outcome could be considered negative as the increase in movement duration would mean that stroke patients training with the system would move the arm slower, but the result could also be considered positive as it might be a consequence of the cognitive load on the stroke patient induced by the visual feedback, which was successfully utilized to increase movement smoothness. Due to the type of extrinsic feedback used in Study II, only stroke patients without visual deficits were included. If the system should be part of a tele-rehabilitation system for stroke patients, other types of extrinsic feedback should be included in order to target the heterogeneous population of stroke patients.

The third and final core component considered in the project was assessment of upper limb motor function in stroke patients. In Study III, the Microsoft Kinect sensor was used to automatize selected parts of a validated motor function test. The outcome from this study showed that the measurements performed using the Microsoft Kinect sensor were comparable to those performed by a therapist, thereby proving the feasibility of using the Microsoft Kinect sensor for assessment of upper limb motor function in stroke patients. The setup used in Study III, however, does only offer limited possibility for analysing full body movements, e.g. trunk movements, which may be important to monitor in stroke patients with poor upper body balance. Though, by adding an additional Kinect sensor to the setup or by placing the Kinect sensor in a different position, facing the whole body of the stroke patient, it would be possible to perform a more extensive kinematic analysis.

## 5.1. FUTURE PERSPECTIVES

The three studies in the current Ph.D. project proved the feasibility of using the Microsoft Kinect sensor as a core component in a framework for a tele-rehabilitation system for stroke patients. The next logical step would be to combine the three Kinect based systems into one, thereby forming a more complete tele-rehabilitation system, and test it on stroke patients. Testing of the combined system could possibly be performed in patients' own homes, in order to challenge the robustness of the system. It is unclear whether the use of the system for unsupervised training developed and tested in the present Ph.D. project, have any positive long-term effect on motor function in stroke patients. Therefore, future studies could focus on clinical trials investigating the effect of long-term unsupervised training on motor function in stroke patients. Future work should also investigate the effect of unsupervised training on non-physical parameters such as motivational level, quality of life, etc.

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# SUMMARY

Stroke is a major cause of death and disability worldwide. The damage or death of brain cells caused by a stroke affects brain function and leads to deficits in sensory and/or motor function. As a consequence, a stroke can have a significantly negative impact on the patient's ability to perform activities of daily living and therefore also affect the patient's quality of life. Stroke patients may regain function through intensive physical rehabilitation, but often they do not recover their original functional level. The incomplete recovery in some patients might be related to e.g. stroke severity, lack of motivation for training, or insufficient and/or non-optimal training in the initial weeks following the stroke. A threefold increase in the number of people living past the age of 80 in 2050, combined with the increasing number of surviving stroke patients, will very likely lead to a significant increase in the number of stroke patients in need of rehabilitation. This will put further pressure on healthcare systems that are already short on resources. As a result of this, the amount of therapeutic supervision and support per stroke patient will most likely decrease, thereby affecting negatively the quality of rehabilitation. Technology-based rehabilitation systems could very likely offer a way of maintaining the current quality of rehabilitation services by supporting therapists. Repetition of routine exercises may be performed automatically by these systems with only limited or even no need for human supervision. The requirements to such systems are highly dependent on the training environment and the physical and mental abilities of the stroke patient. Therefore, the ideal rehabilitation system should be highly versatile, but also low-cost. These systems may even be used to support patients at remote sites, e.g. in the patient's own home, thus serving as tele-rehabilitation systems. In this Ph.D. project the low-cost and commercially available Microsoft Kinect sensor was used as a key component in three studies performed to investigate the feasibility of supporting and assessing upper limb function and training in stroke patients by use of a Microsoft Kinect sensor based tele-rehabilitation system. The outcome of the three studies showed that the Microsoft Kinect sensor can successfully be used for closed-loop control of functional electrical stimulation for supporting hand function training in stroke patients (Study I), delivering visual feedback to stroke patients during upper limb training (Study II), and automatization of a validated motor function test (Study III). The systems described in the three studies could be developed further in many possible ways, e.g. new studies could investigate adaptive regulation of the intensity used by the closed-loop FES system described in Study I, different types of feedback to target a larger group of stroke patients (Study II), and implementation of more sensors to allow a more detailed kinematic analysis of the stroke patients (Study III). New studies could also test a combined version of the systems described in this thesis and test the system in the patients' own homes as part of a clinical trial investigating the effect of long-term training on motor function and/or non-physical parameters, e.g. motivational level and quality of life.

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