A feasibility study of the effect of multichannel electrical stimulation and gravity compensation on hand function in stroke patients: a pilot study

T. Krabben, MSc; J.H. Buurke, PhD; G.B. Prange, PhD; J.S Rietman, PhD, MD

T Krabben, JH Buurke, GB Prange, JS Rietman
Roessingh Research & Development (RRD)
Enschede, the Netherlands
Corresponding author: t.krabben@rrd.nl

JH Buurke, JS Rietman
University of Twente
Enschede, the Netherlands

***Abstract*—Many stroke patients have to cope with impaired arm and hand function. As a feasibility study, gravity compensation (GC) and multichannel electrical stimulation (ES) were applied to the forearm of eight stroke patients to study potential effects on dexterity. ES was triggered by positional data of the subject's hand relative to the objects that had to be grasped. Dexterity was evaluated by means of the Box and Blocks Test (BBT). The BBT was performed with four combinations of support; with and without GC and with and without ES. In all patients, it was possible to induce sufficient hand opening for grasping a block of the BBT by means of ES. There was no significant increase in dexterity as measured with the BBT. GC and/or ES did not improve instantaneous dexterity in a small sample of stroke patients although sufficient hand opening was reached in all patients. More research in a larger sample of stroke patients with more specific and more sophisticated control algorithms is needed to explore beneficial effects of GC and ES on hand function in post stroke rehabilitation.**

Keywords—stroke; upper extremity; gravity compensation; electrical stimulation; Box and Blocks Test

I. INTRODUCTION

Stroke is one of the leading causes of permanent disability in Europe [1] and North America [2]. Around 40 % of the stroke patients have to cope with severely affected arm- and hand function [3] and dexterity is only found in 38 % of stroke survivors 6 months post stroke [4]. Motor problems of the upper extremity following stroke include muscle weakness, spasms, disturbed muscle timing and a reduced ability to selectively activate muscles.

Post stroke rehabilitation training aims to regain (partly) lost functions by stimulating restoration of function or promoting compensational strategies, in order to increase the level of independence during activities of daily living (ADL). Currently, highly intensive, repetitive, task specific training in a motivating environment with (augmented) feedback on movement error and performance, is regarded as the most effective way to promote motor restoration after stroke [5, 6].

The last decades, several robotic training systems have been developed and applied in post stroke upper extremity rehabilitation. Systematic reviews indicated a positive effect on proximal (i.e. shoulder and elbow) arm function [7, 8, 9] and recently also on distal (i.e. wrist and hand) arm function [10, 11] after robot-aided arm rehabilitation training.

One training modality that is commonly integrated in robotics is arm support, or gravity compensation (GC). Arm support decreases the effort by the stroke patient to hold the arm against gravity, which enables the patient to perform more repetitions of the movement that is being relearned. Research has shown that stroke patients can instantaneously increase the ability to extend the elbow due to a reduced effect of involuntary coupling between shoulder abduction/elevation and elbow flexion, when the arm is supported against gravity [12, 13]. This reduced effect of coupled movements leads to an increase of maximal forward reaching [14] and work area of the affected arm [15]. Training with progressively decreasing levels of arm support leads to increased reaching distance [16, 17] and increased work area [18, 19] without any support. In this study [17], the increased maximal forward reaching distance was accompanied by increased activity of the elbow extensors and a decreased involuntary coupling between shoulder and elbow movements in some patients.

Recent research showed that besides movements of the elbow, also movements of the wrist are coupled to shoulder abduction forces [20]. When shoulder abduction forces increase during lifting and reaching tasks, coupled flexion forces of the wrist and/or fingers were measured, together with increasing activation of the flexor digitorum superficialis. This involuntary coupled flexion impedes releasing of grasped objects. Seo et al. [21] reported decreased grip initiation and termination times in the hemiparetic hand, compared to the non-paretic and control hands. Application of gravity compensation leads to decreased delays in grip initiation and termination [21].

Besides (robotic) gravity compensation of the arm, electrical stimulation (ES) is often used to support arm and hand function. A meta-analysis of Glanz et al. indicated a positive effect of ES on muscle strength in both lower and upper extremity after stroke [22]. The ability to voluntarily generate wrist and finger extension increases after ES [23] and

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electromyography (EMG) triggered ES [24, 25], especially when patients have some residual function at the wrist and fingers [23, 26, 27].

When both arm and hand training are combined, goal directed and meaningful movements such as reach-to-grasp tasks can be practiced. Exercise programs in which goal directed tasks are intensively trained are beneficial for stroke patients [28].

For this purpose, a new hybrid Active Therapeutic Device (ATD) is being built, see Fig.1. The ATD will consist of a robotic manipulator with the main purpose to support the arm. Besides counteracting gravitational forces on the arm, the ATD can also provide small assisting or resisting forces by tilting the supporting force vector. A manually adjustable spring delivers a constant primary supporting force. Electric motors apply secondary variations to the magnitude and direction of the primary (supporting) force. Due to these variations in magnitude and direction of force, several training modalities are possible, such as actively assisted training, actively resisted training, and haptic simulation.

Figure 1. Prototype of the Active Therapeutic Device (ATD).

To facilitate hand opening, the ATD is equipped with a custom built multichannel electrical stimulator. This stimulator is capable of stimulating three channels independently. The stimulator can be used both with 12-pad array electrodes and with conventional single electrodes. The stimulator is equipped with a communications port so it can be controlled by an external device. For this purpose, as part of the present study, control algorithms have been developed that enable support of functional tasks and object manipulation. In the present study, a control strategy together with a rule-based system that uses positional data of the hand, relative to objects that subjects have to grasp, to trigger stimulation at the right moment during a functional task, is applied and assessed.

As a feasibility study, GC and multichannel surface ES are applied to the (fore)arm in a small sample of stroke patients. Instantaneous effects on hand opening due to GC and/or ES are examined and the algorithms that control the electrical stimulator are evaluated. The objective is to study the instantaneous effect of multichannel ES and GC on dexterity, which is evaluated in the activity domain [29] of the International Classification of Functioning, disability and health (ICF). It is expected that application of GC [20, 21] and multichannel ES [30] will facilitate hand opening and consequently improve dexterity. The present study was performed as part of the design phase of the ATD.

II. METHODS

A. Subjects

Subjects were recruited from rehabilitation centre 'Het Roessingh' in Enschede, the Netherlands. Subjects had to meet the following inclusion criteria: a history of a single unilateral stroke resulting in single-sided hemiparesis, the onset of the stroke was more than six weeks ago, the ability to voluntarily generate excursions of at least 20 degrees in the plane of elevation (horizontal ab-/adduction) and elevation angle (ab-/adduction, ante-/retroflexion) of the shoulder joint, the ability to voluntarily generate an excursion of at least 20 degrees of elbow flexion/extension, the ability to voluntarily extend the wrist at least 10 degrees from neutral flexion/extension, adequate cognitive function to understand the experiments, follow instructions, and give feedback to the researchers. Subjects were excluded if a fixed contracture deformity in the affected upper limb was present, or pain was a limiting factor for the subject's active range of motion.

B. Procedures

Before the experiment, patient characteristics were gathered and arm and hand function were clinically tested by means of the upper extremity part of the Fugl-Meyer (FM) assessment [31] and the Action Research Arm Test (ARAT) [32]. Because of the strong focus on hand opening and closing in this study, the individual scores on FM items 'mass flexion' (Flex) and 'mass extension' (Ext) of the fingers are reported in the results section. A score of 0 means `no movement`, a score of 1 means ´some, but not full active movement´ and a score of 2 means ´full active movement´. After clinical testing, the electrodes used for electrical stimulation were applied to the forearm. The Box and Blocks Test (BBT) [33] was performed with four different combinations of support, i.e. with and without GC and with and without ES. The order of combinations was randomized across subjects to minimize possible learning effects and effects of fatigue. Each condition was preceded by a trial period of 15 seconds [33] and followed by a rest period of 2 minutes. During the BBT the subject had to move as many as possible wooden blocks (2.5 x 2.5 x 2.5 cm) from one compartment into another within a time frame of one minute.

C. Gravity compensation

The BBT was performed with 0 and 100 % gravity compensation, which means that the arm was either not supported or that the weight of that subject's arm was fully counterbalanced. Since the ATD was not fully ready to be used at the time of the experiments, an alternative GC device 'Freebal' [34] was used to support the arm. The Freebal consists of two adjustable ideal spring mechanisms that were attached to the wrist and elbow of the subject via overhead slings.

D. Electrical stimulation

A 50 x 50 mm square reference (ref) electrode (ti2013, tic Medizintechnik GmbH & Co. KG, Dorsten, Germany) was attached to the dorsal side of the wrist. A similar surface electrode was used to stimulate the m. extensor digitorum (EDI). A 32 mm round surface electrode (ti2011, tic Medizintechnik GmbH & Co. KG, Dorsten, Germany) was used to stimulate the m. abductor pollicis brevis (APB). The electrodes were placed on the muscle belly and connected to a custom built three channel electrical stimulator (tic Medizintechnik GmbH & Co. KG, Dorsten, Germany), that delivered trains of biphasic rectangular pulses with a pulse width of 200 µs and a frequency of 50 Hz.

After application of the electrodes, the amplitudes of both channels were increased in steps of 1 mA, starting at 0 mA to get a proper hand opening. Increasing the amplitude stopped when a natural, proper hand opening was achieved, or when the stimulation led to discomfort for the subject.

E. Control of the electrical stimulator

The electrical stimulator was connected to a computer and controlled via an RS-232 communication protocol by custom written software in Matlab (R2011b, Natick, MA). For this purpose, 3 reflective optical markers (H1 – H3) were attached to the proximal interphalangeal joints of digits 2 and 4 and to the metacarpophalangeal joint of digit 3 of the subject's hand, see Fig. 2. The mean of the positions of H1 – H3 represented the hand position. Three spherical 14 mm VICON markers (M1 – M3) were attached to the BBT, see Fig. 2. The markers were automatically labeled in real-time by VICON Nexus (version 1.8.2). The positions of the VICON markers were acquired in real-time in Matlab via the VICON DataStream SDK version 1.2 by the laptop that controlled ES. Based on the positions of the markers attached to the hand and BBT, commands were sent to the electrical stimulator to support hand opening. When the hand was above the compartment containing the blocks (source) the EDI and APB were stimulated to support opening of the hand. When the z-position (height) of the hand came below a threshold of 15 cm, measured from the bottom of the BBT, stimulation stopped to enable the subject to grasp a block. The stimulation remained off until the subject moves the hand across the divider, above the empty part of the BBT (target). At this point the muscles were stimulated to release the block. The subject moved the hand towards the source part, while the stimulation was still enabled. When the z-position of the hand came below the threshold, the stimulation was stopped again so the subject was able to grasp the next block.

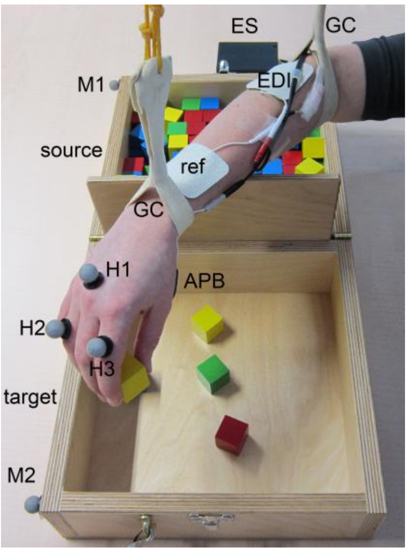

Figure 2. Locations of the VICON markers and surface electrodes used for electrical stimulation (marker M3 is not visible in the picture).

F. Statistics

Because of the explorative character of the study, effects of multichannel electrical stimulation on hand opening are reported descriptively. The primary outcome measure was the number of blocks that had been moved within one minute during the BBT. Individual data are reported in the results section. Data representing group averages are reported as median and interquartile (25^{th} – 75^{th} percentile) range (IQR). To statistically test the effect of GC and ES a related samples Friedman's two-way ANOVA for ranks was applied to the data. Differences were non-parametrically tested for statistical significance due to the small sample size. Effects were considered statistically significant for $p < 0.05$.

III. RESULTS

A. Subjects

Eight sub-acute and chronic stroke patients were included in the study. Demographic data and the clinical FM and ARAT scores of the subjects are presented in Table 1. Five subjects had severe hemiparesis (FM < 25) and three had moderate hemiparesis (25 ≤ FM < 45). Two subjects (S2 and S6) were (almost) not able to close the hand due to weakness/paresis of the finger and wrist flexors which affects closing of the hand.

TABLE I. SUBJECT DEMOGRAPHIC AND CLINICAL DATA

N	8
Gender	7 male / 1 female
Dominance before stroke	8 right / 0 left
Impaired arm	4 right / 4 left
Age (years)	64.4 (IQR: 48.5 – 65.8)
Months post stroke	12.0 (IQR: 6.0 – 59.5)
FM (max. 66)	22.0 (IQR: 19.0 – 28.5)
ARAT (max. 57)	12.0 (IQR: 6.5 – 17.0)

The other subjects were able to partly (S5 and S7) or fully (S1, S3, S4, S8) flex the fingers. Two subjects were not able to volitionally open the hand due to weakness of the finger extensors (S2) or increased muscle tone in the finger flexors (S8), see also Table 2. The other six subjects were able to partly extend the fingers but none of them had a full range of motion.

With two-channel ES it was possible to achieve a hand opening big enough to grasp a wooden block with a vertex length of 2.5 cm in all subjects. The EDI was stimulated with a median amplitude of 32.5 mA (IQR: 25.0 – 40.0 mA). The APB was stimulated with a median amplitude of 14 mA (IQR: 5 – 17.5 mA).

Application of GC did not lead to a visible increase of maximal hand opening. Some subjects (S2 and S8) had difficulty to detect whether or not their hand contained a block, probably due to reduced hand sensibility. Occasionally, S2 moved his hand towards the empty compartment to release a block, while he had not succeeded in grasping a block.

The individual scores of the FM, ARAT and the BBT are presented in Table 2. The median number of blocks transported within one minute on group level was 7 (IQR: 3.5 – 9.5) without ES and without GC. With only ES, the median number of blocks was 5 (IQR: 3.5 – 11). When the arm was supported against gravity (GC), the median number of blocks was 7.5 (IQR: 1.5 – 11). When the arm was supported against gravity (GC) and hand opening was supported by ES, the median number of blocks was 6 (IQR: 5 – 9.5). The number of blocks transported within one minute in each condition is graphically displayed in Fig. 3. On group level, the number of transported blocks did not differ statistically significant across conditions, p = 0.853.

TABLE II. INDIVIDUAL SCORES ON THE FM, ARAT AND BBT

Subject	FM	Flex	Ext	ARAT	GC off		GC on	
					ES off	*ES on*	*ES off*	*ES on*
1	27	2	1	16	14	12	16	12
2	22	1	0	11	5	4	1	5
3	32	2	1	33	10	10	9	8
4	20	2	1	7	2	3	2	7
5	16	1	1	6	5	5	6	5
6	30	1	1	13	9	15	12	11
7	22	1	1	18	9	5	10	5
8	18	0	0	3	0	0	0	0

I. DISCUSSION

As a feasibility study, GC and multichannel ES were applied to the (fore)arm of eight moderately to severely affected stroke patients. In all subjects it was possible to induce sufficient hand opening to grasp a wooden block of the BBT by means of two channel surface ES on the EDI and APB. The instantaneous effect of GC and multichannel ES on dexterity was evaluated by means of the Box and Blocks Test. Contrary to our expectations, application of multichannel ES, GC and the combination of both did not result in an instantaneous improvement in dexterity on group level.

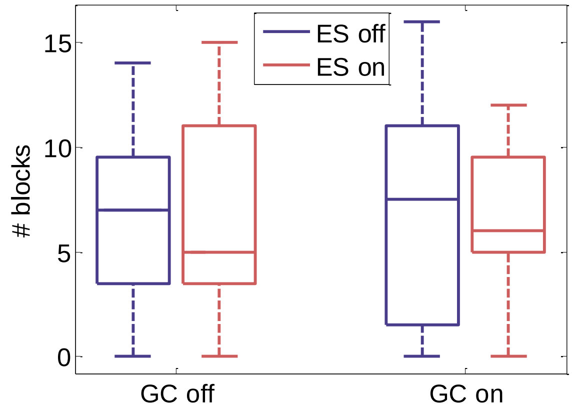

Figure 3. Box and Blocks Test scores in each of the four conditions

The effect of arm support on involuntary wrist and finger flexion as found in Miller et al. [20] did not generalize to instantaneous gains in dexterity as measured with the BBT in the present study. A possible reason is that the amount of shoulder abduction torque needed to perform the BBT is less compared to the movements that subjects had to perform in the experiment carried out by Miller [20]. In that study subjects had to perform lift and reach tasks while maintaining different shoulder abduction forces, resulting in coupled, involuntary wrist and finger flexion forces. During the BBT subjects move their hand relatively close to the body, which implies that shoulder abduction/anteflexion torques are probably less compared to shoulder abduction/anteflexion forces that subjects had to generate in the experiment of Miller [20].

Whether or not application of GC led to increased hand opening, as could be expected from the previous research [20], or decreased time to terminate grip as found in [21], could not be discerned in the present study because hand opening and temporal aspects of hand opening were not measured explicitly. However, if application of GC led to quicker hand opening, it did not lead to an increase in BBT scores, which could imply that this process only has modest impact on dexterity as measured with the BBT.

This statement is strengthened by the observation that the most challenging aspect of the BBT for this patient group was to grasp a single block. Due to poor arm and hand coordination during the experiment, many blocks were moved around by the patient within the BBT compartment when trying to grasp a single block. This resulted in a very dense and compact layer of blocks, making it very difficult to grasp a single block. The stimulator was controlled in such a way that after releasing a block above the target compartment, ES continued until the hand was below the 15 cm threshold in the source compartment. In this case the hand is still opened when the patient lowered his/her hand to grasp the next block. However, when a patient failed to immediately grasp a block, ES stopped and hand opening was no longer supported. To improve these temporal aspects of support in hand opening, the rule-based system that decides whether or not to stimulate should be adapted in such a way that stroke patients can perform several attempts to grasp a single block.

After stroke, dexterity is affected by several mechanisms. A commonly observed mechanism is a reduced ability to generate wrist and finger extension due to muscle weakness [35] and inappropriate co-activation of finger flexors [36] which makes it difficult to open the hand, or to release a block during the BBT. However, some subjects (S2 and S6) who were able to volitionally open the hand to some extent, experienced difficulty in closing the hand as well, due to muscle weakness in the finger flexors. These patients had difficulty in holding a block. In these cases, support of hand opening by ES or GC has (almost) no beneficial effect on dexterity. Therefore in future research the support of arm and hand function should combine stimulation of finger extension with flexion in a functional way.

Previous studies have combined ES and (robotic) GC during functional tasks and object manipulation [37, 38]. The approach presented in this paper differs from [37, 38] in the way ES is triggered. In [37, 38] subjects triggered ES manually by pushing a button with the non-impaired hand, compared to the automatic, positional triggering in the present study.

Limitations and recommendations

In the present study it was possible to use positional information of the subject's hand relative to the objects that had to be manipulated to trigger the electrical stimulator. However, the present approach was rather coarse since only the dimensions of the compartment that contained the 150 blocks (source) and the empty compartment (target) were used. If the position of a single object that has to be transported or manipulated is known, together with the position of the hand, more accurate control algorithms can be developed. Some subjects, who showed weakness of the finger flexors and as a result had difficulty in holding a block, could have benefited from stimulation of the finger flexors together with the finger extensors. New and more sophisticated algorithms need to be developed that target impairments in hand function more specifically, enabling a patient-tailored approach.

The present study did not find any improvement in dexterity as measured with the BBT, after application of gravity compensation and/or electrical stimulation. However, results should be interpreted carefully because of the small sample size. For example, some patients experienced fatigue during the BBT. Although the order of measurements had been randomized, fatigue could have influenced the number of transported blocks and therefore the results. In future research, it is recommended to include a more homogeneous group and increase the number of subjects. It is also recommended to measure fatigue of the arm and hand, for example by using a Visual Analog Scale (VAS).

Two subjects experienced diminished tactile feedback. This loss of sensibility is very likely to interfere with performance on a movement task such as the BBT where subjects have to grasp rather small blocks that are likely to be visually blocked by the subject's hand when grasped. In future research it is recommended to assess sensibility of the hand as well or select subjects also based on their level of tactile feedback.

Clinical implication and future research

Some algorithms that were used in the present study to induce hand opening were successful and will be integrated in the ATD. These algorithms will serve as a starting point to develop more sophisticated and more specific control algorithms with improved decision rules to trigger ES more accurately, taking the present findings into account. A possible next step is to combine the robotic arm manipulator with the updated control algorithms for the multichannel electrical stimulator and reassess the influence of GC + ES with the improved system. The ATD has built-in encoders that can be used to calculate the position of the hand. This means that an external system to measure hand position (VICON in the present study) is no longer necessary which makes the ATD more suitable to be deployed in a clinical setting.

In the present study it was possible to induce sufficient hand opening to grasp a wooden block of the BBT, by means of two-channel surface ES in all participating stroke patients. This enables the patient to train several functional movements that require sufficient hand opening, such as reaching for and grasping an object or other task oriented movements. By supporting the arm against gravity, the patient has to deliver an active contribution during reaching tasks, which is more effective than passive performance of movements [39]. Furthermore, to increase the active contribution during grasping, triggering of ES can be done not only by means of positional data, but also by means of activation levels of muscles involved in hand function (EMG triggered ES). After these steps, therapeutic effectiveness of the ATD needs to be evaluated in a longitudinal experiment.

II. Conclusion

This feasibility study showed that it was possible to induce sufficient hand opening to grasp a wooden block of the BBT in all participating subjects by means of two-channel surface electrical stimulation. The expected effects of application of gravity compensation on hand opening to result in an instantaneously improved dexterity were not observed. The used algorithms, allowing position-triggered electrical stimulation, allowed only a few patients to benefit from this specific support in hand opening. More research in a larger sample of stroke patients with more specific and more sophisticated control algorithms is needed to further explore beneficial effects on hand function in post stroke rehabilitation.

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