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Combining Electrical Stimulation Mediated by Iterative Learning Control with Movement Practice using Real Objects and Simulated Tasks for Post-Stroke Upper Extremity Rehabilitation

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Abstract

Objective: Task specific training and Electrical stimulation (ES) are techniques used in rehabilitation of the upper extremity post stroke. This study describes the feasibility of using a rehabilitation system that combines personalised, precisely controlled levels of ES to the anterior deltoid, triceps and finger and wrist extensors during goal-oriented activity utilising real objects from daily life.
Materials and Methods:
Four chronic stroke participants undertook seventeen intervention sessions, each of one hour duration. During each session, particpants performed goal-orientated tasks while Iterative learning control (ILC) updated the ES signal applied to each muscle group. The update was based on the difference between the ideal and actual movement in the previous attempt at the task, measured using Microsoft Kinect and PrimeSense sensors. The control system applied the minimum amount of ES required with a view to facilitating success at each given task while maximising voluntary effort.
Results: Preliminary results demonstrate that ES mediated by ILC resulted in a statistically significant improvement in range of movement in all four joint angles studied (shoulder flexion; elbow, wrist and index finger extension) over 17 intervention sessions. Additionally, participants required signficantly less extrinsic support for each task. The tasks and system is described and initial intervention data are reported.
Discussion: The feasibility of using this system for assisting upper limb movement has been demonstrated. A large scale pilot RCT is now required.

Keywords— *electrical stimulation; iterative learning control; rehabilitation; stroke; upper extremity*

Introduction

Annually 16 million first strokes occur globally, and 10.3 million people are estimated to survive [1]. As age is a substantial risk factor, the aging of the world population means that a growing number of people are at risk, with associated impacts on the individual, their carers and broader society. Arm dysfunction is a major consequence of stroke; only 41% of people with moderate to severe stroke and 71% with mild stroke regain dexterity [2], which affects performance in activities of daily living [3] and subsequently care. In 2009, stroke alone was estimated to cost the EU economy over €38 billion, of which 50% was due to direct health care costs, 22% was due to productivity losses and 28% was due to informal care costs of people with stroke [4].

Whilst the majority of any functional improvement is seen in the first six months following stroke, functional gains can be observed over several years [5, 6]. A recent review and meta-analysis highlighted that there is strong evidence for physical therapy interventions which include intensive, highly repetitive task-oriented and task-specific training in all phases post stroke [7]. This presents a major challenge to healthcare providers, and is driving the development of rehabilitation technology which can deliver this specific and intense rehabilitation without using additional resources. Technologies such as electromechanical and robot-assisted arm training have been demonstrated to improve activities of daily living and arm function (but not muscle strength) [8]. However few evidence based technologies are routinely used in clinical practice in the UK. Identified barriers which need to be overcome to facilitate translation include usability, knowledge, education, awareness and access to ATs as well as cost [9]. One of the technologies which shows promise in meeting some of these

barriers is Electrical Stimulation (ES) which has a growing evidence base [10], demonstrating improvements in range of movement, strength and spasticity.

The effectiveness of ES is increased when ES is associated with voluntary drive. It is therefore important to carefully control ES in order to support the user's intended movement. ILC is an advanced control paradigm that operates by comparing movement data from a previous attempt at a task to an idealised reference trajectory for the same task. It sequentially adjusts the level of stimulation given to each muscle group with a view to achieving the required reference trajectory. This iterative process applies the minimum level of ES for task attainment while simultaneously encouraging voluntary contribution from the participant. Previous studies combining ES and ILC have demonstrated feasibility of using PayPals electrodes to deliver precisely controlled stimulation to the anterior deltoid, triceps and wrist extensors [11-13]. The GO-SAIL (goal-oriented stimulation assistance through iterative learning) system used in this study, is a multi-channel ES system for the upper extremity that precisely controls ES through advanced iterative learning control algorithms [14]. The technology employed in this study includes three important developments to that used in previous research:

1. An electrode array is located over the wrist and finger extensors to enable functional hand gestures to be performed.
2. A Primesense is used to measure hand and wrist joint angles, reducing set-up time and removing constraints associated with contact-based sensors (e.g. goniometers).
3. A touch table displays the tasks in an interactive manner.

The system directly trains goal-oriented activities and is able to provide greater assistance than in previous research by including an electrode array to support functional hand and wrist gestures. This is expected to lead to further reduction in upper limb motor impairments, as reflected by evidence that effects resulting from training are mostly restricted to the actually trained functions and activities [10]. To be useful in longer term self-management, technologies need to promote adherence through stimulating and motivating rehabilitation. The use of a touch table provides such an environment, and, when combined with inexpensive non-contact sensors (Kinect and Primesense), represent a significant step in the development of technology that is suitable for translation into the home environment.

The aim of this study is to test the feasibility of using the multi-channel ES system to precisely control ES applied to multiple muscle groups in the UE in combination with real and virtual tasks to facilitate functional motor recovery post-stroke. The rehabilitation system has been designed to facilitate recovery of UE motor control and function in chronic stroke participants.

Method

Participants

The inclusion criteria for participants were: i) aged 18 years old or over; ii) stroke causing hemiplegia of at least 6 months duration; iii) impaired upper limb that includes the inability to effectively extend the elbow in reaching and impaired opening and closing of the hand iv) ES produces movement through a functional range; v) able to comply with study protocol; vi) able to communicate effectively; vii) able to provide written informed consent. The exclusion criteria for participants were: i) any active device implant; ii) a metal implant in the affected upper limb; iii) uncontrolled epilepsy; iv) pregnancy and lactation; v) any serious or unstable medical, physical or psychological condition or cognitive impairment that would compromise the subject's safety or successful participation in the study; vi) requirement of an

interpreter; vii) current participation in another study involving physical rehabilitation of the arm. Following ethical approval, to date, a total of 4 participants have been recruited to the trial.

The rehabilitation system

Pals Plus electrodes were applied to the anterior deltoid and triceps, whilst the 24 element electrode array was positioned over the finger and wrist extensors. Multi-channel ES was precisely applied to assist participants' completion of the movement tasks. The system was goal-orientated; tasks included holding an imitation loaf of bread with one hand whilst simulating a cutting task with the other, or moving soap or toothpaste to a different position on the representation of the bathroom sink displayed by the touch screen. The control scheme considered each task to be a general optimisation problem where the desired movement was specified in terms of kinematic variables. For example, the task of moving the soap, involved reaching a certain position in Cartesian space at a predetermined time, with constraints which influenced the posture adopted, and the speed and smoothness of the motion. Healthy participants' movements were used to identify the optimisation components. [24]. ILC iteratively solves the optimisation by learning from experimental data recorded on the previous attempts of the task, in such a way as to solve the optimisation and hence complete the task. Thus, the stimulation signal applied to each muscle group is updated on every trial. In the current system, this involves using kinematic, kinetic and stimulation signals, which are used in combination with an underlying bio-mechanical dynamic model of the arm [14, 15].

Insert Figure 1 about here

Fig. 1. The components of the GO-SAIL system: (1) Microsoft Kinect® and Primesense sensors which provide kinematic data for the ILC algorithm; (2) virtual and real tasks displayed using touch table; (3) SaeboMAS® arm support; (4) FES and multiplexor hardware (5) surface electrode array on forearm.

A schematic overview of the system can be seen in Figure 1. Participants sat on a perching stool in front of a touch table adjusted to their height and reach. Their arm was de-weighted according to individual need and task using a SaeboMAS® arm support (Saebo, Charlotte, USA). Electrodes were positioned on the anterior deltoid, triceps and an electrode array was used over the common extensor complex of the forearm. Joint angles of the shoulder, elbow and wrist were recorded using a Kinect® (Microsoft, Washington) and a PrimeSense (Apple Inc, California). Data from these sensors fed into the control algorithm hardware and software, which updated the ES control signals for each muscle group to provide enough ES to assist performance. The therapist used the operator monitor displaying the GO-SAIL graphical user interface to select appropriate tasks and monitor training. A safety override button could be used to terminate trials with immediate effect if required.

Intervention sessions

The participants repeatedly practiced functional tasks assisted by ES over 17, 1 hour intervention sessions, lasting between 6-8 weeks. Participants sat on the perching stool in front of the touch table, with their hemiplegic arm supported by the SaeboMAS® arm support. The support was adjusted to allow the participant to access a greater range of active

or ES assisted movement without causing abnormal posture in the upper quadrant. The aim was for the participant's hand to rest easily on the table top (see Figure 1). Electrodes were placed on the anterior deltoid, triceps and wrist extensors, ES was applied and the movement pattern was checked. For the wrist array, an automated programme stimulated electrode elements within the array to identify the combination of electrode elements that produced the optimal wrist and index finger gestures required in the tasks. For comfort and safety, upper limit stimulation amplitudes were identified for all muscles, which would not be exceeded in the intervention. Parameters within the model of the arm were also identified.

During each task, joint angles, timings and error magnitudes between the participant's arm movement and the reference movement were recorded to provide a measure of accuracy for each muscle group for unassisted tasks (i.e., movements without ES) and assisted tasks. Unassisted tasks: Four button pushing tasks (at 75% of reach at each of the four locations) and one light switch task (at 75% of reach at the highest location), were completed pre and post each session. These consisted of one trial only.

Assisted tasks: The intervention practice tasks were determined by the therapist according to clinical need, and designed to present an achievable challenge. The tasks began with the participant's hand placed on the touch table in front of their shoulder (see Figure 2) and were typically repeated six times. Participants were instructed to always try to initiate the activity and try to move their arm to complete the task themselves. During each task, ES mediated by ILC, was applied to all three muscle groups. This facilitated the movement of the participant's arm over the six repetitions of the selected task. A custom graphical user interface was used by the therapist to perform the subsequent tests.

Task Design

Daily life tasks were chosen that utilised reach and manipulation across the workspace, and were sufficiently challenging but achievable by the participants (see Figure 2). Four background images were used on the touch table: a default image, a table, a bathroom sink and a chopping board. Tasks included reaching and grasping using real objects relevant to the image. There were 5 main tasks; closing a drawer, switching on a light switch, stabilising an object, button pressing and repositioning an object. As illustrated in Figure 2, the light switch was located at two different heights (low and high) and there were four table-mounted positions in which the buttons could be located or objects repositioned both in the sagittal plane and towards the frontal plane (45° across body, 45° to the hemiplegic side or in line with the shoulder). The objects were placed at different percentages of arm length (60%, 75%, 80% and 90%) from the participant's glenohumeral joint (see Figure 2). The table was positioned at a distance of 45% of arm length away from the glenohumeral joint and 35 cm below the arm when the arm was held 90° horizontal to the shoulder.

Level of Arm support used during FES-assisted tasks

The level of arm support remained the same for the unassisted tasks. For the assisted tasks however, the level of arm support was reduced following consistently successful performance, to encourage voluntary effort. This was monitored and recorded for each task completed.

FES-unassisted and FES-assisted performance

The time it took to complete a task (or until maximum effort was achieved), joint angles and task success (i.e. whether the task was successfully performed) were recorded for each trial. Unassisted tasks: participants completed five unassisted tasks (i.e. without the aid of FES):

the four button pushing tasks (located at 60% or 80% of reach in line with the shoulder, or at 75% of reach, 45° to the left or right of the shoulder), and the high light switch task (located at 75% of reach and 115° of elevation) at the beginning and end of each session. The unassisted tasks consisted of one trial only. These data were used to map changes in these performance measures over time.

In addition, the tracking error (i.e. the mean difference between the measured joint angle signal and the desired reference trajectory) for each muscle group was calculated across the six repetitions of each assisted task to quantify the change in task performance elicited by ILC.

Statistical analysis

FES-Unassisted and FES-Assisted Performance and Level of Arm Support: changes in the FES-unassisted and FES-assisted perfomance, and level of arm support required across the sessions were analysed by calculating best-fit linear regression slopes of performance against session number collapsed across all participants. Significance was associated with a value of $p < .05$.

Results

The feasibility trial took place at the Faculty of Health Sciences, University of Southampton. Data are reported from four participants (3 male and 1 female, aged 44-55) who completed the trial over 6-8 weeks. They have all had a right cerebral vascular event causing left hemiplegia. None of the participants demonstrated any loss in sensation or passive range of movement. With gravitational support, participants had varying degrees of volitional proximal activity but all demonstrated an increasing deficit in activity distally.

The range of unassisted tasks during the intervention reflects different improvements in range of movement at the shoulder, elbow, wrist and index finger joints; the highlight switch demonstrated the most significant gain in shoulder flexion, the contralateral reach in elbow extension, the near reach in wrist extension and the far reach in index finger extension as seen in Table 1.

Analysis demonstrates that the intervention of ILC mediated ES in conjunction with the task practice successfully improved range of movement in the upper limb, at all joints over the intervention. Statistically significant mean range of movement improvements over the course of the intervention can be seen to be 5° in shoulder flexion (High Light Switch), 13° in elbow extension (Contralateral Reach), 42° in wrist extension (Near Reach), and 34° in index finger extension (Far Reach). Greater detail can be seen in Figure 2 which shows range of movement in each intervention session for each participant.

Insert Table 1 and text about here:

Insert Figure 2 about here

Figure 2 a) Changes in Range of Movement over the intervention a) High Light Switch Task: Shoulder Flexion b) *Contralateral Task: Elbow Extension, c) Lateral Task: Elbow Extension, d) Near Reach Task: Wrist Extension, e) Far Reach Task: Index Finger Extension.*

These results indicate reduced motor impairment. This will be further quantified with the clinical assessments post-intervention. Data collection is on-going.

Discussion

This study provides evidence of the feasibility of using the GO-SAIL system, incorporating ES mediated by ILC with real tasks for chronic stroke participants. The electrode array worked to enable hand gestures to be performed leading to changes in unassisted wrist and finger movement. No participants reported discomfort from the wrist array. The Primesense recorded hand and wrist joint angles, reducing set-up time and removing constraints associated with contact-based sensors (e.g. goniometers) and the touch table displayed the tasks in an interactive manner.

The results of this feasibility study are relevant to all studies in which non-contact movement measurement is required. This type of system will become increasingly important in the drive to deliver cost-effective improvements in stroke rehabilitation and to fulfil national clinical guidelines which include recommendations for patients to have every opportunity to practise within their capacity.

The results from this sample indicate reduced motor impairment following the intervention. The different improvements visible in Figure 2 relate to the movement requirements necessary for performing the different tasks. The ipsilateral and contralateral tasks challenged the elbow extension, but not the shoulder flexion. Participants were able to control their shoulder flexion and elbow extension so this may have reduced the degrees of freedom allowing the participants to forcus on their wrist extension. The far reach task challenged all joints, but was the only task to require index finger extension to complete the task; repetitive practice resulted in the most significant improvement in index finger extension.The highlight switch task challenged participants repeatedly in terms of their shoulder flexion, and this is where the changes in movement occurred.

In clinical practice,outcome measurements would generally be recorded in line with the WHO International Classification of Functioning, Disability and Health [16]. However clinical outcomes generally do not measure incremental changes in movements, but solely provide a pre-post perspective. It can be oberved from the graphs that although the trend is in an overall direction, the day to day fluctuations could mean that a pre-post measurement could present a misleading picture of what the participant is achieving. Additionally, feedback is known to be an important factor in rehabilitation, and this type of system could be used to provide feedback.

Nevertheless, despite observing an improvement in range of movement it was still evident that further refinement of fine finger movement is required to optimise transfer of the benefits observed in to activities of daily living. Additionally, whilst the non contact technology worked well, it is still not at a stage where it could be easily transferred into people's homes. On-going refinements, however, mean that this can be expected within 5 years.

Limitations of the study were a small sample size, no control group or follow-up (due to time constraints). Participant had also taken part in previous ILC studies, so it is possible that the improvements seen were not representative of participants who have not had the opportunity of using ES mediated by ILC. Now we have demonstrated the feasibility of using this technology we will seek to verify these results with a larger sample of participants in a randomised controlled trial or cross-over study design in which the effects of no ES (unweighting from the arm support alone) or ES that is not precisely controlled by ILC are compared with ILC controlled ES. In addition further refinement of the hand movement is required.

Conclusion

This study aimed to assess the feasibility of using the innovative GO-SAIL ES system that uses advanced ILC algorithms to precisely control stimulation to the anterior deltoid, triceps, and wrist and finger extensors during task specific upper extremity training. The feasibility of the system has been demonstrated by supplementing activity and promoting the successful completion of a range of functional tasks.

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Table 1:Regression slopes and p-values for range of movement in FES-unassisted tasks over the 17 sessions across all participants

Joint angle	Task	slope	t-stat	p-value
Shoulder Flexion	High Light Switch	0.2814	5.6755	0.0054
Elbow Extension	Contralateral Reach	0.78	6.2702	0.0041
	Lateral Reach	0.4137	3.1752	0.0251
Wrist Extension	Near Reach	2.4521	2.8616	0.0322
Index Finger Extension	Far Reach	1.9814	2.7172	0.0364

Fig 1:

Fig 2:

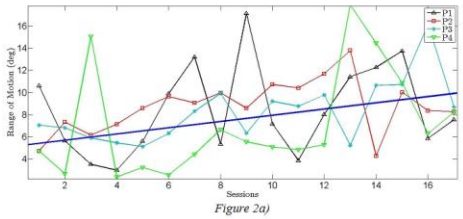

Figure 2a)

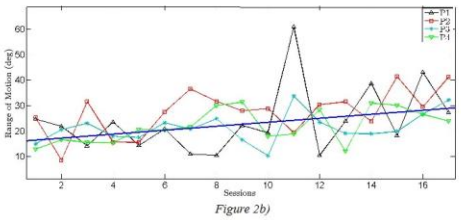

Figure 2b)

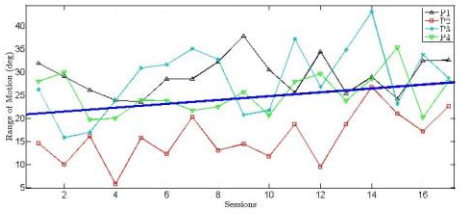

Figure 2c)

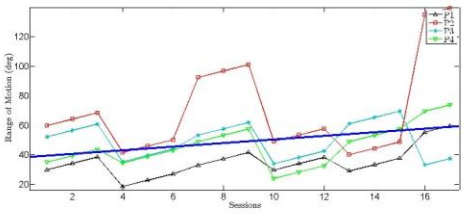

Figure 2d)

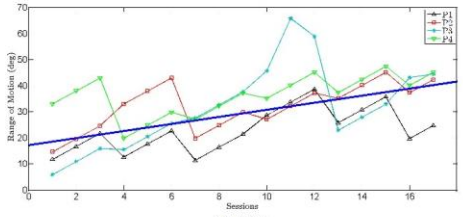

Figure 2e)

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