Electrical Stimulation and Iterative Learning Control for Functional Recovery in the Upper Limb Post-Stroke

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Abstract—**Therapies using functional electrical stimulation (FES) in conjunction with practice of everyday tasks have proven effective in facilitating recovery of upper limb function following stroke. The aim of the current study is to develop a multi-channel electrical stimulation system that precisely controls the assistance provided in goal-orientated tasks through use of advanced model-based 'iterative learning control' (ILC) algorithms to facilitate functional motor recovery of the upper limb post-stroke. FES was applied to three muscle groups in the upper limb (the anterior deltoid, triceps and wrist extensors) to assist hemiparetic, chronic stroke participants to perform a series of functional tasks with real objects, including closing a drawer, turning on a light switch and repositioning an object. Position data from the participants' impaired upper limb was collected using a Microsoft Kinect® and was compared to an ideal reference. ILC used data from previous attempts at the task to moderate the FES signals applied to each muscle group on a trial by trial basis to reduce performance error whilst supporting voluntary effort by the participant. The clinical trial is on-going. Preliminary results show improvements in performance accuracy for each muscle group, as well as improvements in clinical outcome measures pre and post 18 training sessions. Thus, the feasibility of applying precisely controlled FES to three muscle groups in the upper limb to facilitate functional reach and grasp movements post stroke has been demonstrated.**

Keywords: Functional electrical stimulation; Iterative learning control; Stroke rehabilitation; Technology; Upper limb; Wrist.

I. INTRODUCTION

Stroke is a leading cause of death and disability worldwide, leaving many stroke survivors dependent on others for activities of daily living [1], [2]. Motor dysfunction is one of the main outcomes from stroke. It has been estimated that about 60% of patients have mobility problems one year post-stroke [2] and up to 85% are left with impairment of the upper extremity [3]. Of particular importance are upper limb impairments which cause many stroke patients to have difficulty in performing everyday tasks that involve reaching and grasping. This impacts both daily living and well-being [4]. Thus, it is important that rehabilitation systems which facilitate recovery of functional movement in the upper limb are developed.

Research has shown that repetitive, goal-orientated practice of movement is vital for recovery of upper limb function following stroke (see [5]). In addition, voluntary effort is also associated with increased positive therapeutic effects [6], [7]. As such, it is important that rehabilitation technologies incorporate and maximise these aspects of rehabilitation. Functional electrical stimulation (FES) is a promising rehabilitation therapy, as it allows repetitive training of precise movements despite muscle weakness and paralysis often found post-stroke [5]. Indeed, FES has proved effective in improving motor function in the upper limb (e.g., [7], [8], [9], [10], [11], [12]. However, functional movements involve the coordination of multiple muscle groups in the impaired limb, and to date, most rehabilitation systems have applied FES to only one or two muscles in the upper limb [8]. In addition, even though systems employing FES technologies may allow patients to practice for longer, it has been suggested that assistive devices used in rehabilitation, such as robotic devices and FES, may reduce the voluntary effort patients exert during training [13].

To address these issues, a multi-channel stimulation rehabilitation system for the upper limb that precisely controls applied FES through advanced iterative learning control (ILC) algorithms has been developed. This system, termed GO-SAIL: Goal Oriented, Stimulation Assistance through Iterative Learning, builds on previous work that has controlled FES signals using ILC algorithms [14], [15], [16], [17], [18]. ILC operates by using data from previous attempts at the task to update the FES control signal that is applied on the subsequent task attempt independently to each muscle group, with the objective of sequentially increasing tracking performance. This data may comprise kinematic, kinetic and stimulation signals, which are used in combination with an underlying bio-mechanical dynamic model of the arm [17], [18]. In this way, for each trial, the amount of stimulation applied provides a minimal level of assistance to correct

performance whilst still encouraging voluntary contribution. As participants become more accurate in performing the task, the amount of FES reduces, decreasing the amount of assistance and encouraging the participant to exert maximum effort.

A programme of work has demonstrated the clinical feasibility of using this technology in increasingly complex/functional scenarios. Specifically, over the course of a minimum of 18 training sessions using ILC mediated FES, a reduction in upper limb impairment was demonstrated by increased Fugl-Meyer scores, improvements in performance accuracy and reductions in the amount of FES applied [14], [15], [16]. However, to date, studies using ILC have not used real objects in everyday tasks and have applied FES to a maximum of two muscles (anterior deltoids and triceps). The current system includes wrist and finger extension. FES modulated by ILC is hence extended to three muscle groups in the upper arm to assist coordinated practice of functional tasks using real objects.

The aim of the current study is to develop a multi-channel FES system that uses advanced ILC algorithms to precisely control FES applied to three muscles groups in the upper limb to facilitate functional motor recovery post-stroke.

II. Method

A. 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 an 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 subjects 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, 6 participants have been recruited to the trial. Data is reported from the participants (n=3) that have completed the trial to date. These three participants were all male, aged between 40 and 55 years old, and had a right cerebral vascular accident causing left hemiplegia between 22 months and 7 years previously. With gravitational support, two participants had some good proximal activity, with an increasing deficit in activity distally, whereas one participant showed equal (low) activity at all joints. The participants were always encouraged to try to move their arm to complete the task themselves.

B. System Design

The GO-SAIL rehabilitation system has been designed to facilitate recovery of upper limb motor control and function in chronic stroke participants. Participants completed goal-oriented, functional tasks, such as closing a drawer or turning on a light switch with the assistance of FES to the anterior deltoid, triceps and wrist extensors. The novel aspects of the GO-SAIL system were that (1) FES was applied to three muscle groups in the upper limb to facilitate coordinated reach to grasp movements incorporating hand function, (2) for each muscle, FES was precisely controlled by ILC algorithms to facilitate functional motor recovery, and (3) FES was applied during every day, functional reaching and grasping tasks using real objects.

The ILC algorithms used in previous systems (e.g., [17], [18]) required an explicit reference trajectory that was displayed to the patient. The GO-SAIL system can use ILC algorithms that are more complex and do not require an explicit reference (however, in the initial tests completed averaged joint references from unimpaired subjects were used in order to confirm efficacy of standard ILC schemes before progressing to more complex approaches). GO-SAIL is goal-orientated and considers the task to be a more general optimisation problem. This is still solved by learning from errors on the previous attempts. In addition, the current system has the capability for using an electrode array on the forearm of the impaired limb to precisely control fine wrist, hand and finger movement [19], [20].

The GO-SAIL rehabilitation system is comprised of 8 principal components (see Figure 1). Participants are seated at a workstation (1), individualised to each participant. A SaeboMAS® arm support (2) (Saebo, Charlotte, USA) is used to provide support against gravity to the hemiplegic arm. Three sets of electrodes are positioned on the anterior deltoid, triceps and wrist extensor muscles of the participant's hemiplegic arm (3). A Microsoft Kinect® (4) (Microsoft, Washington, USA) and goniometer (5) are used to measure and record joint angles of the shoulder, elbow and wrist. Data from these sensors feed into the control algorithm hardware and software (6), which updates the FES control signals for each muscle group to provide enough electrical stimulation to assist performance. The therapist uses the operator monitor displaying the GO-SAIL graphical user interface (7) to select appropriate tasks and monitor training. The therapist also has an over-ride stop button (8) which can be used to terminate trials with immediate effect. For more information about the GO-SAIL rehabilitation system, including design and model-based control system structure see [20]. Task design and set-up are described in subsequent sections.

C. Task Design

The tasks used were functional reach and grasp tasks performed in everyday life, and designed to span the workspace and offer a range of reaching challenges requiring different amounts of shoulder, elbow and wrist extension (see Figure 2). There were 5 main tasks; closing a drawer, switching on a light switch, stabilising an object, button pressing and repositioning an object. The objects were placed at different percentages of arm length (60%, 75%, 80%, 95%) away

from the participant's glenohumeral joint (see Figure 2), directly in line with the glenohumeral joint, 45° across body, or 45° to the hemiplegic side. As illustrated in Figure 2, the light switch was located at two different heights (low - 90° and high - 115° of elevation). 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.

D. Testing Session

During each session, participants repeatedly practiced functional tasks with real objects with assistance from FES. Participants were positioned at the workstation and the arm being tested was loosely strapped into the SaeboMAS®, a dynamic mobile arm support system. The arm support was adjusted so that the participant received enough support that it felt as though the arm were floating but that the hand could rest easily on the table top (see Figure 1). Movement produced by FES in the anterior deltoid, triceps and wrist extensors was established. Maximum stimulation levels were identified for all muscles and used as an upper limit for participant comfort and safety. Parameters necessary for the model of the arm were also identified [21]. A custom graphical user interface was used by the therapist to perform the subsequent tests.

During training, the therapist selected the tasks to be trained, according to each individuals training need. Tasks were chosen to challenge the participant but so that completion was not unrealistic. Each task was typically repeated 6 times. Participants always started each task with their hand resting on the red square in front of their shoulder (see Figure 2) and the therapist gave a verbal three-second countdown prior to the commencement of each trial. During each task, FES was applied to the anterior deltoid, triceps
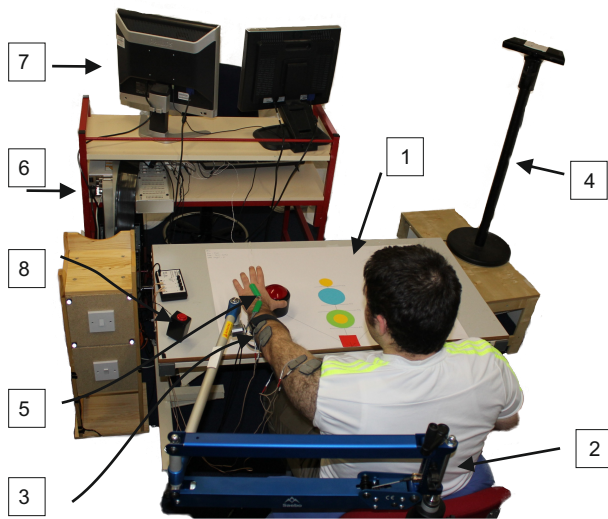

Fig. 1.   The components of the SAIL system. (1) workstation; (2) SaeboMAS® arm support; (3) Surface electrodes and arrays on anterior deltoid, triceps and wrist extensor muscles; (4) MicrosoftKinect® ; (5) goniometer; (6) Control algorithm hardware and software; (7) Operator monitor displaying the GO-SAIL GUI; (8) stop button.
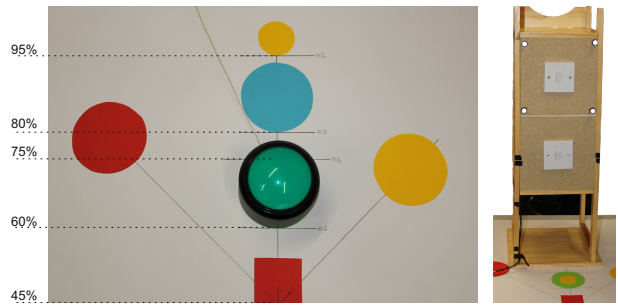

Fig. 2.   Functional tasks that were performed during rehabilitation.

and wrist extensor muscles in order to assist performance of the movement. Participants were instructed to always try to move their arm to complete the task themselves. The FES was mediated by ILC to facilitate the movement of their arm over the six repetitions of the selected task. ILC updated the FES signal after each trial to increase or decrease the amount of stimulation applied as required.

At the beginning and end of each session, participants also completed five unassisted tasks: four button pushing tasks (located at 60% or 80% of reach in line with the shoulder, or at 75% of reach, 45° across body or 45° to the hemiplegic side), and the high light switch task (located at 75% of reach and 110° of elevation). The unassisted tasks consisted of one trial only.

III. OUTCOME MEASURES

A. Unassisted and Assisted Performance Accuracy

Joint angles, timings and error magnitudes between the participant's arm movement and the reference movement were recorded for each task. These provided a measure of accuracy for each muscle group for unassisted tasks (i.e., movements without FES) and assisted tasks. Unassisted performance was measured at the beginning and end of each training session so that changes in unassisted performance could be mapped over time. In addition, the change in error for each muscle group could be measured across the six iterations of each assisted task. This gave an indication of whether the ILC was successfully reducing error in performance.

B. Clinical Assessments

The Fugl-Meyer Assessment and Action Research Arm Test (ARAT) were administered to assess upper limb impairment and function. These assessments were conducted by an independent assessor pre and post the 18 training sessions.

IV. RESULTS

A clinical feasibility trial has recently commenced at the Faculty of Health Sciences, University of Southampton. The following results report data from the three participants who have completed the trial.

The FES successfully facilitated movement in the upper limb, at all three joints. Furthermore, using ILC to mediate the FES applied, performance error for each joint was shown

to reduce over a set of six trials. For example, Figures 3 and 4 show performance for button pressing at 80% of reach, where there was an improvement of 63% for the wrist, 41% for the elbow and 22% for the shoulder from trial 1 to trial 6. However, note that some FES was always applied during trial 1 of a set of tasks, and improvements were generally larger when compared to unassisted performance. For example, the improvements for the button pressing at 80% of reach (as shown in Figures 3 and 4) increased to 70% for the wrist, 68% for the elbow and 56% for the shoulder when compared to unassisted performance.

We also found improvements for all three participants in unassisted performance when comparing performance over the 18 sessions (see Table I). The Button Press at 80% reach, Contralateral Button (75% of reach, 45° to the hemiplegic side) and High Light Switch tasks (75% of reach, 110 ° of elevation) were the three most challenging of the unassisted tasks.
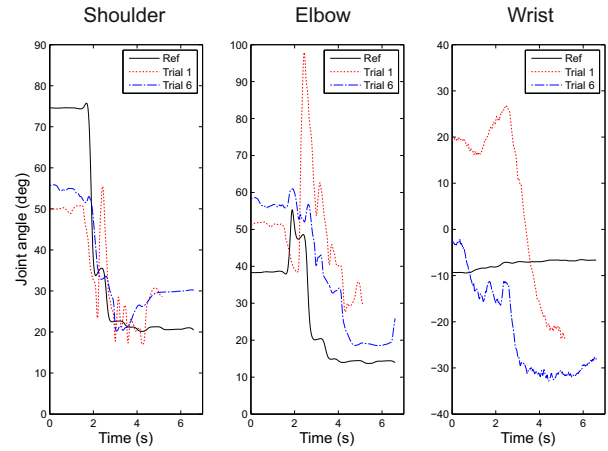

Fig. 3. Example of changes in performance for pressing a button located in line with the shoulder at 80% of reach over six trials at the shoulder, elbow and wrist. Joint angles are shown for the ideal reference (solid line), trial 1 (dotted line) and trial 6 (dashed line).

	Unassisted Task		
	Button at 80% Reach	Contralateral Button	High Light
P1	50%	54%	35%
P2	45%	63%	51%
P3	13%	20%	38%
Average	36%	46%	41%

TABLE I
CHANGES IN UNASSISTED PERFORMANCE FOR THE BUTTON PRESS AT 80% OF REACH, THE BUTTON PRESS ON THE CONTRALATERAL SIDE, AND THE HIGH LIGHT SWITCH TASKS.
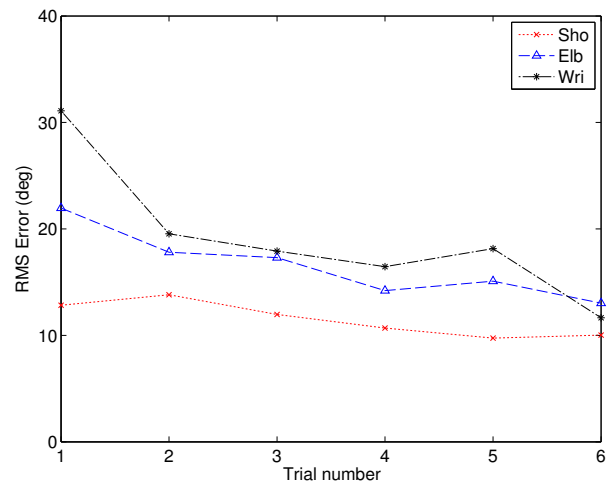

Fig. 4. Example of normalised root mean squared (RMS) changes in performance for pressing a button located in line with the shoulder at 80% of reach. Note that the participant received FES on all 6 trials. Error is shown for the shoulder (cross), elbow (triangle) and wrist (star).

A. Clinical Assessments

The improvements found in unassisted performance were also reflected in the clinical outcome measures. As illustrated in Table II, both the Fugl-Meyer and ARAT scores significantly increased from baseline to post-intervention. One-tailed, paired t-tests confirmed that the overall 10% increase in Fugl-Meyer scores ($t(2) = 3.93$, $p = .01$) and 9% increase in ARAT scores ($t(2) = 6.43$, $p = .03$) were significant improvements. Thus, our preliminary data demonstrate a reduction in motor impairment and an increase in motor activities.

	Fugl-Meyer (max score = 66)		ARAT (max score = 57)	
	baseline	post-intervention	baseline	post-intervention
P1	15	24	0	7
P2	19	24	3	7
P3	17	21	4	10
Average	17	23	2.3	8

TABLE II
BASELINE AND POST-INTERVENTION CLINICAL OUTCOME MEASURES

V. CONCLUSION

A multi-channel FES system has been developed to help stroke patients train their upper limb muscles during functional reaching tasks to facilitate motor recovery. The GO-SAIL system uses advanced ILC algorithms to precisely control FES applied to three muscle groups in the upper limb (the shoulder, elbow and wrist). The GO-SAIL clinical trial with chronic stroke participants is on-going; however, preliminary results confirm that FES, mediated by ILC, assists participants in the completion of functional tasks and reduces performance error for all three arm joints. In addition, participants clinical outcome measures demonstrated a significant reduction in motor impairment and an increase in ability to complete motor tasks that require distal hand function. Thus, the feasibility of applying precisely controlled FES to the shoulder, elbow and wrist extensors simultaneously to facilitate functional reaching and grasping movements post stroke has been demonstrated. These positive results indicate that the application of GO-SAIL technology is promising with respect to chronic stroke rehabilitation and

may prove effective in reducing upper limb impairments following stroke. Following completion of the current trial, future work aim to develop the ILC controllers to assist training of more specific hand and arm movements, complete a larger scale study in which ILC mediated FES will be compared to a more conventional application of FES, and will look to transfer this technology into patient's homes using low cost components.

VI. ACKNOWLEDGEMENTS

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