Goal-orientated Functional Rehabilitation using Electrical Stimulation and Iterative Learning Control for Motor Recovery in the Upper Extremity Post-Stroke

Emma Hallewell
[1]School of Health and Social Care
Bournemouth University
Bournemouth, UK
[2]Faculty of Health Sciences
University of Southampton
Southampton, UK

Timothy Exell, Katie Meadmore,
Chris Freeman and Mustafa Kutlu
[3]Electronics & Computer Science
University of Southampton
Southampton, UK

Anne-Marie Hughes and Jane Burridge
[2]Faculty of Health Sciences
University of Southampton
Southampton, UK

Abstract— **There is increasing evidence that electrical stimulation (ES) combined with task specific training is effective in the recovery of upper extremity dysfunction following stroke. The aim of this study is to develop a rehabilitation system that delivers precisely controlled levels of stimulation to the shoulder, elbow and wrist during goal-oriented activity which utilises everyday real objects. Iterative learning control (ILC) is used to mediate the ES and updates the stimulation signal applied to each muscle group based on the error between the ideal and actual movement in the previous attempt. The control system applies the minimum amount of stimulation required, maximising voluntary effort with a view to facilitating success at each given task. Markerless motion tracking is provided via a Microsoft Kinect, with hand and wrist data measured by an electrogoniometer. Preliminary results show that ES mediated by ILC has successfully facilitated movement across the shoulder, elbow and wrist of chronic stroke patients. Overall, joint error has reduced for all participants with the mean error across all joints showing reductions for all participants. Furthermore, there was a significant reduction in extrinsic support necessary for each task. The system is described and initial intervention data are reported.**

Keywords— *electrical stimulation; iterative learning control; upper extremity; rehabilitation; stroke; task; technology; wrist and hand*

I. Introduction

Stroke is a major cause of long-term neurological disability in adults worldwide (1, 2). Seventy percent of survivors experience altered arm function after a stroke; 40% are left with a non-functional arm (3). A substantial number of activities of daily living (ADLs) involve the use of the upper extremity; therefore, retraining reach and grasp function is vital for return to a full quality-of-life. Consequently there is a move towards technology to facilitate activity in the upper limb and provide intense rehabilitation, implemented independently of a therapist.

Technology-assisted training of arm-hand skills with electrical stimulation (ES) has been well documented (4, 5). ES has been cited as a useful treatment option because it can economically deliver intensive periods of treatment (3). A wide body of evidence supports ES in improving function, especially when associated with voluntary drive (6).

Neuroplastic changes are greater if practise is meaningful, repetitive and intensive in nature (7, 8). ES, together with task-orientated training with arm support enables patients to practise, meaningful tasks intensely, regularly and effectively without therapist supervision.

The study utilised ES, mediated by iterative learning control (ILC), combined with task specific training. ILC has its origins in numerous industrial applications, ILC has now been employed in three studies of UE stroke rehabilitation (9-11). In these studies the level of ES applied to the triceps and/or anterior deltoid muscles in the impaired upper limb of chronic stroke participants was adjusted by the ILC in response to the user's performance during tracking tasks. ILC operates by comparing data from a previous attempt at a task to reference data of the same task. This sequentially adjusts the level of stimulation given at each muscle group with a view to facilitating success at each given task. This iterative process applies the minimum level of ES for task attainment while encouraging voluntary contribution from the participant.

Hughes et al. (9) and Meadmore et al.(10) reported that the level of ES decreased over the course of the intervention and a reduction in impairment was demonstrated by increased Fugl-Meyer scores. The results of these studies (9-12) suggest that ILC as a method of controlling ES is more beneficial than standard ES as it enables a gradual reduction in dependency on ES and encourages independent volitional muscle activity.

The system used in this study, named GO-SAIL (goal-oriented stimulation assistance through iterative learning), represents a multi-channel ES system for the upper extremity that precisely controls ES through advanced iterative learning control algorithms (9, 12-15). In this study real objects are used to perform everyday tasks and includes ES of wrist and finger extension to enable functional hand activity.

The aim of this study is to develop a multi-channel ES system that uses advanced ILC algorithms to precisely control ES applied to three muscle groups in the UE 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 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 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 3 participants have been recruited to the trial.

B. System Design

The GO-SAIL rehabilitation system applied ES to three muscle groups, the anterior deltoid, triceps and wrist and finger extensors; for each muscle, ES was precisely controlled by ILC algorithms, and ES was applied whilst participants completed functional tasks, such as closing a drawer or turning on a light switch.

Each task is considered to be a general optimisation problem. For example, pushing a light switch involves reaching to a certain position at a predetermined time, with constraints that influence the posture, speed and smoothness of the motion. The components involved in the optimisation have been identified through extensive tests with unimpaired participants (15). ILC 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 level of stimulation given at 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 (15, 16).

The system comprises 8 components (see Fig. 1). Participants are seated at a personalised workstation (1). A SaeboMAS® arm support (2) (Saebo, Charlotte, USA) de-weighs the arm according to individual need and task. Electrodes are positioned on three muscle groups, the anterior deltoid, triceps and over the common extensor complex of the forearm (3). A MicrosoftKinect® (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 ES control signals for each muscle group to provide enough ES to assist performance. The therapist uses the operator monitor displaying the graphical user interface (7) to select appropriate tasks and monitor training. The therapist has an over-ride stop button (8) to terminate trials with immediate effect.

C. Task Design

Functional reach and manipulation / grasp tasks that are typically performed in everyday life were designed to offer a range of reaching challenges across the workspace (see Fig. 2). 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 Fig. 2, the light switch was located at two different heights and there were four 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 95%) from the participant's glenohumeral joint (see Fig. 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.

D. Intervention Sessions

Participants were asked to attend three times a week for 1 hour for a total of 18 sessions. All intervention was completed in 6-8 weeks to accommodate missed sessions. Participants were positioned at the workstation and the arm being tested was secured in the SaeboMAS®. The arm support was adjusted to facilitate free range of movement either volitionally or when ES was applied without the arm being lifted too high causing abnormal posture and allowing the hand to rest easily on the table top (see Fig. 1). Movement produced by ES 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.

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 the rehabilitation need of each individual. 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 Fig. 2). During each task, ES was applied to the anterior deltoid, triceps and

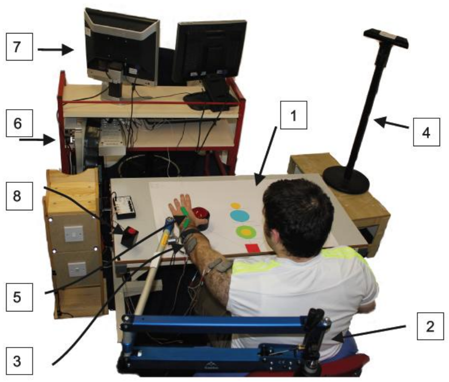

Fig. 1. The components of the GO-SAIL system. (1) workstation; (2) SaeboMAS® arm support; (3) Surface electrodes and arrays on anterior deltoid, triceps and wrist extensor muscles; (4) MicrosoftKinect® ; (5) goniometer; (6) Control algorithm hardware and software; (7) Operator monitor displaying the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

wrist extensor muscles in order to assist performance of the movement. Participants were instructed to initiate the activity and try to move their arm to complete the task themselves. A key role of the therapist was to provide verbal encouragement; motivational feedback was available in the form of the number of successful tasks completed out of each set of six, the reducing level of support needed from the Saebo MAS® and the percentage of available stimulation used in each task. The ES was mediated by ILC to facilitate the movement of the arm over the six repetitions of the selected task. At the beginning and end of each session, participants also completed five 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). The unassisted tasks consisted of one trial only.

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 ES) and assisted tasks.

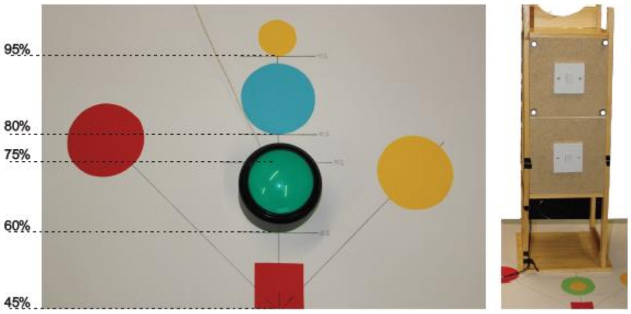

Fig. 2. A personalised workstation template to standardise the reaching tasks for each participant according to arm length. Five main tasks; closing a drawer, switching on a light switch (high and low) stabilising an object, pressing a button and repositioning an object. The green button is placed at 60% of arm length. The other coloured circles denote the predetermined position of the far reach, ipsilateral and contra-lateral reaching tasks.

E. Clinical Assessment Sessions

The Fugl-Meyer Assessment (FMA) 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.

III. RESULTS

A feasibility trial is ongoing at the Faculty of Health Sciences, University of Southampton. Preliminary results report data from the three participants who have started the trial and have completed between 9 and 14 intervention sessions over a period of 3-4 weeks. The three participants are all male and are aged between 40 and 55 years old. They have all had a right cerebral vascular event causing left hemiplegia. Time from stroke is 22 months, 4 years and 4 months and 7 years. None of the participants demonstrate sensory loss and all participants have functional passive range at all joints. With gravitational support, participants had varying degrees of volitional proximal activity but all demonstrated an increasing

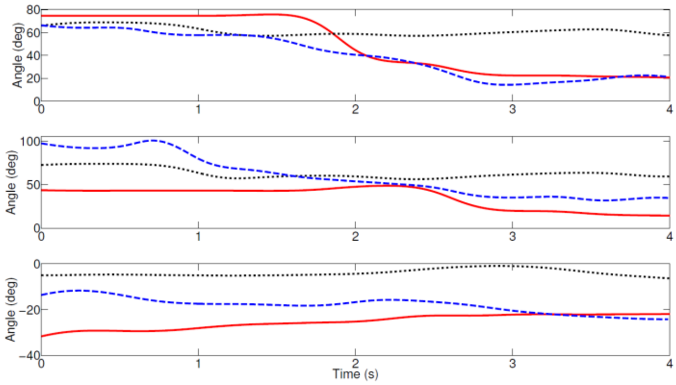

Fig. 3. Example of tracking performance for pressing a button located in the saggital plane at 80% of reach. Top represents shoulder, middle elbow and bottom wrist. Solid lines show reference, dotted thin line are for unassisted trial and thicker dashed line are with FES.

deficit in activity distally. The FMA scores at pre-intervention assessment were between 15/66 and 19/66 and ARAT were 0/57 and 4/57. Note that as the trial is on-going, the post-assessment data are not reported here.

Initial analysis suggests that the ES successfully facilitated movement in the upper limb, at all three joints. For example, Fig. 3 and 4 show the performance for button pressing at 80% of reach. Fig. 3 illustrates the joint angles recorded at the shoulder, elbow and wrist during both an unassisted task and a stimulated task; both are mapped against the reference. The joint angles demonstrate that very little movement took place during the unassisted task compared to when stimulation was applied. During the stimulated task the joint angles showed more congruence with the reference and were therefore more akin to normal movement and task attainment. This demonstrates that the applied ES was successful in facilitating upper limb movement.

Fig. 4 shows the stimulation applied to each muscle group during a typical trial of the far button pushing task and the resulting joint angle changes. The participant was able to initiate and participate with volitional activity at the shoulder and elbow resulting in smaller amounts of stimulation being

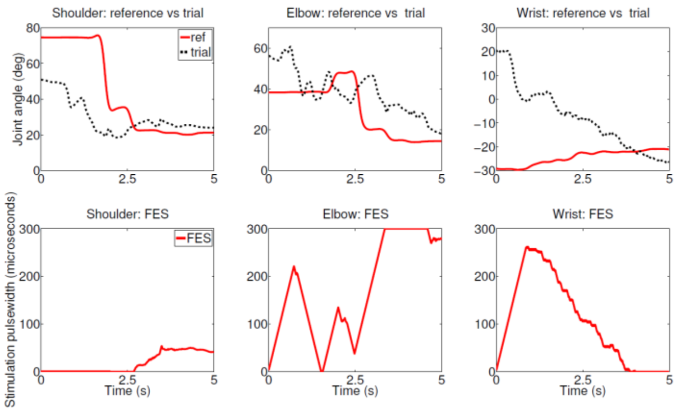

Fig. 4. Example data from the far button pushing task. Top row = performance for shoulder, elbow and wrist joint (reference angles = solid, patient performance = dashed); Bottom row = ES applied to each muscle group.

applied for these joints. However, this was seen to be more inconsistent at the elbow and therefore corresponding spikes in ES assistance are seen. There was little voluntary movement recorded at the wrist therefore greater levels of stimulation were delivered.

The unassisted tasks performed at each intervention session show significant improvements from the first intervention to the most recent intervention session for each participant. After 9 intervention sessions participant (P3) demonstrates 30° more shoulder flexion/elevation and 35° more elbow extension. P2 (after 14 sessions) has 35° more wrist excursion into extension and P1 is able to maintain wrist extension in neutral from a previous position of 25° flexion. Overall joint error has reduced for all participants with the mean error across all joints showing reductions of ~50% for all participants. Furthermore, de-weighting from the SaeboMAS® arm support has reduced significantly in all participants with reduction ranging from 35% in the high level tasks to 67% in the mid to low range tasks. These results all indicate reduced motor impairment. This will be further quantified with the clinical assessments post-intervention. Data collection is on-going.

V. Conclusion

The aim of this study was to further develop a multi-channel ES system (GO-SAIL) that uses advanced ILC algorithms to precisely control ES applied to three muscle groups in the UE. The GO-SAIL system successfully applied ES to three muscle groups to include the wrist and hand to supplement activity and promote the successful completion of a range of functional tasks. For each task the ES was independently controlled by advanced ILC algorithms thus providing the minimum levels of stimulation assistance to augment volitional activity and ultimately facilitate goal attainment at any given task. Recruitment and intervention is on-going in this feasibility study. On conclusion of the trial it is anticipated that the post-intervention clinical assessments will demonstrate if any functional change has been identified. The results to date are positive and indicate that the GO-SAIL system that delivers ES mediated by ILC is a promising rehabilitation modality in the field of upper extremity rehabilitation in chronic stroke.

VI. Acknowledgements

This work is supported by the Engineering and Physical Sciences Research Council (EPSRC). Grant No. EP/I01909X/1 and a Wessex Innovation Grant.

VII. References

[1] BHF. Stroke statistics:British Heart Foundation Health Promotion Research Group. In: Health DoP, editor. Oxford: Department of Public Health; 2009.

[2] RCP. National Sentinel Stroke Audit. In: Physicians RCo, editor. London: RCP; 2010.

[3] RCP. National clinical guidelines for stroke In: Physicians RCo, editor. 3rd ed. Suffolk: The Lavenham Press Ltd; 2008.

[4] Pelton T, van Vliet P, Hollands K. Interventions for improving coordination of reach to grasp following stroke: a systematic review. International Journal Of Evidence-Based Healthcare. 2012;10(2):89-102.

[5] Hayward K, Barker R, Brauer S. Interventions to promote upper limb recovery in stroke survivors with severe paresis: a systematic review. Disability & Rehabilitation. 2010;32(24):1973-86.

[6] de Kroon JR, van der Lee JH, Ijzerman MJ, Lankhorst GJ. Therapeutic electrical stimulation to improve motor control and functional abilities of the upper extremity after stroke: a systematic review. Clinical Rehabilitation. 2002;16(4):350-60.

[7] Van Peppen RPS, Kwakkel G, Wood-Dauphinee S, Hendriks HJM, Van der Wees PHJ, Dekker J. The impact of physical therapy on functional outcomes after stroke: what's the evidence? Clinical Rehabilitation. 2004;18(8):833-62.

[8] Kwakkel G. Intensity of practice after stroke: More is better. Schweizer Archiv fur Neurologie und Psychiatrie. 2009;160(7):295-8.

[9] Hughes AM, Freeman CT, Burridge JH, Chappell PH, Lewin PL, Rogers E. Feasibility of iterative learning control mediated by functional electrical stimulation for reaching after stroke. Neurorehabilitation and neural repair. 2009;23(6):559-68. Epub 2009/02/05.

[10] Meadmore K, Cai Z, Tong D, Hughes A-M, Freeman C, Rogers E, et al. Upper Limb Stroke Rehabilitation: The Effectiveness of Stimulation Assistance through Iterative Learning (SAIL). International Conference on Rehabilitation Robotics; Zurich, Switzerland2011.

[11] Meadmore K, Cai Z, Tong D, Hughes A-M, Freeman C, Rogers E, et al. SAIL: A 3D rehabilitation system to improve arm function following stroke. Progress in Neurology and Psychiatry. 2011;15(2):6-10.

[12] Meadmore K, Hughes AM, Freeman CT, Cai Z, Tong D, Burridge J, et al. Functional electrical stimulation mediated by iterative learning control and 3D robotics reduces motor impairment in chronic stroke. Journal of neuroengineering and rehabilitation. 2012;9:32.

[13] Freeman CT, Rogers E, Hughes A-M, Burridge JH, Meadmore KL. Electrical Stimulation and Robotic-assisted Upper-Limb Stroke Rehabilitation. Ieee Control Systems Magazine. 2012;32(1):18-43.

[14] Freeman CT, Hughes AM, Burridge JH, Chappell PH, Lewin PL, Rogers E. A model of the upper extremity using FES for stroke rehabilitation. Journal of biomechanical engineering. 2009;131(3):031011. Epub 2009/01/22.

[15] Freeman CT, Exell T, Meadmore K, Hallewell E, Hughes AM, Burridge J. Computational models of upper limb movement during functional reaching tasks for application in electrical stimulation based stroke rehabilitation. Technically Assisted Rehabilitation. 2013.

Freeman CT, Tong D, Meadmore K, Cai Z, Rogers E, Hughes AM, et al. Phase-lead iterative learning control algorithms for functional electrical stimulation-based stroke rehabilitation. Proceedings of the Institution of Mechanical Engineers Part I-Journal of Systems and Control Engineering. 2011;225(I6):850-9.