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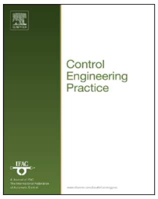

# Iterative learning control for robotic-assisted upper limb stroke rehabilitation in the presence of muscle fatigue

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ABSTRACT

The use of iterative learning control to regulate assistive functional electrical stimulation applied to the muscles of patients undergoing robotic-assisted upper limb stroke rehabilitation has been followed through small scale clinical trials. These trials confirmed that an increase in patient ability to complete the specified task also led to a reduction in the level of electrical stimulation required. This previous work assumed that the effects of muscle fatigue could be neglected but if a patient suffers fatigue during a rehabilitation session then their the session goals are not achieved or, more likely, the session must be abandoned due to the time limits imposed by the ethical approval required to conduct such sessions. In this paper the results of the first investigation into enhancing the control scheme to remove or lessen the effects of fatigue and hence make better use of the time available for a session are given. The scheme considered adds a feedback loop around the muscle model used, where the performance results given are based on a model for the dynamics constructed using patient data collected in previous clinical trials.

## 1. Introduction

A common cause of a stroke is blockage of a blood vessel in the brain, where as a result regions downstream are starved of blood. Consequently, the connecting nerve cells die and this usually leads to partial paralysis on one side of body, termed hemiplegia. Annually, 15 million people world-wide suffer a stroke and up to a third of these are left with permanent impairment. Other demographic patterns and, in particular, aging populations place even more strain on the resources for patient care and rehabilitation. Stroke is an age-related disease (National Audit Office, 2004) and all of these factors contribute to an increasing burden on long-term health and related resources. Hence there is a pressing need to improve the effectiveness of treatments to achieve independence.

The brain cells that die as a result of a stroke cannot regrow but new connections can be made using the brain's spare capacity. In particular, the brain is continually and rapidly changing and as new skills are learned, new connections are formed and redundant ones disappear. Relearning skills after a stroke is the same process as a person learning an everyday task, such as reaching out to a cup, and requires sensory feedback during repeated practice of a task. This requires movement skills but the effects of the stroke mean that these are almost always very poor and hence feedback on performance is not obtained.

Stroke survivors commonly have a complex pattern of upper limb motor impairments with a loss in functional abilities such as reaching. The coupling between reaching and independence is reflected in measures of function independence, including the Barthel index (van der Putten, Hobart, Freeman, & Thompson, 1999), where the ability to reach is essential for approximately 50% of activities that make up daily living tasks. Currently, the level of upper limb recovery following a stroke is poor and it has been reported (Hendricks, van Limbeek, Geurts, & Zwarts, 2002) that complete recovery occurs in less than 15% of patients with initial paralysis. This and the age-related factor are among the major reasons why there is a critical need to improve the effectiveness of treatments. If the stage were reached where rehabilitation could be moved outside the hospital, which requires mobile technology, then improved rehabilitation and reduced costs could be achieved.

The literature on conventional therapy plus motor learning theory, e.g. De Kroon, Ijzerman, Chae, Lankhorst, and Zilvold (2005), provides evidence that functional recovery can be achieved through the facilitation of motor control and skill acquisition and restoration of muscle power through repetitive resistance exercises (Krebs et al., 2003), in addition to the variety of tasks and feedback. This knowledge has motivated the development of novel treatments, such as robot-aided therapy, which could provide the basis longer-term for a translation of rehabilitation clinics from

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labor-intensive work to technology-assisted operations and also an opportunity for repetitive movement practice. Reviews of the robotic therapy literature, see Freeman, Rogers, Hughes, Burridge, and Meadmore (2012) and the cited references, for the upper limb suggest that robot-assisted treatment improves motor control of the proximal upper limb and may improve functional outcomes.

Rehabilitation robots are power driven or mechanically supported devices that assist a patient with limited physical capability to undertake repetitive exercises. The resulting sensory feedback is known to be associated with cortical changes that facilitate the recovery of functional movement. Functional electrical stimulation (FES) has been found to be applicable as another method of promoting cortical connectivity to enable recovery, which is supported by a growing body of clinical evidence and theoretical support from neurophysiology and motor learning research, again see Freeman et al. (2012) for references to the literature and Lynch and Popovic (2008) for an overview of FES with a control systems perspective. Application of FES to a muscle causes electrical impulses to travel along the nerves in the same way as electrical impulses from the brain and if the stimulation is carefully regulated a useful movement can be made. In stroke rehabilitation FES is applied in combination with the patients voluntary effort with the aim of a specific recovery of voluntary power (Rushton, 2003).

A wide range of algorithms have been applied to the control of FES for both the upper and lower limbs, where again the literature is covered in Freeman et al. (2012) and the cited references. In recent work iterative learning control (ILC) (Ahn, Chen, & Moore, 2007; Bristow, Tharayil, & Alleyne, 2006) has been applied to regulate the FES applied in robotic-assisted upper limb stroke rehabilitation. Earlier research on ILC regulated FES applied to human limbs includes Dou, Tan, Lee, and Zhou (1999).

Research on the application of ILC in this area started with a planar daily living motivated task, reaching out over a table top, where the patient was asked to track a supplied reference trajectory whilst attached to a robotic arm with assistive FES applied to the relevant muscle, i.e., the triceps. During each attempt, the error between the desired trajectory and that produced by the patient was measured, the arm was then reset to the starting location and in the time taken to complete this operation, plus a rest time, an ILC law was used to compute the FES to be applied on the next attempt. A clinical trial for this design was undertaken, which confirmed that as the patients ability to complete the task improved from trial-to-trial the required stimulation decreased. (Freeman et al., 2009a, 2009b; Hughes et al., 2009). This application area for ILC has been extended to 3D tasks, such as reaching and extending the forearm, where there is a need to stimulate more than one muscle and again clinical trial results are available (Freeman et al., 2012; Meadmore et al., 2012).

In application, FES applied to muscles is at a higher frequency and is hence a contributory factor to muscle fatigue. If the muscle suffers from fatigue then the force output drops and the treatment session has to stop to allow recovery, which almost certainly means the session must end and the patient return at another time, see Lynch and Popovic (2008) for a detailed control systems/modeling discussion of this area. The previous research on ILC for upper-limb stroke rehabilitation did not explicitly account for muscle fatigue in the model used for control law design but this aspect must be addressed if the use of model based control laws in this and related problem areas is to proceed. This paper revisits the 3D task considered in the previous work (Freeman et al., 2012; Meadmore et al., 2012), introduces a representation for the effects of fatigue into the model for the response of the muscle to applied FES and adds a compensating feedback control loop. Using this new representation, nonlinear model based ILC design is undertaken and the results of a detailed simulation based evaluation of the new design given, where the dynamic model describing the uncontrolled dynamics is constructed from data collected from patients participating in the previous clinical study reported in Freeman et al. (2012) and Meadmore et al. (2012). Such an evaluation is an essential step before seeking ethical approval for patient-based trials.

## 2. ILC for stroke rehabilitation

In this section, the robotic-assisted upper extremity stroke rehabilitation system used is introduced, together with a detailed description of the modeling of fatigue.

### 2.1. The system setup

Consider a gantry robot that performs the following sequence of operations (i) collects an object from a fixed location, (ii) transfers it over a finite duration, (iii) places it at a fixed location or on a moving conveyor under synchronization, (iv) returns to the starting location and (v) repeat (i)–(iv) as many times as required or until a stoppage for maintenance or other reasons is required. Each execution is termed a trial and the duration the trial length. Once each trial is complete all information generated is available for use in computing the control law for the next trial and ILC was developed for such cases.

Introduce the notation $y_k(t)$, $0 \le t \le T$, $k \ge 0$, where $y$ is the vector or scalar valued variable under consideration, the integer $k$ denotes the trial number and $T < \infty$ is the finite trial length. Also let $r(t)$ denote the supplied reference signal, which is the same on all trials. Then the error on trial $k$ is $e_k(t) = r(t) - y_k(t)$ and the basic ILC problem is to enforce convergence of the sequence $\{e_k\}$ in $k$ where, if $u$ is the input signal, a commonly used form for the control law computes the input for trial $k+1$ as the sum of that used on trial $k$ plus a correction term whose computation is based on previous trial information and, in particular, the previous trial error. Once a trial is complete all information generated over $[0, T]$ is available for use and, in particular, information in $t$ that is non-causal in the standard sense provided it is generated on a completed trial.

One starting point for the background and literature on ILC is the survey papers (Ahn et al., 2007; Bristow et al., 2006). In ILC the control input is directly updated between trials and it is this feature that makes it suitable for robotic assisted stroke rehabilitation. The previous section gave some of the supporting literature on how a patient with hemiplegia can relearn everyday skills by repeated practice with assistive FES. Moreover there is the requirement that if the patient is improving with each successive attempt, or trial, the level of voluntary effort should increase and the assistive FES decrease. Hence the premise that ILC could be used to regulate the FES applied.

The first research (Freeman et al., 2009a, 2009c) on the application of ILC in this area focused on a planar task, such as reaching out over a table top to an object such as a cup. A lighted path to follow, the reference signal in ILC terms, was beamed down from above and the patient's affected arm was attached to a robot with the task being to follow this prescribed path as closely as possible using a combination of voluntary control and surface FES applied to muscles in their impaired shoulder and arm. The subject's arm was returned to the starting position after each trial and following a short rest period the task was re-attempted. In this resetting time, ILC was used to update the FES applied during the subsequent trial of the task. The FES must operate in the presence of the patient's remaining voluntary effort and the robot is used to provide additional assistance, whilst allowing FES to drive the task completion.