On the Use of Adaptive Control in Stimulation-Assisted Neuromotor Therapy

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Abstract

Neuromuscular stimulation may provide an efficient means to enhance the effectiveness of neuromotor therapy. In previous work, we developed an adaptive control system (PG/PS control system) that may be particularly useful in neuromotor retraining paradigms that seek to supplement volitional activity with electrical stimulation to generate cyclic movements. This system has previously demonstrated very good performance in controlling single-joint movements at a given movement period. In this work, we further characterized the capabilities of this system with a focus on issues that are likely to arise in neuromotor retraining paradigms: varying movement periods, intermittent rest periods, and multi-joint movements. Preliminary results suggest that the PG/PS system can address each of these issues and therefore may be well-suited for use in neuromotor therapy.

1 Introduction

1.1 Stimulation-Assisted Therapy

Several studies have indicated that functional recovery of locomotor function after spinal cord injury may be enhanced by performing repetitive stepping movements on a treadmill with a harness for partial body weight support and passive assistance provided by therapists [1,2]. The putative mechanism that underlies this recovery is activity-dependent plasticity of neural circuits both in the spinal cord and in supraspinal centers. Although results in some subjects have been encouraging, in general, the functional gains that have been demonstrated from locomotor therapy are moderate and there is a high variability across subjects. The standard form of this therapy (treadmill/harness with passive assistance from therapists) appears to be soundly based on well-established principles of motor learning, but the manner in which the therapy is delivered may not enable maximization of the therapeutic effect.

Therapeutic paradigms that supplement the passive movement therapy with neuromuscular electrical stimulation may enhance functional recovery through a variety of mechanisms [2,5]. Stimulation may enable more repeatable movements, activate sensory pathways to produce coordinated sensorimotor patterns, and/or increase muscle strength and endurance. Any or all of these factors may contribute to enhanced plasticity and accelerated recovery. Our approach seeks to integrate neuromuscular stimulation assistance into neuromotor retraining paradigms to achieve a more efficient and effective therapeutic technique.

1.2 Adaptive Control of Movement

In previous work, we have developed a technique to control cyclic movements [3,4]. The system uses a 2-stage control system in which the pattern generator (PG) produces an oscillatory pattern at the desired movement frequency and the pattern shaper (PS) adaptively filters that signal to determine the stimulation to be delivered to a particular muscle. Details of the PG/PS system are described in [3,4].

Fig. 1 PG/PS control system structure. The PS unit uses measurements of system outputs to adapt parameters in a single-layer neural network, thus acting as an adaptive filter to customize stimulation patterns for a given individual.

This adaptive controller has been tested in several studies using human subjects and has been shown to provide very good performance under a number of circumstances. To-date, these studies have mostly been limited to the control of movement at a single-joint by stimulating one muscle to move against gravity. The key features of this system are that it rapidly learns an appropriate stimulation pattern for a given muscle and it adapts the pattern to account for fatigue.
1.3 Objectives

In on-going projects, we seek to utilize this adaptive system in the context of a neuromotor training paradigm. We believe that this approach can not only reap the benefits of using neuromuscular stimulation, but can also provide enhanced effectiveness due to the ability of this control system to generate repeatable movements. In this work, we utilize a combined approach that includes experiments using human subjects with spinal cord injury as well as experiments with a rodent model to investigate the properties of this control system and its effectiveness in a neuromotor retraining paradigm.

For the proposed use, the control system must adjust the stimulation pattern to account for changes in cycle period. Additionally, when used in a therapeutic environment, rest periods will be required in order to allow for sessions that include many movement cycles in a given day. These rest periods may adversely affect the performance of an adaptive system. Finally, the system should be capable of controlling multi-segment movements. In the work described here, we present results from a number of experiments using both human and animal subjects to demonstrate how this control system addresses each of these issues.

2 Experimental Results

2.2 Changes in Cycle Period

To generate cyclic movements such as those required for stepping, there are many factors that can contribute to the determination of movement cycle period. For the swinging leg task, it is possible to generate movements at a pre-specified movement period in a metronome-like manner. For stepping, either overground or on a treadmill, the cycle period may be influenced by step length, walking speed, limb dynamics and other factors. In our previous work, the PG/PS control system was tested for controlling movement at a specified movement period.

Here, we present results from a set of experiments in which we investigated the ability of the PG/PS controller to adjust to account for changes in movement cycle period. This experiment used the same swinging leg setup that had been used in the past [3], except that the participant was an able-bodied subject. The PG/PS controller was first used to control a movement with a nominal value of cycle period (2 seconds) and the controller was allowed to adapt for 50 cycles; then the desired movement cycle period was changed to a new value and the controller was allowed to re-adapt. Results shown in Fig. 2 indicate that the controller adapted well during the initial period, error increased when the desired movement pattern switched, but then the controller re-adapted to achieve good tracking performance. The controller performed better for slow movements (long cycle periods) than for quick movements. These results demonstrate that the PG/PS system can handle changes in desired movement period and therefore online adjustments of cycle period during treadmill stepping may be possible.

![Fig. 2. Effects of changes in desired movement cycle period on tracking performance. Results are shown for movement tracking of swinging lower leg trials with an able-bodied subject. Each trial had 50 cycles at the nominal cycle period (2 seconds) and then 50 at a different cycle period. The hatched bar in the center indicates the average error of the first 10 cycles at the beginning of the trials; the stipled bar indicates the error for the last 10 cycles at the nominal movement period (cycles 41-50). Each black bar indicates the error after the change to a new movement period (cycles 51-60) and the neighbouring white bar indicates the error at the end of the trial (cycles 91-100). Results indicate good adaptation at the nominal period, increased error after the change, and improvement due to subsequent adaptation.](image-url)
consisted of 100 5-cycle bouts of swinging leg movement with 20-second rest periods interspersed. Results indicated that the tracking error varied slightly from cycle-to-cycle and that the cycle after the rest period usually had a higher tracking error than the cycle that preceded the rest period (Fig. 3). The fact that the drop in performance after a rest period was small and that it rapidly improved within a few cycles suggest that the PG/PS controller may be well-suited for use in a therapeutic paradigm that uses bouts of movement cycles with interspersed rest periods.

The first cycle of each bout is indicated by a ‘●’; all other cycles by a ‘+’. The ‘●’ marks to the lower right of the diagonal indicate that first cycle of a bout often had a higher error than the cycle that preceded the rest period. The fact that all error values are low and that most marks fall near the diagonal indicate very good and consistent movement tracking performance.

2.4 Multi-joint control

Most testing of the PG/PS system has been on single-degree-of-freedom systems, but for use in a motor retraining paradigm, multi-joint control is critical. We have begun to implement and investigate the multi-joint capabilities of the control system in experiments using the rodent model with implanted electrodes. In the experiment shown in Fig. 4, implanted electrodes were used to activate knee extensors and flexors and a hip flexor. Results indicate good tracking of knee movement and of the hip flexion phase. Hip extensors were not stimulated and therefore hip extension was not observed in this trial. These preliminary results indicate that the PG/PS controller may be capable of multi-joint control and that the inter-segmental dynamics are accounted for by this adaptive algorithm. Future work will focus on more extensive evaluation of the multi-joint capabilities of this system.

Fig. 4. Example traces during multi-joint control using the PG/PS controller in an anaesthetized rat. Desired and actual movement patterns during a multi-joint movement (extension is positive). Note that the controller achieves good tracking at the knee at during the hip flexion phase. Hip extensors were not activated in this trial.

3 Literature


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