ADAPTIVE CONTROL OF CYCLIC MOVEMENTS IN A MULTI-SEGMENT SYSTEM

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Abstract
Partial body weight support (PBWS) during locomotion on a treadmill has been used to improve gait for persons with incomplete spinal cord injury (SCI). Combined therapy that uses functional neuromuscular stimulation (FNS) to assist in generating locomotor movements may lead to improvements in PBWS locomotor training. The effectiveness of this combined approach may strongly depend on the ability of the FNS system to control movements accurately and repeatably.

In previous work, we developed the Pattern Generator/Patter Shaper (PG/PS) controller and demonstrated that it effectively controlled cyclic single-joint movements. The objective of this study was to evaluate the ability of the PG/PS controller to control cyclic stepping-like movements in a multi-segment system. In these studies, the PG/PS control system automatically customized stimulation patterns to generate the desired cyclic movement, thus suggesting that it may be a useful component of a system for FNS-assisted locomotor therapy in people with incomplete SCI.

Introduction/Background
People with partial paralysis resulting from spinal cord injury are candidates for intense rehabilitation with a long-term goal of achieving independent locomotion. With an incomplete lesion, there is a high likelihood of recovery of function in the months post-injury, presumably due to reorganization of spinal circuits and reflexes, as well as descending pathways. Incomplete spinal cord injury often causes gait deviations due to inadequate weight acceptance by the lower extremities, which can cause a delay in the initiation of gait training in the upright position. Partial body weight support (PBWS) in combination with locomotion on a treadmill has been used to improve gait for persons with neurological impairments [4]. During the gait training, the patient’s body weight was partially supported by an overhead harness while the person walked on a treadmill. This strategy produced improvements in the subject’s gait performance off the treadmill.

Methods
The PG/PS neural network used in this study consists of two major components: the pattern generator (PG) and the pattern shaper (PS), which is shown in Fig. 1. The PG generates an oscillatory pattern of activity at the frequency of desired movement, which is a periodic signal that was held fixed throughout the study. The PS adaptively filters this signal to determine the specific stimulation patterns in order to make the desired movements. Therefore, the PG would be the same for all individuals, but the PS parameters would be customized.

Conclusion
The PG/PS controller demonstrated the ability to control cyclic movements in a multi-segment system, suggesting its potential for use in FNS-assisted locomotor therapy.
to elicit the flexion withdrawal reflex (FWR). This stimulation generates the swing phase of gait by producing hip and knee flexion and ankle dorsiflexion.

In the experiment, the subject stood between parallel bars using both hands to provide support. One leg had stimulation provided to the hip and knee extensors and the foot was placed on a wooden block. The other leg was allowed to swing freely. The objective of the controller was to generate movements to follow the desired segment angle trajectories shown in Fig. 2. Gluteus maximus, hamstrings, quadriceps and common peroneal nerve for both legs were stimulated through electrodes placed on the surface of the skin (PALS self-adhering surface electrodes, Axelgaard Manufacturing Co., CA) from an eight-channel neuromuscular stimulator (Octostim Electrical Muscle Stimulator, Freiler, Santa Cruz, CA) controlled by computer-based PG/PS controller. Stimulation patterns to hamstrings and quadriceps were adaptively specified by the PG/PS controller, but patterns to gluteus maximus and FWR were fixed through the experiment.

Figure 1. Diagram of the control system. The controller determines the stimulation to hamstrings and quadriceps in order to generate the specified hip angle and knee angle trajectories. The controller used the error signal (error = \( \theta_{\text{des}} - \theta_{\text{actual}} \)) for thigh segment angle and shank segment angle to adapt the output weights on the PS neural network [1]. Stimulation patterns to gluteus maximus and FWR were fixed through the experiment.

Figure 2. Leg movement and stimulation level during the first 3 (left column) and last 3 cycles (right column) in one trial. (a) Thigh segment angle (hip joint angle). (b) Shank segment angle. (c) Knee joint angle calculated from thigh and shank segment angles. Note that the controller used the thigh and shank segment angles in its calculations, the knee angle trajectories were calculated off-line for display and analysis only. (d) Fix stimulation patterns to FWR and gluteus maximus. (e) Stimulation patterns to quadriceps and hamstrings controlled by the PG/PS controller. By the end of the trial (the last 3 cycles), tracking performance had substantially improved due to the action of the PG/PS controller.
Experiments were performed on 3 days with 6 trials per day (3 for each leg), and 8 minutes rest between trials. Each trial had 50 cycles with 1.5 seconds per cycle. Measurements of the thigh and shank segment angles were made using a kinematic tracking system (Flock of Birds, Ascension Tech Corp., Burlington, VT). The research subject was a 38 year-old male with a complete spinal cord injury at the T-6 level.

Results

The plots on the left column in Figure 2 show the movement during the first 3 cycles, in which neither the knee nor hip followed the desired trajectory well, because the PG/PS controller had not yet adapted sufficiently. As the trial proceeded, the PG/PS controller gradually adjusted the stimulation to the quadriceps and gluteus maximus. By the end of the trial (the last 3 cycles), the controller had learnt to track the desired trajectories such that the root mean square (RMS) values were very small (Figure 3).

Discussion/Conclusions

This study shows that the adaptive PG/PS controller automatically adjusted the stimulation levels to repeatably and accurately control cyclic movements in this multi-segment system. The controller learned appropriate stimulation patterns for each leg without any subject-specific information. This study is different from our previous work in that the controller was also required to account for inter-segmental skeletal coupling. These results demonstrate that the PG/PS controller successfully addressed this problem. Throughout the 50-cycle trial, we expect that there would have been substantial fatigue of the directly stimulated muscles and habituation of the flexion withdrawal reflex. Despite these on-line changes in system properties, the controller was able to perform well throughout the trial.

In future work, we plan to further evaluate this control system on additional subjects and then test it during treadmill locomotion with partial body weight support.

References


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