Novel FES System To Stimulate Both Dorsi- and Plantar-Flexor Muscles During Stroke Gait

Perumal R 1, Kesar TM 2, Wexler AS 3, Binder-Macleod SA 1,2

1 Department of Physical Therapy, 301 McKinly Laboratory, University of Delaware, Newark, Delaware 19716, USA
2 Interdisciplinary Graduate Program in Biomechanics & Movement Science, University of Delaware, Newark, Delaware, USA
3 Mechanical and Aeronautical Engineering, One Shields Ave., UC-Davis, CA-95616, USA.

ramu@udel.edu

Abstract

One of the primary challenges for individuals with stroke is regaining the ability to become a community ambulator. Functional electrical stimulation (FES) of paralyzed muscles enables individuals with upper motor neuron lesions to stand and walk. However, all commercially available systems focus on stimulating only the dorsiflexor muscles during gait on stroke subjects and ignore other swing phase and stance phase deficits. In addition, all currently available FES systems use constant-frequency stimulation to activate muscles. Hence, the purpose of this study is to develop and test a FES system that will use variable-frequency trains (VFTs) that take advantage of the catchlike property of the muscle to stimulate both the plantar flexors and dorsiflexors at appropriate times during the gait cycle to maximize improvements in hemiparetic walking patterns.

1 Introduction

Approximately 7.7 million Americans are living with the effects of stroke and over 700,000 will experience a stroke or recurrence of a stroke annually [1]. Because gait dysfunction due to stroke greatly limits community mobility, many patients perceive improvement in their walking ability as the ultimate goal of rehabilitation. Consequently, significant effort is focused on gait retraining during rehabilitation following a stroke.

In individuals with hemiparesis following stroke, stimulation of ankle dorsiflexor muscles for the treatment of foot drop is the most common application of FES. Although the role of the plantar-flexor muscle group during gait has been established both in able-bodied and in patient population, most research studies and all commercially available systems focus on stimulating only the dorsiflexor muscles during gait on stroke subjects and ignore other swing phase (decreased knee and hip flexion) and stance phase (decreased propulsive push-off force) deficits [2]. In addition, all of the currently available FES systems use constant-frequency stimulation to activate muscles and only increase stimulation intensity to maintain forces as the muscles fatigue. Interestingly, our laboratory and others have shown that variable-frequency trains (VFTs) that take advantage of the catchlike property of skeletal muscle been shown to enhance both isometric and nonisometric muscle performance compared to constant-frequency trains of similar frequency, especially when muscles are fatigued, in both able-bodied and paralyzed muscles [3]. Hence, the purpose of this study is to develop and test a FES system that will use VFTs to stimulate both the plantar flexors and dorsiflexors at appropriate timing during the gait cycle to maximize improvements in hemiparetic walking patterns.

2 Methods

2.1 Development of the FES system

A real-time FES system was developed using National Instruments’ Compact Reconfigurable Input Output (CompactRIO) embedded system (Fig. 1). Unlike LabVIEW on a PC based system, the CompactRIO features a dedicated...
processor and a reconfigurable field programmable-gated array (FPGA) that can execute LabVIEW programs reliably and deterministically in real-time. The FES system consists of the CompactRIO system, a laptop, a Grass S8800 stimulator with a SIU8T isolation unit (not shown), and foot-switches. The algorithm to stimulate the dorsi- and plantar-flexor muscles was implemented on the CompactRIO system. Foot switch data were acquired via the 8-channel analog input (AI) module (NI 9210). Transistor Transistor Logic (TTL) pulses necessary to drive the Grass stimulator were provided by the 8-channel digital output (DO) module (NI 9401). The AI and DO module and the real-time controller were housed in the CompactRIO system (see Fig.1). Using the foot-switch data, the real-time control system was used to trigger the DO module to deliver TTL pulses that would then trigger the stimulator to deliver stimulation pulses to the muscles. The real-time controller was used to specify the timing and duration of each pulse. The pulse amplitude was set using the Grass stimulator. The laptop was used to display the sensor data from the CompactRIO system and to control the CompactRIO to start and stop the real-time controller.

2.2 Timing of stimulation to dorsi- and plantar-flexor muscles

![Fig. 2: Dorsiflexor muscle group of the paretic limb (right) is stimulated from the toe-off of the paretic limb to heel-strike of the paretic limb (swing phase). The plantar-flexor muscle group is stimulated from heel strike of the non-paretic limb (left) to toe-off of the paretic limb (terminal double-support period of the paretic limb). Note the use of an initial high frequency burst for stimulating both the muscle groups.](image)

Foot-switches placed under the heel and toe of each foot were used to detect the different phases of gait during treadmill walking. For the dorsiflexors, stimulation was initiated at toe-off of the paretic limb and terminated at heel-strike of the paretic limb (Fig. 2). A VFT that contained an initial high frequency burst (3 pulses with a frequency of 200-Hz) followed by a 30-Hz constant frequency train was used to stimulate the dorsiflexors. The high-frequency burst was used to take advantage of the catch-like property of the muscle [4]. The 30Hz constant-frequency portion was selected based on our recent results that showed that 30-Hz was the best initial frequency trains to activate human muscles [5]. For the plantar flexors, we compared two logics (Logics 1 and 2) to increase plantar-flexor force generation during the push-off phase of gait. Logic 1 was designed to stimulate the plantar-flexors with a 20-Hz constant-frequency train during the early stance phase to decelerate the tibia and ‘preload’ the plantar-flexor muscles prior to the 30-Hz VFT being delivered during the push-off phase (terminal stance). Stimulation was started (20-Hz train) when the foot switches detected toe-off of the non-paretic limb. At heel-off of the paretic leg, the FES-controller switched to a 30-Hz VFT. Plantar-flexor stimulation was turned off when the foot switches detected the paretic leg’s toe off. Logic 2 was designed to stimulate the plantar flexors during push-off at terminal stance. For Logic 2, plantar-flexor stimulation was timed to start at heel strike of the non-paretic limb (30-Hz VFT), which coincided with terminal stance for the paretic leg (Fig.2). Similar to Logic 1, the FES controller terminated plantar-flexor stimulation when toe-off of the paretic leg was detected.

2.3 Testing of hemiparetic stroke subject with our FES system

Four subjects (three left hemiparetic) with hemiparesis following stroke were recruited for the study. All the subjects signed the informed consent approved by the Human Subjects Review Board of University of Delaware. Surface stimulation electrodes were placed over the dorsi- and plantar-flexor muscle groups. Gait data were collected using a 6-camera Motion Analysis Corporation system at 120-Hz and processed using an automated real-time motion analyses system (Eva Realtime Version 4.3). A Helen-Hayes marker set was used. Ground reaction force data were collected while subjects walked on custom-made split-belt treadmill that was instrumented with force plates (Bertec Corporation, Columbus, OH, USA). Testing was carried out with and without FES. Testing with FES involved stimulation of both the dorsi- and plantar-flexors. The outcome measures that were to used test the
effectiveness of our approach were peak dorsiflexion angle during swing, peak posterior ground reaction force, and peak knee flexion angle during swing of the paretic limb.

3 Results

For the dorsiflexors, we found that stimulating from toe off to heel strike of the paretic limb led to increased dorsiflexion during swing and enabled all the four subjects to walk without any foot-drop (Fig.3).

Our results showed that FES of plantar flexors using the two logics increased the posterior ground reaction force (push-off force; see Figs. 4A and 4B) and the knee-flexion angle during swing (Fig. 5) compared to no FES for two subjects, while the other two subjects showed very little change with stimulation. In addition, our results also showed that Logic 2 was superior to Logic 1 in producing both increased posterior ground forces (Fig.4) and increased knee flexion during the swing phase of the paretic leg (Fig. 5).

4 Discussion and Conclusions

The above results show that our FES system can deliver VFTs accurately to both dors- and plantar-flexors during appropriate phases of gait in individuals with hemiparesis following stroke. The dorsiflexor stimulation enabled all the four subjects to walk without a foot-drop. However, the plantar flexor stimulation was only effective in two of the four subjects tested. This suggests that patient selection criteria are important for the success of FES in a clinical application. In addition, these data show that the timing of onset and termination of plantar-flexor FES (Logic 1 versus Logic 2) during the gait cycle has a marked influence on the effects of FES on hemiparetic gait. Hence, different stimulation timing strategies may be needed for different subjects to optimize performance during gait.

References


Acknowledgements

This work was supported by NIH grants No.HD36797 and HD38582.