FES-supported standing after paraplegia: traditional versus event-driven closed-loop strategies

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Abstract

Standing after spinal cord injury by means of FES is a topic of interest in neurorehabilitation research. This study compared a hand-controlled (HC) strategy to avert knee-buckle during stance with two event-driven anti-fatigue strategies automated by the use of motion sensors. The control variable modulated was the quadriceps m. stimulation amplitude. The two automated strategies differed in their rate of increases of stimulation when knee unlock was detected. Two ASIA-A subjects participated in standing trials over a standing frame. Surface stimulation was applied to quadriceps and glutei. For both subjects, the total standing times over three trials per day showed significant advantages in using the automated strategies. From total standing times of approximately 10min using HC, the best automated strategy improved this time by 2min15s and 2min51s for subjects S1 and S2, respectively. An automated approach demonstrated efficient control of knee extension, which minimized muscle work and improved user safety.

1. INTRODUCTION

The use of functional electrical stimulation (FES) to restore standing in paraplegia is a technique widely used in several clinics and research centers worldwide. Upright stance can be achieved by applying electrical stimulation over the quadriceps and gluteal muscles [1]. By allowing SCI individuals to reach for objects at higher places, including making transactions at counters and enabling communication at the eye level of upright humans; FES-evoked standing has significant psychosocial benefits.

Physiologically, FES-evoked muscle contractions have been reported to reduce the risks of fractures and occurrence of pressure sores, as well as to improve muscle blood flow and cosmesis [2].

One major complication of FES on paralyzed lower limbs is the progressive fatigue of quadriceps, which may result in severe knee buckling during stance [3]. The re-establishment of knee extension can be accomplished by increasing either stimulation pulse width or amplitude over the quadriceps muscles, thereby recruiting a greater percentage of muscle fibers in this muscle group [4, 5].

Several strategies have been applied to titrate the electrical stimulation to quadriceps in order to maintain knee extension. After knee unlock, Mulder et. al (1992) increased the stimulation amplitude to maximal levels, and then ramped down the levels until the next knee unlock [3]. Fuhr and colleagues (2001) applied a linear modulation of pulse width stimulation [4]. A preliminary study performed in our laboratory demonstrated the greater efficacy of step increments of 10mA to generate knee extension in relation to ramp increments of 10 mA•s⁻¹ [6].

2. METHODS

Our FES system consisted of an electrical stimulator (Exostim [7]) and laboratory based motion sensors [8]. These devices were controlled by a PocketPC (Cassiopea EG-800) running a control algorithm programmed in the host computer via MATLAB Simulink®. The stimulation was applied with surface electrodes over the quadriceps and gluteal muscles with biphasic pulses (charge-balanced, constant current) at 33Hz and 150µs. The sensors were strapped over the thighs and shanks, and sampled at 10Hz by the PocketPC computer.

In the current study, 2 automated closed-loop strategies were compared to a traditional hand-controlled (HC) approach, whereby the stimulation amplitude could be increased via
button presses in steps of 10mA. The automated A (AU-A) strategy applied a step increment of 10mA when a knee flexion angle ($\theta_k$) higher than 10° (‘knee unlock’) was detected. If $\theta_k$ was between 5 and 10° (‘knee extension’), the stimulation amplitude was maintained. If $\theta_k$ was below than 5° (‘knee lock’), the stimulation was ramped down by 5mA over 2s and maintained to reduce the components of isometric contractions.

The automated B (AU-B) strategy differed from the AU-A only during the knee unlock condition: the first increment was 5mA, and the progressive increments were 10, 15 and 20mA. When knee lock was achieved, increments were restarted from the value of the last successful increment. For both AU-A and AU-B, after an increment, a period of 1s passed, until the next step increment if knee was still unlocked. After standing up, the sensors were auto-calibrated within the first 8s of stable stance. Sensors collected real-time angular data during the HC strategy. In all strategies, the stimulation amplitude at glutei was set to 80% of the amplitude applied at the quadriceps.

The subjects were two paraplegics (S1: T4, ASIA-A; age 39 yr; post-injury 13 yr | S2: T8, ASIA-A; age 52 yr; post-injury 12 yr). They undertook 10 days of assessment with 3 trials per day and resting intervals of 5 minutes between trials. The tests comprised three days of each of the 3 strategies (HC, AU-A and AU-B) and 1 test using supra-maximal stimulation (SM), as a control condition. The order that strategies were applied on different days was counter-balanced. Tests were not carried out on consecutive days, however without recovery intervals longer than 2 days. As a safety measure, subjects were supported by a harness system. They also stood using light hand touch over a walking frame and wore ankle guards. All trials were finished when $\theta_k$ was higher than 30°.

3. RESULTS

Table 1 shows HC and AU standing times normalized by the SM standing time for the 1st, 2nd and 3rd standing trials. The total standing times for each strategy is also presented in boldface. For both subjects, the highest total HC times were shorter than any of the days where the automated strategies were employed. From total standing times of approximately 10min using HC, the best automated strategy improved this stance duration by 2min15s and 2min51s for subjects S1 and S2, respectively.

![Figure 1 – Comparison of the stimulation patterns and knee displacement between HC (black lines) and AU-B (gray lines) for subject S2 (left leg). Note that under the HC condition, most of the stimulation increases were made outside of the knee extension zone (5° ≤ $\theta_k$ ≤ 10°), requiring more stimulation to maintain stance.](image.png)
4. DISCUSSION AND CONCLUSIONS

The use of evoked-EMG signals over the quadriceps has been reported to demonstrate changes due to fatigue even before the knee buckles [9]. However, the quantification of these changes prior to knee buckling has yet to be determined, and the HC results demonstrated that early increases in stimulation were not beneficial to maximize the standing times.

To obtain longer periods of stance, the use of a higher number of percutaneous electrodes or fully implantable systems and hip bracing have been suggested [10, 11]. In a review paper, Bajd and colleagues (1999) suggested that the use of surface stimulation of the knee extensors combined with “compliant shoes” might be an useful [12]. For this reason, the current study used ankle guards to increase ankle joint stiffness and this seemed to be beneficial. This approach was also in accordance with Fujita and colleagues (1995), especially with regards to the simultaneous increase of the stimulation in the quadriceps (hip flexor) and glutei (hip extensor) as minimal joint moments are known to require less muscle force [11].

Studies in the past have applied resting intervals between standing trials of 0.5 to 1.5h [5, 6]. However, our interval of 5min was considered more realistic in terms of applicability to activities of daily living. Surprisingly, our results have shown only small variations in the standing times between 1st and 2nd trials – perhaps this was because our subjects were well trained to FES.

As reported in a previous review article in 1988, standing times are extremely variable [13]. Nevertheless, the automated closed-loop strategies deployed in the current study increased standing times over HC open-loop prevention of knee-buckle. Given the poor predictability of knee buckling events during stance, the automated approach demonstrated good feasibility as an event driven anti-fatigue strategy. In future we intend to refine the sensitivity of our event-detecting algorithm and deploy the automated strategy both for bilateral stance, as well as for closed-loop control of the standing support leg during FES-stepping.

References


Acknowledgements

This research was supported by National Health and Medical Research Council project grant #302013 and the NSW Ministry of Science and Medical Research. This work comprises a component of PhD studies of the first author, sponsored by the Brazilian Government – CAPES – Brazil.