Shoulder Functional Electrical Stimulation During Wheelchair Propulsion in Spinal Cord Injury Subjects

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Background: Subjects with spinal cord injury (SCI) propel their wheelchairs by generating a different level of muscle activity given their multiple deficits in muscle strength. Exercise training programs seem to be effective in improving wheelchair propulsion capacity. Functional electrical stimulation (FES) therapy is a complementary tool for rehabilitation programs. **Objectives:** To determine the accuracy of the synchronization between the FES activation and the push phase of the propulsion cycle by using hand pressure sensors that allow anterior deltoids activation when the hand is in contact with the pushrim. **Methods:** We analyzed 2 subjects, with injuries at C6 American Spinal Injury Association Impairment Scale (AIS) A and T12 AIS A. The stimulation parameters were set for a 30 Hz frequency symmetrical biphasic wave, 300 μ s pulse width. Data were collected as participants propelled the wheelchair over a 10-m section of smooth, level vinyl floor. Subjects were evaluated in a motion analysis laboratory (ELITE; BTS, Milan, Italy). **Results:** Subject 1 showed synchronization between the FES activation and the push phase of 87.5% in the left hand and of 80% in the right hand. Subject 2 showed synchronization of 95.1% in the left and of 94.9% in the right hand. **Conclusion:** Our study determined a high accuracy of a novel FES therapeutic option, showing the synchronization between the electrical stimulation and the push phase of the propulsion cycle. **Key words:** functional electrical stimulation, functional electrical therapy, physical activity, rehabilitation, spinal cord injury, wheelchair propulsion

Introduction

Subjects with spinal cord injury (SCI) propel their wheelchairs by generating a different level of muscle activity given their multiple deficits in muscle strength.^{1,2} Exercise training programs seem to be effective in improving wheelchair propulsion capacity. The task-oriented training enhances the capacity to use a manual wheelchair by improving muscle mechanical efficiency.^{3,4}

Functional electrical stimulation (FES) therapy is a complementary tool for rehabilitation programs. FES training consists of using a multiple-channel electrical stimulator controlled by a microprocessor to recruit muscles in a programmed synergistic sequence that will allow accomplishment of a specific functional movement pattern.⁵ It has been used to improve voluntary walking and balance in individuals with

SCI⁶⁻⁹ and grasping function by stimulating the wrist and finger muscles to increase activities of daily living and quality of life.^{10,11}

Only few articles have reported the use of FES during wheelchair propulsion. Yang et al¹² showed that FES on the trunk musculature had potential advantages in helping manual wheelchair users with SCI without placing additional demands on shoulder musculature. In the same direction, Triolo et al¹³ showed that stabilizing the pelvis and trunk with FES can positively impact the mechanics of manual wheelchair propulsion. Although the use of FES stimulation of the trunk to provide a base of support during wheelchair propulsion has been studied, the utility of a FES device applied to shoulder muscles and activated when the hand is in contact with the pushrim during the push

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phase of wheelchair propulsion has not been studied. Mulroy et al¹ reported that between the muscles with dominant activity during the push phase, the anterior deltoid showed onset activity ranges from 87% (low paraplegia) to 99% (C7, C8). In addition, patients with tetraplegia in the acute stage usually do not have normal strength in the anterior deltoids due to inactivity atrophy, fatigue, or deficient innervation. Because of the important role of the anterior deltoids during propulsion, we decided to focus our study on those muscles.

The purpose of our study was to determine the accuracy of the synchronization between the FES activation and the push phase of the propulsion cycle by using hand pressure sensors that allowed anterior deltoids activation when the hand was in contact with the pushrim. We present a technical report of the execution of this novel FES therapeutic option and a descriptive analysis in 2 patients with SCI.

Methods

Participants

We collected a convenience sample of 2 experienced wheelchair participants: subject 1 with C6 American Spinal Injury Association Impairment Scale (AIS) A, upper extremity motor

score (UEMS) 20, without grasping function; and subject 2 with T12 AIS A, UEMS 50, with normal grasping function in the upper limbs. The participants used a manual wheelchair as primary mobility mode, and both of them provided informed consent. Subjects' characteristics are shown in **Table 1**. This study was approved by the ethics committee of FLENI.

Device design

A double-channel stimulator with dual output of infrared LEDs (Flexicar FES device, Castelar, Argentina) and 2 event switches with a 15-mm sensor area on a 100-mm flexible tail (Motion Lab Systems Inc., Baton Rouge, LA) were used to stimulate the anterior deltoids with 2 self-adhering surface electrodes (Superior Silver circular electrodes, size 2 in) (**Figure 1**). The stimulation parameters were set for a 30 Hz frequency symmetrical biphasic wave, 300 μ s pulse width, and up to the maximum amplitude of 120 mA depending on the participants' tolerance levels. The maximal tolerable level of stimulation was defined as the maximum comfortable tolerable amplitude as reported by the participants while making anterior flexion shoulder movement.

Table 1. Subject characteristics

Parameters	Subject 1		Subject 2	
Demographics				
Age, years	40		34	
Gender	M		M	
Weight, kg	71		65	
Height, cm	170		165	
Time since injury, years	8		1	
Level of injury	C6		T12	
AIS	A		A	
Kinematics				
Speed, m/s	0.98		1.16	
Cadence, cycles/min	50.47		58.44	
Acceleration, m/s²	0.64		0.61	
Push phase angle, sagittal plane	Left	Right	Left	Right
Degrees	42.85	38.6	58.07	61.03

Note: AIS = American Spinal Injury Association Impairment Scale.

Figure 1. Experimental setup. Inset indicates placement of the event switches.

Procedure

Both participants used their own rigid-frame manual wheelchairs. The FES device was attached to the wheelchair backrest. Two groups of 6 infrared LEDs, one per channel, were attached to the corresponding push handle. Two pairs of self-adhering surface electrodes were placed in the following positions: 1 pair on right anterior deltoids and 1 pair on left anterior deltoids. The pressure sensors were attached to the hypothenar region. Subject 1 used Gloves for Life and subject 2 used conventional gloves.

The FES device starts to stimulate on the corresponding channel when the subject places the palm of their hand on the wheelchair pushrim to start pushing forward, and it sends an infrared signal that is captured by 8 infrared cameras during the pressure sensor's contact with the pushrim. There was no delay between the time that

the event switch was activated and the FES turned on and the contraction of the muscles.

Data were collected as the participants propelled their wheelchairs over a 10-m section of smooth, level vinyl floor. Prior to data collection, each subject had a 5-minute warm-up session. During this time, the correct position for the event switches was identified. Subjects were instructed to propel their wheelchairs for 5 trials at comfortable speed. The first 2 trials served as practice sessions during which the subjects could become familiar with test conditions. Subjects then continued with the following 3 trials, which were used for data recording. Each trial consisted of 1 ramp upstroke from standstill and 2 full start-up strokes (which were analyzed).

Motion analysis laboratory

Participants were evaluated in a motion analysis laboratory (ELITE; BTS, Milan, Italy). Eight infrared cameras (100 Hz) were positioned surrounding a capture volume of 600 cm x 150 cm x 180 cm. The system collected the coordinates of retroreflective markers attached to right acromial end, seventh cervical vertebrae, sacrum, right olecranon, styloid process of the radius and ulna, third metacarpal head, and wheel axis. Upper limb angular kinematics was calculated using the method described by Rab et al.¹⁴ Data acquisition and processing were performed using Biomech-Analyzer software (BTS, Milan, Italy). Initial contact was obtained by visual cues using the vertical coordinates from the wrist rotation center. Six additional infrared sensors were placed 40 cm above the wheelchair backrest in order to transmit the contact between the hand with the pushrim during the push phase.

Data collection

To estimate the push angle, a vector (V_i) was defined between the wheelchair axis marker and the wrist marker. In this way, the propulsion angle was defined as the angle between V_i and the laboratory's horizontal axis in the anterior-posterior direction. The push phase was defined as the time during which the subject's hand was in contact with the wheel pushrim. To measure this phase, we defined 2 events: initial (EvIniManual) and final (EvFinManual). Determination of the corresponding timing for each

event was carried out through visual inspection performed by an expert technician based on the changes in the slope of the distance between wrist marker and axis wheelchair axis marker. During the time that the hand is in contact with the pushrim, the distance between these 2 markers remains constant in a value near to the ratio of the pushrim. Before and after contact, this distance is variable and the inflection point between the contact and noncontact phases is easily detectable. The estimated error in the visual localization of the inflection points of the curve of distance is about ± 10 ms. We recorded the initial contact's moment as time 0.

Simultaneously with determining the push phase, effective contact of the event switches with the pushrim was also determined through the LED groups placed on the wheelchair backrest. The moment the hand makes contact with the pushrim, the corresponding infrared LEDs become active and define the initial EvIniFES time, which corresponds with beginning of stimulation. When the hand stops making contact with the pushrim, the infrared LEDs turn off, thus defining EvFinFES, which corresponds with the end of stimulation. Interruptions in infrared LEDs between EvIniFES and EvFinFES times were interpreted as discontinuous contact between event switches and pushrim, producing an interruption in stimulation.

Results

The procedure was well tolerated by both patients without adverse reports. For subject 1, the stimulation parameters were set for a 30 Hz frequency symmetrical biphasic wave, 300 μ s pulse width, and 36 mA of the intensity for the left anterior deltoids and 48 mA for the right. For subject 2, the stimulation parameters were set for a 30 Hz frequency symmetrical biphasic wave, 300 μ s pulse width, and 30 mA of the intensity for the left anterior deltoids and 35 mA for the right.

We found the following in the synchronization time between push phase and FES activation: For subject 1, in the left hand, the push phase time was 0.32 seconds and the FES activation time was 0.28 seconds (87.5% of the push phase). In the right hand, the push phase time was 0.25 seconds and the FES activation time was 0.20 seconds (80% of the push phase). For subject 2, in the left hand, the push phase time was 0.41 seconds and the FES activation time was 0.39 seconds (95.1% of the push phase). In the right hand, the push phase time was 0.39 seconds and the FES activation time was 0.37 seconds (94.9% of the push phase). We registered one interruption in the FES activation of 0.04 seconds (0.11-0.15 seconds) in the right hand in the second trial (**Table 2**).

Table 2. Synchronization between functional electrical stimulation (FES) and push phase

	Left		Right	
	Push phase	FES activation (on-off)	Push phase	FES activation (on-off)
Subject 1				
Trial 1	0.33	0.29 (0.02-0.31)	0.26	0.22 (0.02-0.24)
Trial 2	0.30	0.29 (0.00-0.29)	0.26	0.23 (0.02-0.25)
Trial 3	0.32	0.27 (0.01-0.28)	0.24	0.16 (0.04-0.20)
Mean	0.32	0.28	0.25	0.20
Subject 2				
Trial 1	0.44	0.40 (0.03-0.43)	0.41	0.40 (0.01-0.41)
Trial 2	0.40	0.39 (0.01-0.40)	0.38	0.33 ^a (0.01-0.38)
Trial 3	0.40	0.39 (0.01-0.40)	0.38	0.37 (0.01-0.38)
Mean	0.41	0.39	0.39	0.37

Note: All values are given in seconds.

^aInterruption in the FES activation of 0.04 seconds (0.11-0.15 seconds).

Discussion

FES has been used extensively to improve functional outcomes in SCI.¹² Prior research used walking pressure sensors activating the FES device to improve the quality of gait.¹⁵ Only few studies applied continuous electrical stimulation during wheelchair propulsion. Yang et al¹² used FES to stimulate abdominal and back muscle groups, and Triolo et al¹³ applied FES to the hip and trunk extensor muscles. Both studies showed improvement in the mechanical efficiency during self-propulsion. In our study, we applied electrical stimulation on both anterior deltoids muscles during the push phase. We used pressure sensors in the palms of the hands to activate both anterior deltoids only at the moment that the pressure sensors were in contact with the pushrim (push phase of the cycle propulsion).

Our results show a synchronization at least of 80% between pushrim contact and FES activation time during the push phase, even in the subject with tetraplegia, who typically produces a medially directed force on the wheel as a substitution for impaired grip function.¹ Five out of 6 trials did not show interruptions. Therefore, the event switches used were shown to be safe and feasible.

Our study determined a high accuracy of a novel FES therapeutic option, showing the synchronization between the electrical stimulation and the push phase of the propulsion cycle. One of the limitations of our study was that we analyzed only 2 subjects with different injury complete levels; this was not sufficient to translate these results to the entire mixed SCI wheelchair user population. This FES device requires assistance to be attached in position, which makes this task dependent.

Further studies are needed to determine the effectiveness of this therapeutic option as a way to achieve self-propulsion, to improve the strength and the fatigue resistance after disuse atrophy, and to minimize the necessity of high tech wheelchair prescription.

Our study determined the high accuracy of a novel FES therapeutic option by showing the synchronization between the electrical stimulation and the push phase of the propulsion cycle.

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