A systematic method to determine customised FES cycling patterns and assess their efficiency

Lana Popović-Maneski, Amine Metani, François Le Jeune and Vance Bergeron

Abstract — **Functional electrical stimulation (FES) cycling can be used as a rehabilitation tool and also a recreational activity for spinal cord injured (SCI) patients. It provides cardiovascular exercise, increases muscle mass and therefore lowers the incidence of secondary diseases associated with paralysis. However, FES cycling is limited by the power that can be produced and the rapid muscle fatigue that occurs. This study proposes a systematic method to determine customised cycling stimulation patterns, by assessing the contribution of specific muscle groups, in order to optimize muscular synergies and maximize recruitment.**

We measured the tangential forces exerted by the pilot's feet on the pedals during the cycling process, and calculated the resulting power output for a tetraplegic patient on a commercial cycling device. We found that our pattern is more efficient than the recommended pattern from the literature. Thus, direct pedal force measurement appears to be a relevant method to optimize the muscle stimulation pattern during FES cycling.

Index Terms — **FES; SCI; cycling; paralysis; paraplegic; tetraplegic; pedal force measurements;**

I. INTRODUCTION

Functional electrical stimulation (FES) is a method of delivering short electrical pulses to muscle nerves to elicit muscle contractions and functional movements [1]. FES cycling consists in using FES on several muscle groups in a defined order to produce cyclic movements, enabling the patient to turn the pedals of an adapted bicycle or tricycle. These devices can be stationary or mobile and therefore designed for indoor or outdoor exercise, respectively. However, FES cycling activities are limited by two factors. First, due to unfavorable biomechanics and because the stimulation delivered from the surface of the skin can activate only superficial muscles, the power that can be produced is one order of magnitude lower for paralyzed people compared to healthy individuals. A typical power output for a healthy person would be of 100W magnitude, compared to 10W for a paralyzed patient. Second, FES cycling is limited by the rapid muscle fatigue due to the non-physiological recruitment of muscle fibers; unlike natural muscle contraction, FES-induced muscle contraction involves mainly type II muscle fibers contraction (fast twitch, fast fatiguing fibers) with a higher activation rate and instantaneous recruitment of all available fibers [2]. Therefore, the distances covered by FES cycling are rather short, and speed is low. For instance, during the first cybernetic Olympic games ("Cybathlon" [3]), held in Zurich in October 2016, fastest non-implanted FES cycling pilot ran 750 meters in 3m59s.

In the available literature, there is a lack of quantitative methods to determine the efficiency of different stimulation protocols. Most common outcome measures include instant and average speed, along with indirect averaged power output. In this study, we measured instantaneous tangential and normal forces exerted on the pedals, and therefore were able to assess instantaneous power output for a tetraplegic patient during FES cycling. We determined the contributions of three main muscle groups responsible for cyclic movements on the trike.

II. MATERIAL AND METHODS

A. Subjects

The study included one tetraplegic patient, aged 37, injury level C6 right C7 left, ASIA score B and time from injury 60 months. He signed informed consent form. The study protocol and informed consent form followed the Helsinki declaration and all later amendments.

B. Instrumentation

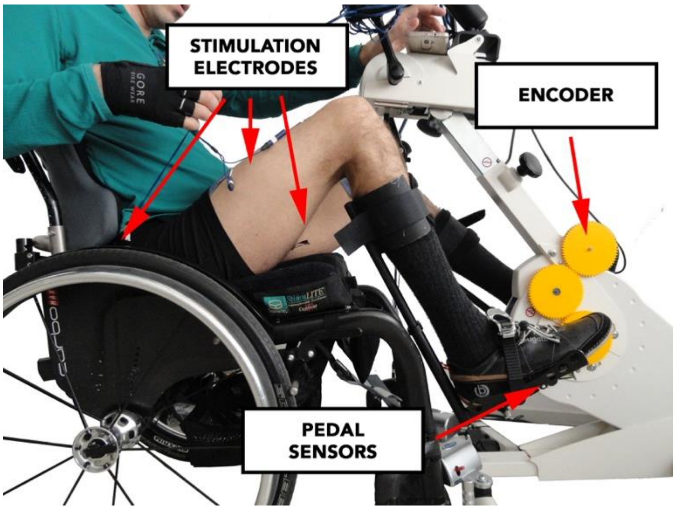

Fig. 1. Experimental setup

We directly measured the crank angle and tangential forces exerted on the pedals while stimulating individual and synergistic muscle groups to establish a direct link between muscle stimulation and cycling performance. The device used is a modified force pedal system developed in collaboration with Radlabor GmbH [4], and is based on Hall-effect force transducers mounted between the cranks and the pedals. The Radlabor system was mounted on a RT300 cycling system [5] which was used to provide rotation of pedals with constant speed by regulating the resistance to the motion and/or

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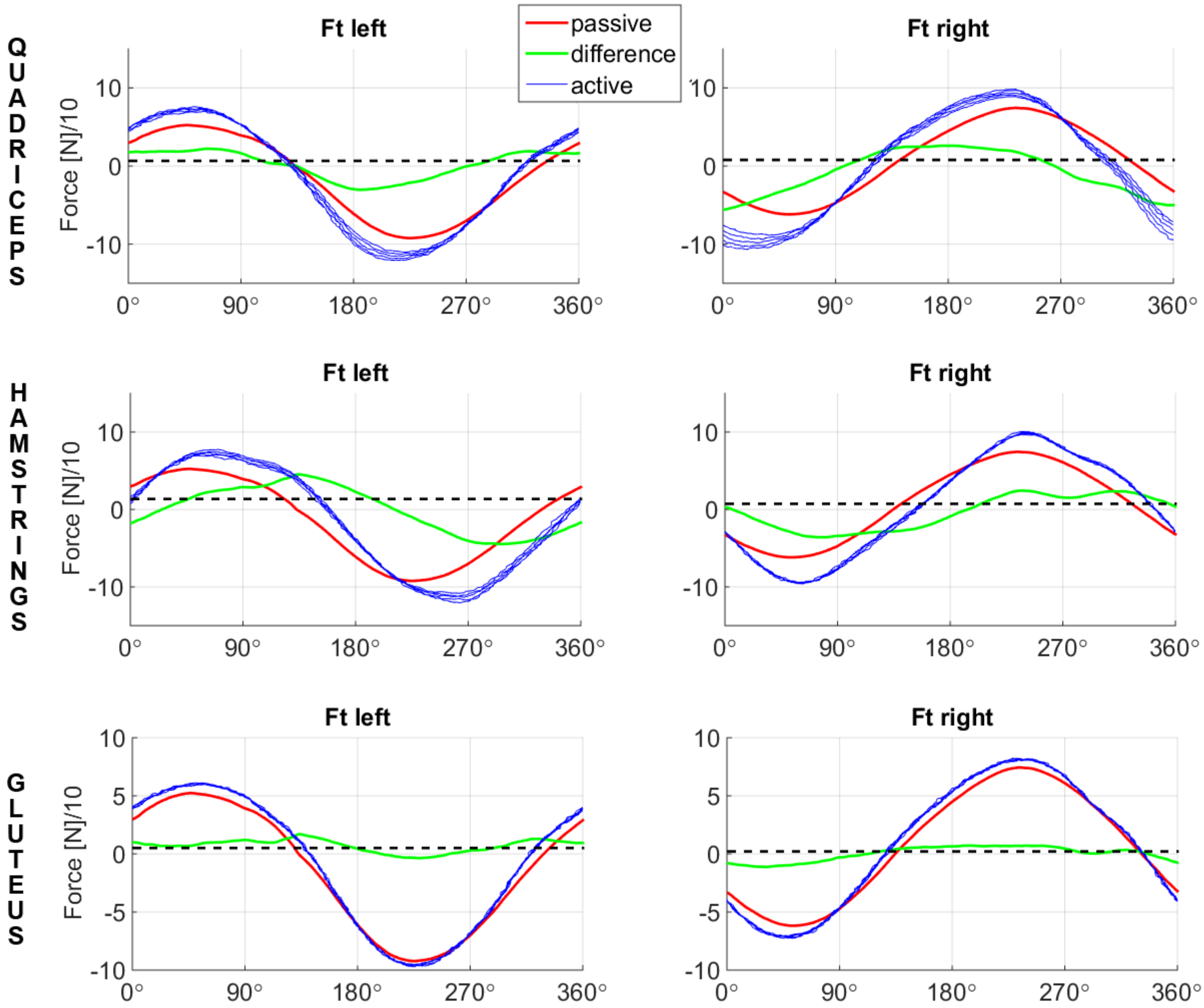

Fig. 2. Tangential forces on the left and right crank while passively moving the legs (red lines) and while stimulating quadriceps, hamstrings or gluteus of both legs throughout the whole pedaling cycle (blue lines). Green is the difference between the active (blue) and passive (red) average values. Dashed black line represents 30% of the maximal positive value of the difference (green line).

providing active assistance to move the legs. To provide the electrical pulses we used a Rehastim system (Rehastim I, Hasomed, Germany) [6]. It has 8 stimulation channels that can be controlled through a "cycle port" that receives the saw tooth signal from an analogue absolute encoder. The onset/offset of stimulation can be programmed in steps of ten degrees.

C. *Protocol*

The subject was trained with FES cycling during previous twelve months on four muscle groups: quadriceps, hamstrings, gluteuses and tibialis anterior. The measurements protocol comprised three phases.

Phase I — The RT300 was set to passively move the legs while the stimulation was turned off. The speed was set to 30 rpm. Force transducers measured the forces elicited by the weight and inertia of the legs.

Phase II — The stimulation was set to stimulate one muscle on both legs for 5 cycles (5 full rotations of the pedals) with constant stimulation parameters (pulse width 490µs, frequency 40Hz) throughout the whole cycle. Stimulating both legs at the same time resulted with similar torques exerted by each leg in opposed directions. This minimized the resulting torque on the crank, and required only minimal driving torque from RT300 to turn the legs with constant rate. The angular velocity was kept at 30 rpm with resistance set to high value (20 Nm), so that the legs could never turn the pedals without assistance of RT300. This procedure was repeated for three muscles groups (quadriceps, hamstring and gluteus) independently. The intensities of stimulation were set to 40, 50 and 60 mA for quadriceps, hamstrings and gluteus, respectively.

Phase III — We calculated the timings (absolute angles) in which each muscle pair contributed positively to the produced force compared to the passive forces. In phase *IIIa* we used the calculated onset/offset angles to stimulate single muscles independently in the following order: quadriceps, hamstrings gluteus. In phase *IIIb*, we stimulated antagonist and agonist pairs of muscles, i.e. quadriceps plus hamstrings and quadriceps plus gluteuses. In phase *IIIc* we stimulated the three groups of muscles following the previously determined timings.

In each step of phase III the measurements were repeated for a classical stimulation pattern recommended for RT300 [7]. The average power outputs were compared for the two different stimulation patterns. After all the measurements were completed, the first force measurement in the protocol was repeated to assess for potential muscle fatigue.

D. Data processing

Data processing was done offline, in custom Matlab (Natick, USA) program. Produced forces were plotted versus angle, and average values were calculated for each leg and each measurement. Average power output was calculated as function of velocity and forces produced.

III. RESULTS

The tangential forces measured while passively moving the legs by RT300 (phase I) and while stimulating one muscle on each leg throughout the whole pedal cycle (phase II) are shown in Fig. 2. The difference between the forces exerted actively during stimulation (blue lines) and without stimulation (red lines) was considered for determination of phases in which each muscle contributed positively to the cycling motion. To determine our cycling stimulation pattern, we empirically set the threshold (dashed black line) at 30% of maximal positive value of this difference (green line). In the phase III, the muscles were stimulated only in phases in which the green line was greater than the threshold. To take into account the delay between electrical pulse and muscle contraction, we also started the stimulation ten degrees before the threshold angle (Fig. 3). For the sake of simplicity, we ignored the small differences in the results from left and right leg, and we used the pattern with shorter duration on both legs, symmetrically. The final pattern is shown in Fig. 4.

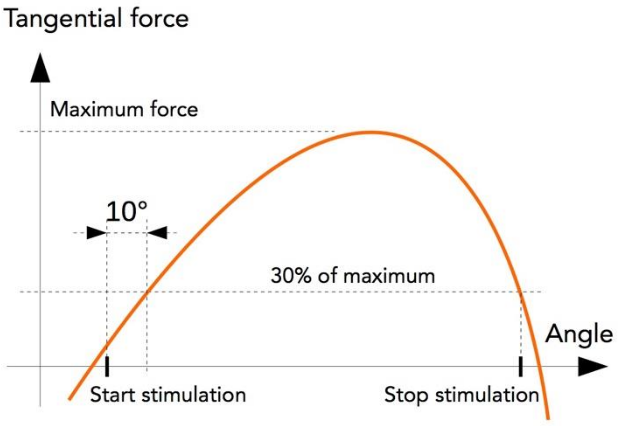

Fig. 3. To determine customised pattern, we set a threshold at 30% of maximal obtained force, and the stimulation onset angle was rounded to ten degrees before reaching threshold, to compensate for muscle activation delay.

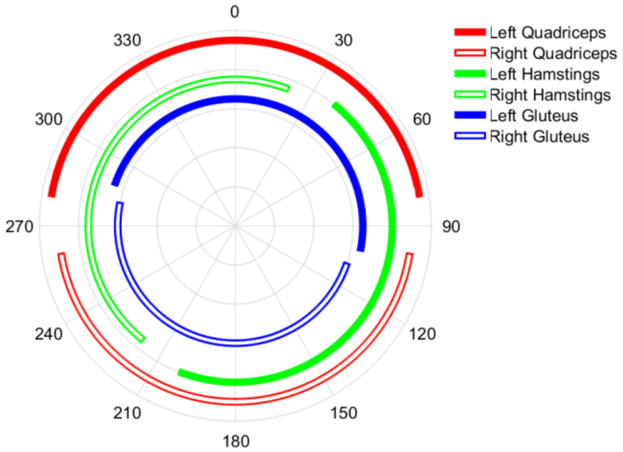

Fig. 4. Stimulation pattern used in experiment phase III. Zero angle represents the position in which the left leg is in the top vertical position, and starts moving forward and downwards.

The resulting stimulation pattern was applied in set of measurements in phase III, where the average power outputs were compared with the recommended stimulation pattern for RT300, as shown in Fig.5. The first measurement from the phase III (custom pattern on quadriceps) was repeated at the end of all measurements, and showed that there was no effect of muscle fatigue (the power output was the same as in the first measurement).

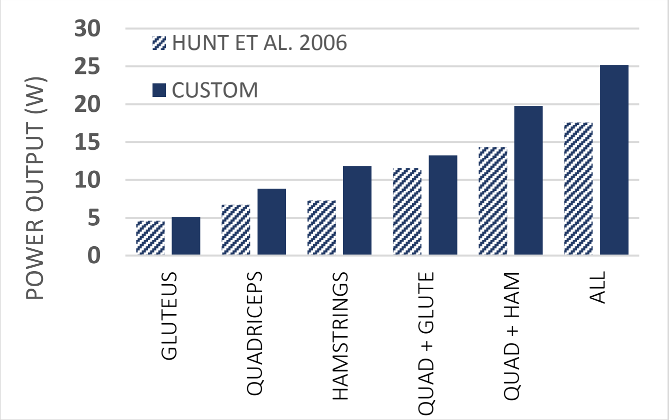

Fig. 5. Power outputs for tests in phase III where only one muscle was stimulated on both legs, or a combination of two or three muscles was stimulated using the pattern from Fig.3 (plain bars) or a pattern recommended for RT300 (dashed bars)

IV. CONCLUSION

We proposed a new systematic method to determine customised stimulation patterns for FES cycling. The determined pattern proved to produce significantly more power (33% in average) than a recommended pattern. This proves the relevance of our method but still needs to be confirmed by further comparison to other standard stimulation patterns.

The contributions of single muscles add up almost linearly: the average power for pairs of muscles and for all the muscles are lower than the sum of individual power for 3.9% in average. This has yet to be confirmed by statistically significant set of measurements.

This study was limited to three muscle groups. Further studies should include additional muscle groups that are expected to have a significant contribution in overall power output. These muscles are: tibialis anterior and gastrocnemius, that both might help overcome the dead point (position in which one leg is fully extended and other is fully flexed); and back muscles (latissimus dorsi) that might help transmit the leg muscles' forces to the pedals by strengthening the upper body and increasing the interaction between the body and the chair backrest.

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