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Comparing Fatigue Reducing Stimulation Strategies During Cycling Induced by Functional Electrical Stimulation: a Case Study with one Spinal Cord Injured Subject

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Abstract— **This case study was designed starting from our experience at CYBATHLON 2020. The specific aim of this work was to compare the effectiveness of different fatigue reducing stimulation strategies during cycling induced by Functional Electrical Stimulation (FES). The compared stimulation strategies were: traditional constant frequency trains (CFTs) at 30 and 40Hz, doublet frequency trains (DFTs) and spatially distributed sequential stimulation (SDSS) on the quadriceps muscles. One Spinal Cord Injured (SCI) subject (39 years, T5-T6, male, ASIA A) was involved in 12 experimental sessions during which the four strategies were tested in a randomized order during FES-induced cycling performed on a passive trike at a constant cadence of 35 RPM. FES was delivered to four muscle groups (quadriceps, gluteal muscles, hamstrings and gastrocnemius) for each leg. The performance was evaluated in terms of saturation time (i.e., the time elapsed from the beginning of the stimulation until the predetermined maximum value of current amplitude is reached) and root mean square error (RMSE) of the actual cadence with respect to the target value. SDSS achieved a statistical lower saturation time and a qualitative higher RMSE of the cadence with respect to CFTs both at 30 and 40Hz.**

Clinical relevance— **Conversely to previous literature, SDSS seems to be ineffective to reduce muscle fatigue during FES-induced cycling. Further experiments are needed to confirm this result.**

I. INTRODUCTION

Spinal Cord Injury (SCI) disrupts the descending motor fibers from the motor cortex to the spinal motor neurons [1]. Functional Electrical Stimulation (FES) provides a way for mobilizing intact lower limbs and is effective in preventing secondary complications of SCI. Positive psycho-social adaptations have also been reported among SCI individuals who undergo FES exercises [2]. In the first half of the 1980s, first examples of people with SCI able to produce cyclical leg movements were shown. A sequential stimulation controlled on the basis of the crank angle was used on large leg-actuating muscles (typically quadriceps, hamstrings, and gluteal muscle groups) [3]. Although most previous studies have used stationary ergometers, a number of mobile devices were also proposed [4], [5], raising the idea that FES-cycling might become a recreational outdoor activity [3] for people with SCI. One of the main limitations of FES-cycling, especially when performed outdoor, is the low efficiency, i.e., the ratio of external work output to metabolic energy input, which is much lower than that of able-bodied subjects cycling under volitional control. Therefore, maximization of cycling efficiency is one of the most important challenges in mobile cycling [3], since the power peaks produced by FES (approximately 25 W) are not adequate to overcome rough surfaces, slight inclines, or headwinds [6].

The other major factor that limits the use and effectiveness of FES in all contexts is the well-known problem of the early onset of muscle fatigue [7], mainly due to the synchronous excitation of muscle fibers and to the altered recruitment order.

Traditionally, FES uses constant frequency trains (CFTs), i.e., brief stimulation pulses separated by regular inter-pulse intervals [8]. Other stimulation strategies, such as variable frequency trains (VFTs) and doublet frequency trains (DFTs) have shown the capacity to postpone the onset of muscle fatigue and to be more efficient to generate force in fresh and fatigued muscles as compared to CFTs [9]. VFTs consist of trains characterized by an initial doublet, i.e., two closely spaced pulses, typically 5-10 ms apart, followed by pulses at a constant frequency [10]. Instead, with DFTs, closely spaced pulse pairs ($\sim$5 ms interpulse intervals) are separated by longer intervals (inter-doublet intervals) [8]. Since one reason for rapid muscular fatigue is the activation of only a subset of motor units of the corresponding muscle [11], multi-electrode setups have been recently developed. Such approach, referred as Spatially Distributed Sequential Stimulation (SDSS), allows stimulation patterns that target different motor units within the same muscle group, showing some advantages in reducing fatigue during isometric FES-induced muscle contractions [12], [13] or dynamic knee extensions at low stimulation intensity [7]. SDSS consists in sending stimulation pulses sequentially to each single electrode, resulting in a fused response from the low-frequency unfused responses of individual electrodes.

Up to date, no previous studies evaluated the performance of SDSS and DFTs with respect to conventional stimulation at constant frequency in terms of muscle fatigue during FES-induced cycling. Therefore, this study aims to overcome this knowledge gap by experimentally comparing the effectiveness of CFTs at 30 and 40Hz, DFTs, and SDSS strategies during FES-cycling in a longitudinal case study with one FES-trained individual with SCI.

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Fig. 1. Experimental setup used in the case study. 1) ReheMove3 stimulators, 2) Trike (Ice VTX), 3) Encoder, 4) Control unit, 5) Push buttons and emergency button, 6) Screen, and 7) AFOs.

II. MATERIALS AND METHODS

A. Subject

One single subject (39 years, 70 kg, 1.75 m) with complete SCI (T5-T6, ASIA A, 2 years post-injury) participated in this case study. The participant gave his informed consent to the study. The Ethical Committee of Politecnico di Milano approved the study in September 2019. The participant conducted regular training with FES twice a week for three months before the beginning of this study.

B. Experimental setup

The experimental setup is shown in Fig. 1 and consisted of a commercial recumbent trike (Ice VTX™, 2017) - adapted for use by paraplegic cyclists - in conjunction with two four-channel current-controlled stimulators (RehaMove3™, Hasomed GmbH). The trike pedals were replaced by two ankle-foot orthoses (AFOs) to keep the movement of the legs in the sagittal plane. A magnetic encoder was placed at the crank to measure in real-time the crank angle. Based on the current value of the crank angle, the different muscle groups of the lower limbs (i.e., quadriceps, gluteal muscles, hamstrings, and gastrocnemius) are stimulated. The control system ran on a BeagleBone Black using MATLAB/Simulink® Real-time toolbox in external mode. Pals® surface self-adhesive electrodes from Axelgaard Manufacturing Co. Ltd. were used to deliver the current pulses to the muscle groups. The waveform of the pulses was rectangular biphasic, completely balanced in terms of charge. This setup was the one we used to participate to CYBATHLON 2020 Global Edition (`https://cybathlon.ethz.ch/en`).

C. Experimental protocol

The four compared stimulation strategies were:

- Stimulation with CFTs at 30Hz.
- Stimulation with CFTs at 40Hz.
- Stimulation with DFTs with an inter-pulse interval of 5.8 ms and an inter-doublets interval of 50 ms, i.e., two closely spaced impulses sent with a frequency of 20Hz.
- SDSS on the quadriceps muscle, with a single electrode placed proximally and four smaller electrodes placed distally. The pulses were sent sequentially to the small electrodes, with each small electrode active at 10Hz, whilst the overall stimulation frequency was 40Hz.

Fig. 2 shows the pulse sequence for the tested stimulation strategies. The number of pulses delivered per unit time was the same for all stimulation strategies, but CFTs at 30Hz. Regarding CFTs and DFTs, one proximal 13 cm x 5 cm electrode and one distal 9 cm x 5 cm electrode were used, while for SDSS, the distal electrode was replaced with four 5 cm x 5 cm electrodes, as shown in Fig. 2. SDSS was performed using anti-fatigue units (AFU, model 3F-AFU-10 from 3F-Fit Fabricando Faber).

The experimental protocol consisted of 12 sessions performed on different days. During each session, the four stimulation strategies were evaluated in a randomized order in consecutive trials, with 5 minutes of rest between them. The work rate was kept constant to ensure a fair comparison. Thus, the gear of the trike and the cadence were fixed for all trials during each session. A smart trainer (KICKR from Wahoo Fitness™) was mounted in place of the back wheel before performing the acquisitions and its resistance value was kept fixed at 5% for all the trials. A closed-loop control over the stimulation amplitude was implemented to keep the cadence constant, using a discrete-time Proportional-Integral (PI) controller, which parameters were tuned using a trial-and-error procedure. The PI action was the same for all muscle groups, and the controller kept the pedaling cadence constant by increasing the current amplitude until saturation was reached. Each trial was stopped one minute after reaching stimulation saturation or after 15 minutes from the beginning of stimulation. The initial stimulation current was set at 60 mA for quadriceps, gluteal muscles, and hamstrings; and 55 mA for gastrocnemius. The saturation limit was fixed at 120 mA for quadriceps, gluteal muscles, and hamstrings; and 115 mA for the gastrocnemius. Ramps were used at the beginning and at the end of the stimulation range. All muscles were stimulated with a constant pulse width of 400 µs for each phase of the biphasic pulse.

D. Outcome measures

The outcome measures used to compare the cycling performance and the effect of neuromuscular fatigue were the saturation time, T_{sat} (namely the time elapsed from the beginning of the stimulation, until the maximum current amplitude was reached) and the root mean square error $RMSE_{cad}$ of the actual cadence with respect to 35 RPM (target cadence). A statistical analysis was carried out to compare the different stimulation strategies using the Kruskal-Wallis test. If significant differences were found, a post-hoc analysis with Bonferroni correction was performed.

III. RESULTS

Fig. 3 shows the current amplitude modulated by the PI controller and the respective value of the cadence with respect to the target one during an exemplary SDSS trial. It can be noticed that at the beginning the cadence was higher than the target level, which indicates that the initial current values induced a faster pedaling movement (please

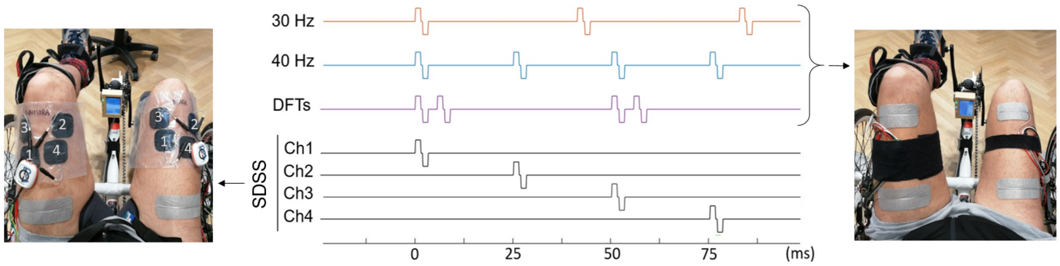

Fig. 2. Pulse sequence for all tested stimulation strategies. The electrode configuration used for CFTs and DFTs was the conventional one, shown on the right, while for SDSS the distal electrode was replaced by four smaller electrodes, as shown on the left.

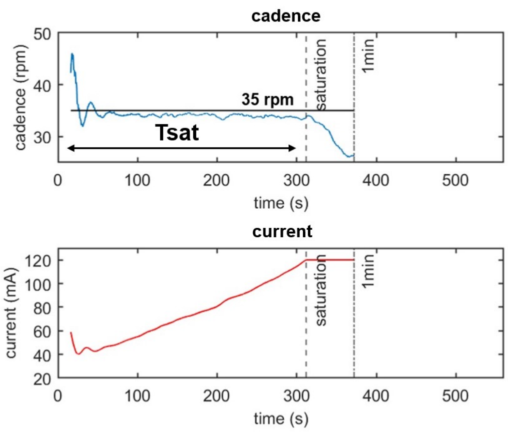

Fig. 3. Cadence (in blue, upper panel) and current amplitude (in red, lower panel) collected during an exemplary trial in which SDSS was tested. The reported current amplitude refers to quadriceps, gluteal muscles and hamstrings; the one delivered to gastrocnemius was the same, but 5 mA less. The black solid line in the upper panel represents the target cadence.

consider that, before FES was switched on, the leg of the subject were moved by an operator in order to maintain a pedaling cadence of about 35 rpm). Therefore, the PI controller reduced the current amplitude in order to reach the target cadence. After about 50 s of stimulation, an almost linear increase of current was needed to maintain the target cadence in order to counteract the increase of muscle fatigue. When saturation was reached, the PI was disabled and the cadence reduced till the end of the trial.

Fig. 4 reports the box-plots of the saturation time and the RMSE_{cad} for the different stimulation strategies. The value of T_{sat} for SDSS resulted to be statistically significant lower than stimulation at constant frequency both at 30Hz (p-value = 0.014) and at 40Hz (p-value = 0.021). A marked difference between the values of SDSS and DFTs is also observable form the box-plot, with median of DFTs higher than the one of SDSS, but no significant difference was found. For what concerns RMSE_{cad}, no statistically significant differences were found. Nevertheless, it can be noticed that the median value and the interquartile range of RMSE_{cad} for SDSS were qualitatively higher than for the other stimulation strategies.

IV. Discussion

This case study aimed to investigate the influence of different stimulation strategies on the performance obtained during FES-induced cycling in terms of muscle fatigue.

Postponing the onset of muscle fatigue is particularly relevant to transfer FES-cycling in daily life as a sport-therapy option for people with SCI. Indeed, to foster the design of less-fatiguing stimulation strategies, CYBATHLON rules were updated from 2016 to 2020, doubling the distance to be covered within the same time limit.

The results of the case study highlighted a significantly lower performance of SDSS as compared to constant and doublet frequency trains. These findings are in contrast with previous studies on SDSS [12], [13], [7] that evidenced a positive effect of SDSS in reducing FES-induced muscle fatigue. However, two of these, namely [12] and [13], evaluated SDSS during isometric contractions. Thus, their conclusions cannot be directly transferred to dynamic tasks, such as cycling. The third study [7] focused on dynamic knee extension movements comparable to FES-cycling but with lower stimulation intensities than the ones used in the present study. Also, in these previous studies [12], [13], [7], untrained subjects were recruited in the study, while our pilot regularly practiced FES-cycling for 3 months prior to the study. In a more recent study [14], different electrode configurations for SDSS were compared with the conventional two-electrodes configuration during isokinetic contractions of the quadriceps similar to the one described in [7]. Schmoll and colleagues [14] applied stimulation amplitudes higher than the ones used in [7] and comparable to the ones used in the present study on SCI subjects who regularly trained with FES for 14 months prior to the study. They did not find a remarkable effect in fatigue reduction for any of the tested SDSS configurations and they hypothesized that the use of higher stimulation amplitudes in SDSS could cause a certain degree of spillover, leading to the recruitment of additional motor-units indented to be stimulated by a neighboring electrode. Therefore, they concluded that the effects of SDSS could be less pronounced at higher stimulation amplitude as a result of the loss of intra-muscular selectivity.

One possibility is that the low performance of SDSS observed in the present study could be related to the spill-over phenomenon hypothesized by Schmoll et al. On the other hand, Schmoll et al. didn't report a lower perfor-

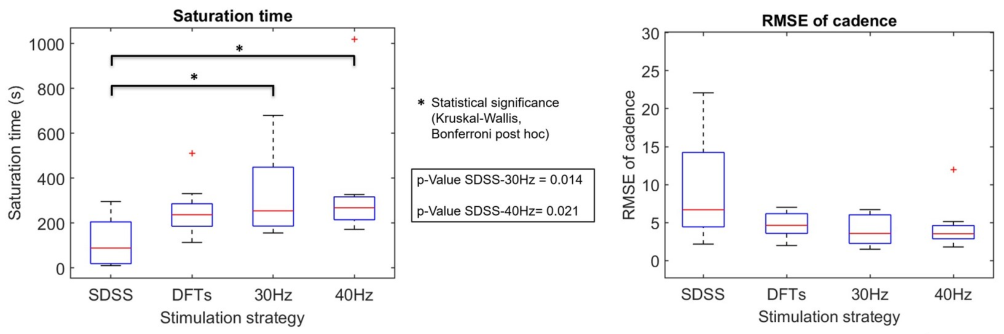

Fig. 4. Box-plots of saturation time (on the left) and RMSE$_{cad}$ (on the right) for the different stimulation strategies.

mance for SDSS, just a performance similar to the one obtained with conventional single electrode stimulation. Another highly relevant element to be taken into account is electrode placement. We splitted the distal electrodes and, in order to minimize the spill-over phenomenon, we placed the small electrodes relatively distant to each other. This might have caused the quadriceps not to reach a complete tetanic contraction, reducing the produced power at same stimulation amplitudes and, therefore, lowering the overall performance of SDSS. However, in order to take a final conclusion on the performance of SDSS during FES-induced cycling, more experiments are needed and different configurations for electrodes placement should be evaluated.

For what concerns doublets frequency trains, a clear advantage with respect to constant frequency train was not observed, as well as no difference was found between 30Hz and 40Hz. Probably, the high variability between various sessions might have covered small differences. The main limitation of the current study is that just one subject was involved in the experimental protocol. Furthermore, no torque measurements at the pedals were acquired which did not allow to compare the different strategies in terms of power output.

V. Conclusion

This case study showed a lower performance of SDSS compared to other stimulation strategies (DFTs, CFTs at 30Hz and 40Hz) during FES-induced cycling in one individual with SCI. These conclusions are of high relevance since no previous study evaluated the performance of SDSS during cycling. However, experiments involving more than one subject have to be performed in order to drive final conclusions.

VI. Acknowledgment

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References

[1] S. Hamid and R. Hayek, "Role of electrical stimulation for rehabilitation and regeneration after spinal cord injury: an overview," *European Spine Journal*, vol. 17, pp. 1256–1269, Sept. 2008.

[2] G. M. Davis, N. A. Hamzaid, and C. Fornusek, "Cardiorespiratory, metabolic, and biomechanical responses during functional electrical stimulation leg exercise: health and fitness benefits," *Artificial Organs*, vol. 32, pp. 625–629, Aug. 2008.

[3] K. J. Hunt, C. Ferrario, S. Grant, B. Stone, A. N. McLean, M. H. Fraser, and D. B. Allan, "Comparison of stimulation patterns for FES-cycling using measures of oxygen cost and stimulation cost," *Medical Engineering & Physics*, vol. 28, pp. 710–718, Sept. 2006.

[4] D. J. Newham and N. d. N. Donaldson, "FES cycling," in *Operative Neuromodulation: Volume 1: Functional Neuroprosthetic Surgery. An Introduction* (D. E. Sakas, B. A. Simpson, and E. S. Krames, eds.), Acta Neurochirurgica Supplements, pp. 395–402, Vienna: Springer, 2007.

[5] K. J. Hunt, B. Stone, N.-O. Negård, T. Schauer, M. H. Fraser, A. J. Cathcart, C. Ferrario, S. A. Ward, and S. Grant, "Control strategies for integration of electric motor assist and functional electrical stimulation in paraplegic cycling: Utility for exercise testing and mobile cycling," *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, vol. 12, no. 1, pp. 89–101, 2004.

[6] J. McDaniel, L. M. Lombardo, K. M. Foglyano, P. D. Marasco, and R. J. Triolo, "Setting the pace: insights and advancements gained while preparing for an FES bike race," *Journal of NeuroEngineering and Rehabilitation*, vol. 14, p. 118, Nov. 2017.

[7] M. Laubacher, E. A. Aksoez, A. K. Brust, M. Baumberger, R. Riener, S. Binder-Macleod, and K. J. Hunt, "Stimulation of paralysed quadriceps muscles with sequentially and spatially distributed electrodes during dynamic knee extension," *Journal of Neuroengineering and Rehabilitation*, vol. 16, p. 5, Jan. 2019.

[8] S. Qiu, A. E. Draghici, G. Picard, and J. A. Taylor, "Muscle Fatigue in Response to Electrical Stimulation Pattern and Frequency in Spinal Cord Injury," *PM & R: the journal of injury, function, and rehabilitation*, vol. 12, pp. 699–705, July 2020.

[9] Y.-J. Chang and R. K. Shields, "Doublet Electrical Stimulation Enhances Torque Production in People With Spinal Cord Injury," *Neurorehabilitation and Neural Repair*, vol. 25, pp. 423–432, June 2011.

[10] B. M. Doucet, A. Lam, and L. Griffin, "Neuromuscular electrical stimulation for skeletal muscle function," *The Yale Journal of Biology and Medicine*, vol. 85, pp. 201–215, June 2012.

[11] C. M. Gregory and C. S. Bickel, "Recruitment patterns in human skeletal muscle during electrical stimulation," *Physical Therapy*, vol. 85, pp. 358–364, Apr. 2005.

[12] L. Z. Popovic and N. M. Malesevic, "Muscle fatigue of quadriceps in paraplegics: comparison between single vs. multi-pad electrode surface stimulation," *Annual International Conference of the IEEE Engineering in Medicine and Biology Society. IEEE Engineering in Medicine and Biology Society. Annual International Conference*, vol. 2009, pp. 6785–6788, 2009.

[13] R. Nguyen, K. Masani, S. Micera, M. Morari, and M. R. Popovic, "Spatially distributed sequential stimulation reduces fatigue in paralyzed triceps surae muscles: a case study," *Artificial Organs*, vol. 35, pp. 1174–1180, Dec. 2011.

[14] M. Schmoll, R. Le Guillou, D. Borges, C. Fattal, E. Fachin-Martins, and C. Azevedo-Coste, "Standardizing fatigue-resistance testing during electrical stimulation of paralysed human quadriceps muscles, a practical approach," *Journal of NeuroEngineering and Rehabilitation*, vol. 18, Jan. 2021.