Proceedings on Automation in Medical Engineering
Proc AUTOMED, 2026, Vol. 3, No 1, Article ID 2507, 2 Pages

Infinite Science Publishing

A Multimodal Platform for Adaptive Functional Electrical Stimulation Cycling

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Abstract: Functional Electrical Stimulation (FES) cycling is typically operated in open-loop configurations, limiting the ability to investigate neuromuscular and mechanical responses during exercise. To enable comprehensive assessment of stimulation effects and to support future development of adaptive control strategies, we developed a synchronized multimodal experimental platform integrating HD-EMG, instrumented pedals, optical motion capture, crank-angle sensing, and a multi-channel stimulator. A custom hardware trigger provides sub-millisecond synchronization across devices, while a Python-based real-time interface manages data acquisition, safety functions, and online stimulation adjustments. The objective of this work was to design and validate the synchronization accuracy and temporal alignment of this integrated setup. Across three test sessions, the mean angular timing error between the commanded stimulation pattern and the EMG-measured muscle activation was 13.25° (44.1 ms at 50 RPM), confirming accurate temporal alignment between stimulation delivery and sensor measurements.

I. Introduction

Functional Electrical Stimulation (FES) cycling is a well-established modality for rehabilitation in individuals with neuromuscular impairments [1]. The mechanically constrained nature of FES-cycling, being primarily limited to the sagittal plane, ensures it remains an attractive environment for refining neuromodulation strategies before they are translated to more complex tasks such as walking. Unlike open-loop patterns, closed-loop FES-cycling adapts to fatigue and variability in real-time, enhancing safety and endurance by modulating stimulation parameters to delay force decline and prevent over-stimulation.
However, accurately quantifying fatigue and modulating stimulation parameters accordingly remains a major limitation [2]. Muscle fatigue is typically inferred from a decrease in the force produced and changes in EMG features [3], yet most commercial FES-cycling systems lack high-resolution neuromuscular recordings or synchronized multimodal sensor data. To address these gaps, a fully synchronized experimental setup in FES-cycling is required to characterize how stimulation frequency, pulse width, and amplitude affect fatigue onset during cycling. This study presents a multimodal platform that enables high-resolution neuromuscular and mechanical measurements, laying the groundwork for fatigue-aware closed-loop FES control.

II. Material and methods

A commercially available passive stationary recumbent bike (LifeSpan R5i) has been integrated with sensing and stimulation subsystems (Figure 1):

1. **High-density EMG (HD-EMG):** Muscle activity is recorded using a Sessantaquattro+ system (OT Bioelettronica) equipped with two 32-electrode grids with a sampling frequency of 2000 Hz, enabling conduction velocity estimation and spectral fatigue analysis.
2. **Instrumented pedals:** Bilateral tangential and radial pedal forces are measured using SmartPedals (SRM), which operate at an internal sampling frequency of 200 Hz and are transmitted via Bluetooth Low Energy (BLE).

Figure 1: Experimental Setup.

3. **Optical motion capture:** Three-dimensional joint trajectories are reconstructed using a Vicon marker-based optical motion capture system, which provides very high spatial accuracy with errors below 0.15 mm and a sampling frequency of 100 Hz.
4. **Electrical stimulator:** Neuromuscular stimulation is delivered through a RehaStim P24 unit (Hasomed), an eight-channel stimulator using surface self-adhesive electrodes (Pals®, Axelgaard Manufacturing Co. Ltd.) to activate the target leg muscles.
5. **Crank angle sensing:** Crank angle measurements are recorded using an x-IMU3 unit (x-io Technologies), with a sampling frequency of 200 Hz.

A custom hardware trigger has been designed to generate synchronization pulses that are delivered to both the Vicon system and the OT Bioelettronica unit through their respective synchronization modules.

An intuitive Python-based graphical user interface (GUI) was developed in Visual Studio Code to enable patient-specific stimulator calibration based on activation level and FES tolerability, while providing direct communication with the instrumentation. The GUI manages real-time data streaming from the instrumented pedals and an IMU, transmitting crank-angle information to the stimulator via a serial API. It also integrates safety features, including an emergency stop, watchdog routines, and channel-status monitoring, and provides dual visualization of the crank angle from both the pedals and the IMU.

Dedicated evaluation sessions were conducted to quantify the effective end-to-end latency of the stimulation control chain, specifically between the stimulator, the EMG acquisition system, and the crank-angle sensing unit. Three experimental sessions were performed on the same healthy subject, each consisting of 5 minutes of cycling at 50 RPM with FES assistance. The accuracy of FES activation timing was assessed by comparing the commanded stimulation pattern with the stimulation-induced electrical artifact detected in the EMG signal. EMG signals were recorded from the Rectus Femoris (RF) and Biceps Femoris (BF) muscles, filtered, and processed to obtain RMS envelopes. Given the substantially higher amplitude of the stimulation-induced artifact relative to the residual voluntary EMG activity, the analyzed signal transients were attributed to FES delivery. This assumption was adopted exclusively for estimating system-related latency and not for quantifying physiological muscle activation. Pedal cycles were identified from the IMU crank-angle local maxima, and EMG and force signals were temporally normalized cycle-by-cycle to a 0–359° scale. The normalized cycles were averaged to obtain mean activation profiles and corresponding standard deviations. Activation periods were identified using dynamic thresholds defined as a percentage of the signal range. A single activation threshold (0.5) was selected based on the activation profiles observed across all sessions. Using this threshold, the timing error between the commanded FES activation window and the EMG-detected stimulation artifact was computed cycle-by-cycle for each session. The measured error therefore reflects end-to-end system latency, including communication delays and hardware response times. To summarize overall performance, the mean error across sessions was calculated. The associated standard deviation of the mean was obtained by combining the individual session errors under the assumption of independence. Specifically, the individual session errors have been calculated as $x_i \pm \sigma_i$, where x_i is the session mean and σ_i is the associated standard deviation for that i-th session. The combined standard deviation has been calculated as $\sigma_{mean} = \frac{\sigma_2+\sigma_2+\sigma_3}{3}$.

III. Results and discussion

The multimodal acquisition platform enabled both experimental evaluation and detailed review of hardware specifications to assess sensor communication reliability and quantify synchronization. Based on manufacturer data and experimental measurements, the theoretical upper-bound latency of the complete instrumentation framework was estimated at approximately 46.7 ms. This value accounts for cabled trigger propagation (< 1 ms), the fixed 33.2 ms radio delay introduced by the Sessantaquattro+ SyncSE adapter, stimulator latency (≤ 2 ms), x-IMU3 Bluetooth communication (maximum 6 ms), and the experimentally measured 4.5 ms delay of the Vicon LockLab analog input.

The evaluation sessions reported an error equal to 13.25° ± 1.40° (Figure 2), corresponding to 44.1 ± 4.6 ms at 50 RPM, relative to the stimulation control chain.

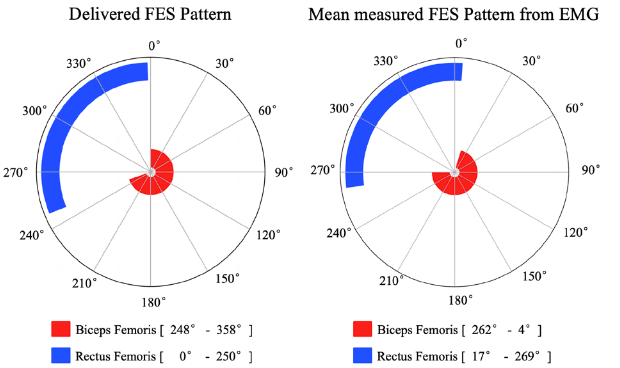

Figure 2: Stimulation pattern comparison for the right leg.

IV. Conclusions

A synchronized multimodal platform for FES-cycling has been developed, integrating HD-EMG, instrumented pedals, IMU-based and optical motion capture systems, and a programmable stimulator with real-time control. This system enables precise adjustment of stimulation parameters and systematic assessment of neuromuscular and mechanical responses. Theoretical analysis of hardware delays allowed the estimation of an upper-bound system latency, while experimental validation of the stimulation pathway confirmed the effective end-to-end latency of the stimulation control chain. Although basic cycling control can be achieved only using IMU and stimulator inputs, the objective of assessing neuromuscular changes during exercise required the integration of EMG and optical motion capture data. Quantifying total system latency was therefore essential to validate the synchronization accuracy of the multimodal platform and ensure its suitability for future analyses, including joint torque estimation. Future work will focus on adapting reference activation patterns to individual needs to improve participant-specific FES control, as well as integrating machine learning approaches for predictive modeling of fatigue and proactive stimulation adjustment.

Author's statement

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them. This work was supported by the European Union's Horizon Europe Framework Programme for Research and Innovation under AERIALIST (Grant Agreement No. 101169197). Additional contributions were supported by the Horizon Europe MSCA Cofund AIHUB programme through the ALLIES Project (Grant Agreement No. 101126626) and by the "la Caixa" Foundation (ID LCF/BQ/DFR25/12000059).

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