

# Patient-Driven Hybrid FES-Exoskeleton Control with Adaptive Band-Based Assistance

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**Abstract**—Spinal Cord Injuries (SCIs) are a prevalent condition worldwide, leading to a loss of motor function that significantly hinders Activities of Daily Living (ADLs). Optimized rehabilitation is essential to mitigate these challenges, promoting neuroplasticity and motor relearning. One of the most promising approaches combines Functional Electrical Stimulation (FES) of muscles with forces generated by exoskeletons. However, previously developed systems have limitations, particularly in fostering active patient engagement. This proposal introduces a cooperative and Assist-As-Needed hybrid system (FES-EXO) designed for ADL-oriented rehabilitation. The primary objective of the control strategy is to enhance patient performance and independence through a Human-In-The-Loop (HITL) approach. The assistance is dynamically adjusted to the user's needs in real time, featuring three operational modes, no assistance, FES-only assistance, and hybrid assistance, based on the user's motor state. Additionally, the system addresses challenges related to muscle fatigue and insufficient active participation. The proposed control framework will be integrated into the hybrid system and, in future work, will be validated with healthy individuals and, subsequently, with SCI patients in a case study at Guimarães' Hospital.

**Index Terms**—Spinal Cord Injuries, Exoskeleton, Functional Electrical Stimulation, Rehabilitation, Neuroplasticity, Daily Activities, Patient-Driven Assistance.

## I. INTRODUCTION

Spinal Cord Injuries (SCIs) affect over 15 million people worldwide [1], often leading to loss of sensory and/or motor function below the injury level. This results in severe mobility limitations and difficulties performing Activities of Daily Living (ADLs), often accompanied by secondary complications like spasticity, pressure ulcers, and osteoporosis [1].

These limitations significantly reduce patients' independence and Quality of Life (QoL), frequently requiring as-

sistive devices such as crutches or wheelchairs [1]. Effective rehabilitation can help overcome these challenges by leveraging neuroplasticity for motor relearning [3]. However, current clinical rehabilitation is expensive, time-consuming, and often lacks real-life relevance and personalization [1].

Hybrid FES-Exoskeleton systems show promise for promoting functional recovery beyond clinical settings. Yet, challenges remain: patient involvement is often limited, and existing protocols rarely account for long-term progression or adaptation [4]. Chapter II further explores limitations specific to each system.

This project aims to enhance patients' functional performance in daily activities through a hybrid FES-Exoskeleton system that delivers ADL-oriented, repetitive training. It adopts an Assist-as-Needed (AAN) strategy, combining FES-generated internal forces with exoskeleton-based external support. The contribution of each subsystem is dynamically adjusted to meet the user's evolving needs, fostering autonomy in ADL execution. A Human-In-The-Loop (HITL) control framework is proposed, placing the user at the center of system behavior.

The scientific contribution of this work lies in a novel, user-centered hybrid control strategy that integrates volitional effort, adaptive FES-Exoskeleton cooperation, and personalized assistance. By prioritizing user intention and minimizing unnecessary aid, the system encourages active engagement and supports more effective, natural rehabilitation for ADL tasks [5]. This work presents the current state-of-the-art and the challenges identified, and describes the proposed solution.

## II. STATE-OF-THE-ART ON REHABILITATION

Exoskeletons and orthoses are wearable devices that assist locomotion, either passively or via actuators. However, in rehabilitation, they may reduce patient engagement, a phenomenon known as "slacking," where the user becomes passive [4].

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FES applies electrical currents to trigger muscle contractions, enabling movement even in paralyzed muscles. Its main limitations are rapid muscle fatigue and potential discomfort [6].

Conventional rehabilitation relies heavily on physiotherapists to mobilize limbs [1]. While FES is increasingly used, exoskeleton adoption remains limited, as clear advantages over traditional methods have not yet been firmly established.

Integrating FES with exoskeletons or orthoses is a growing approach to overcome their individual limitations [4]. This review examines the current state of the art in hybrid rehabilitation systems combining both technologies. The literature search was conducted from October to December 2024 using Scopus, IEEE Xplore, and PubMed.

Following the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) guidelines, 12 relevant articles were selected for full-text reading and analysis.

#### A. Exoskeleton-FES-User Roles

The user's role varied widely across studies. In some cases, like Lyu *et al.* (2023) [7], patients were instructed to relax, with their movement treated as a disturbance. However, most systems encouraged active participation [4], [6], [8]–[12]. Some even placed the user at the center of control, providing assistance only when needed, as in Christou *et al.* (2024) and Jung *et al.* (2024) [6], [8].

In many systems, the exoskeleton served as the main source of assistance [7], [10], [11], [13], [14], whereas in Christou *et al.* (2024) [8], it acted as a secondary support, used only when necessary.

When the exoskeleton was the primary assistive device, FES typically played a supporting role, reducing reliance on the robot and promoting muscle activation [9]. Notably, FES was often limited to specific joints due to channel constraints.

#### B. Sensors

The hybrid systems reviewed employed a variety of sensors to support both the exoskeleton and FES controllers.

Joint position sensors, including potentiometers and optical/inductive encoders, are often integrated into exoskeletons to measure joint angles [7], [8], [10]–[12], [14]. Interaction forces were typically measured using load cells and strain gauges [4], [6], while ground reaction forces (GRFs) were captured using force-sensitive resistors (FSRs) or insole pressure sensors [4], [6], [9], [13], [15].

Inertial Measurement Units (IMUs), commonly placed on the foot or torso, facilitated gait event detection and orientation tracking [9], [13]. Additionally, electromyography (EMG) sensors, often located on muscles such as the hamstrings, Tibialis Anterior (TA), and Soleus, were utilized to monitor muscle activity and support volitional control [6].

#### C. System Control

1) *Exoskeleton Control*: In hybrid systems, exoskeleton control often involved adjusting motor stiffness and damping to support movement [4], [8]. Adaptive strategies allocated

torque based on joint position or muscle weakness [8], [12], while impedance models used real-time joint feedback for optimized assistance [13].

Most studies focused on joint trajectory tracking with fixed references [4], [7]–[11], [14]–[16], using low-level PD or PID controllers. A less common approach by Christou *et al.* (2024) [8] applied Iterative Learning Control (ILC) to improve performance through repetition.

2) *FES Control*: FES control in hybrid systems varied widely. Adaptive methods adjusted stimulation based on real-time feedback, including muscle fatigue or strength estimates, while simpler approaches used thresholds or Finite State Machines (FSM) [9], [13]. More advanced techniques involved Iterative Learning Controllers (ILC) [8] and Deep Neural Networks (DNN) generating FES patterns from EMG [16].

Commonly modulated parameters were pulse width (PW) and amplitude (PA), whereas pulse frequency (PF), which can reduce fatigue [17], was less explored. Stimulation timing was typically synchronized with movement phases like the gait cycle [6].

3) *Exoskeleton-FES Collaboration*: Collaboration strategies between FES and exoskeletons included torque allocation via fixed or dynamic coefficients [7], [14]. The adaptation of the coefficients could be decided based on muscle fatigue/strength, or movement phase [12]. Other methods involved hybrid control matrices and phase-based switching [8], [15].

Real-time torque distribution could be optimized using Model Predictive Control (MPC) [14] or coordinated through synergy-based control [12]. Christou *et al.* (2024) proposed a band-based system that dynamically selects between no assistance, FES, or hybrid modes based on joint angle tracking error [8].

4) *User Intention*: Most of the analyzed hybrid system articles did not incorporate user intention. However, one study by Jung *et al.* (2024) [6] measured volitional EMG signals to establish a baseline torque, with the hybrid system supplying additional torque as needed.

5) *Muscle Fatigue*: Muscle fatigue is a major limitation of FES and is often addressed in control strategies. Some studies assessed fatigue retrospectively via questionnaires [4] or EMG metrics [6], while others incorporated real-time fatigue estimation to adjust stimulation or shift effort between FES and exoskeleton support. Methods ranged from qualitative assessments to quantitative models and threshold-based approaches [4], [8], [11], [12], [14]. However, no consensus existed on the best controller response: most reduced stimulation when fatigue was detected [8], [11], [12], [14], only one system increased it to maintain performance [4].

#### D. ADLs

Most studies focused on walking assistance, including treadmill [6], [8], [9], [15] and overground walking [4], [11], [12], while fewer addressed sit-to-stand (STS) movements [7], [10], [13], [14], [16].

Muscle targets varied with the activity: STS studies mainly stimulated knee muscles, especially the quadriceps [7], [13], [14], [16], with one including hamstrings [10]. Gait studies typically stimulated both quadriceps and hamstrings [4], [8], [9], [11], [12], [15], sometimes adding ankle muscles [6], [9]. Ankle stimulation was notably absent in STS protocols, reflecting different muscular demands.

### E. Validation

Validation protocols for hybrid systems varied according to the ADLs targeted for assistance. Participant numbers were generally small, ranging from 1 to 6 individuals. Study cohorts included exclusively healthy subjects [4], [6]–[9], [13], [15], mixed groups of healthy and SCI patients [12], [14], [16], or solely SCI patients [10], [11].

Evaluations typically focused on trajectory tracking performance, using metrics such as Root Mean Squared Error (RMSE) between desired and actual joint angles [7], [8], [12], [14]–[16] and average joint angle values [4], [6], [9]–[11], [13]. Internal system parameters, including stimulation over time [4], [7], [8], [15], torque [6], [7], [10], [11], [13], [15], and stiffness [4], [8] were also assessed. Some studies incorporated user perception measures, such as Visual Analog Scales (VAS) for comfort and fatigue [4], [6].

## III. PROPOSED CONTROL SOLUTION

To address the limitations of existing hybrid strategies, this article presents a control framework for a hybrid system designed to assist gait. The system comprises an 8-channel stimulator (MotionSTIM8, Medel, Germany) and a 1-DoF unilateral ankle orthosis (Ankle-H3, Technaid, Spain). Since the system targets the ankle, it provides hybrid assistance to the Tibialis Anterior (dorsiflexor) and Soleus (plantarflexor).

To facilitate real-time user feedback and assess individual needs, additional sensors aside from those embedded in the orthosis are integrated, including Delsys Trigno EMG, FSRs and IMUs.

All future participants must provide informed consent in accordance with the ethical guidelines established by Ethics Committee of Guimarães' Hospital (77/2023-CAF and PIC\_57/2023).

Figure 1 illustrates the control diagram, depicting all the components that constitute the proposed control solution.

The solution proposal control can be divided into 5 main blocks: i) Volitional Estimation; ii) Hybrid Controller; iii) FES Controller; iv) Exoskeleton/Orthosis Controller; v) Exoskeleton-FES-Human block.

The volitional EMG is extracted from the measured muscular activity within the Volitional block. Since EMG data is acquired concurrently with FES stimulation, the raw signal,  $EMG_{raw}$ , contains stimulation artifacts. Therefore, artifact removal is necessary to isolate the volitional component of the EMG recordings.

This preprocessing follows the procedure described in [6]. After artifact elimination using a blanking method, the filtered EMG signal,  $EMG_f$ , is obtained, enabling the extraction of

the volitional EMG signal,  $EMG_{vol}$ , through a comb filter followed by a 2 Hz low-pass filter.

The hybrid block is responsible for selecting the appropriate reference trajectories,  $EMG_{ref}$  and  $\theta_{ref}$ , to guide the assistance of both Exoskeleton and FES components, as well as identifying the required torque of the system to complement the user's exerted torque,  $\tau_{sys}$ . For that, it receives data from FSRs and IMUs to identify the gait phase and detect walking speed. Based on those inputs, the adequate control references are selected.

Within this block, EMG references are converted to estimated reference torque,  $\tau_{ref}$  using a CNN model as in Moreira *et al.* [18], similar to [6]. This model is also responsible for converting the volitional EMG,  $EMG_{vol}$ , extracted from the measured muscle activity of the user in the Volitional block, to the volitional torque of the user,  $\tau_{vol}$ . Having  $\tau_{ref}$  and  $\tau_{vol}$ ,  $\tau_{sys}$  can be calculated as the difference between the two.

The system torque,  $\tau_{sys}$ , as a torque error, determines the level of assistance via a band system inspired by Christou *et al.* [8]. As the error increases, the system transitions through three regions: No assistance (low error), FES-only assistance (moderate error), and Hybrid assistance (high error).

After selecting the appropriate assistance level based on the user's exerted torque and the reference torque, each component, FES and Exoskeleton, is controlled using torque error-based feedback controllers.

Regarding FES controller, a PID controller is used to compute the PA value at each moment.

Notably, the feedback controller also contains a torque-to-PA converter, converting the original PID output to a PA value,  $u_{FES}$ .

The FES controller integrates a Muscle Fatigue Estimator based on the model proposed by Bao *et al.* (2020) [14], which characterizes fatigue dynamics. The estimator relies on patient-specific fatigue and recovery time constants, identified through torque or EMG monitoring, and requires individualized calibration to ensure accuracy. The estimator outputs a muscle fatigue index,  $\mu$ , ranging from 0 (full fatigue) to 1 (no fatigue). This index scales the original PA value, so higher fatigue results in reduced stimulation.

Concerning the exoskeleton/orthosis controller, it employs a feedback controller, PID, to provide a torque control signal,  $u_{EXO}$ .

Both FES and exoskeleton controllers incorporate an ILC to exploit the cyclic nature of gait by refining control signals over repetitions. Although both systems use ILC, they adapt different parameters. In the exoskeleton controller, stiffness ( $k$ ) is updated over gait cycles. In contrast, the FES controller adjusts an ILC gain parameter,  $\lambda$ , as in [8], which ranges from 0 to 1. This gain, combined with the muscle fatigue index, scales the FES PID output.

The ILC operates based on the parameter values from the previous cycle ( $k_{k-1}$  and  $\lambda_{k-1}$ ) as well as real-time feedback from the current iteration from the current cycle,  $\theta_t$  and  $\tau_t$ .

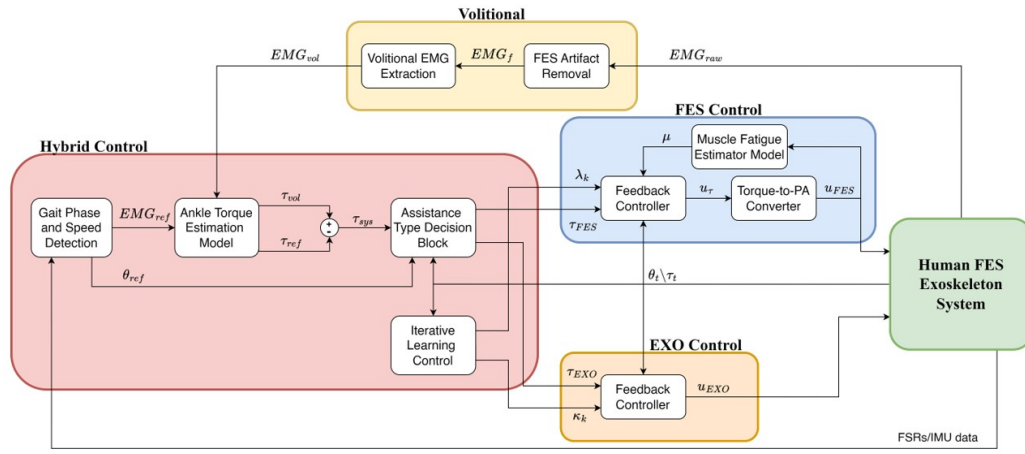


Fig. 1. Proposed Control Diagram for the Hybrid System.

#### IV. CONCLUSION

This work presents a novel, patient-tailored hybrid rehabilitation framework that synergistically combines internally generated forces via FES with externally applied support from a robotic exoskeleton. By dynamically integrating real-time user needs and variable assistance levels, the system fosters more natural and effective rehabilitation.

The cooperative control framework continuously adapts assistance according to the user's motor recovery, aiming to enhance autonomy in performing ADLs. Its validation is expected to offer valuable insights into the customization of rehabilitation strategies for individuals with SCI.

This approach lays the groundwork for a new rehabilitation paradigm, aiming to achieve patient recovery beyond current methodologies.

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