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Feasibility tests of a hybrid FES-robotic lower limb exoskeleton to support locomotion in neurological patients

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Abstract: Spinal Cord Injuries (SCI) and strokes are debilitating conditions that cause irreversible damages to neurological tissues, resulting in partial or complete loss of sensory and/or motor functions. Such diseases significantly affect the patients' quality of life, impairing their functions and social participation. Various assistive technologies, such as Functional Electrical Stimulation (FES) and robotic exoskeletons, aim to rehabilitate and restore walking in these patients. However, when used alone, each system carries some disadvantages, mainly the high encumbrance for exoskeletons and the early muscle fatigue induction for FES. For this reason, in recent years, the combination of these two systems has emerged as a promising approach, able to provide safer, more robust and efficient neurological rehabilitation. These solutions are referred to as Hybrid Robotic Rehabilitation Systems and allow the realization of lighter exoskeletons, with limited induction of muscle fatigue. At the same time, they achieve the benefits of intense, task-oriented, repetitive training and maintenance of muscle tone, reduction of spasticity, and increased blood flow. The main difficulty remains the realization of an efficient integration of the two technologies, mainly because of the actuation redundancy.
The FESleg project aims to overcome the existing limitations by developing a hybrid device with a cooperative control system, with both the motor and FES components actively contributing to knee swing movements during walking. The prototype is initially tested on healthy subjects and, later, on two SCI patients, one complete and one incomplete. Usability, acceptability, user experience and safety of the hybrid system are evaluated and compared to the condition in which the sole exoskeleton is used. Comparing the walking performances between the conditions with and without FES (in the first case with depowered motors), no statistically significant differences are retrieved, demonstrating the ability of FES to compensate for the reduced motors' participation. Additionally, the integration of stimulation offers relevant therapeutic benefits for patients. In conclusion, the obtained results pave the way for further developments in the production of hybrid systems employed as neurorehabilitation technologies.

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1. Introduction

Spinal Cord Injury (SCI) is caused by diseases that damage the neurological tissue of the spinal cord or by a trauma that compresses, stretches or severs this tissue. Such injury is often irreversible and can result in partial or total loss of sensory and/or motor functions below the injury level. A stroke is caused by the sudden closure or rupture of a cerebral blood vessel and the subsequent damage to brain cells, due to the lack of oxygen and nutrients supplied by the blood (ischemia) or due to the compression from the blood leaking out of the vessel (cerebral hemorrhage). Approximately one-third of affected individuals survive with a high degree of disability, making them non-autonomous [14, 45]. The functional problems resulting from these two types of injuries have significant consequenses on the individual's quality of life, as they affect the person's functions and social participation. The ability to maintain an upright posture and to ambulate are two fundamental aspects that counteract the onset of secondary problems related to the disability condition, such as pressure ulcers, musculoskeletal issues, bladder problems, deep venous thrombosis, respiratory problems, spasticity in the lower limbs, weight gain and pain.
Various assistive technologies for functional rehabilitation are available, such as Functional Electrical Stimulation (FES) and robotic exoskeletons. FES consists of delivering low-energy electrical pulses to muscles in order to induce contractions and use the developed forces as physiological actuators to promote balance and improve gait. However, this technique exploits a non-physiological activation of muscle fibers, which leads to the early appearance of muscular fatigue; moreover, it exhibits a non-linear relation between the injected current and the resulting movement, causing poor control of joint trajectories. On the other hand, exoskeletons have shown significant benefits for intensive, task-oriented and repetitive training, but such devices are not yet mature due to several drawbacks associated with physical and cognitive interaction, energy management and portability issues, often causing discomfort due to their substantial weight [1].
Considering the disadvantages of each system, the combination of FES with an exoskeleton, often referred to as Hybrid Robotic Rehabilitation System, has emerged as a promising approach to aid gait restoration as it provides a safer, more robust and more efficient neurological rehabilitation. These systems aim to achieve motor recovery or compensate for motor function, by combining the torque deriving from electrically stimulated muscles with the one deriving from motors. This hybrid approach has the potential to become a valid solution in the field of rehabilitative robotics. It emphasizes the advantages of both applications, while mitigating their drawbacks: the addition of FES may allow the development of lighter exoskeletons, while the use of exoskeletons may delay the appearance of muscle fatigue, prolonging training duration [8].
However, in most cases, these two technologies are simply overlapped without demonstrating complete integration [9, 14]. The FESleg project, conducted in collaboration with INAIL (Istituto Nazionale per l'assicurazione contro gli Infortuni sul Lavoro, Italy) Prosthetic Center, aims to overcome some limitations of the current approaches by developing a hybrid walking device that integrates FES into a motorized exoskeleton [9]. This involves the definition of a joint control that reduces the overall motor torque demand and increases active patient participation.
The primary objective of the project is to validate usability, acceptability, user experience, human-exoskeleton interaction and safety in the TwinFES prototype, a wearable robotic exoskeleton, developed by the Italian Institute of Technology, integrated with two RehaMove 3 neuromuscular stimulators from Hasomed. The control system of Twin has been modified to provide a motor-FES hybrid control mode. The goal is to understand which are the advantages introduced by the stimulation addition, compared to using the sole exoskeleton.
The system is initially tested on healthy subjects to verify the feasibility of the device. Initially, tests are carried out at the single joint level, which represents a simplified condition as it does not involve the stability of the entire body. Subsequently, complete walking tests are carried out. Lastly, the same tests are also performed on post-stroke patients and individuals affected by complete and incomplete SCI.

2. Background

2.1. Target population

Spinal Cord Injury Spinal cord injury (SCI) is a neurological and pathological state that causes major motor, sensory and autonomic dysfunctions. Over the past three decades, its global prevalence has risen from 236 to 1.298 cases per million people. It is estimated that between 250.000 and 500.000 individuals worldwide experience SCI each year [22]. Despite these numbers, SCI understanding is still limited and its treatment is challenging, due to the complexity of its characteristics and pathophysiological consequences [38]. In normal spinal cord physiology, multiple cell types, including astrocytes, neurons, microglia and oligodendrocytes, interact harmoniously. However, after a spinal injury, these cellular interactions are disrupted and become disorganized, leading to impaired spinal cord recovery. Despite extensive research and the availability of various

regenerative treatment strategies, the recovery process following a SCI remains debated and methods that could potentially prevent or reverse the consequences of SCI are constantly being explored [20]. As this injury has a traumatic origin, the mean age of SCI patients is significantly low. It is therefore crucial to find new ways to improve their quality of life. To this aim, assistive technologies for functional rehabilitation and walking restoration are needed, such as robotic exoskeletons and Functional Electrical Stimulation (FES).

Stroke Stroke is an acute cerebrovascular disease associated with high morbidity, mortality and disability rates [46]. It ranks as the second leading cause of death globally, contributing to 11.6% of all fatalities. Stroke often leads to persistent sensory, cognitive and visual impairments, as well as compromised motor function in the limbs, ultimately affecting various bodily functions [21]. Motor dysfunction is the most prevalent complication following a stroke, with approximately 80% of patients experiencing hemiplegia. Half of these individuals will live with these symptoms for the rest of their lives, which significantly impacts their daily activities [23]. Research has indicated that hemiplegia is the primary cause of long-term disability in stroke patients in the United States, Japan and France [29]. While the fatality rate has decreased significantly due to advances in stroke treatment, 80% of survivors continue to suffer from severe after-effects [26]. Effective rehabilitation training can help to mitigate functional disability, restore motor function in hemiplegic limbs and expedite the recovery process for post-stroke patients [28]. Currently, the rehabilitation for patients with limb movement disorders following a stroke places a significant emphasis on early intervention, often neglecting interventions during recovery. This approach can lead to a decline in the patients' quality of life and exacerbation of their medical conditions. Therefore, enhancing the limb motor function in stroke patients through rehabilitation is crucial. Rehabilitation therapies, including physiotherapy and electrical stimulation, have been widely utilized in clinical practice [33].

2.2. Functional Electrical Stimulation

Low-energy electrical impulses are delivered to muscle fibers in order to generate their contraction. By coordinating the stimulation of different muscles acting on a joint, a functional movement of that joint is achieved and can be controlled by modulating the intensity of the stimulation delivered to flexors and extensors. This technology is used in rehabilitation after SCI, stroke, head trauma and potentially for managing the effects of other neuromuscular diseases and conditions [6, 15]. The term *functional* refers to the fact that it produces movements that are functional to a given task, which may coincide, in our case, with the rehabilitation training. FES activates both nerves and muscles, as long as lower motor neurons are excitable and neuromuscular junctions and muscles are healthy. The joint angle or torque can be regulated by varying the tension produced in the flexor and extensor muscles of the joint, which depends on pulse amplitude and duration, or stimulation frequency. FES represents a promising technology bearing physiological and neurological benefits: the former consists of a reduction in the risk of thrombosis, osteoporosis and pressure sores, while the latter is related to brain neuroplasticity, promoting motor relearning. However, due to the non-physiological recruitment of muscle fibers during stimulation, the primary limitation of FES is the early onset of muscle fatigue, which prevents long-lasting rehabilitation sessions and complicates the modulation of muscle contractions. Additionally, this method has limited control on the electrically induced movements, as the relation between the injected current and the obtained movement is non-linear and strongly dependent on inter-subjects differences. To address these limitations, there is increasing interest in the possibility of developing innovative *hybrid systems* that integrate FES with robotic devices such as exoskeletons.

Electrodes FES delivers electrical impulses through electrodes, which can be [40]:

1. Transcutaneous: placed on the surface of the skin;
2. Percutaneous: placed inside the muscle;
3. Subcutaneous (implanted):
    - Epimysial: placed on the surface of the muscle;
    - Intramuscular: inserted into the muscle;
    - Epineural: placed on the surface of the nerve;
    - Cuff: wrapped around the nerve that innervates the muscle of interest.

Surface electrodes are the most commonly used since they are easy to use and cost effective. These electrodes are placed on the skin above the nerves or motor points of the muscles to be activated, the motor point being defined as the stimulation site producing the strongest and most isolated contraction at the lowest stimulation level [24]. Once placed on the skin, the electrodes are connected via flexible cables to a stimulator that can be worn around the waist, arm or leg. The advantages of surface systems lie in their non-invasiveness and relative technological simplicity. The fundamental elements for this type of electrode are: low impedance at the interface, low current dispersion, ease of application and removal, flexibility and minimal skin irritations [41]. The favorable outcomes of the superficial stimulation depend on both their placement on the patient's skin and their size. In fact, the electrode-skin interface defines the current conductivity, while the size of the electrodes

determines the stimulation area and thus the current density.
However, these electrodes are associated with some disadvantages:

- high precision is required for the repeated placement of electrodes in the appropriate positions to achieve the desired response;
- isolated contraction or deep muscles activation may be complicated or sometimes impossible [31];
- painful skin sensations may be triggered because the stimulation activates pain receptors in the skin;
- the appearance of the system itself can trigger involuntary reactions, especially in cases with many stimulation channels and wires, along with continuous wearing, removing and managing of external components, that can make the situation unacceptable. These disadvantages have motivated research towards the design of implantable systems [3].

FES physiology FES recruits all motor units in the stimulation area synchronously, thus activating all of them at the same time, instead of establishing a turnover among fibers as happens in the natural condition. As a consequence, a much higher stimulation frequency (20-40 Hz) is needed to achieve tetanic contractions compared to the frequency used physiologically by the nervous system (6-8 Hz). The increased stimulation frequency is the main cause of the early fatigue associated with FES-induced muscle contractions compared to contractions initiated by the central nervous system. Additionally, FES uses the non-physiological recruitment, meaning that fast twitch fibers are recruited before slow twitch ones. This happens because the axons innervating fast twitch fibers have a larger diameter and are thus more sensitive to electric field stimulation [30]. This also increases the fatigue level compared to natural stimulation, because fast twitch fibers are more prone to fatigue.

Stimulation techniques There are two commonly used techniques for delivering FES: monopolar and bipolar stimulation, which differ in the placement of electrodes on the skin [42]. In the monopolar configuration, a small electrode is used near a nerve or muscle-motor point, while a larger one is placed over the antagonist muscle or in front of the active electrode. This configuration allows for localized stimulation of specific populations of cells. On the other hand, bipolar stimulation involves using two equally sized electrodes: an active one placed near the target area and a reference one placed at a distance. This technique allows for more diffuse and widespread stimulation. Both techniques play a significant role in studying and improving neuromuscular functions.

2.3. Robotic rehabilitation

Robotic rehabilitation is a discipline that has been gaining importance in recent years and has interfaced with both recent innovations and preexisting tools and technologies. A number of clinical studies support the effectiveness of intensive gait training, particularly in patients with Spinal Cord Injury and stroke. Therefore, since the beginning of the 21st century, researchers have developed a wide range of robotic exoskeletons to actively move the lower limbs of the user through a variety of motor activities, especially related to walking [43]. Wearable exoskeletons are devices whose mechanical structure mirrors the skeletal structure of the limb with which they are associated. This ensures precise control over the movements of the limb joints. These devices have the potential to provide neurorehabilitation by moving the legs reproducibly and cyclically. Traditional models have two degrees of freedom in each leg to achieve flexion-extension of the knee and hip joints, generally driven by electric motors [39].
Rehabilitation robots are a promising therapeutic approach because they compensate for the subject's reduced motor skills by providing intense, task-oriented and repetitive training, key elements of neurorehabilitation and motor relearning [12]. They can provide longer therapies, with adjustable training intensity and treatments tailored to the individual patient's needs and problems. Moreover, since robotic technology can provide accurate kinetic and kinematic measurements, it is easier to quantify a person's functional improvement.
However, especially lower limb exoskeletons, have obvious drawbacks: they are characterized by considerable weight, since they must ensure the continuous operation of motors with high energy consumption, which makes them uncomfortable for the user and limits their usability and acceptability. In particular, the high weight is usually determined by the batteries that power the device and the motors built into it. With increasingly long rehabilitation sessions, larger batteries are needed, resulting in bulkier and heavier devices [10].

2.4. Hybrid systems

In this scenario, hybrid solutions represent a novelty capable of combining stimulation with the use of exoskeletons. Through this cooperation, the benefits of limb mobilization provided by exoskeleton motors are combined with the typical therapeutic benefits of FES, greatly limiting their respective weaknesses. While wearable robotic devices are designed to assist limb movements or support users' stability, FES exploits the power produced by muscles to reduce the energy demand of the robotic device [9]. This energy saving induced by the stimulation would allow robotic devices to require less power and thus make thinner and lighter exoskeletons,

favoring their usability. On the other hand, the support given by motors allows lower current intensities to be sent to the patient's muscles compared to those cases where the sole FES is used, delaying muscle fatigue and allowing longer and more efficient rehabilitation sessions [8, 35].
With an intelligent control, hybrid systems can adjust their stimulation parameters in response to the muscle contraction provoked, ensuring that the user's response contributes positively to the activity. They can provide better control over joint trajectories and significantly reduce muscle fatigue compared to cases where FES is used alone.
There are two types of orthotic-based hybrid systems [1]:

1. FES is used to stimulate muscles and produce joint torque, while the robotic system acts as energy dissipating device (the robotic systems are mostly passive gait orthosis);
2. FES and robotic systems are both torque-generating devices.

In this work, we focus on the second alternative because the use of active actuators on the exoskeleton joints has been reported as an effective strategy to reduce muscle fatigue caused by continuous exaggerated muscle stimulation. In fact, active actuators not only increase joint power but also assist the joint trajectory when the muscle is not capable of generating enough torque for the target movement. In the following section, some main orthotic-based hybrid technologies have been identified for the restoration and support of gait functions where FES and the robotic system are both torque-generating devices.

Examples The GT II is an electromechanical gait trainer developed by Hesse et al. [17, 18] and is equipped with a body weight support system and two-foot plates controlled by a servo motor controller. These components mimic symmetrical stance and swing phases of gait and are integrated with Functional Electrical Stimulation (GT-FES). The gait trainer controller is synchronized with a Two-Channel FES stimulator, ensuring precise coordination between gait phases and stimulation timings. During the stance phase, the subjects received standardized stimulation to the quadriceps, aimed at facilitating weight acceptance. In contrast, during the swing phase, stimulation was applied to the peroneal nerve to promote ankle dorsiflexion and knee flexion. Results demonstrated that the GT-FES group exhibited significant improvements in the lower limb strength, mobility, ambulation ability and walking speed when compared with a control group.
In 2007, Obinata et al. [37] introduced HyPO, a novel hybrid powered orthosis incorporating both a functional neuromuscular stimulator and a control system featuring four actuators. The actuators' controller enabled the execution of preprogrammed joint trajectories, while the functional neuromuscular stimulator system generated muscular forces through electrical stimulation. This orthotic device included two active joints, one at the knee and one at the hip, in each leg. Notably, the HyPO system featured two innovative mechanical aspects: firstly, it employed parallel linkages instead of traditional gear systems or timing belts to transmit torque generated by the exoskeleton's joint actuators. Secondly, it allowed for frontal wear while the user remained seated in a wheelchair. The linkage mechanism consisted of simple parallel four-links connected to the actuators, effectively transferring torque generation. This design facilitated front-side placement of the actuator on the lower limb, minimizing lateral protrusion. Moreover, the linkage mechanism imposes constraints on the range of motion, limiting it to 0 to 120 degrees for the knee and -10 to 120 degrees for the hip, preventing excessive extension and flexion at the joints.
In 2008, McCabe et al. [32] integrated the Lokomat gait robot system (Hocoma Inc.) with a multichannel Functional Electrical Stimulation system using intramuscular electrodes (FES-IM) to enhance coordinated gait training. The Lokomat system consisted of a robotic orthosis, a body weight support system and a treadmill, providing subjects with controlled knee joint, hip joint and sagittal plane motion. The FES-IM system featured eight intramuscular electrodes strategically placed on muscles including Tibialis Anterior, Semimembranosus, Peroneus Longus, Vastus Lateralis, Gastrocnemius, Biceps Femoris, Gluteus Medius and Semitendinosus of both legs. Custom FES-IM patterns were tailored for each subject to address deficiencies in both the stance and swing phases of gait, striving to maintain a gait pattern as close to normal as possible. Results demonstrated the feasibility of simultaneously delivering FES-IM patterns in conjunction with Lokomat assistance. The Lokomat system facilitated nearly natural movements during the knee flexion phase of the swing, while FES-IM stimulated the knee flexor muscles to actively flex the knee joint. A similar combined effect was observed during the stance phase.
Just in a few literature attempts, there are indirect estimates of the FES-induced muscle contribution to the overall movement. In fact, in most cases, the two technologies are purely overlapping, without demonstrating complete integration. This is because the development of shared controllers in multi-joint movements, such as gait, is still challenging due to implementation redundancy and uncertainty of muscle response [14].
In the FESleg project, carried out in collaboration with INAIL Prosthetics Center, we aimed to overcome some limitations of the current approaches, by developing a hybrid walking device that integrates FES into a motorized exoskeleton, using a closed-loop control for both components.

3. Objectives

The main objective of this study was to develop a hybrid walking device through the integration of FES into a motorized exoskeleton, using a closed-loop control for both components. First of all, the feasibility of integrating such systems was verified and proved. Subsequently, some tests were conducted on healthy subjects, both during single-joint movements and walking. This step aimed to verify the feasability of such tests and compare possible differences in the use of the device under different conditions. Lastly, these tests were also carried out on post-stroke and complete/incomplete SCI patients. In particular, we were interested in comparing the conditions with and without stimulation addition, to prove possible advantages deriving from FES introduction. The parameters used to evaluate the effectiveness of the hybrid system were:

- Trajectory tracking: a comparison between the actual and the target trajectory to retrieve the ability of the system to track the desired trajectory under different operating modes;
- Torque integral: to evaluate differences in energy expenditure between the various tested modes;
- Stimulation current: to control the degree of fatigue induced to muscles.

The results obtained were used to drive conclusions about the possible advantages deriving from the use of hybrid systems in rehabilitation.

4. Materials and methods

4.1. Twin structure

Exoskeleton Twin is a motorized lower limb exoskeleton developed at the Rehab Technologies Lab of the Italian Institute of Technology (IIT), as part of research activities in collaboration with INAIL Prosthesis Center. Twin supports the walking movement by providing torque input at the knee and hip level. It is designed for neuromotor rehabilitation of gait in patients with lower limb mobility deficits; specifically, it is intended for individuals with Spinal Cord Injuries (SCI) or stroke. These individuals often experience a partial or complete loss of muscle functions in their lower limbs, preventing normal walking [25].
The exoskeleton's overall structure (shown in Figure 1) consists of four motor modules positioned at the hip and knee joints of both legs and five rigid connecting links: a pelvic component and two separate segments for the right and left femur and tibia. Movement transmission between the structure and the patient's limbs is achieved through five ergonomic fabric interfaces (braces) attached to the patient's pelvis, thighs and lower legs on both sides. At the ankle level, there are two ankle-foot orthoses (AFO) made of steel and connected to shoes. Both links and braces come in various sizes to adapt easily to individuals with different anthropometric characteristics [10]. At the trunk level, the exoskeleton is equipped with a backpack containing batteries (Lithium batteries), IMUs, the emergency button and the Central Control Unit (CCU) of the exoskeleton. The emergency button, when pressed, cuts power and releases all joints slowly, due to friction, thus allowing an operator to assist the patient in due time. The CCU is the exoskeleton's motherboard, referred to as SMEx (Scheda Madre Exo), which consists of an ARM Cortex-M4 microcontroller based on Linux operating system and programmed in C++.

Figure 1: TwinFES prototype consisting of the Twin exoskeleton and two electrical stimulators.

The device is used in conjunction with walking aids, such as crutches or walkers, since the exoskeleton is not self-balancing and thus the patients are required to use their upper limbs to maintain balance. As a consequence, patients must have sufficient trunk and upper limb function. Based on the inclusion criteria, SCI patients are accepted if their injury level is below T4, while post-stroke patients should be able to support themselves with at least one arm on a walker. They must learn to balance and shift their weight in order to achieve an efficient walking pattern.
Twin is intended for rehabilitative use only and is confined to rehabilitation sessions within dedicated facilities, under close supervision of healthcare professionals. Since Twin cannot prevent falls, therapists must assist patients throught the activity. A session with the device requires at least two operators, one ensuring patient safety and the other managing the overall training via a tablet.

Stimulator Within the FESleg project, the research team at Politecnico di Milano integrated two neuromuscular stimulators (RehaMove3, Hasomed, Germany) into the Twin exoskeleton's control system. The addition of FES allows artificial contractions and, additionally, an overall improvement in the patient's physiological state: increased muscle mass, improved cardiorespiratory capacity, maintenance and enhancement of joint mobility, reduction of muscle spasms and prevention or delay of muscle atrophy due to disuse.
The stimulator includes 4 stimulation channels, enabling simultaneous stimulation of four different muscle groups. In our specific case, the following muscles were selected: Quadriceps, Hamstring, Gastrocnemius and Tibialis Anterior. Each channel is connected to a pair of self-adhesive surface electrodes whose shape and size (5x9 cm or 5x13 cm) are selected based on the patient's characteristics and the size of the muscle to be stimulated. The stimulation waveform is rectangular and biphasic, fully balanced in terms of charge. Regarding the stimulation parameters, frequency and pulse width remain constant (f = 40 Hz, PW = 400 μs), while amplitude is modulated over time. Stimulators are directly controlled by the CCU of the exoskeleton, via a USB connection. The integration is not only at the physical (hardware) level but also at the software level. In fact, the stimulators control is directly integrated into the exoskeleton software, modified accordingly to work in conjunction with the exoskeleton.
The interface between the operator and the device is facilitated through a tablet running the Android application "TwinFES." This app allows for the configuration of specific patient parameters for each session, the calibration of FES, the selection of operating modes and the management of the overall session, saving patients progress over time.

4.2. Calibration

Before starting a therapeutic session with TwinFES, the patient must undergo a calibration of stimulation parameters to determine his most suitable current levels. The calibration procedure only involves current intensity, as frequency and pulse width are set identically for all muscles and are maintained constant (40 Hz and 400 μs, respectively). The calibration procedure is performed with the subject in a seated position, with his feet not touching the ground, allowing free knee flexion/extension movements. The exoskeleton is not worn in this phase because the goal is to observe stimulation-induced movements, which would be limited by the presence of the device. The procedure is performed with the TwinFES application for one muscle at a time and repeated identically for all eight muscles involved in the treatment. A gradually increasing current ramp is sent and two intensity levels are defined:

- Level 1 (Movement threshold - L1): the value that produces a first limb movement;
- Level 2 (Maximum threshold - L2): the minimum value between the one producing a full joint movement and the maximum one tolerated by the subject.

Additionally, the minimum possible stimulation amplitude delivered by the program is a priori set in this phase equal to 4 mA. These levels define the ranges of stimulation intensity used in the two operating modes of TwinFES, described in the next section. In proprioceptive mode, the current varies between the minimum level and Level 1; in hybrid mode, instead, it varies between Level 1 and Level 2. The calibration procedure is repeated before each session because, even if dealing with the same subject, a varying electrode placement or muscular activity could result in different calibration values.

4.3. Operating modes

There are two operating modes for Twin: proprioceptive and hybrid. They can both have the option of a rigid or active ankle. In the first case, the ankle orthosis is fixed at 90° and the Tibialis Anterior and Gastrocnemius muscles are stimulated with low intensities, to exploit the physiological advantages of FES, while not producing a movement that would act against the AFO. In the second case, the ankle orthosis is released, allowing dorsiflexion and plantarflexion movements (+/- 20° from vertical) and the maximum muscle stimulation intensity is sufficient to induce movements for "foot clearance" and "push-off." In this work, the ankle is always kept rigid.

4.3.1 Proprioceptive mode

Motor control In the mode shown in Figure 2, the exoskeleton implements a rigid position control, defining a target trajectory for the 4 joints, to generate a physiological gait pattern in both spatial and temporal terms, without requiring any patient involvement. In particular, the motor is controlled using Pulse Width Modulation (PWM) and a Proportional Integral (PI) controller is employed to calculate the PWM duty cycle and drive the motor, taking the difference between the target and actual angles as input. The overall control works with the objective of reducing this difference as much as possible, in order to get a precise tracking of the target trajectory.

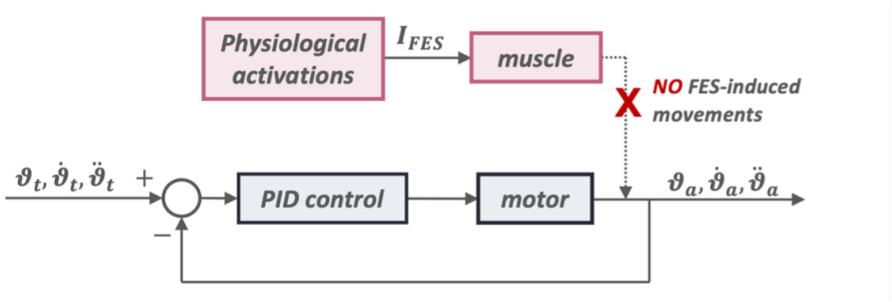


Figure 2: Control scheme of the proprioceptive mode: blue components are relative to the motor control, pink components to the FES one.

FES control FES stimulation is applied to the previously mentioned muscle groups (Quadriceps, Hamstring, Gastrocnemius and Tibialis Anterior in both legs) with an amplitude and timing, referred to as *biomimetic* activation, that is designed to mimic the muscular activations occurring in the different phases of the natural gait. The stimulation intensity is defined as *proprioceptive*, meaning that it is able to reach proprioceptive sensory fibers but it is not strong enough to activate motor fibers and thus induce movements. Indeed, the FES goal here is not to induce functional movements but to exploit the stimulation advantages (muscle tone maintenance, reduction of spasticity, increase in blood flow, ...) and the neuroplastic benefits deriving from sending sensory inputs to the brain, coordinated with the executed movement. This mode is suitable for individuals who completely lack any possibility of voluntarily contribute to movements and thus require full assistance from the exoskeleton. For each channel, at time i, the current amplitude delivered is defined as follows:

$$I_{\text{stim}}(i) = I_{\text{min}} + (I_{L1} - I_{\text{min}}) \cdot \text{index}_{\text{activation}}(i)$$

where I_{min} and I_{L1} represent the minimum current value (set at 4 mA by default) and Level 1 (movement threshold) obtained from calibration. The $\text{index}_{\text{activation}}(i)$ is an index ranging from 0 to 1, indicating the muscle activity level at instant i of the gait cycle. This index is modeled to replicate biomimetic activation patterns and is based on physiological EMG recordings found in the literature [16]. The final result is a predefined current profile over the gait cycle, specific for each muscle, aiming at coordinating the delivered current with the executed movement.

4.3.2 Hybrid mode

This mode is the actual hybrid mode implemented in Twin as it foresees a real integration between the motor component and the stimulation in generating the movement.

Motor control All motors implement the same position control already explained for the proprioceptive mode, except for the knee joint during the swing phase, which implements a *cooperative* control. Its objective is to have both the motor and FES actively contributing to flexion-extension, with the additional contribution from the subject residual muscle activity, if present. In this case, the motor control is softer compared with the case of the position control, because it has to comply with other elements participating in the movement. The decision not to implement this control for the knee and hip joints during the stance phase is justified by the high rigidity required, in order to ensure subject's stability. For the hip joint in the swing phase, instead, it does not implement the cooperative control, as this type of control is not feasible at a multi-joint level. Both Quadriceps and Hamstrings, in fact, are bi-articular muscles, exerting influence over both the hip and knee joints, often in opposing ways. Consequently, it was not possible to coordinate motors and stimulation to simultaneously induced hip and knee flexion (during the first half of the swing) or extension (during the second half of the swing). As a result, the most viable approach was to employ cooperative control at a single joint level and, in this study, the swing knee joint was selected, as it is more difficult to get stimulation-induced hip

movements. A first-order implicit impedance control was implemented, as shown in Figure 3. Instead of rigidly enforcing precise tracking, as in the case of position control, this strategy encourages a more compliant behavior, allowing deviations from the equilibrium point when external forces induced by FES are applied. The proposed impedance control architecture includes two nested loops: an internal torque loop, responsible for calculating the total torque sent to the motor to support motor/FES compliance, and an external position-feedback loop, that corrects trajectory-tracking errors. Since the system is not equipped with a torque sensor at the joint level, it is impossible to directly measure the actual torque generated at the joint's output shaft [7]. Therefore, this control is referred to as implicit and the torque control is achieved through an open-loop based on the motor's current flow.

The torque sent to the motor can be divided into two main components: feedforward torque (τ_{FF}) and feedback torque (τ_{FB}). The first one is defined as the torque needed to support the movement and it is computed as the sum of inertia and gravity contributions from both the exoskeleton and the subject's shank. Thus, τ_{FF} can be defined as the motor's contribution to the movement: it is designed to fully compensate for the exoskeleton's weight, while the patient's weight is compensated up to a certain percentage, defined allocator index $\alpha \in [0,1]$, which can be selected from the tablet and adjusted over time, based on the patient's needs and the fatigue induced by FES, following an assist-as-needed paradigm. τ_{FF} is computed in the following way:

$$\tau_{FF} = (J_E + J_S\alpha)\ddot{\theta}_t + (m_E + m_S\alpha)g\frac{l}{2}\sin(\theta_t)$$

θ_t and $\ddot{\theta}_t$ are the target position and acceleration; J_S, J_E and m_S, m_E are the moments of inertia and masses of the subject and the exoskeleton, respectively; l is the shank length and g is the gravitational constant. On the other hand, the feedback torque is a first-order impedance-based corrective torque. It is realized as a Proportional-Derivative controller, which adjusts the torque sent to the motors by considering position and velocity errors in the following manner:

$$\tau_{FB} = K_s(\theta_t - \theta_a) + K_d(\dot{\theta}_t - \dot{\theta}_a)$$

K_s and K_d are the stiffness and damping gains, weighting the deviations from the target position and from the target velocity, respectively. These parameters define the desired rigidity and viscosity of the system. The sum of τ_{FF} and τ_{FB} is the total torque (τ_{TOT}) sent to the motor, which determines the actual limb movement (θ_a, $\dot{\theta}_a$, $\ddot{\theta}_a$).

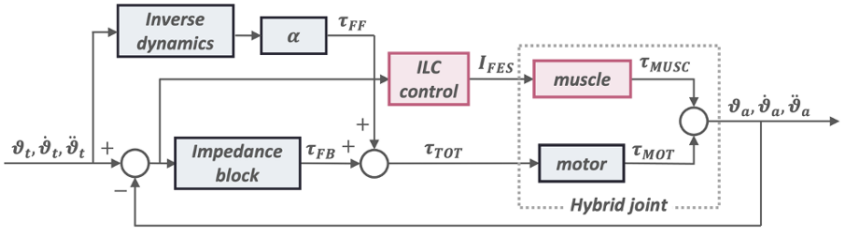


Figure 3: Control scheme of the hybrid mode: blue components are relative to the motor control, pink components to the FES one.

FES control For all muscles (Quadriceps, Hamstrings, Gastrocnemius and Tibialis Anterior) of the stance leg, the stimulation is managed by the same biomimetic control described in the previous section (*Proprioceptive Mode*). Thus, for this leg, we do not have an integration of the motor and stimulation components which are instead independent. This is done because the motors of this leg implement a rigid position control to guarantee the stability of the patient. Thus, a sub-threshold stimulation is applied in this case, not inducing movements that could contrast those from motors. The same occurs for the Gastrocnemius and Tibialis Anterior muscles of the swing leg because such muscles act at the ankle joint level, which is not motorized and thus, also in this case, it is not possible to implement the cooperative control. In conclusion, the only muscles foreseeing a cooperation of the robotic and stimulation components are the Quadriceps and Hamstrings (knee extensors and flexors, respectively) of the swing leg. These muscles are stimulated during the knee flexion-extension phase of walking with constant frequency (40Hz) and pulse width (400μs), while the amplitude is modulated through an Iterative Learning Controller (ILC). This approach involves iterative adjustments of the input variable to minimize a cost function evaluated at the previous step [36]. Thus, the signal is updated only at the end of a complete iteration (i.e. step), making this approach well-suited for repetitive movements like walking [34]. In this specific case, the input variable is the current amplitude and the goal is to minimize the trajectory tracking error from the previous step. In particular, amplitude modulation is carried out so that positive tracking errors (under-tracking of the target trajectory) result in a current increase, while negative tracking errors lead to its

decrease. The range of motion for FES amplitude is determined by user-specific thresholds I_{L1} (movement threshold) and I_{L2} (maximum current), experimentally established during the calibration phase. According to the proposed ILC strategy, for each step (k), the current of each channel is defined, at each time instant (i), as:

$$I^k(i) = I_{L1} + c \cdot u^k(i)$$

where c represents a constant and u^k is the control vector (i.e. cost function) updated at every movement repetition k with the formula:

$$u^k = u^{k-1} + f(e^k_{\text{pos}})$$

where $f(e^k_{\text{pos}})$ is a function of the vector containing angular position errors for the k^{th} repetition. The latter is computed as:

$$f(e^k_{\text{pos}}) = \lambda Q e^k_{\text{pos}}$$

where λ is the gain coefficient and Q is a Gaussian window filter, defining the amplitude of the considered errors window. In fact, this function at the instant i does not only take into account the i^{th} error, but a symmetric interval of errors centered around it. As the length of the window increases, the convergence towards the desired trajectory accelerates. However, simultaneously, there is a sharper increase in the current. The window length is set to 5 samples, to strike a suitable balance, ensuring rapid convergence within few repetitions while avoiding substantial current increments.

4.4. Inclusion and exclusion criteria

Before using TwinFES, it is necessary to verify that the patient meets the following inclusion/exclusion criteria. Recruited subjects must have adequate trunk and upper limb control for the intended function and anthropometric parameters and joint ranges must ensure proper positioning in the exoskeleton and walking dynamics. The possible presence of spasticity should not hinder the use of the device. The patient should not have pain that would impede device usage and there should be no skin lesions in the areas that interface with the exoskeleton and/or electrodes. Subjects should not have severe osteoporosis, dysfunctions of the autonomic nervous system relevant to the rehabilitation function or psychopathological comorbidities. Surface FES must be well tolerated by the subject and there should be no contraindications to its use.

Inclusion criteria:

- Age $>$ 18 years;
- Height range: 150 - 192 cm;
- Weight: maximum 90 Kg;
- Femur length: 355 – 475 mm;
- Tibia length: 405 – 485 mm;
- Hip circumference: 690 - 990 mm
- Shoe size: 36 - 45;
- Spinal cord injury level (if applicable): from T4 and lower;
- Spasticity: Modified Ashworth ≤ 2;
- Sufficient upper limb strength to use crutches or a walker safely;
- Ability to use FES.

Exclusion criteria:

- Pregnancy or breastfeeding;
- Previous or concurrent malignant neoplasia (cancer);
- Previous severe neurological damage (such as multiple sclerosis, cerebral palsy, amyotrophic lateral sclerosis, traumatic brain injury, etc.);
- Chronic inflammatory diseases affecting lower limb joints;
- Severe osteoporosis affecting the hips and/or spine;
- Pelvic fractures or unstable spine;
- Heterotopic ossification restricting the range of functional movement;
- Significant limitations in the range of motion of hips and knees;
- Severe and/or uncontrolled spasticity;
- Uncontrolled autonomic dysreflexia;
- Skin integrity problems at the interface surfaces with the device and/or stimulation electrodes or that would hinder sitting;
- Presence of a cardiac pacemaker;
- Complete lack of response to FES;
- Presence of swollen, inflamed or infected areas or skin rashes such as phlebitis, thrombophlebitis or varicose veins.

4.5. Protocol

4.5.1 Testing protocol on healthy subjects

We used three distinct conditions that involved altering the degree of knee motor assistance (α) and the presence of stimulation. Specifically, the following tests were carried out and compared:

1. EXO100: this serves as the baseline condition, where maximum motor support was provided ($\alpha = 100\%$) and stimulation was turned off. In this scenario, the entire movement was carried out solely by the exoskeleton's motor.
2. FES0: in this condition, the feedforward contribution of the motor was reduced ($\alpha = 0\%$), with the knee motor compensating for the weight of the exoskeleton but not for the one of the leg. Stimulation was introduced to provide the necessary additional input to execute the correct movement.
3. EXO0: here α was set to 0% and no stimulation was added. Consequently, this condition was expected to result in suboptimal performances, as the provided input was insufficient to complete the movement. This served as a proof-of-concept condition to validate the advantages of incorporating FES when the motor contribution was reduced.

Single joint Considering the complexity of walking, which involves various muscle activations and co-contractions, the first tests of the hybrid control were carried out during simpler single-joint movements. Specifically, participants were instructed to wear the Twin device while seated and perform knee flexion-extension movements, ranging from -90° (flexed-knee position) to 0° (extended-knee position) and back, with each phase lasting 2 seconds. Here the integration of FES with the knee motor was only done during the extension phase, while flexion was supported by the sole motor. This was done to involve only one muscle group (Quadriceps) and to perform an anti-gravity movement.
A group of 6 healthy participants participated in these tests. The subjects were seated in the Twin exoskeleton and were instructed to remain as passive as possible, so that movements were only executed by the motor and FES components. For each subject, three tests were conducted, varying the percentage of knee motor contribution (α) and the presence of stimulation: EXO100, FES0 and EXO0. For each condition, 50 repetitions were performed.

Walking A group of 21 healthy participants were involved in these experiments. The participants were instructed to engage in walking sessions using the Twin exoskeleton in hybrid mode, in the three distinct conditions: EXO100, FES0 and EXO0. For the EXO conditions (without FES), 20 steps per leg were executed, for a total of 40 steps; for the FES condition, 50 steps per leg were executed, for a total of 100 steps. The duration of the FES condition was extended because we were interested in studying muscle fatigue appearance over time.
Before starting, the anthropometric measures of the patient were acquired to understand the correct sizes of the exoskeleton to be used, through the Patient Assessment Conversion Tables. Then, Quadriceps and Hamstrings calibration was carried out. For healthy subjects, in fact, only thigh muscles were stimulated, while Tibialis Anterior and Gastrocnemius were excluded. This was done because these muscles foresee a proprioceptive current which is supposed to be beneficial for spinal injured patients, but it is not expected to induce any effect on healthy subjects. Furthermore, with fewer stimulation cables the practical execution of tests was simplified.
The Ethical Committee of Politecnico di Milano (Nr 13/2021) approved this study and all subjects provided their written informed consent before starting the acquisition. Their personal data were collected and and ID number was assigned to each one of them. This ID was then used in the data-saving procedure, to maintain them anonymous during the following phases of data analysis.
At the beginning of the test, subjects needed to get familiar with the device and learn to walk with it, which was done in the proprioceptive mode. Indeed, thanks to its rigid position control, this mode required no participation from the patient and guaranteed greater safety. Specifically, subjects must learn to shift their weight on the standing leg at each step, allowing the leg performing the swing movement to move freely. After the initial learning phase, individuals started with the official tests in the three previously specified conditions, remaining as passive as possible to minimize interferences with the FES-motor control.
During all tests an operator was always behind the subject for safety reasons and for handling the tablet to manage the training and send the step command.

4.5.2 Testing protocol on patients

The aim was to test the protocol on 10 subjects with Spinal Cord Injury, including 5 with complete and 5 with incomplete injury, and on 5 post-stroke subjects. Before the start of the training (T0), some anamnestic/anthropometric data such as age, gender, height, weight and previous experience with FES and/or lower limb exoskeleton use were collected for all participants. For subjects with SCI, the type and level of injury,

time since the injury and the ASIA scale were recorded. For post-stroke subjects, the type and location of the stroke, time since the event and the National Institute of Health Stroke Scale were recorded.
At T0, baseline assessments were performed for all recruited subjects:

1. Assessment of the Autonomic Nervous System (ANS): this assessment is performed using a battery of tests commonly used in clinical practice, to reproduce the stress conditions that the cardiovascular system is normally subjected to during daily activities. The tests include:
    - Tilt-up test: passive verticalization by tilting the bed from static to 60°, maintaining this position for 5 minutes.
    - Stepping in place using an automatic step induction system (Erigo, Hocoma) at a cadence of 60 steps per minute for 5 minutes.
    - Cold pressor test: the patient's hand is kept for 90 seconds in a container filled with ice cubes.
    - Cold face test: applying a cold stimulus (ice cubes) to the patient's forehead in the territory of the first branch of the trigeminal nerve for 60 seconds.
    - Arithmetic calculation test: the patient is asked to perform a series of consecutive subtractions, such as 1000-13 or 100-7 (depending on education), for 3 minutes.
2. Assessment of Osteoporosis Degree: this assessment is done using MOC and TAC of the tibia.
3. Bladder and Bowel Functionality Assessment: this is done using questionnaires commonly used in clinical practice, such as the Bristol scale [5] and NBD Score [11].
4. Assessment of Spasticity Level: spasticity in plantar flexors, knee flexors-extensors, hip intrarotators and hip adductors is assessed using the Modified Ashworth Scale [2].
5. Pain Level Assessment: the pain level is assessed using the Numerical Rating Scale (NRS) [19].
6. Assessment of Global Well-Being: the patient's overall well-being is assessed using the PGWBI (Psychological General Well-Being Index) questionnaire [13].
7. Muscle Response to Electrical Muscle Stimulation: the major target muscles (Quadriceps and Hamstrings) should exhibit a muscle response induced by FES capable of producing a movement of at least 10°.

If the subjects met all assessment criteria, they started the familiarization phase with the Twin device without FES (EXO100 mode). A maximum of 10 familiarization sessions, each lasting one hour, were planned.
Right after these sessions, patients underwent FES familiarization sessions of 30 minutes, where all leg muscles were stimulated, but with the subject sitting on a chair and not being inside the exoskeleton. The same stimulators integrated with Twin were used and the stimulation intensity varied following a ramp, respecting specific muscle thresholds, set during the previous calibration phase. The goal of this phase was to allow the patient to become familiar with the stimulation in a simpler context, without the exoskeleton.
The end of the familiarization phase was defined as time T1. Once verified that the subjects could walk 10 meters with the Twin exoskeleton and that they could stand FES, the testing phase of the TwinFES cooperative control was carried out. It included a maximum of 4 sessions with the TwinFES device in the FES0 mode. The end of this TwinFES testing phase was defined as time T2.
For safety reasons, the EXO0 condition was not tested on subjects with Spinal Cord Injuries or stroke because, as the provided input was not sufficient to complete the movement, it might threaten patients' safety.
Acceptability, usability, user experience and interaction with the system were evaluated at T1 and at T2. Patients were also administered the questionnaires in *Appendix A and B*:

- Technological Acceptance Measure 3 (TAM-3) [44] aimed at evaluating the acceptability of the device.
- System Usability Scale (SUS) [4] to assess the system's usability.
- User Experience Questionnaire (UEQ) [27] to collect user judgment on the lived experience.
- Semi-Structured Ad-Hoc Interview to assess human-machine interaction both physically (ergonomics) and psychologically/well-being. The interview was audio-recorded for subsequent analysis.

At T1 and T2, the electromyographic evaluation of the muscles of the upper and lower limbs was performed while walking with the device. The Ethical Committee (Nr 03_14/10/2022 session of the 14/10/2022) approved this study and all patients provided their written informed consent before starting the acquisition.

4.6. Data analysis

Data analysis was performed in the MatLab 2022b environment (MathWorks).

4.6.1 Healthy subjects

Single joint Regarding data analysis for the single joint, each movement was divided into extension and flexion phases. For flextion, the following data were considered:

- Real and target position (θ_{real} and θ_{target})
- Motor current (I_{MOT})
- Total theoretical torque given to the motors (τ_{TOT})

- Current amplitude of Channel 0 (Quadriceps) and Channel 1 (Hamstrings).

From these, the following metrics were calculated:

- Root Mean Square Error of the position (RMSE)
- Motor current integral (I_{MOT} integral)
- Total torque integral (τ_{TOT} integral)
- Current integral of Channels 0 (Quadriceps) and 1 (Hamstrings), normalized to the maximum current value recorded during calibration (L2).

Subsequently, the median, 25th, and 75th percentiles of all data and metrics were calculated for all 50 performed flexions to obtain the median movement in the 3 conditions (EXO0, EXO100 and FES0). For the FES0 condition, we also decided to divide the data into groups of 5 successive flexion-extensions to visualize the presence of any fatigue in the subject with the use of FES. The same metrics were calculated for these groups of steps.

Walking For the proprioceptive mode, each step was divided into swing and stance phases. For each of these phases, the following data were considered, for both hip and knee joints:

- Real and target position (θ_{real} and θ_{target})
- Current amplitude of Channel 0 (Quadriceps).

Only the RMSE of the position was calculated from these. Subsequently, the median, 25th, and 75th percentiles of all data were calculated for all oscillations and stances performed to obtain the average movement in the two conditions (FES and noFES).

For the hybrid mode, each step was divided into swing and stance phases, and particular attention was given to the swing knee joint, as it is the only one implementing the impedance control. For this mode, the same data and metrics of the single joint case were considered. The median, 25th, and 75th percentiles of all data and metrics were calculated for all performed strides (20 for EXO0 and EXO100 conditions and 50 for the FES0) to obtain the median movement in the 3 conditions. In this case, as well, we decided to divide the data for the FES0 condition into groups of 5 successive strides, to visualize the presence of any fatigue in the subject, induced by the use of FES. The same metrics were calculated for these groups of steps.

4.6.2 Patients

Each patient underwent multiple sessions in both EXO100 and FES0 modes and for each session, multiple tests were performed. The same data and metrics considered for healthy subjects were taken into account for patients and, also in this case, the median movement was retrieved. Considering that patients performed many tests within a session, the median value of all tests in a single session was calculated. Results were compared between T1 and T2.

4.7. Statistical analysis

For healthy subjects, both in single joint and walking trials, a three-fold statistical analysis was conducted to compare the outcomes of interest in the 3 modes (EXO100, EXO0 and FES0). Additionally, for the FES0 condition, an analysis between blocks of 5 flexion-extensions (or 5 strides) was carried out to verify the appearance of FES-induced muscle fatigue in subjects over time. For patients, a double-fold statistical analysis was carried out between the two modes (EXO100 and FES0) on different training sessions. The statistical analysis was performed using the IBM SPSS software. Specifically, the generalized linear model was used and the Fisher's exact test, because of the small sample size. Pairwise comparisons between conditions were executed and differences between conditions were considered significant in case of p-value < 0.05.

5. Results and discussions

In this section, the results of the overall data analysis are presented and discussed. To maintain consistency with the entire work, outcomes are divided into two subsections: healthy subjects and patients.

5.1. Healthy subjects

5.1.1 Single joint

The table in Figure 4 includes gender, age and calibration values of the 6 subjects (2 males and 4 females, with an average age of 24.3 $\pm$ 2.4 years). Figure 5 displays, for a representative subject (J1), the data over a complete flexion-extension, while Figure 6 reports the test metrics.

GENERALITIES			RIGHT	
			Quadriceps	
ID	Sex	Age [years]	L1 [mA]	L2 [mA]
J1	M	24	16	26
J2	F	27	16	23
J3	F	20	10	17
J4	M	25	17	30
J5	F	26	15	30
J6	F	24	17	28

Figure 4: Table with general information and calibration values of the subjects who perform the single joint bench tests.

When comparing the actual and target position, it can be seen that it is similar both for the EXO100 and FES0 conditions, while for the EXO0 condition, the performed angular range is smaller than the target one.
As expected, the total torque shows higher values for the EXO100 condition than for the other two cases, as the feedforward component is higher in the alpha = 100% case. The EXO0 and FES0 conditions, instead, have alpha = 0% and so they have the same feedforward component. The higher total torque showed by the EXO0 condition is due to the fact that this condition is characterized by a greater feedback component, given by the higher trajectory error. As for the current given to quadriceps (only for FES0), it is observed that it quickly reaches the maximum value defined during calibration (L2), saturating.

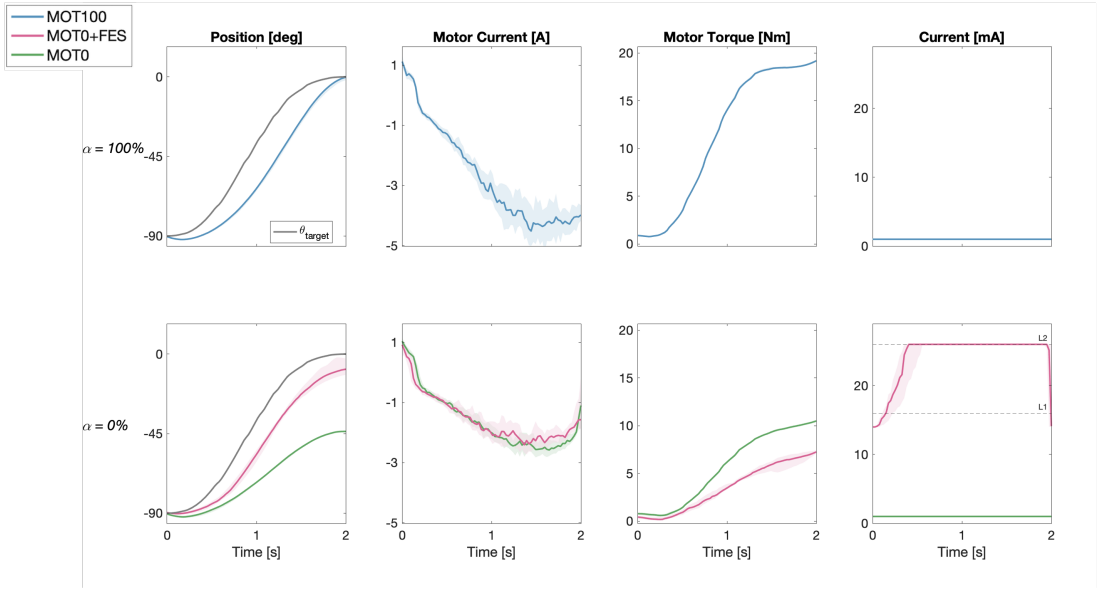


Figure 5: Data over time for J1 in the 3 conditions.

The same observations can be made for the metrics. The RMSE is smaller and similar for EXO100 and FES0, given the small difference between the real and target trajectories in these cases; instead, it takes on much larger values for EXO0, significantly different form the previous one. The integral of the motor current and the one of the total torque are always significantly higher for the EXO100 condition than for the other two.

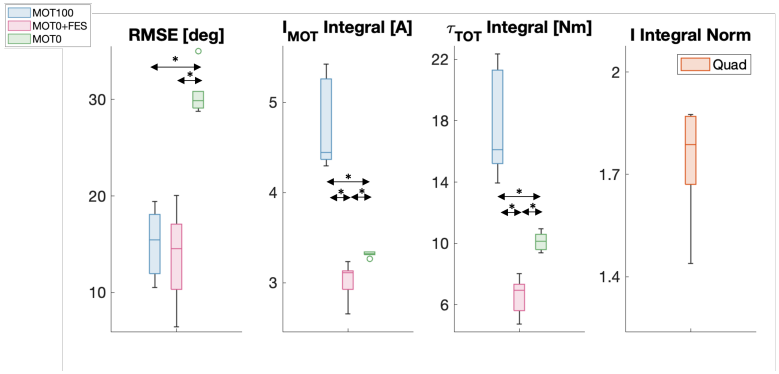


Figure 6: Motor and current metrics for the single joint tests of all subjects (differences between conditions were considered significant in case of p-value < 0.05 and marked with an asterisk).

Analyzing the boxplots of the metrics for groups of 5 successive flexion-extensions in Figure 7, it can be seen that the RMSE decreases over time, as does the value of the total torque, emphasizing that the error made by the patient decreases as the number of repetitions increases, taking advantage of the cooperative exoskeleton-FES control. Regarding the integral of the current to the quadriceps, normalized with respect to L2, it can be observed that, after the first few repetitions, it remains constant.

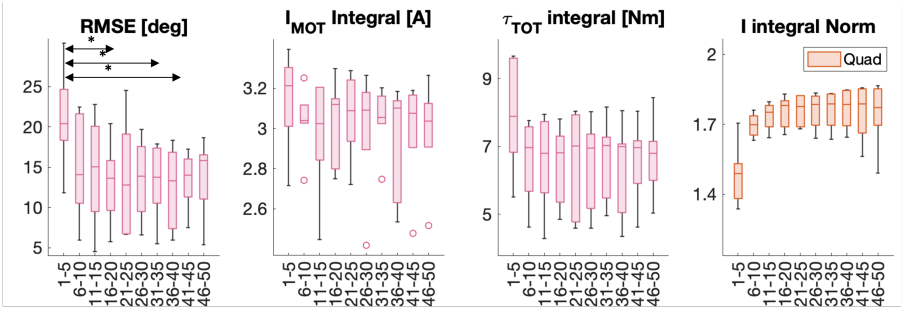
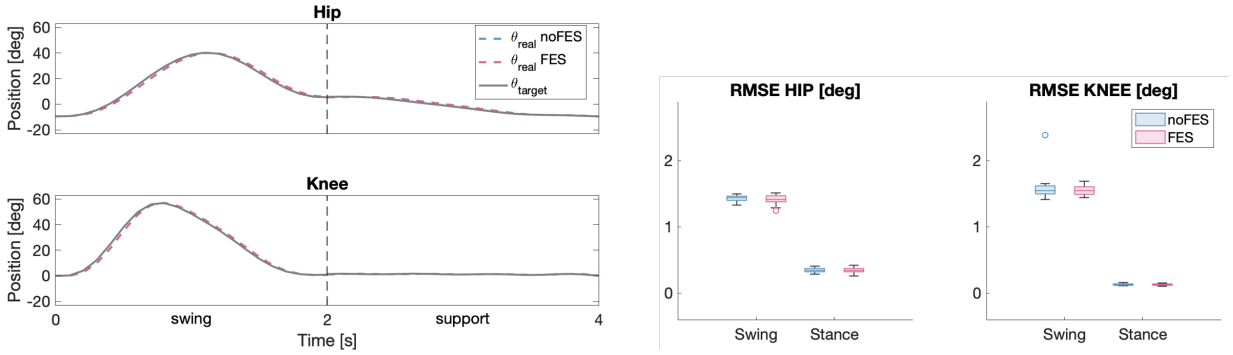


Figure 7: Motor and current metrics for the single joint tests of all subjects, considering groups of 5 successive flextion-extensions (differences between conditions were considered significant in case of p-value < 0.05 and marked with an asterisk).

5.1.2 Walking

Proprioceptive mode This mode has a rigid position control for motors and low FES current values, capable of reaching proprioceptive sensory fibers, but not strong enough to activate motor fibers and, thus, induce movements. It was included in the study to verify the feasibility of adding the stimulation to the device, both at the hardware and software level. Additionally, we wanted to verify the biomimetic activation timing with respect to the step phases, as it is also used for the non-cooperative muscles in the hybrid mode.
Results confirm the feasibility of adding FES, as it does not affect the gait in any way. In fact, the patterns of actual versus target positions is identical for both hip and knee in the two noFEs and FES conditions, as seen in Figure 8a. The RMSE also shows no significant differences in the two cases, as shown in Figure 8b.



(a) (b)

Figure 8: (a) Data over time for ID24 in the 2 conditions; (b) RMSE metric for the proprioceptive modality.

Hybrid mode For this study, 21 subjects were recruited (8 males and 13 females, with an average age of 24.9 $\pm$ 3.9 years), as specified in the flowchart in Figure 9. 6 subjects were excluded from our analysis. Among them, 4 subjects (ID14, ID17, ID20 and ID32) were considered ineligible as they actively participated in the movement. An example of this behaviour is shown for subject ID14 in Figure 10a, where the real knee position during swing in all 3 conditions is about 30° higher than the target one. We concluded that this behaviour indicates that subjects could not remain passive within the Twin exoskeleton. The other 2 subjects, ID34 and ID35, were excluded due to problems with the stance knee joint which exhibited off-normal motor current trends, causing the perception of a collapsing knee during stance, which should not have occurred. An example is provided in Figure 10b, relative to subject ID34.

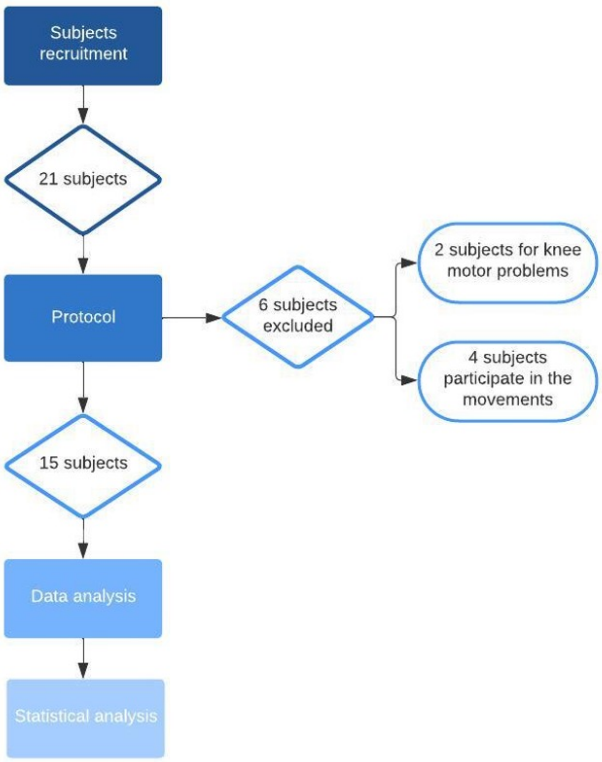
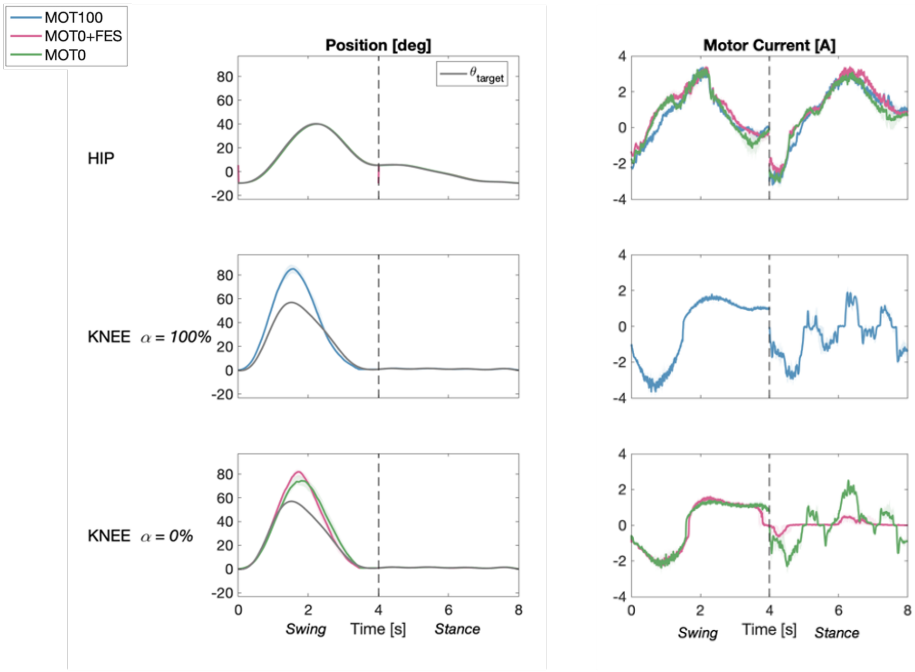


Figure 9: Flow chart of the acquisition protocol.



(a) (b)

Figure 10: (a) Position over time for ID14; (b) Motor current over time for ID34.

To sum up, only 15 participants were included in the analysis. Among them, 3 subjects were able to correctly perform the tests, but due to Twin exoskeleton shutdown issues, they were unable to complete 50 strides in FES0 mode. They were included in the study with the number of strides they managed to complete (24 strides fort ID15, 44 strides for ID25 and 40 strides for ID33). The last 12 subjects were able to complete the official protocol. The table in Figure 11 reports sex, age and calibration values of participants, along with the number of actual strides in the FES0 mode. Figure 12 and 13 show the motor and stimulation data over time for a representative subject (ID24).

GENERALITIES			LEFT				RIGHT				
			Quadriceps		Hamstrings		Quadriceps		Hamstrings		
ID	Sex	Age [years]	L1 [mA]	L2 [mA]	L1 [mA]	L2 [mA]	L1 [mA]	L2 [mA]	L1 [mA]	L2 [mA]	N strides FES
11	F	24	34	44	17	26	24	29	23	34	50
12	F	22	15	27	19	26	15	26	21	28	50
13	F	23	15	29	18	27	16	28	15	22	50
15	F	23	21	25	15	21	13	19	12	16	24
16	F	40	8	25	11	30	8	25	9	25	50
18	F	26	12	24	10	15	13	23	15	18	50
19	F	24	29	35	23	29	27	37	19	25	50
21	F	23	17	28	30	41	18	27	26	32	50
22	F	23	26	35	30	41	27	33	30	39	50
23	F	26	24	40	23	33	27	34	20	27	49
24	F	22	18	27	21	32	21	32	21	29	50
25	F	26	26	33	34	38	27	38	33	38	44
26	M	24	13	25	27	30	21	28	27	35	50
31	M	27	33	40	16	23	29	39	17	27	50
33	M	24	21	27	15	27	22	28	16	21	40

Figure 11: Table with general information and calibration values of the subjects who perform the walking test.

Regarding the real position compared to the target one, the trend in the three modes only changes for the swing knee, as expected, as it is the sole joint implementing the FES-motor cooperative control. The real trajectory is closer to the target in the EXO100 and FES0 cases than in the EXO0, because in this latter condition, part of the contribution is missing. Similarly to the tests performed at the single joint level, in the EXO100 case the total torque and motor current values are higher than in the other two conditions.

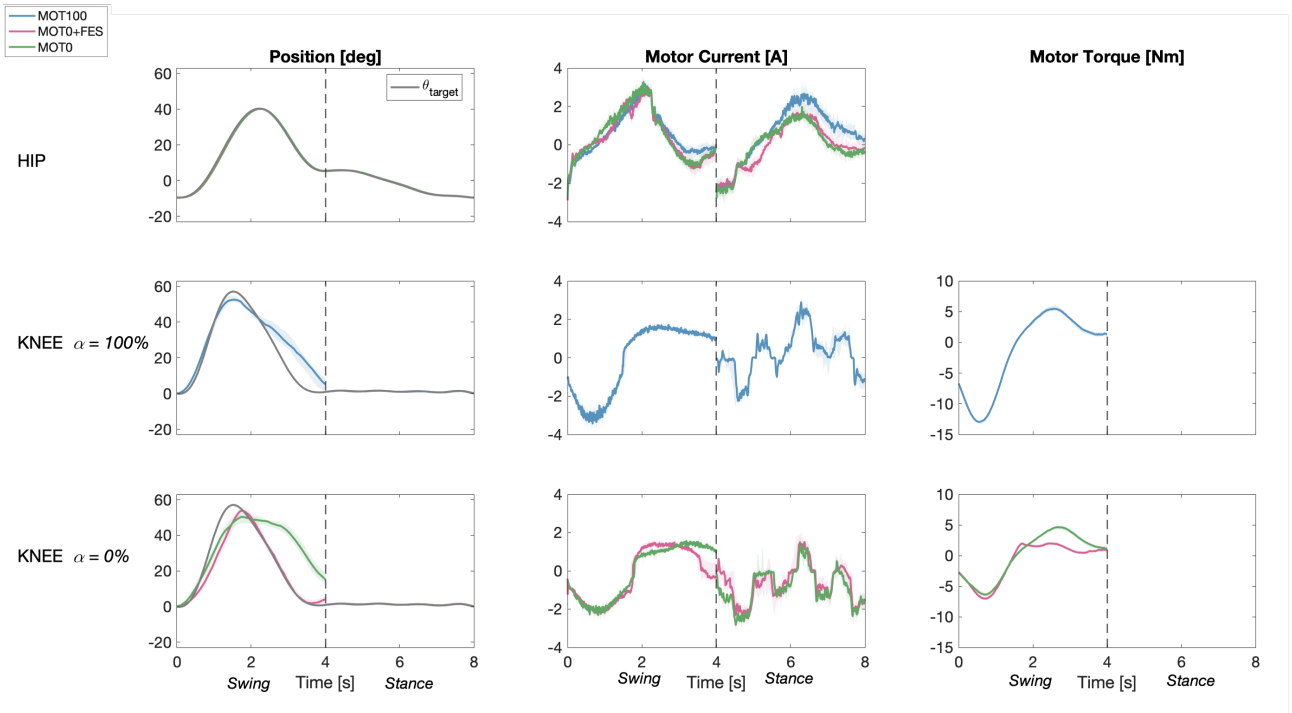


Figure 12: Data over time for ID24 in the 3 conditions.

Observing the current pattern, we see that Hamstrings are stimulated with higher amplitudes in the first half of the string as the aim is to induce a knee flexion. Conversely, Quadriceps are subjected to higher amplitude in the second half of the swing where a knee extension is desired. Both muscles reach the maximum value L2 defined in the calibration phase, saturating.

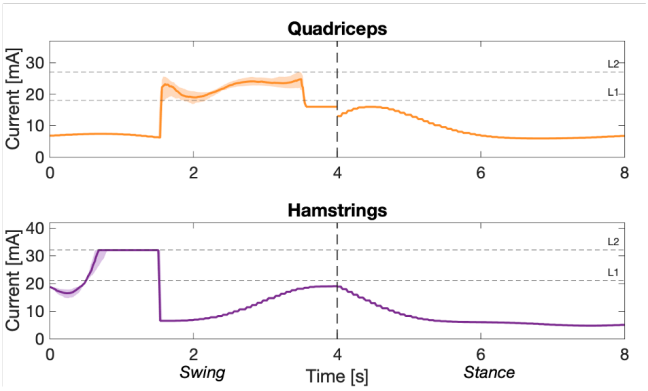


Figure 13: Current trend over time for ID24.

Figure 14 and 15 contain the boxplots of the test metrics for all 15 subjects. Taking into account the RMSE, it assumes very low values for the hip and knee in the stance phase and for the hip in the swing phase, while it is higher for the knee in the swing phase. In detail, a lower RMSE was registered for the EXO100 and FES0 modes (values of about 6°), while it was higher for the EXO0 (values of about 10°). The total torque integral shows significantly greater values for the EXO100 case for the reasons described above. In the two cases with $\alpha = 0\%$, even if they receive the same feedforward torque, the total integral is higher for the case without FES because, executing larger tracking errors, it has a bigger feedback contribution.

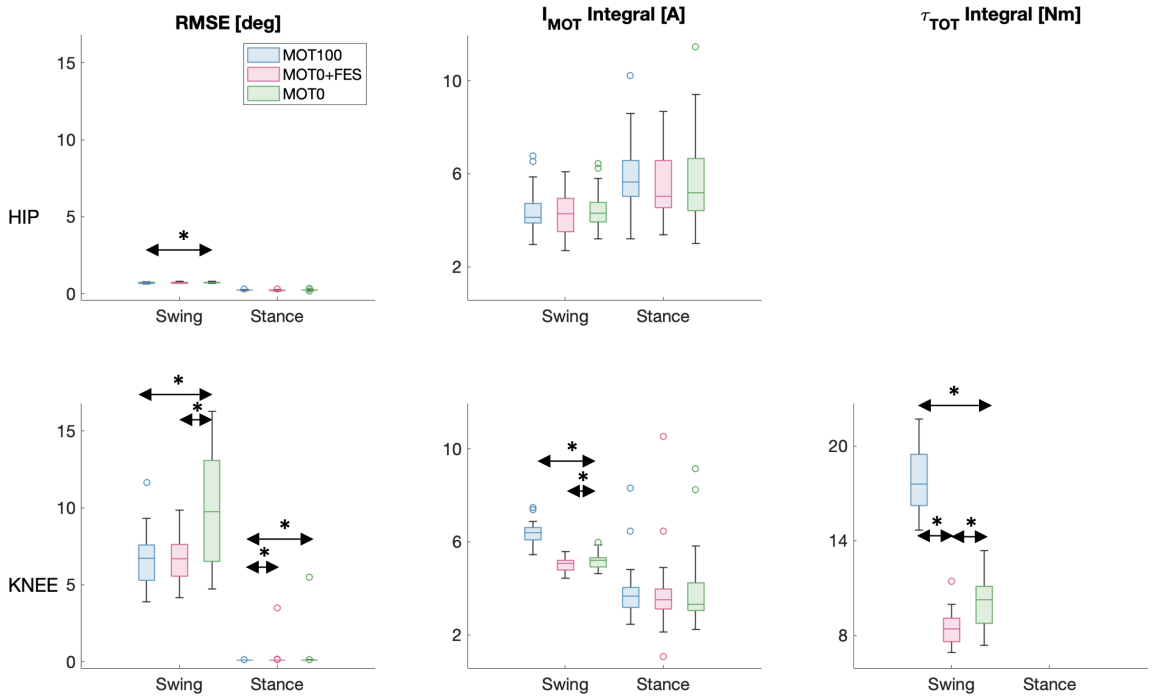


Figure 14: Motor metrics for the walking tests of all subjects (differences between conditions were considered significant in case of p-value < 0.05 and marked with an asterisk).

The normalized integral of the muscle current value is higher in the swing phase than in the stance one. This happens because the former implements the cooperative control and thus the current assumes values between L1 and L2, while the latter uses the rigid control which foresees a maximum current equal to L1.

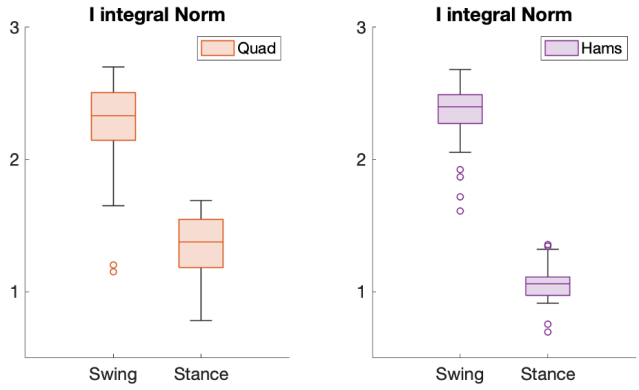


Figure 15: Current metrics for the walking tests of all subjects.

Regarding the boxplots of the metrics divided into groups of 5 strides in Figure 16, the RMSE displays higher initial values, probably due to an initial adjustment, but then it decreases as the cooperative control helps the subject reduce the error. However, it increases again at the end, due to the onset of muscle fatigue, which leads to poorer movement performances and thus to higher trajectory errors. For the motor current and total torque integrals, the trend is similar, but less pronounced. Lastly, considering the normalized FES current integral, it can be observed that, after the first few repetitions, the current saturates and so the integral remains fairly constant.

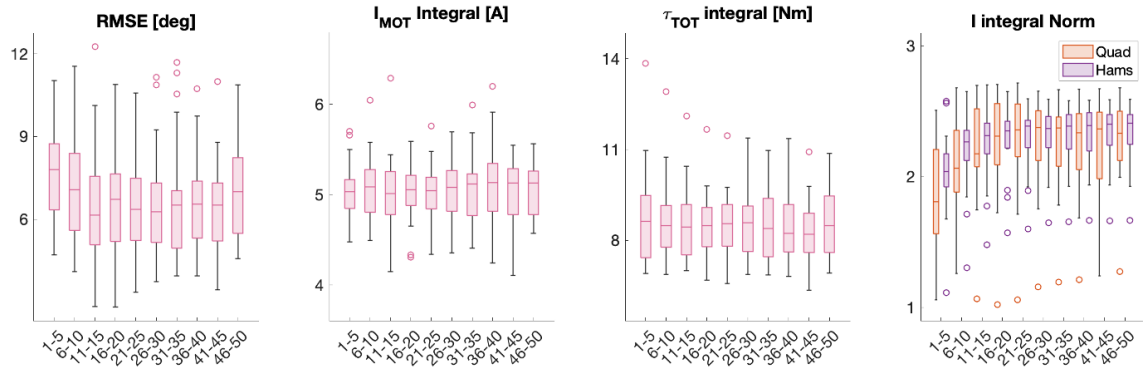


Figure 16: Motor and current metrics for the walking tests of all subjects, considering groups of 5 successive strides (for RMSE p-value < 0.05 between steps1-5 and steps11-15, steps16-20, steps21-25, steps26-30, steps31-35, steps36-40, steps41-45; for normalized integral of the current at the Quadriceps p-value < 0.05 between steps1-5 and steps16-20, steps21-25, steps26-30, steps31-35, steps36-40, steps41-45, steps46-50).

5.2. Patients

Due to timing problems, we were only able to complete the protocol on two patients, one complete and one incomplete SCI. The results of the baseline assessments are highlighted in the table in Figure 17 and 18.

Patient	Age [years]	Level of the lesion	ASIA	Complete/ incomplete	Event date	Comment	Spasticity (Modified Ashworth Scale)	Level of pain (NRS)	Tests performed
P1	34	T7	A	Complete	11/08/21	Non-ambulatory patient	The patient has a spasticity level between 2 and 3, symmetrical between right and left	4	8 sessions: - 1-5: EXO100 - 6-8: FES0
P2	38	L3	D	Incomplete	18/09/17	Ambulatory patient with 2 Canadian canes and with Peroneal Electrical Stimulation on the left -> 194m in 6 min	The patient has a spasticity level between 0 and 2, greater on the left	0	6 sessions: - 1-3: EXO100 - 4-6: FES0

Figure 17: Baseline assessments at T0 for the patients.

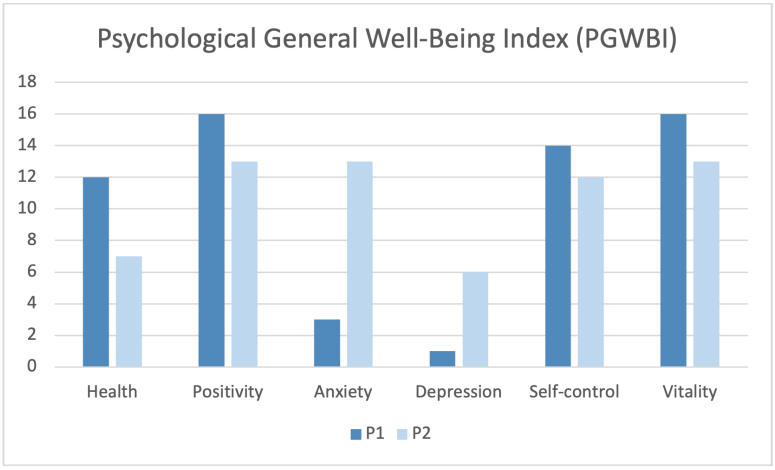


Figure 18: Results for the Psychological General Well-Being Index.

5.2.1 Complete Spinal Cord Injury patient

A complete SCI patient underwent 8 sessions using Twin: the first 5 sessions in EXO100 mode and the following 3 in FES0 mode. In Figure 19, the patient's data for the last sessions performed without and with the addition of stimulation are plotted. It is evident from the position graph that the subject deviates slightly from the target trajectory when FES is added. The value of total torque decreases significantly between the two modes, as had also been observed for healthy patients. As retrieved from calibration values in Figure 20, the patient can tolerate progressively higher current values due to training, but during the stimulation the L2 limit value is never reached.

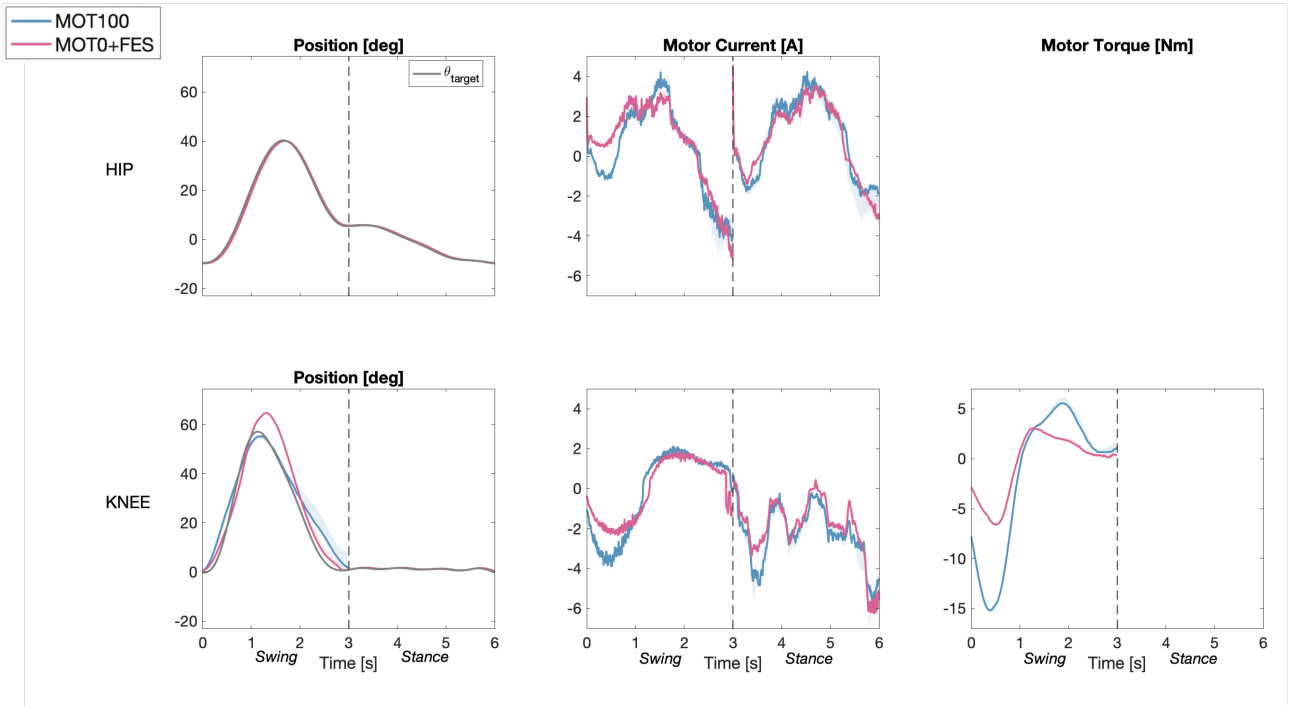


Figure 19: Data over time for P1 in the 2 conditions.

GENERALITIES				LEFT				RIGHT			
				Quadriceps		Hamstrings		Quadriceps		Hamstrings	
ID	Sex	Age [years]	Session	L1 [mA]	L2 [mA]	L1 [mA]	L2 [mA]	L1 [mA]	L2 [mA]	L1 [mA]	L2 [mA]
P1	M	34	6	23	45	29	50	33	57	26	42
			7	33	50	32	47	25	46	31	44
			8	38	48	42	63	18	36	36	55

Figure 20: Current trend over time for P1.

The boxplots of the metrics for the two modes are shown in Figure 21 and 22. For the RMSE of the knee in swing, it has the same order of magnitude as the tests performed on healthy subjects. Despite being slightly higher for the FES0 case, the value of the total torque integral is much lower. Therefore, effectively depowering the motor and adding stimulation does not compromise the success of the walking process. The value of the motor current integral is maintained at slightly lower values for the FES0 condition. The normalized FES current integral is greater for the swing phase as the cooperative control allows the higher L2 level to be reached.

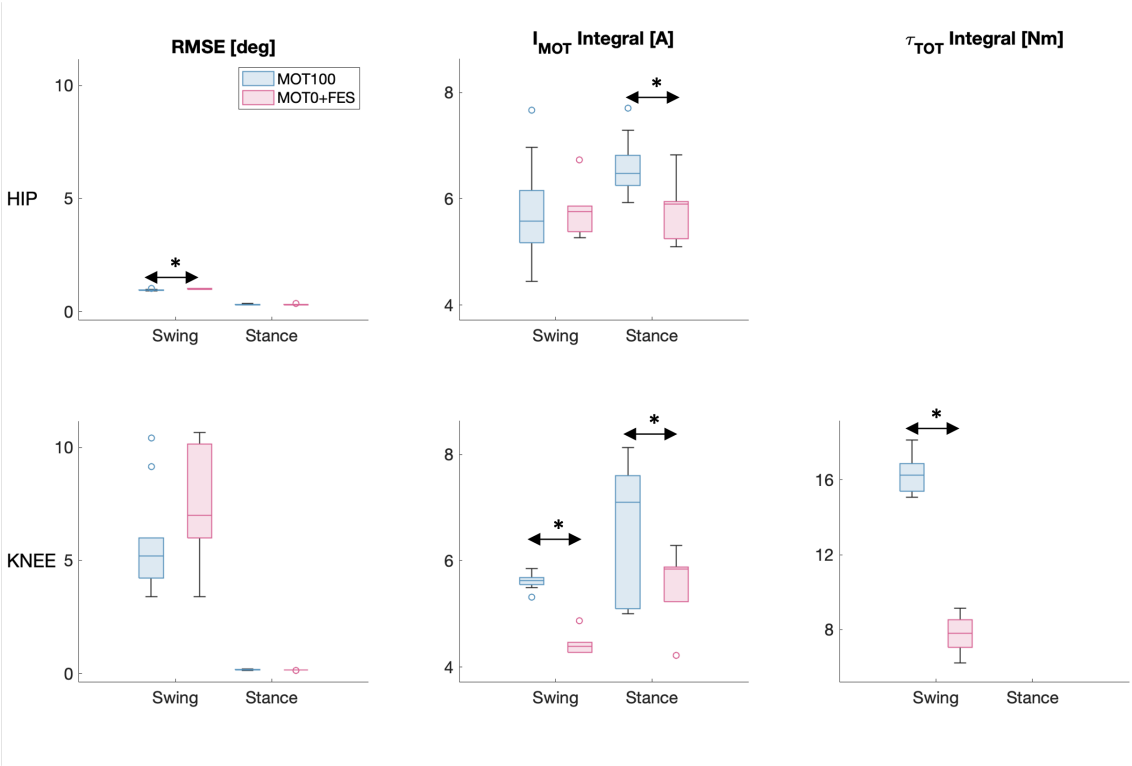


Figure 21: Motor metrics for P1 in the 2 conditions (differences between conditions were considered significant in case of p-value < 0.05 and marked with an asterisk).

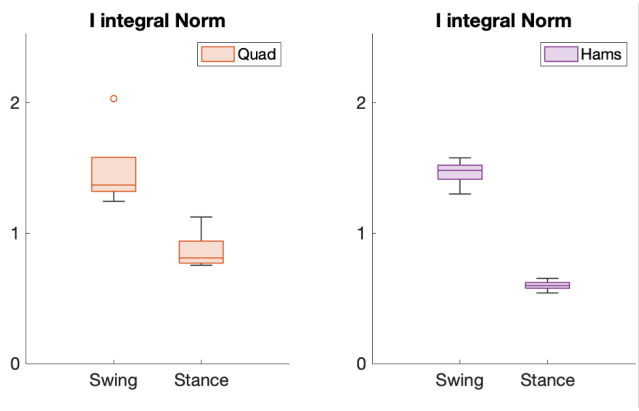
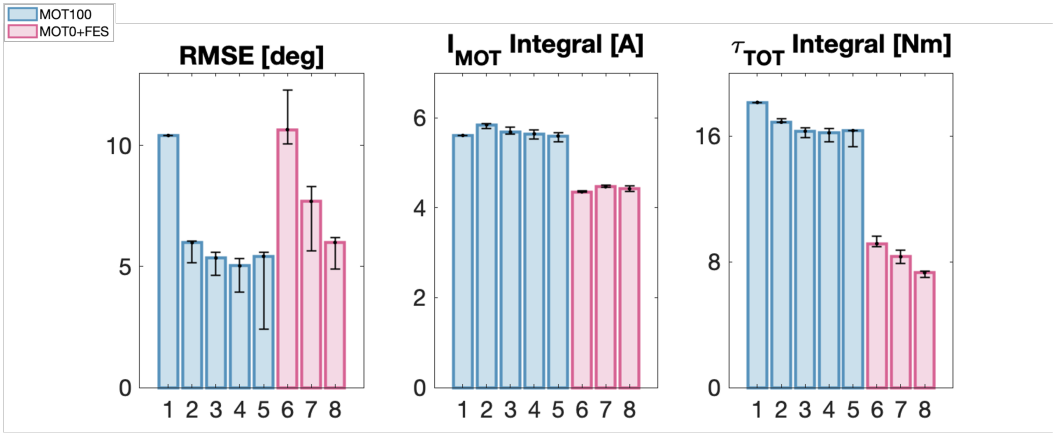
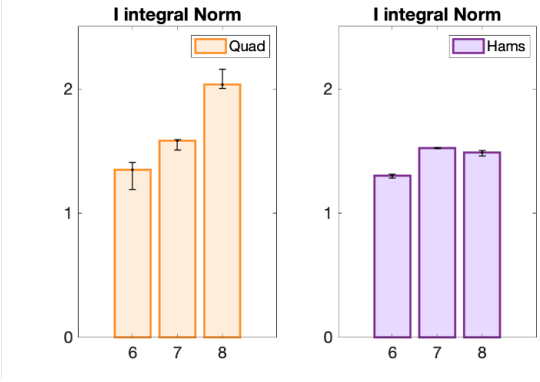


Figure 22: Current metrics for P1.

Figure 23 shows the improvements achieved during training, considering the swing knee outcomes. The RMSE decreases as the sessions proceed and only increases after the stimulation addition. The value of the current integral remains fairly constant between sessions conducted in the same mode. The total torque integral shows a slight decreasing trend for both modes: with the same feedforward torque, the feedback torque decreases with exercise.



(a)

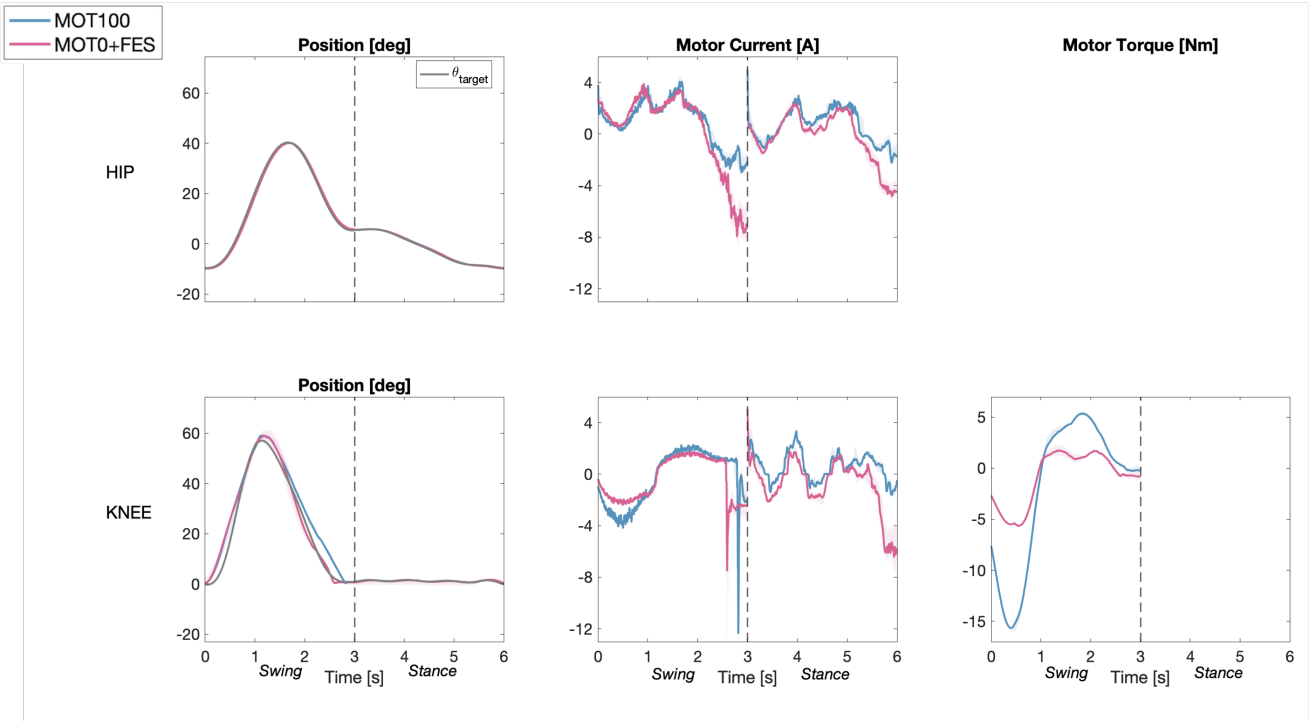


(b)

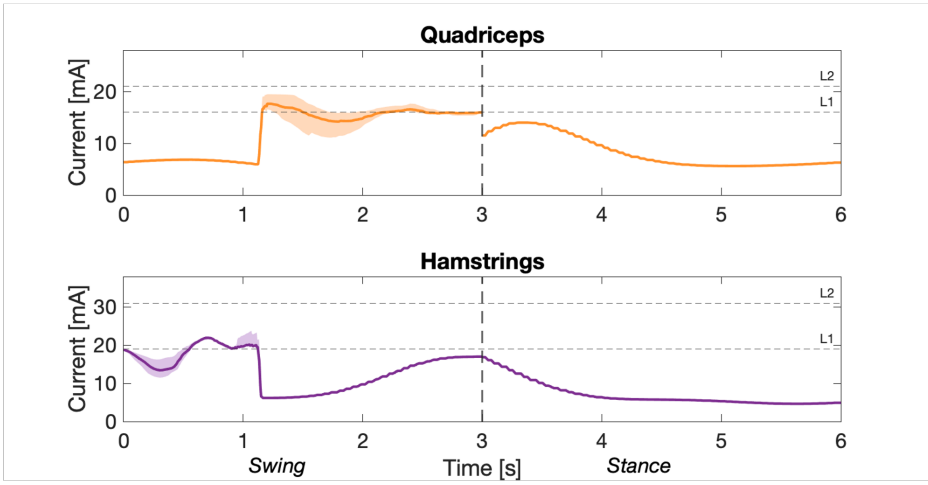
Figure 23: (a) Bars for motor metrics for all sessions of P1 of the swing knee in the 2 conditions (for RMSE p-value < 0.05 between 1 and 2-3-4-5-7-8, 2-4-5 and 6-7, 3 and 6, 6 and 7-8, 7 and 8; for I_{MOT} integral p-value < 0.05 between 1-2-3-4-5 and 6-7-8, 6 and 7-8; for τ_{TOT} integral p-value < 0.05 between 1 and 3-4-6-7-8, 2-3-4-5 and 6-7-8, 6 and 7-8, 7 and 8); (b) Bars for current metrics for all sessions of P1 of the swing knee (for normalized integral of Hamstrings p-value < 0.05 between 6 and 7-8, 7 and 8).

5.2.2 Incomplete Spinal Cord Injury patient

A patient with incomplete SCI underwent 6 sessions using Twin: the first 3 in EXO100 mode and the subsequent 3 in FES0 mode. Figure 24a shows the difference between the data collected in the latter sessions, without and with stimulation. No differences were observed between the real and target position in the two modes. As expected, a decrease in torque value is instead visible. Like the first patient, the current values never reach the L2 threshold, unlike in healthy subjects, where saturation is achieved in the majority of cases.



(a)

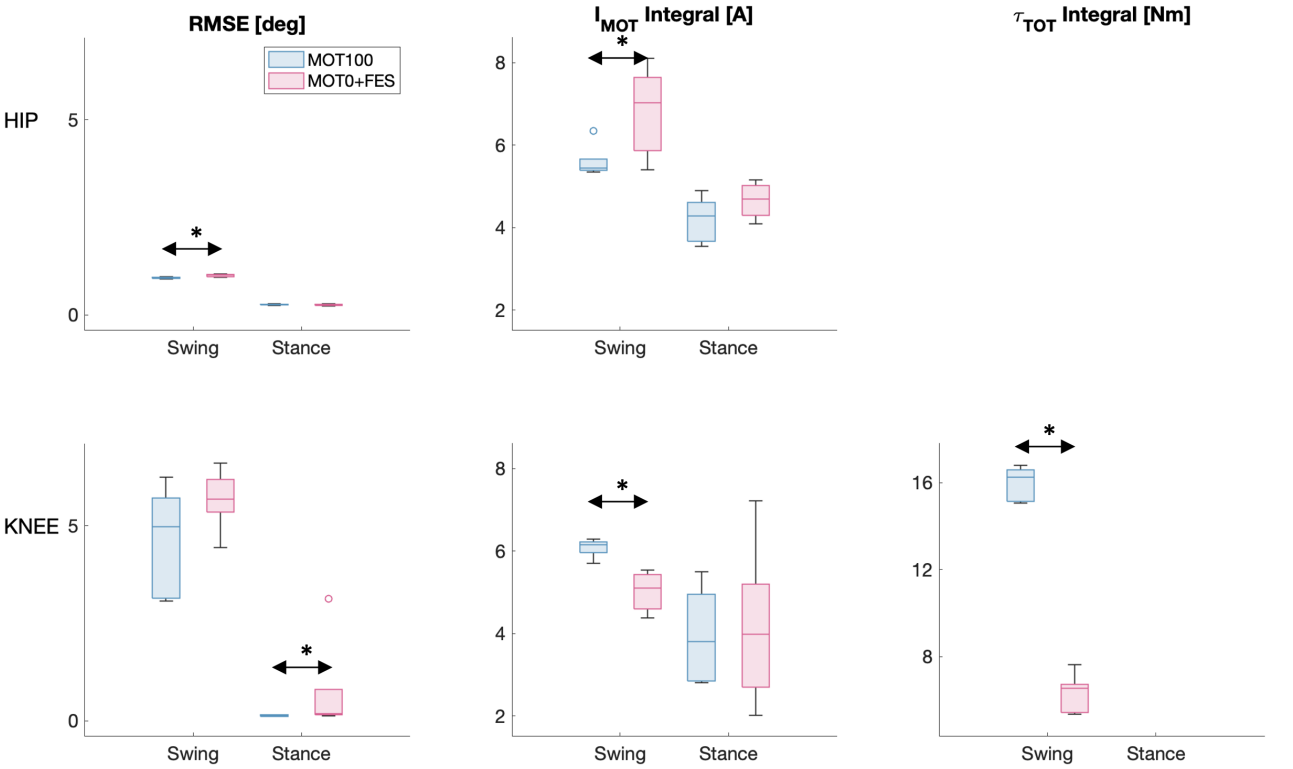


GENERALITIES				LEFT				RIGHT			
				Quadriceps		Hamstrings		Quadriceps		Hamstrings	
ID	Sex	Age [years]	Session	L1 [mA]	L2 [mA]	L1 [mA]	L2 [mA]	L1 [mA]	L2 [mA]	L1 [mA]	L2 [mA]
P2	M	38	4	18	30	21	31	18	31	21	36
			5	16	33	19	34	21	38	12	28
			6	16	21	19	31	17	36	25	36

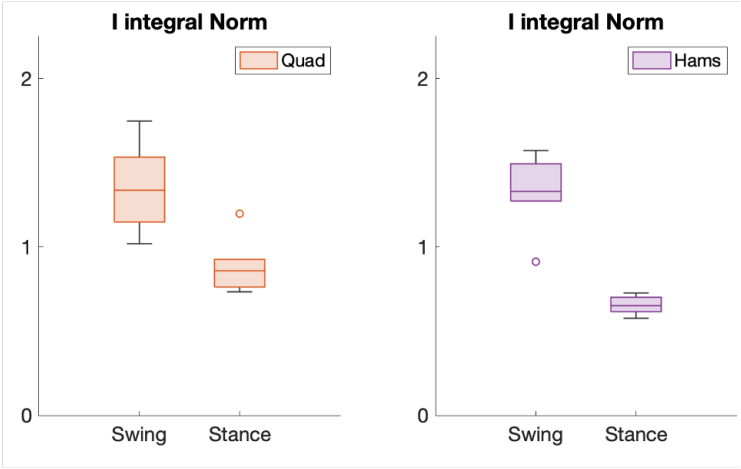
(b)

Figure 24: (a) Data over time for P2 in the 2 conditions; (b) Current trend over time for P2.

The two modes, EXO100 and FES0, can be compared through the metrics in Figure 25. The swing knee RMSE for FES0 is slightly higher than that for EXO100. At the other joints, RMSE values are close to zero for both modes. At the same time, the total torque integral is significantly lower for the FES0 case.



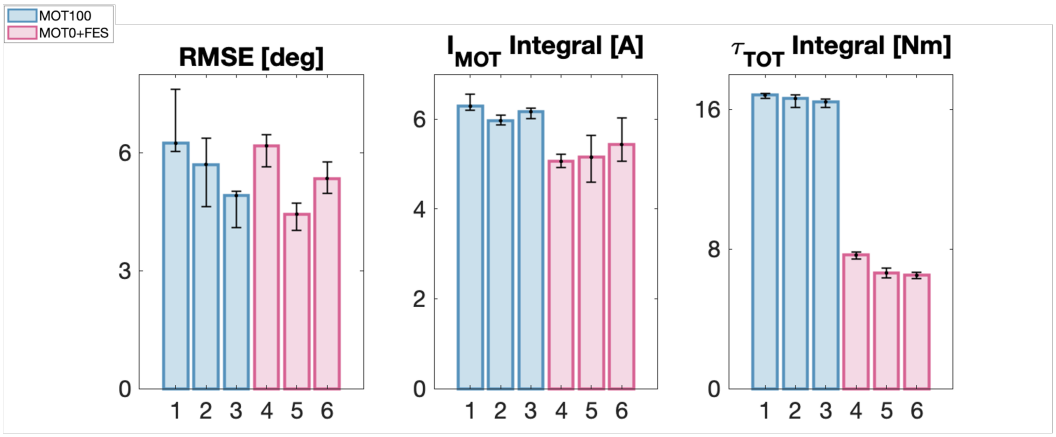
(a)



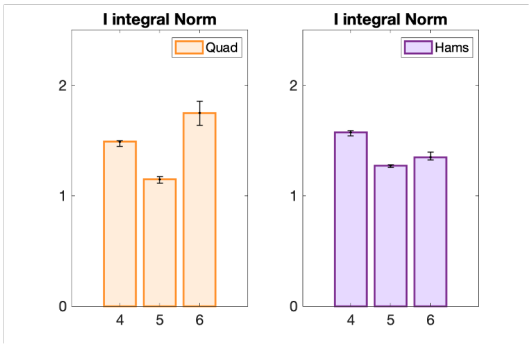
(b)

Figure 25: (a) Motor metrics for P2 in the 2 conditions (differences between conditions were considered significant in case of p-value < 0.05 and marked with an asterisk); (b) Current metrics for P2.

Figure 26 shows the improvements achieved by patient 2 through training for the swing knee. The RMSE decreases as the number of sessions advances, as does the torque integral.



(a)



(b)

Figure 26: (a) Bars for motor metrics for all sessions of P2 of the swing knee in the 2 conditions (for RMSE p-value < 0.05 between 1 and 3, 2 and 4, 3 and 4; for I_{MOT} integral p-value < 0.05 between 1-2-3 and 4-5-6, 4-5 and 6; for τ_{TOT} integral p-value < 0.05 between 1-2-3 and 4-5-6, 4 and 5-6); (b) Bars for current metrics for all sessions of P2 of the swing knee (for normalized integral of Quadriceps p-value < 0.05 between 4 and 5-6, 5 and 6).

5.2.3 Questionnaires

At T1 and T2 the following questionnaires were administered to the patients: TAM, SUS and UEQ.
TAM-3 analysis shows that for P1, the use of TwinFES results in improvement in terms of quality output and self-efficacy, while the other items remain the same or worsen. In contrast, for P2, the introduction of FES into the exoskeleton results in improved behavioral intention, subjective norm, valuntariness and quality output.

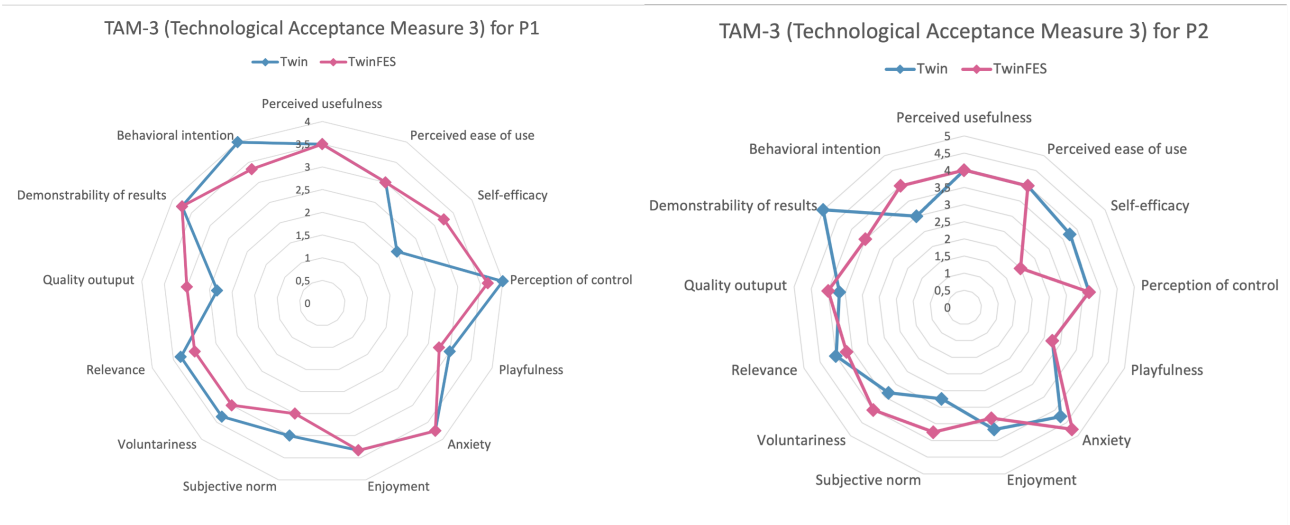


Figure 27: Results for the Technological Acceptance Measure 3 (TAM-3) questionnaire.

SUS analysis shows a higher value for the TwinFES device than for the sole Twin exoskeleton for both subjects, but with generally low values of grade D (poor).

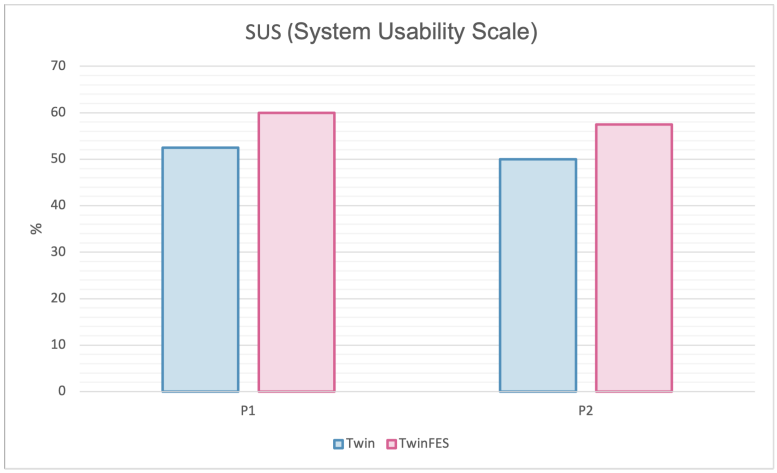
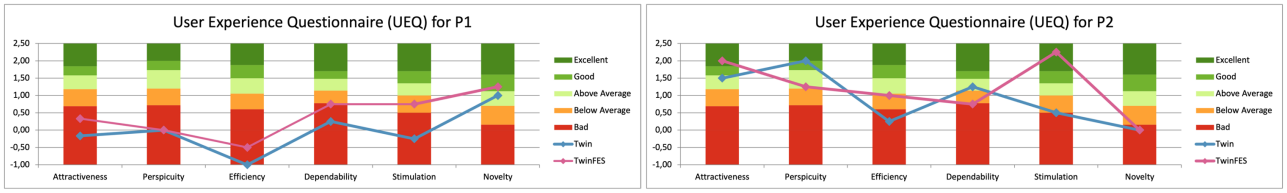


Figure 28: Results for the System Usability Scale (SUS) questionnaire.

Regarding the UEQ analysis, for patient 1 the scales values increase slightly when stimulation is added, but with bad and below-average results for all parameters except *novelty*. On the other hand, for patient 2, the addition of stimulation achieves excellent results for *attractiveness* and *stimulation*, which are never reached for the case without stimulation.



Twin

Scale	Mean	Comparisson to benchmark	Interpretation
Attractiveness	-0,17	Bad	In the range of the 25% worst results
Perspicuity	0,00	Bad	In the range of the 25% worst results
Efficiency	-1,00	Bad	In the range of the 25% worst results
Dependability	0,25	Bad	In the range of the 25% worst results
Stimulation	-0,25	Bad	In the range of the 25% worst results
Novelty	1,00	Above Average	25% of results better, 50% of results worse

Twin

Scale	Mean	Comparisson to benchmark	Interpretation
Attractiveness	1,50	Above average	25% of results better, 50% of results worse
Perspicuity	2,00	Good	10% of results better, 75% of results worse
Efficiency	0,25	Bad	In the range of the 25% worst results
Dependability	1,25	Above Average	25% of results better, 50% of results worse
Stimulation	0,50	Bad	In the range of the 25% worst results
Novelty	0,00	Bad	In the range of the 25% worst results

TwinFES

Scale	Mean	Comparisson to benchmark	Interpretation
Attractiveness	0,33	Bad	In the range of the 25% worst results
Perspicuity	0,00	Bad	In the range of the 25% worst results
Efficiency	-0,50	Bad	In the range of the 25% worst results
Dependability	0,75	Bad	In the range of the 25% worst results
Stimulation	0,75	Below Average	50% of results better, 25% of results worse
Novelty	1,25	Good	10% of results better, 75% of results worse

TwinFES

Scale	Mean	Comparisson to benchmark	Interpretation
Attractiveness	2,00	Excellent	In the range of the 10% best results
Perspicuity	1,25	Above Average	25% of results better, 50% of results worse
Efficiency	1,00	Below Average	50% of results better, 25% of results worse
Dependability	0,75	Bad	In the range of the 25% worst results
Stimulation	2,25	Excellent	In the range of the 10% best results
Novelty	0,00	Bad	In the range of the 25% worst results

Figure 29: Results for the User Experience Questionnaire (UEQ).

6. Conclusions

In recent years, hybrid robotic rehabilitation systems have emerged as a promising approach for individuals with Spinal Cord Injuries or stroke, combining the benefits of wearable robotic devices and Functional Electrical Stimulation. In this study, a new cooperative control system is tested, integrating the motor and the FES component in the execution of knee swing movements during walking. The idea is to obtain the walking movement by reducing the motor-generated power and exploiting the one produced by FES-stimulated muscles and, if present, the voluntary residual one from the patient. This control system is initially tested on healthy individuals and, subsequently, on patients. These tests demonstrate that the integration of stimulation into a depowered exoskeleton is feasible and yields comparable results, in terms of movement performance, to using solely the exoskeleton. The same is not observed when depowering the exoskeleton, but without the FES integration. Additionally, the presence of FES carries significant physiological advantages for spinal-injured patients, as it engages their paralyzed muscles in the activity, inducing their contraction that would be otherwise unfeasible. Furthermore, enabling the reduction of the exoskeleton motor power, while maintaining proper movement execution, it reduces the overall system energy consumption. This conclusion is promising in view of

developing novel systems with lower encumbrance and weight, making their use easier.
Regarding the early onset of muscle fatigue, which is one of the main problems when using FES as a rehabilitation technique, the exoskeleton support allows to reduce it. Indeed, from our tests, we don't notice significant performance worsening over time, meaning that patients' muscles are not fatigued.
Beyond the above-listed promising results, some limitations have been identified:

- Regarding the acquisition protocol on patients, it has been performed only on 2 SCI and so, it is not possible to make general considerations. Additionally, no information about the effect on stroke patients is available.
- It must be underlined that the positioning of FES electrodes is affected by the operator's experience.
- The twin exoskeleton is heavy and difficult to handle both for the patient, who has to correctly move the load at each step and for the physical therapist, who stands behind the subject. The development of lighter and less cumbersome exoskeletons could ease these processes and lead to better results.
- The single-step triggering made by the therapist with the app limits the performance of a smoother walk without interruptions. Alternative solutions could be developed, such as a control based on subjects' torso movement or on commands given directly by the patient, via a button on the crutches for example, without requiring the operator's intervention.

Despite these limitations, the proposed TwinFES prototype is innovative and high-performing, as demonstrated by the results. It therefore represents a significant starting point in the attempt to realize new hybrid robotic rehabilitation systems.

References

[1] Francisco Anaya, Pavithra Thangavel, and Haoyong Yu. Hybrid fes–robotic gait rehabilitation technologies: a review on mechanical design, actuation, and control strategies. *International journal of intelligent robotics and applications*, 2:1–28, 2018.

[2] Richard W Bohannon and Melissa B Smith. Interrater reliability of a modified ashworth scale of muscle spasticity. *Physical therapy*, 67(2):206–207, 1987.

[3] Alberto Botter, Gianmosè Oprandi, Fabio Lanfranco, Stefano Allasia, Nicola A Maffiuletti, and Marco Alessandro Minetto. Atlas of the muscle motor points for the lower limb: implications for electrical stimulation procedures and electrode positioning. *European journal of applied physiology*, 111:2461–2471, 2011.

[4] John Brooke. Sus: a "quick and dirty'usability. *Usability evaluation in industry*, 189(3):189–194, 1996.

[5] Bruno P Chumpitazi, Mariella M Self, Danita I Czyzewski, Sydney Cejka, Paul R Swank, and Robert J Shulman. Bristol stool form scale reliability and agreement decreases when determining rome iii stool form designations. *Neurogastroenterology & Motility*, 28(3):443–448, 2016.

[6] CD Cozean, William S Pease, and SL Hubbell. Biofeedback and functional electric stimulation in stroke rehabilitation. *Archives of physical medicine and rehabilitation*, 69(6):401–405, 1988.

[7] Stefano Dalla Gasperina, Loris Roveda, Alessandra Pedrocchi, Francesco Braghin, and Marta Gandolla. Review on patient-cooperative control strategies for upper-limb rehabilitation exoskeletons. *Frontiers in Robotics and AI*, 8:745018, 2021.

[8] Antonio J Del-Ama, Ángel Gil-Agudo, José L Pons, and Juan C Moreno. Hybrid fes-robot cooperative control of ambulatory gait rehabilitation exoskeleton. *Journal of neuroengineering and rehabilitation*, 11(1):1–15, 2014.

[9] Antonio J Del-Ama, Aikaterini D Koutsou, Juan C Moreno, Ana De-Los-Reyes, Ángel Gil-Agudo, and José L Pons. Review of hybrid exoskeletons to restore gait following spinal cord injury. *Journal of Rehabilitation Research & Development*, 49(4), 2012.

[10] F Dell'Eva, S Dalla Gasperina, M Gandolla, L De Micheli, A Pedrocchi, E Ambrosini, et al. A hybrid fes-motor cooperative control over a knee joint movement: A feasibility study. *ARTIFICIAL ORGANS*, 46(11):307–311, 2022.

[11] D Erdem, D Hava, P Keskinoğlu, ÇİĞDEM Bircan, Ö Peker, K Krogh, and S Gülbahar. Reliability, validity and sensitivity to change of neurogenic bowel dysfunction score in patients with spinal cord injury. *Spinal Cord*, 55(12):1084–1087, 2017.

[12] Dennis Grasmücke, Amrei Zieriacks, Oliver Jansen, Christian Fisahn, Matthias Sczesny-Kaiser, Martin Wessling, Renate C Meindl, Thomas A Schildhauer, and Mirko Aach. Against the odds: what to expect in rehabilitation of chronic spinal cord injury with a neurologically controlled hybrid assistive limb exoskeleton. a subgroup analysis of 55 patients according to age and lesion level. *Neurosurgical focus*, 42(5):E15, 2017.

[13] E Grossi, P Mosconi, N Groth, M Niero, and G Apolone. Questionario psychological general well-being index. *Versione Italiana*, 2002.

[14] Kevin H Ha, Spencer A Murray, and Michael Goldfarb. An approach for the cooperative control of fes with a powered exoskeleton during level walking for persons with paraplegia. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, 24(4):455–466, 2015.

[15] Elizabeth Hardin, Rudi Kobetic, Lori Murray, Michelle Corado-Ahmed, Gilles Pinault, Jonathan Sakai, Stephanie Nogan Bailey, Chester Ho, and Ronald J Triolo. Walking after incomplete spinal cord injury using an implanted fes system: a case report. *Journal of Rehabilitation Research & Development*, 44(3), 2007.

[16] André Heck and Caroline van Dongen. Gait analysis by high school students. *Physics Education*, 43(3):284, 2008.

[17] S Hesse. Recovery of gait and other motor functions after stroke: novel physical and pharmacological treatment strategies. *Restorative Neurology and Neuroscience*, 22(3-5):359–369, 2004.

[18] Stefan Hesse, Dietmar Uhlenbrock, Cordula Werner, and Anita Bardeleben. A mechanized gait trainer for restoring gait in nonambulatory subjects. *Archives of physical medicine and rehabilitation*, 81(9):1158–1161, 2000.

[19] Mark P Jensen, Paul Karoly, and Sanford Braver. The measurement of clinical pain intensity: a comparison of six methods. *Pain*, 27(1):117–126, 1986.

[20] Hiroyuki Katoh, Kazuya Yokota, and Michael G Fehlings. Regeneration of spinal cord connectivity through stem cell transplantation and biomaterial scaffolds. *Frontiers in cellular neuroscience*, 13:248, 2019.

[21] Irene L Katzan, Andrew Schuster, Christopher Newey, Ken Uchino, and Brittany Lapin. Patient-reported outcomes across cerebrovascular event types: More similar than different. *Neurology*, 91(23):e2182–e2191, 2018.

[22] MirHojjat Khorasanizadeh, Mahmoud Yousefifard, Mahsa Eskian, Yi Lu, Maryam Chalangari, James S Harrop, Seyed Behnam Jazayeri, Simin Seyedpour, Behzad Khodaei, Mostafa Hosseini, et al. Neurological recovery following traumatic spinal cord injury: a systematic review and meta-analysis. *Journal of Neurosurgery: Spine*, 30(5):683–699, 2019.

[23] Joosup Kim, Tharshanah Thayabaranathan, Geoffrey A Donnan, George Howard, Virginia J Howard, Peter M Rothwell, Valery Feigin, Bo Norrving, Mayowa Owolabi, Jeyaraj Pandian, et al. Global stroke statistics 2019. *International Journal of Stroke*, 15(8):819–838, 2020.

[24] Aikaterini D Koutsou, Juan C Moreno, Antonio J Del Ama, Eduardo Rocon, and José L Pons. Advances in selective activation of muscles for non-invasive motor neuroprostheses. *Journal of neuroengineering and rehabilitation*, 13(1):1–12, 2016.

[25] Matteo Laffranchi, Stefano D'Angella, Christian Vassallo, Chiara Piezzo, Michele Canepa, Samuele De Giuseppe, Mirco Di Salvo, Antonio Succi, Samuele Cappa, Giulio Cerruti, et al. User-centered design and development of the modular twin lower limb exoskeleton. *Frontiers in neurorobotics*, 15:709731, 2021.

[26] Peter Langhorne, Janice M Collier, Patricia J Bate, Matthew NT Thuy, and Julie Bernhardt. Very early versus delayed mobilisation after stroke. *Cochrane Database of Systematic Reviews*, 2018.

[27] Bettina Laugwitz, Theo Held, and Martin Schrepp. Construction and evaluation of a user experience questionnaire. In *HCI and Usability for Education and Work: 4th Symposium of the Workgroup Human-Computer Interaction and Usability Engineering of the Austrian Computer Society, USAB 2008, Graz, Austria, November 20-21, 2008. Proceedings 4*, pages 63–76. Springer, 2008.

[28] Kate E Laver, Zoe Adey-Wakeling, Maria Crotty, Natasha A Lannin, Stacey George, and Catherine Sherrington. Telerehabilitation services for stroke. *Cochrane Database of Systematic Reviews*, 2020.

[29] Didier Leys, Yannick Béjot, Stéphanie Debette, and Maurice Giroud. Burden of stroke in france. *International Journal of Stroke*, 3(2):117–119, 2008.

[30] Cheryl L Lynch and Milos R Popovic. Functional electrical stimulation. *IEEE control systems magazine*, 28(2):40–50, 2008.

[31] Nebojša M Malešević, Lana Z Popović, Laszlo Schwirtlich, and Dejan B Popović. Distributed low-frequency functional electrical stimulation delays muscle fatigue compared to conventional stimulation. *Muscle & nerve*, 42(4):556–562, 2010.

[32] Jessica P McCabe, Mark E Dohring, E Byron Marsolais, Jean Rogers, Richard Burdsall, K Foenigk, Svetlana Pundik, and Janis J Daly. Feasibility of combining gait robot and multichannel functional electrical stimulation with intramuscular electrodes. *Journal of Rehabilitation Research & Development*, 45(7), 2008.

[33] Colin M McCrimmon, Christine E King, Po T Wang, Steven C Cramer, Zoran Nenadic, and An H Do. Brain-controlled functional electrical stimulation therapy for gait rehabilitation after stroke: a safety study. *Journal of neuroengineering and rehabilitation*, 12(1):1–12, 2015.

[34] Philipp Müller, Antonio J Del Ama, Juan C Moreno, and Thomas Schauer. Adaptive multichannel fes neuroprosthesis with learning control and automatic gait assessment. *Journal of neuroengineering and rehabilitation*, 17(1):1–20, 2020.

[35] Spencer A Murray, Ryan J Farris, Michael Golfarb, Clare Hartigan, Casey Kandilakis, and Don Truex. Fes coupled with a powered exoskeleton for cooperative muscle contribution in persons with paraplegia. In *2018 40th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)*, pages 2788–2792. IEEE, 2018.

[36] Robert Nguyen, Andres M Gonzalez, Silvestro Micera, and Manfred Morari. Increasing muscular participation in robot-assisted gait training using fes. In *16th Annual International FES Society Conference*. International Functional Electrical Stimulation Society (IFESS), 2011.

[37] Goro Obinata, Shunro Fukada, Toshiki Matsunaga, Takehiro Iwami, Yoichi Shimada, Kazuto Miyawaki, Kazunori Hase, and Atsushi Nakayama. Hybrid control of powered orthosis and functional neuromuscular stimulation for restoring gait. In *2007 29th Annual International Conference of the IEEE Engineering in Medicine and Biology Society*, pages 4879–4882. IEEE, 2007.

[38] Timothy M O'Shea, Joshua E Burda, Michael V Sofroniew, et al. Cell biology of spinal cord injury and repair. *The Journal of clinical investigation*, 127(9):3259–3270, 2017.

[39] James L Patton and Ferdinando A Mussa-Ivaldi. Robot-assisted adaptive training: custom force fields for teaching movement patterns. *IEEE Transactions on Biomedical Engineering*, 51(4):636–646, 2004.

[40] Dejan Popovic and Thomas Sinkjaer. *Control of movement for the physically disabled: control for rehabilitation technology*, volume 80. Springer, 2000.

[41] Dejan B Popović. Advances in functional electrical stimulation (fes). *Journal of Electromyography and Kinesiology*, 24(6):795–802, 2014.

[42] Martin Schmoll, Ronan Le Guillou, David Lobato Borges, Charles Fattal, Emerson Fachin-Martins, and Christine Azevedo Coste. Standardizing fatigue-resistance testing during electrical stimulation of paralysed human quadriceps muscles, a practical approach. *Journal of NeuroEngineering and Rehabilitation*, 18:1–14, 2021.

[43] Christian Vassallo, Samuele De Giuseppe, Chiara Piezzo, Stefano Maludrottu, Giulio Cerruti, Maria Laura D'Angelo, Emanuele Gruppioni, Claudia Marchese, Simona Castellano, Eleonora Guanziroli, et al. Gait patterns generation based on basis functions interpolation for the twin lower-limb exoskeleton. In *2020 IEEE International Conference on Robotics and Automation (ICRA)*, pages 1778–1784. IEEE, 2020.

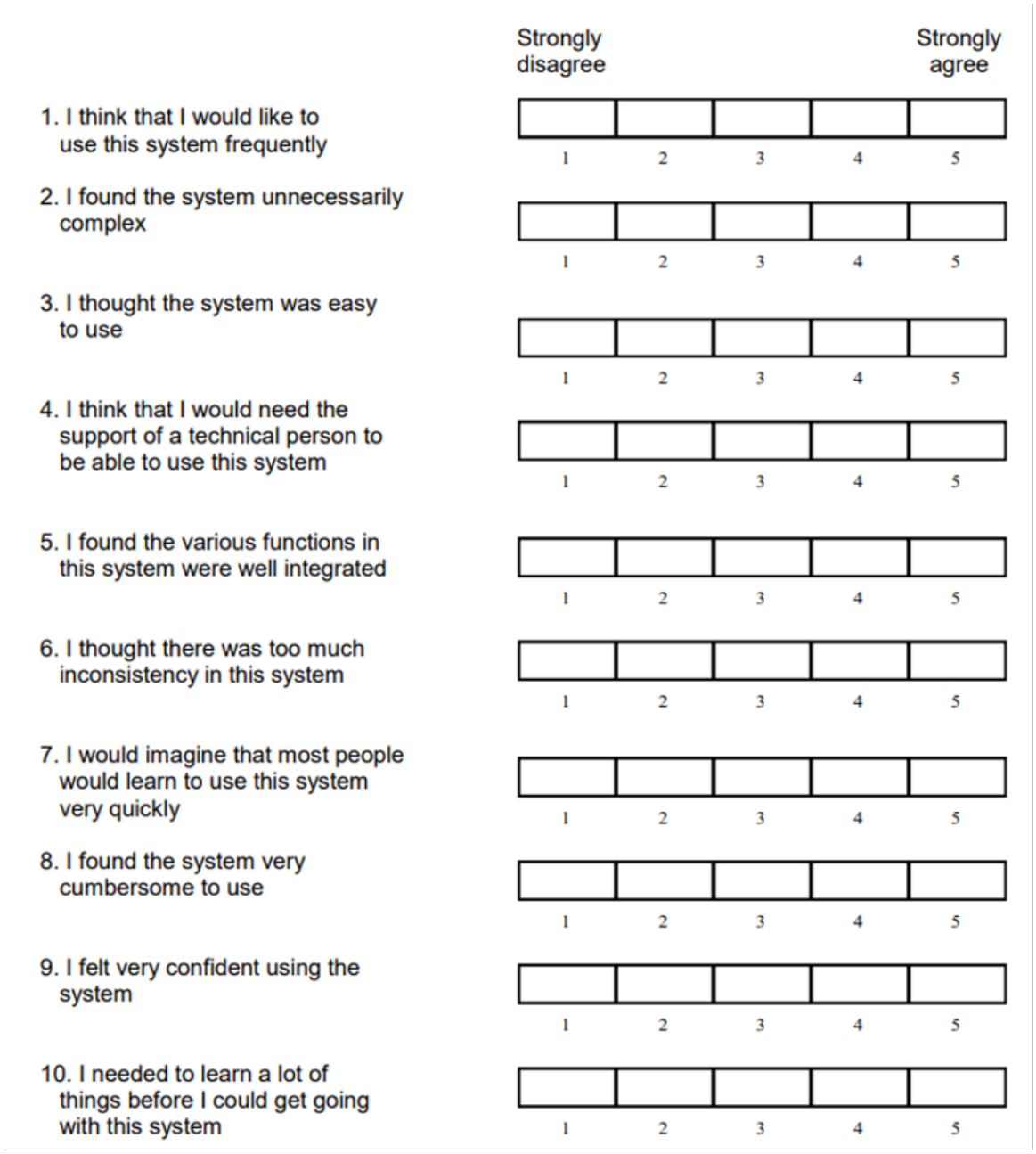
[44] Viswanath Venkatesh and Hillol Bala. Technology acceptance model 3 and a research agenda on interventions. *Decision sciences*, 39(2):273–315, 2008.

[45] Michel Wyndaele and Jean-Jacques Wyndaele. Incidence, prevalence and epidemiology of spinal cord injury: what learns a worldwide literature survey? *Spinal cord*, 44(9):523–529, 2006.

[46] Fei Xiong, Xin Liao, Jie Xiao, Xin Bai, Jiaqi Huang, Bi Zhang, Fang Li, and Pengfei Li. Emerging limb rehabilitation therapy after post-stroke motor recovery. *Frontiers in Aging Neuroscience*, 14:863379, 2022.

A. Appendix A

System Usability Scale (SUS) questionnaire.



B. Appendix B

User Experience Questionnaire (UEQ).

	1	2	3	4	5	6	7		
annoying	○	○	○	○	○	○	○	enjoyable	1
not understandable	○	○	○	○	○	○	○	understandable	2
creative	○	○	○	○	○	○	○	dull	3
easy to learn	○	○	○	○	○	○	○	difficult to learn	4
valuable	○	○	○	○	○	○	○	inferior	5
boring	○	○	○	○	○	○	○	exciting	6
not interesting	○	○	○	○	○	○	○	interesting	7
unpredictable	○	○	○	○	○	○	○	predictable	8
fast	○	○	○	○	○	○	○	slow	9
inventive	○	○	○	○	○	○	○	conventional	10
obstructive	○	○	○	○	○	○	○	supportive	11
good	○	○	○	○	○	○	○	bad	12
complicated	○	○	○	○	○	○	○	easy	13
unlikable	○	○	○	○	○	○	○	pleasing	14
usual	○	○	○	○	○	○	○	leading edge	15
unpleasant	○	○	○	○	○	○	○	pleasant	16
secure	○	○	○	○	○	○	○	not secure	17
motivating	○	○	○	○	○	○	○	demotivating	18
meets expectations	○	○	○	○	○	○	○	does not meet expectations	19
inefficient	○	○	○	○	○	○	○	efficient	20
clear	○	○	○	○	○	○	○	confusing	21
impractical	○	○	○	○	○	○	○	practical	22
organized	○	○	○	○	○	○	○	cluttered	23
attractive	○	○	○	○	○	○	○	unattractive	24
friendly	○	○	○	○	○	○	○	unfriendly	25
conservative	○	○	○	○	○	○	○	innovative	26

Abstract in lingua italiana

Le lesioni del midollo spinale (SCI) e gli ictus sono condizioni debilitanti che causano danni irreversibili ai tessuti neurologici, con conseguente perdita parziale o completa delle funzioni sensoriali e/o motorie. Queste patologie incidono significativamente sulla qualità della vita dei pazienti, compromettendone le funzioni e la partecipazione sociale. Diverse tecnologie di assistenza, come la Stimolazione Elettrica Funzionale (FES) e gli esoscheletri robotici, mirano a riabilitare e ripristinare la deambulazione in questi soggetti. Tuttavia, se utilizzato da solo, ogni sistema comporta alcuni svantaggi, soprattutto l'elevato ingombro per gli esoscheletri e l'induzione precoce dell'affaticamento muscolare per la FES. Per questo motivo, negli ultimi anni, la combinazione di questi due sistemi è emersa come un approccio molto promettente, in grado di fornire una riabilitazione neurologica più sicura, robusta ed efficace. Queste soluzioni sono definite Sistemi Ibridi di Riabilitazione Robotica e permettono di realizzare esoscheletri più leggeri, con un limitato affaticamento muscolare indotto. Allo stesso tempo, permettono di ottenere i benefici di un allenamento intenso, ripetitivo e orientato al compito e del mantenimento del tono muscolare, della riduzione della spasticità e dell'aumento del flusso sanguigno. La difficoltà principale rimane la realizzazione di un'integrazione efficiente delle due tecnologie, soprattutto a causa della ridondanza di attuazione.
Il progetto FESleg mira a superare le limitazioni esistenti sviluppando un dispositivo ibrido con un sistema di controllo cooperativo, in cui sia il motore che i componenti FES, contribuiscano attivamente ai movimenti di oscillazione del ginocchio durante la deambulazione. Il prototipo è stato inizialmente testato su soggetti sani e, successivamente, su due pazienti affetti da SCI, uno completo e uno incompleto. L'usabilità, l'accettabilità, l'esperienza dell'utente e la sicurezza del sistema ibrido sono state valutate e confrontate con la condizione in cui veniva utilizzato il solo esoscheletro. Paragonando le prestazioni di deambulazione tra le condizioni con e senza FES (nel primo caso con motori depotenziati), non sono state rilevate differenze statisticamente significative, dimostrando la capacità della stimolazione di compensare la ridotta partecipazione dei motori. Inoltre, l'integrazione della FES offre rilevanti benefici terapeutici ai pazienti. In conclusione, i risultati ottenuti aprono la strada ad ulteriori sviluppi nella realizzazione di sistemi ibridi impiegati come tecnologie di neuroriabilitazione.

Parole chiave: lesioni del midollo spinale (SCI), ictus, Stimolazione Elettrica Funzionale (FES), sistemi di riabilitazione robotica ibrida, esoscheletro

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