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On the road to Cybathlon 2024: lessons learned from the Polimi FES-bike team

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Abstract

Background Cybathlon competition is designed to promote innovation and usability of assistive technologies. Among its disciplines there is the Functional Electrical Stimulation (FES) bike race for people with Spinal Cord Injury (SCI). The aim of the race in 2024 was to cover 1960 m under 8 min. This work sums up the experience of the Polimi team on the road to Cybathlon 2024.

Methods A commercial recumbent trike was instrumented to enable FES-cycling. Moreover, a motor was added to the setup. While this motor was not mounted during the competition, it was used to optimize the stimulation angular ranges based on measurements of tangential forces and during the training sessions. Two subjects with complete SCI were recruited as pilots of our team. One of them completed the entire training protocol, which was based on the periodization principle to organize the training regimen in terms of training volume and intensity.

Results and discussion The stimulation ranges, which were experimentally optimised on the pilot who participated in the Cybathlon, resulted in a 99% increase in the time required for the cadence-based proportional-integral (PI) controller, used to modulate the stimulation currents, to reach saturation. The designed training regimen was successfully implemented and contributed to our pilot's qualification for the final, where he achieved third place.

Conclusion The proposed solution demonstrated its efficacy within the context of the FES-bike race. Events such as Cybathlon highlight the potential of FES-cycling and underscore the importance of promoting its widespread adoption beyond clinical settings, including among people with SCI and other user populations.

Keywords Cycling, Functional electrical stimulation, FES-cycling, Recumbent trike, Spinal cord injury, Sport-Therapy, Training protocol, Cybathlon, Case study

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Background

Since the first edition in 2016, Cybathlon has emerged as a promising platform for driving innovation, enhancing collaboration, and advancing technologies that support people with disabilities [1–3]. By challenging participating teams to improve technical performance and everyday usability of their solutions, Cybathlon promotes a design approach that prioritises the real needs and perspectives of the pilots, the end users of the assistive devices [4, 5]. More than just competition, Cybathlon creates a dynamic environment that not only supports the development of effective, user-oriented systems but also generates valuable insights that inform future research and contribute to advancements in the field of assistive technology [6].

Among the various disciplines featured in Cybathlon, the Functional Electrical Stimulation (FES) bike race has been a core event since the beginning [7]. The race is designed for individuals with complete Spinal Cord Injury (SCI) and is based on cycling powered by FES, a technology that has been in use with paraplegic subjects since the 1980s [8]. Since its initial adoption, recreational and locomotion aspects have been key drivers with the development of mobile devices [8–10] and the organisation of a competition held in England at the beginning of the 2000s [11]. As research progressed, alongside the leisure advantages, the therapeutic potential of FES-cycling became increasingly evident. Known benefits include enhanced cardiorespiratory fitness and augmented muscle volume and strength [12–15]. Over time, this activity has evolved into a rehabilitation exercise for individuals with various neurological conditions, commonly used in clinical practice with stationary cycle ergometers [16–18].

Through its competition framework, Cybathlon provides a valuable environment for investigating improved devices and stimulation strategies aimed at enhancing the performance achievable during exercise. In the 2024 edition of the FES-bike race, the objective was to cover 1960 m within 8 minutes, extending the target distance from previous editions, where the goal was 742 m in 2016 and 1200 m in 2020, all within the same time limit [19]. The technical requirements for the teams included the use of mobile devices; however, except for 2016, the race was conducted in a stationary format using a smart trainer in the latest editions, allowing teams to participate remotely.

Cybathlon has sparked renewed academic interest in the topic and prompted further investigation of the field [20]. Several teams have documented their competition experiences through case reports, offering detailed and practical examples of system design and pilot preparation. These contributions describe pilot progression, device development, and the evolution of customized trikes [21–34]. Key areas of focus include performance optimization, training protocol, muscle and electrode selection, as well as the refinement of control systems and stimulation strategies [20]. These efforts address persistent limitations that hinder FES-cycling performance and accessibility, such as the early onset of muscle fatigue due to non-physiological motor unit recruitment and mechanical inefficiencies [35, 36]. However, except for some examples like Berkel bike [37], there are still few commercial solutions that allow people to perform FES-cycling outdoors. Most of the developed systems are academic prototypes, which limits the widespread adoption of this technology for outdoor and independent practice by users. As a result, their real-world applicability remains restricted, particularly outside controlled research or clinical environments [6]. Nevertheless, a recent work on user experience shows that people with SCI appreciate the FES-cycling system and their use, providing evidence in support of the need for continued research on this activity [38].

Building on our team's participation in the 2024 FES bike race, this study aims to provide further insights into the Polimi FES-bike prototype and to expand the existing body of knowledge derived from previous case studies of the participating teams. We focus on the strategies adopted to enhance the pilot's performance and improve the overall mechanical efficiency of the exercise during the competition, with the ultimate objective of achieving a competitive result. We describe the customization and the autonomous use of the setup, the stimulation strategy, and the training plan designed for our pilots in preparation for the event. Moreover, an overview of the pilot's experience, contribution and feedback on the setup is included.

Methods

Pilots

Two pilots who met the eligibility criteria established by the Cybathlon organization committee provided their written informed consent to join the team and participate in the study. The Ethical Committee of Politecnico di Milano approved the study in December 2023 (number: 50/2023). Both participants have a sporty attitude, particularly Pilot 1, who regularly played table tennis. Only Pilot 1 completed the entire training protocol and took part in the competition. Pilot 2 experienced a health issue unrelated to the use of FES and did not compete at Cybathlon 2024. Demographic and clinical data about both pilots are summarized in Table 1.

FES-bike prototype

The Polimi FES-bike prototype (Fig. 1) is based on a commercial recumbent trike (Catrike 700) modified to allow

Table 1 Description of the pilots of the Polimi team

Pilot	Age (years)	Weight (kg)	Height (cm)	AIS	Level of injury	Years from the lesion (years)
1	43	76	175	A	T5	5.6
2	31	65	173	A	T3	2.6

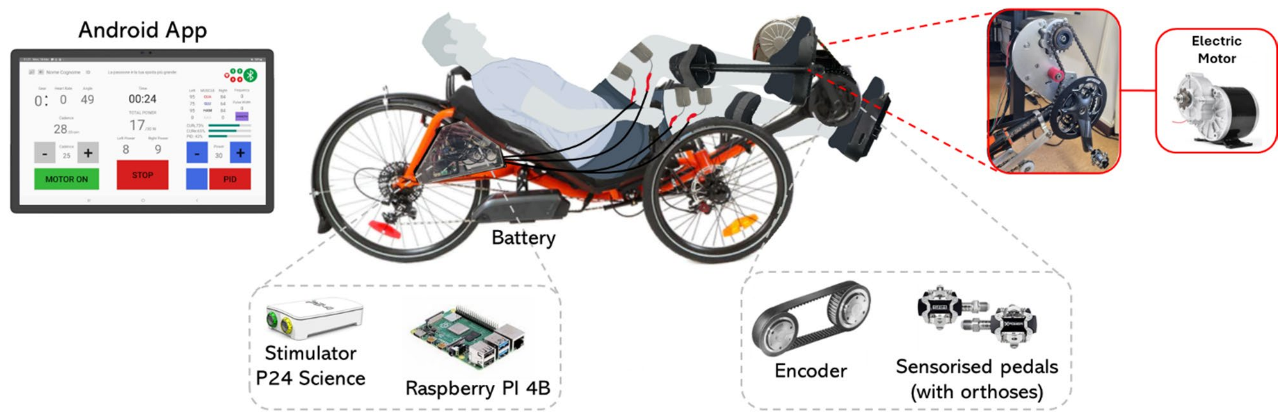

Fig. 1 FES-bike prototype. A commercially available trike (Catrike 700) with an absolute magnetic encoder (AS5047P, ams OSRAM) and sensorised pedals on the crank side. Behind the seat, there is a battery, as well as a box containing a Raspberry Pi 4B, a neurostimulator (P24 Science, Hasomed) and other electronics. Highlights in red show a detail of the motor mounted on the trike frame and coupled with a second transmission chain, enabling assisted pedalling and moving the passive legs. This element of the setup was then removed for the race. On the left a detail of the main page of the Android control application. The figure is composed using BioRender.com

individuals with reduced mobility to engage in FES-cycling [39].

A custom 3D-printed enclosure mounted on the rear of the trike houses the system's core components: (i) a Raspberry Pi 4B running the control software, written in C++, in real-time; (ii) an eight-channel neuromuscular stimulator (P24-Science, Hasomed GmbH) for muscle activation; and (iii) all the electronics needed for power management, motor drive and sensor readings. The system is powered by a 24 V, 10.4 Ah battery (GreenCell). A magnetic absolute encoder (AS5047P, ams OSRAM), coupled to the crank via a custom pulley–belt mechanism, measures the crank angle to synchronize muscle stimulation.

The proposed prototype also includes a brushed electric motor (MY1016Z2, 24 V DC supply, L-Faster) that can be used to assist the user, especially in outdoor use. The motor is mounted on the trike frame with a custom-made aluminium support that allows for a mid-drive configuration. When the motor is active, it moves the transmission line and the crank arms simultaneously, through a second transmission chain mounted on the external chainring, assisting the pedalling action by directly moving the legs. In this way, the motor applies torque at the crank, which in turn transmits the rotation to the rear wheel through the main chain. In addition, the motor shaft is connected to a freewheel sprocket. This means that the motor, which is set to move the pedals at the desired minimum cadence, does not contribute if the user pedals at a higher cadence. This feature was used during the pilot training to assist and perform specific tests. Then, to meet all the technological eligibility criteria for the FES race at the Cybathlon, the motor was dismounted.

To control the stimulation current intensities, the system employs a Proportional Integral (PI) closed-loop control that adjusts the delivered currents across all muscle groups to maintain a target cycling cadence. The software includes a FES pattern generator that takes the PI controller output and based on predefined stimulation angular ranges and minimum/maximum current amplitude, activates the muscles as a function of the crank angle.

To interact via Bluetooth with the system, an Android App was developed and used to modify all the parameters of interest and visualize useful information about the session. Furthermore, the pilot can control the stimulation through on-board physical buttons and can interrupt both the stimulation and motor assistance with an emergency stop button.

The proposed device is fully mobile, but most training sessions were conducted indoors with the trike mounted on a smart trainer (Wahoo Kickr Smart, Wahoo Fitness, USA), which enables users to connect to a third-party device via Bluetooth to adjust the resistance and monitor real-time power, speed, and distance.

Two custom-made ankle-foot orthoses (AFOs) were used to lock the ankle at 90° and restrict leg movement in the sagittal plane. Sensorised pedals were attached to the AFOs and included in the system. Two types of force pedals were used. For the optimisation procedure described in Paragraph 2.3.1, X-Power pedals (SRM GmbH) were used. For the training sessions and the Cybathlon race, Wahoo POWRLINK ZERO power meter pedals (Wahoo Fitness, USA) were used to provide riders with real-time power and cadence metrics via the Wahoo app. For measuring the power and cadence during the Cybathlon Competition, the Wahoo Powerlink Zero power meter pedals or the stationary bike trainer Wahoo Kickr were used.

Stimulation strategy

To induce the cycling movement, quadriceps, hamstrings and gluteus maximum of both legs were stimulated. Stimulation was delivered as balanced biphasic square-wave pulses at a default frequency of 30 Hz and a pulse width of 400 µs. An onboard button was programmed to activate a 'boost' phase, enabling the pilot to increase these parameters to 40 Hz and 500 µs, respectively. The "boost" was added to be used specifically during the final minutes of the race to provide additional stimulation to the muscles. If the "boost" button was activated, the frequency and pulse width remained at the increased value till the end of the training session. A 120 ms electromechanical delay was incorporated to ensure synchronization between muscle activation and crank position [40].

The stimulation current intensity was modulated by the PI controller based on cadence, within predefined minimum and maximum limits. These limits were determined for each muscle through a manual calibration procedure: the minimum was defined as the lowest intensity capable of eliciting a visible leg movement, while the maximum value was defined according to the pilot's comfort or the maximum output of the stimulator. This calibration was performed at the beginning of the training programme, and the resulting parameters were saved in a configuration file that was subsequently used for the following training sessions. If necessary, or at the pilot's request, these values could be adjusted during the training programme.

Stimulation was delivered through self-adhesive electrodes (Pals® from Axelgaard Manufacturing Co. Ltd.) placed on the skin with dimensions equal to 50 mm × 90 mm. Two electrodes for each stimulated muscle group were placed over the muscle belly [41, 42].

Personalisation procedure

The procedure described in [40, 43–45] was used to derive a personalised stimulation pattern for each pilot, exploiting the FES-bike's electric motor and the X-Power force pedals. This protocol focused on the quadriceps and hamstring muscles, which play the most significant role in power production.

Initially, the tangential forces exerted on the pedals were recorded for 1 min of 'passive cycling', meaning the legs were moved solely by the motor, at cadences of 25 and 35 RPM for Pilot 1 and 25, 35 and 45 RPM for Pilot 2. These cadences are representative of those used during training sessions. Afterwards, each muscle group in both legs was stimulated individually and continuously throughout the entire pedal revolution for 2 min, at a fixed frequency of 30 Hz, with a pulse width of 400 µs and a current amplitude sufficient to produce visible muscle contractions. Meanwhile, the motor maintained a constant cadence of 25, 35 or 45 RPM.

For each target cadence and stimulated muscle, the active force profile was obtained by subtracting the mean force profile during 'passive cycling' from that recorded during continuous stimulation. The angular range over which a positive active force was observed, indicating that the muscle group actively contributed to the cycling motion rather than opposing it, was then identified. The stimulation ranges for the quadriceps and hamstrings were determined by averaging the angular intervals of positive active force identified across all cadences and both legs. Finally, the obtained stimulation ranges were adjusted in order to minimize the overlap between antagonist muscles.

The personalized stimulation ranges were compared with an empirical set derived through a trial-and-error procedure informed by literature findings and adjusted based on pilot's feedback [46]. The comparison was made by means of two series of 4-min trials, performed at constant gear and target cadence, all in a pseudo-randomised order. The time to PI saturation was analysed, i.e. the time taken to reach the maximum stimulator current output to maintain the target cadence. In all trials, the gluteus muscles were stimulated but using always the empirical range. Indeed, the personalised procedure was not applied to the gluteus muscle due to its lower contribution to power production [47] and the lower level of current applied to this muscle, particularly with Pilot 1, to prioritise his comfort.

Training plan

Developing a training protocol based on sports science principles can be effective in preparing for the FES-cycling race, as demonstrated in [30]. One of the most widely used methods for athlete preparation is linear periodization, which involves dividing the training protocol into distinct phases or cycles. Each cycle focuses on specific physiological and performance goals that are aligned with the athlete's progression. The intensity and volume of training vary throughout the cycles to optimize adaptation and ensure the athlete reaches peak performance during the race [48].

For our preparation, we performed an initial period dedicated to conditioning and set-up adjustments between February 2024 and April 2024. Then, a 6-month macrocycle was established as the primary training period for the pilot and organized following the periodization principle into two main mesocycles: the Preparation Phase (PP) and the Competitive Phase (CP). The macrocycle followed a progressive model, from high-volume, low-intensity sessions and gradually to lower-volume, higher-intensity work as the competition approached. Low-intensity sessions were aimed at developing endurance, characterised by moderate effort over extended durations, typically using low cadences and gears. Conversely, high-intensity sessions consisted of short, explosive efforts, performed at higher cadences and with increased gear resistance. The definition of work during the mesocycle session was organised according to the session's volume and intensity. In particular, volume refers to the duration of the stimulation and the distance travelled within a session, while intensity was quantified using the mean linear velocity maintained during the activity, which is the result of the combination of the gear ratio and the pedalling cadence. This parameter was used to provide an accessible and consistent parameter to guide session workload.

The PP accounted for approximately 60% of the total training period and was composed of two types of sessions: the General Preparation (GP) ones and the Specific Preparation (SP) ones. Within the PP, training sessions were distributed in a 2:1 ratio, allocating twice as many sessions to GP as to SP. In the GP, the core training activity consists of "variations" sessions. These sessions usually included four repetitions of a continuous run over 2 km, with 5–10 min of rest between each repetition. During the run, we alternated between 300 m at low intensity and 200 m at medium intensity. In the SP, instead, we performed the so-called "pyramid training". This involved running intervals that progressively increase in distance from 300 to 800 m and then back down again to the starting distance. This formed a pyramid structure, with resting periods of around 2 min between intervals. As each repetition increased in length, the imposed speed decreased correspondingly. Conversely, as the distance shortened again, the intensity increased. Between different pyramids, a resting period of around 5–10 min was also planned.

In the competitive phase, we performed sprints over distances of 400–500 m as the main training activity. Each sprint was followed by a long rest period of around 10 min to allow recovery and ensure high performance throughout the session.

Each session was organised in the following way: the setup phase, where the electrodes were placed on the pilot and he transferred from the wheelchair, then the workout. The workout was composed of the warm-up (at low intensities), then the main activity accordingly to the phase in which we were working and then a cool down again at low intensities. During the session, the specific activity was alternated with resting phases in which stimulation was not provided and the motor kept the cycling movement. This was used to provide active rest phases, maintaining passive movement without requiring any effort from the pilot.

During the entire training protocol, in each session, the distance travelled, the gears used, the linear velocity, the stimulation time and the cadence were recorded. Moreover, the health status of the pilot was monitored during the sessions using a heart rate belt (Polar H10).

Flexibility in the training plan was maintained to accommodate variations in the pilot's health status, highlighting the importance of adaptability in long-term performance planning.

Every 4 weeks, race tests were performed to evaluate the progress towards the goal of the competition: 1960 m in 8 minutes.

A schematic representation of the developed training programme can be found in Fig. 2.

Other than the two training sessions with the trike each week, Pilot 1 also performs some home sessions. Pilot 1 used an electrostimulator (RehaStim, Hasomed GmbH) while he was lying in bed or sitting in a wheelchair and stimulated his quadriceps. Accordingly to his availability, the pilot chose the frequency and the number of repetitions of a 20-min training programme (usually 2 or 3 repetitions for each session). Current pulses were set at 30 Hz and with a pulse width of 400 μs. Current intensities were adjusted to the pilot's training level from 36 to 60 mA.

Another aspect studied during the preparation was the race strategy. Our approach was designed to maximize the benefits of the PI cadence control and Boost function. Specifically, the strategy was to start the race with a high target cadence of 55 RPM and to stay in the highest gear possible. Then, the rider reduces both the gear and target cadence to reach the maximum stimulator current output near the middle of the race. After reaching the saturation point, the rider can use the Boost to maintain performance. For the rest of the race, the rider adjusts the gear to prevent the cadence from dropping too much.

Results

Personalisation procedure

Figure 3 shows an example of the passive and active forces and the areas within the pedalling revolution where the difference is positive. These data were acquired during a trial at 35 RPM with Pilot 1.

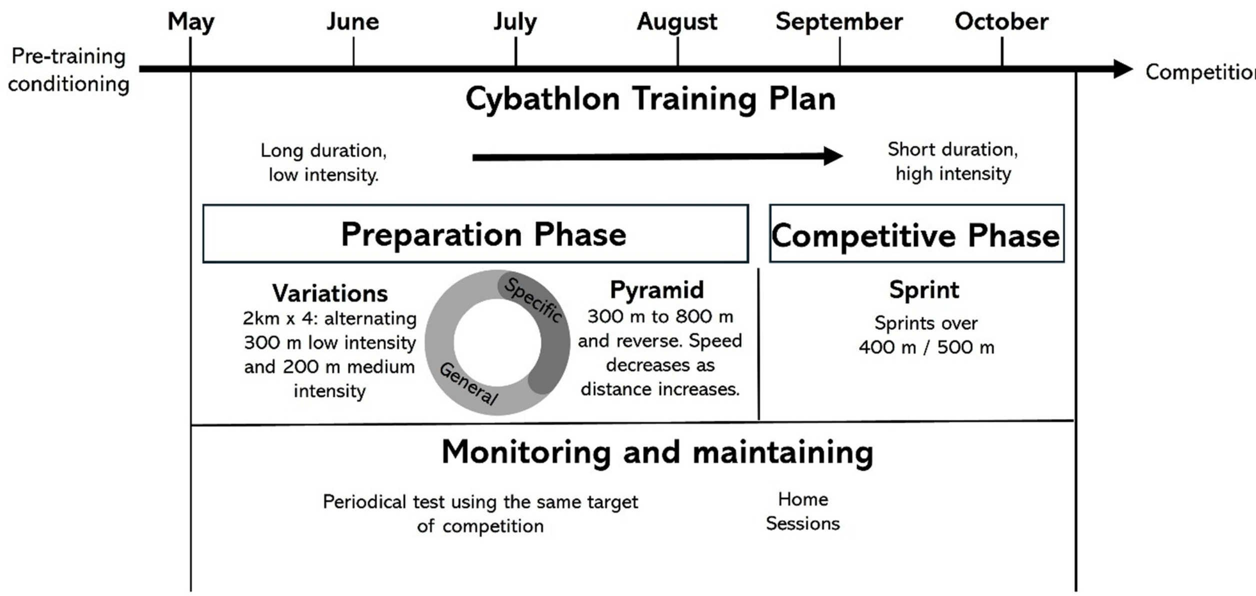

Fig. 2 An overview of the training programme followed in preparation for the race. The training plan was followed between May and October 2024. The main phases are highlighted with the specific training activity performed in the laboratory. Race tests used to monitor performance and home-based sessions for maintenance are also included to give a complete picture of the programme

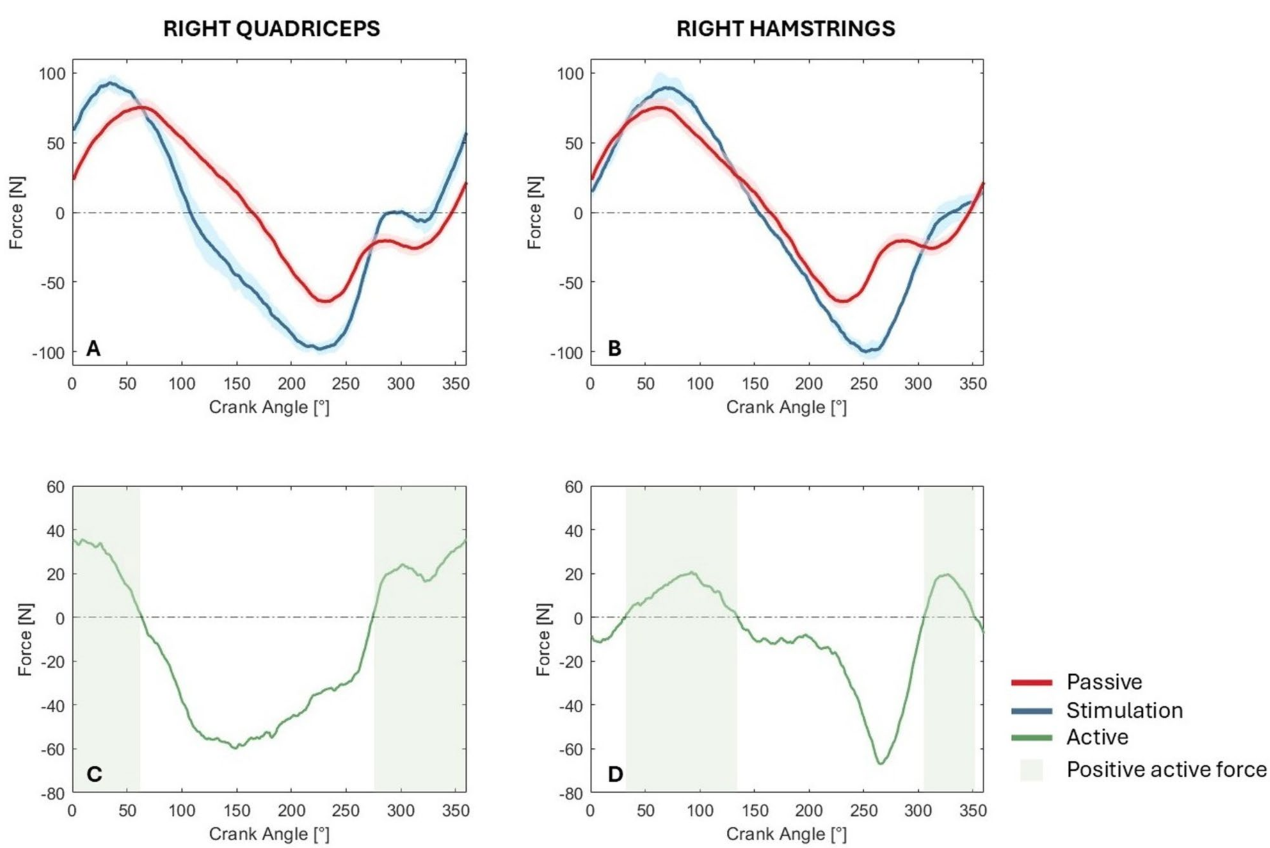

Fig. 3 An example of the methodology used to identify the angular ranges with the personalisation procedure applied to Pilot 1 in the trial at 35 rpm. The tangential forces exerted on the pedals during passive cycling and when the muscle is stimulated over the entire pedal revolution are depicted for both the right quadriceps (**A**) and the right hamstrings (**B**), as a function of the crank angle. The solid line shows the mean profile and the shaded area shows the standard deviation (SD). **C** and **D** report the corresponding FES-induced active forces, which are defined as the positive difference between the passive and stimulated profiles. The 0° represents the right crank in the top position

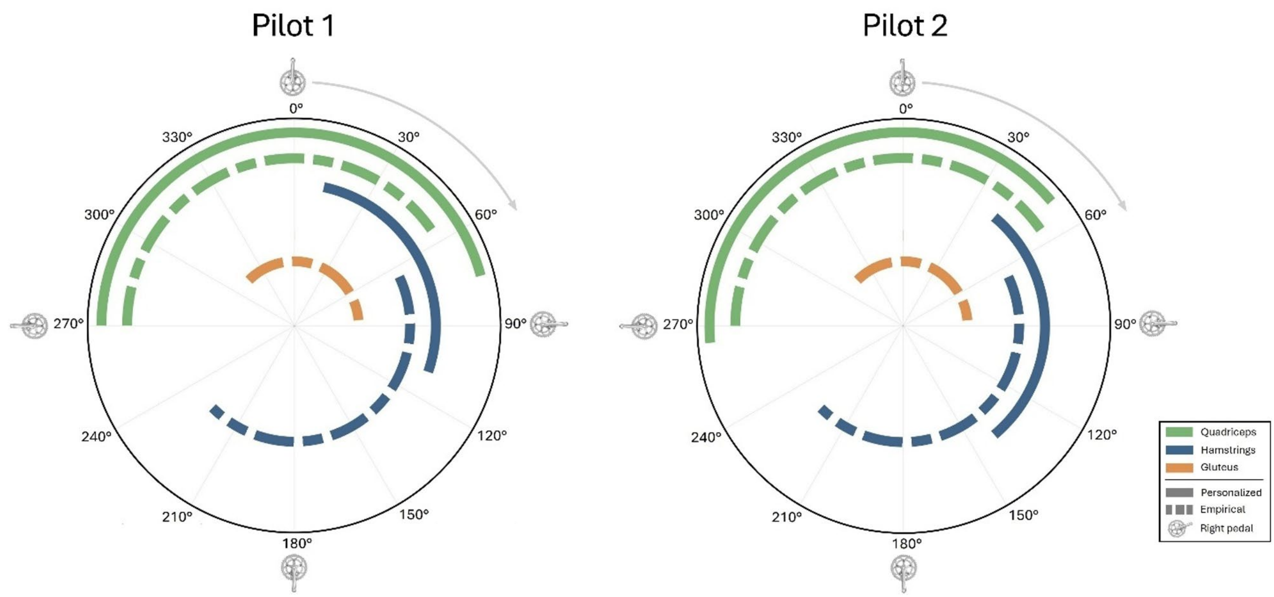

Fig. 4 The personalised muscular activation ranges for the right leg of both subject as a function of the crank angle. Zero degrees corresponds to the right pedal being at the top. Dashed lines show empirical ranges

Table 2 Time taken for the PI controller to reach saturation for both pilots, using both the empirical and personalised angular ranges. The target cadence set for the PI controller was 40 RPM for each trial

	Time to saturation (s)			
	Pilot 1		Pilot 2	
	Empirical ranges	Personalised ranges	Empirical ranges	Personalised ranges
T1	215	242	44	148
T2	129	230	56	92
T3	108	242	52	56
T4	107	165	30	55
Median	118.5	236	48	74
Variation %	99.2%		54.2%	

Figure 4 illustrates the stimulation ranges derived from the personalisation procedure for both subjects along with the empirical ones.

For the hamstrings ranges of Pilot 1, two peaks of active force were observed (Fig. 3D), likely due to the hamstrings' dual role in knee flexion and hip extension during pedalling. In order to define the hamstring activation ranges, it was selected only the first active force peak in Pilot 1, to minimise the overlap between the stimulation of quadriceps and hamstrings.

Time to PI saturation, which indicates a more efficient stimulation pattern when higher, as it requires less current amplitude to achieve the same velocity, nearly doubled for Pilot 1 and notably increased for Pilot 2 (Table 2).

Table 3 Minimum and maximum value of current amplitude for Pilot 1.

Muscle group	Minimum value (mA)	Maximum value (mA)
Quadriceps	50	130
Hamstrings	60	130
Gluteus	45	90

Training plan

Considering that only Pilot 1 completed his preparation, only his training progress will be presented. We report in Table 3 the minimum and maximum values of current amplitude used during the training with the trike by Pilot 1. The values were equal for the right and left leg.

During the 6 months of preparation, Pilot 1 attended a total of 40 lab training sessions out of the 46 planned, showing a high adherence to the programme. The lab training was interrupted during the vacation of the pilot which are highlighted in Figs. 5 and 6 with grey areas. Pilot 1 additionally completed 29 home sessions on separate days. In Fig. 5, the mean value of linear velocity, the stimulation time for each lab training session, the total distance covered during the lab training session, and the maximum value of heart rate are reported. The trend for each quantity is highlighted in each subplot to show how it evolved during the training period.

Figure 6 shows the results of each race test. In the distance-covered panel, an initial improvement trend is observed, followed by a decline in performance after the pilot's vacation. Afterwards, a stronger improvement trend is observed in the final race tests. A similar trend can be observed in the cadence panel. With respect to the panel related to the saturation time, which is the time the

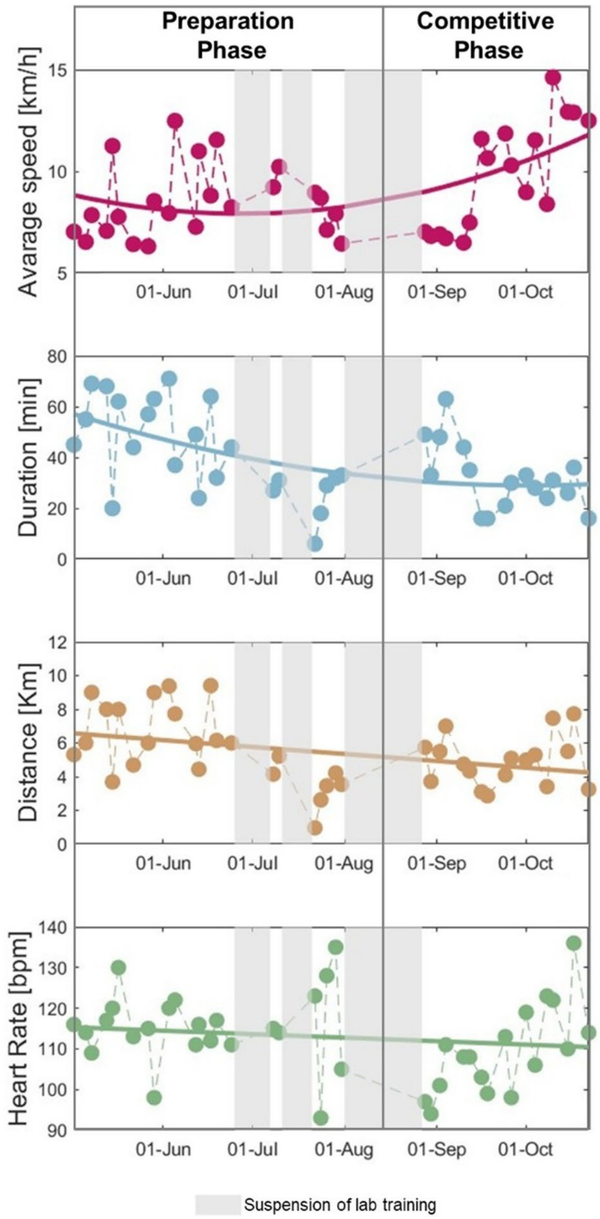

Fig. 5 Lab training results. From the top panel to the bottom panel, the parameters are displayed in the following order: average speed, session duration, total distance covered, and maximum heart rate. Each point represents the value of a specific quantity in each training session

pilot reaches the maximum level of current amplitude, a similar behaviour to that of distance and cadence parameters can be observed in the first part of the preparation. In the final part of preparation, near the competition, this test was used to refine the race strategy and define when it was better to activate the boost, so that saturation was reached around the middle of the test, thereby identifying the window in which activate this modality. Trials using higher gear ratios were also conducted in this phase to increase the intensity, resulting in an earlier onset of PI saturation and a higher covered distance.

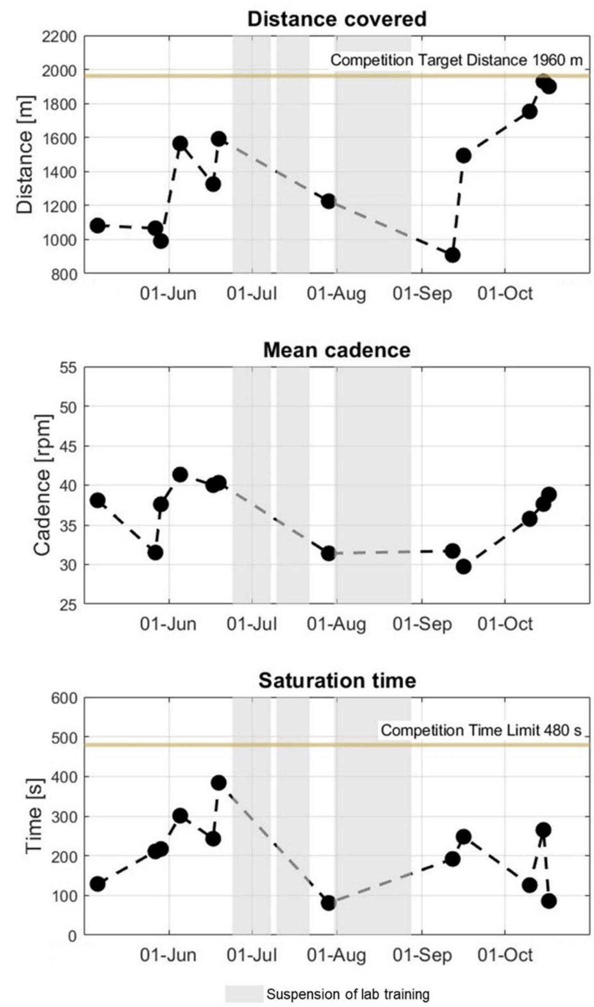

Fig. 6 Results of the 8-min race tests. In the upper panel, each point represents the distance in meters covered in each race test. In the middle panel, each point represents the mean cadence maintained during the test. In the lower panel, each point represents the time at which saturation occurred. Grey areas indicate suspension of lab sessions

Race results

Our pilot secured a spot among the four finalists thanks to his qualifying performance. He concluded the race, covering 1840 m in 7 min and 38 s, with an average speed of 14.46 km/h and an average power output of 30.7 W. He won his qualification session. Figure 7 shows data acquired during the qualifying race by the device and the powers measured by the pedals. The gear used during the race is also provided. Only the current amplitude of the quadriceps is reported, as the trend is similar for the other muscles. In the first phase of the race, the pilot started pedalling at a target cadence of 55 rpm and a gear ratio of 39/14 (front/rear teeth). During this phase, the PI controller began to increase the current amplitude to track the desired cadence. After approximately 36 and 115 s, the pilot downshifted to a 39/15 and 39/17

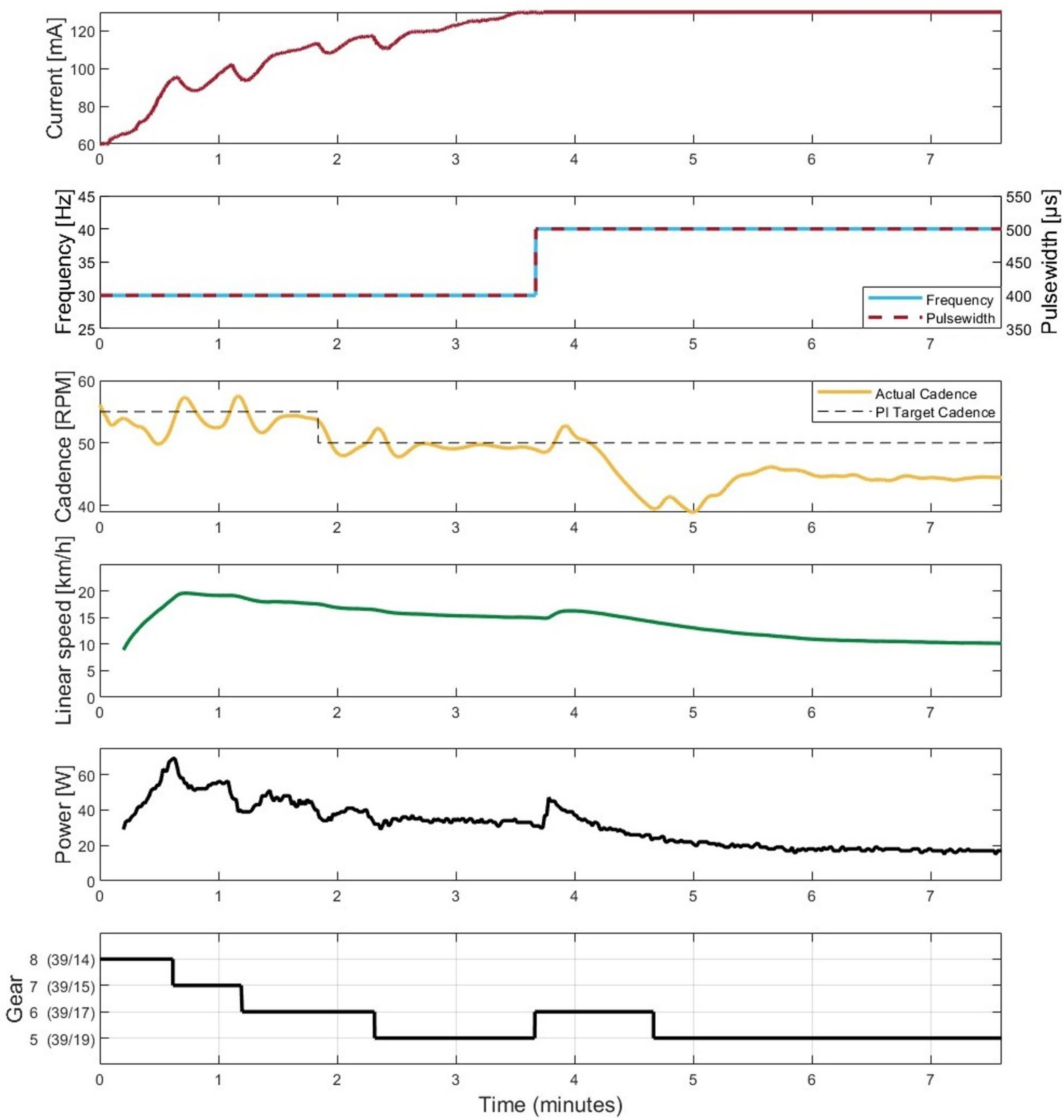

Fig. 7 Quadriceps current amplitude, stimulation frequency and pulse width, cadence, linear speed, exerted power, gear ratio (front/rear teeth), during the qualification race

gear ratio, respectively. This resulted in a temporary drop in current amplitude, delaying saturation. After around 2 min, the pilot decreased the target cadence to 50 rpm and shortly afterwards downshifted the gear ratio to 39/19. Around 4 min into the race, the PI controller saturated, the pilot activated the boost, and the gear was increased again, resulting in an instantaneous peak in power exerted. Less than 1 min later, the cadence and power exerted started to drop. At this time, the pilot reduced the gear, stabilising the cadence at around 45 rpm and the power exerted at around 20 W until the end of the race.

Regarding the final, he completed the race with an average power output of 35.2 W and successfully met the target with an average pace of 15.54 km/h: he covered the target distance in 7 min and 34 s, achieving his personal best. Ultimately, he secured third place in the overall competition.

Insights from the pilot

The name of our pilot who competes in Cybathlon 2024 is Andrea Gatti. In 2019, while on a cycling excursion with friends, he was the victim of an incident that left him paralyzed. Despite this life-changing incident, he remains busy, strong-willed, and focused, with a strong passion for sports. He was first introduced to our team in 2019 when he was encouraged by his doctors to try FES-cycling to maintain his muscle tone. Soon after, we invited him to be our pilot for Cybathlon 2020, marking the start of a long-lasting collaboration. Here's his thoughts about our experience together.

"The experience of preparing for the 2024 race with this group of students and researchers was a beautiful one, especially compared to the 2020 edition, which was affected by the pandemic. The training sessions not only focused on refining the system and optimizing performance but also became moments of genuine human connection and intellectual exchange. We discussed possible improvements for the trike, and I came up with the idea of a platform to make the transfer between the wheelchair and the trike easier. Moreover, we talked about a wide range of topics, going far beyond the scope of the competition, fostering a strong sense of team spirit and shared growth. The race itself was an unforgettable moment, filled with emotion and significance. Thanks to the dedication, commitment, and support of my team and family, we were able to reach the podium. That achievement, filled with joy, relief, and pride, was stunning. My hope for the future is to make the trike more adaptable to outdoor and environmental conditions, which can often be challenging. I strongly emphasize the importance of usability and the need to create a welcoming, harmonious community that engages even more people in using this type of device." A video of the transfer using the platform can be found in the Supplementary Material.

Discussion

To compete effectively in the Cybathlon FES bike race, a comprehensive approach is important, considering that a variety of different aspects should be addressed. The set-up should be optimized and adjusted to the specific characteristics of the pilot. Moreover, a structured training programme and the dedication of the pilot are essential to reach peak performance. In this study, we share our journey to highlight key insights and discuss their broader applicability beyond participation in Cybathlon.

While our set-up encompasses the fundamental components that each FES-cycling device should include, our team's device also incorporates a motor that was used only during the training phase and for the refinement of the stimulation strategy. We used the motor to perform an automated method for deriving angular ranges. Other research groups have illustrated how a procedure based on forces and torques can serve as a valuable and scalable tool for the optimization of stimulation patterns. Previously, this process was conducted using a cycle ergometer [40, 44], and in the case of the trike, it relied solely on manual operation by a user instead of a motor [43] or using a stationary platform like in [45]. With the motor mounted on the trike, it is now possible to perform the procedure in a repeatable and automatic way using a mobile platform. The obtained ranges were used with the pilots, and the validation tests shows how the personalised ranges enhance the cycling performance. Moreover, we used the motor to perform passive cycling during the pause between stimulation phases in training sessions [49]. This provided an 'active rest' period, which can be useful given that passive cycling has been shown to offer benefits such as enhanced blood circulation, reduced spasticity and maintenance of the musculoskeletal system [50]. The flexibility and modularity of our system enable straightforward customisation, making it adaptable to a wide range of end-user functional abilities and training goals. In particular, the motor can be leveraged to enable prolonged and fully automated training sessions [49].

The training protocol followed during the 6 months before the competition demonstrated its efficacy. After a long preparation, the pilot was able to reach the target distance imposed by the Cybathlon organization within the time limit. Looking at the collected data, it is possible to derive some considerations. First, the pilot adhered strictly to the protocol throughout the training period. This is essential for effective muscle development and his preparation condition. We successfully followed the original plan and an inverse relationship between speed and stimulation time can be observed: as we increased intensity, we reduced the volume of each session. Another important insight that can be drawn from the results of the training protocol is that, as reported in previous studies, physiological parameters such as heart rate are not reliable indicators of exertion in individuals with spinal cord injuries. Due to autonomic dysfunction, heart rate does not accurately reflect the level of effort in this population. Therefore, exercise programs based on measurable outputs such as distance covered or resistance levels are more appropriate for structuring and monitoring training in these cases [51, 52]. In our case, we opted to use the linear velocity maintained during the session, since, as can be observed, there is no clear trend in the heart rate of our pilot. Finally, inspection of the race test results (Fig. 6) shows that, although performance declined after a period of inactivity, the subjects rapidly returned to their previous fitness level, consistent with findings reported by Botzheim et al. [53].

Consistent with other case studies [30], we include in this study the experience of our pilot who took part in

Cybathlon 2024 to offer additional insights and a comprehensive perspective. The pilot's testimony highlights the effectiveness of FES-cycling and its potential to positively impact the lives of people with disabilities. During his experience with us, he provided valuable suggestions to enhance the usability of the trike, in line with the user-centred design approach promoted by Cybathlon. In particular, he came up with an idea to support a more independent use of the trike: by adding a foot platform, he was able to transfer between the trike and wheelchair entirely on his own.

Events like Cybathlon, with the inherent dynamics of their competitive environment, offer valuable opportunities to refine technical setups and increase public awareness. Although such events are sporadic and do not provide continuous access to FES-cycling practice [5], they represent a pragmatic means of steering research toward high-impact topics that often fall outside mainstream academic or industrial priorities. Among these topics is the promotion of sport as a fundamental tool for enhancing both the physical fitness and psychological well-being of people with disabilities. In this context, technology and research play a key role in developing innovative solutions that make sport genuinely accessible. The FES-motorized trike developed by our team represents a significant step in this direction. Its flexible platform, capable of automatically optimizing the stimulation strategy to suit each individual user, integrated with motorized assistance, enable sporting engagement not only for individuals with spinal cord injuries, but also for a broader population, including stroke survivors and other vulnerable groups. By supporting use in non-competitive settings, the system can maximize inclusivity and promotes both the social and physical benefits associated with the activity. However, as stated in our pilot interview, there are still some barriers that limit accessibility of FES-cycling. Efforts should be directed to enhance the ease of use of the device, focusing on aspects like transferring and electrodes placement. With respect to this last point, the use of customized pants with integrated electrodes could be an interesting proposal [28]. Finally, there remains a pressing need to integrate FES-cycling into broader, structured programmes fully embedded within the healthcare system, ensuring continuity of training and long-term user engagement. One promising direction is the development of home-based systems, as demonstrated in several existing cases [54], which enable remote monitoring and ensure greater sustained use.

This work presents some limitations. First, only two pilots were initially involved in the study, and following the withdrawal of Pilot 2, only the training results of a single pilot could be reported. Nonetheless, this is fully consistent with the Cybathlon experience. Second, because the platform evolved over time, particularly due to the replacement of the sensorised pedals required to comply with Cybathlon rules, we were unable to obtain consistent power measurements across all training sessions. Finally, although the training program was designed according to the linear periodisation method, full adherence to the protocol was not achievable due to the pilot's availability.

Conclusion

This case study describes our journey toward participation in the FES-bike race of Cybathlon 2024. The contribution of our pilot was fundamental in refining both the setup and its practical use, which he found valuable and effective. The implemented training plan and the recorded performances demonstrate the critical role of physical conditioning in achieving high performance in FES-cycling. The developed device is modular, incorporating additional components that, while not essential for the race itself, are fundamental to training and to promote its use also in wider contexts. Considering the multiple benefits of this activity, greater efforts should be directed toward supporting the widespread adoption of sport-therapy programs based on FES-cycling, also with other user populations.

Abbreviations

SCI	Spinal cord injury
FES	Functional electrical stimulation
PI	Proportional Integral
AFOs	Ankle-Foot Orthoses
PP	Preparation phase
CP	Competitive phase
GP	General preparation
SP	Specific preparation

Supplementary Information

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Supplementary Material 1. The manuscript includes a video of the pilot using the platform during the transfer from the wheelchair.

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Author contributions

DS drafted the protocol, developed the prototype, assisted pilots during their training, handled data curation and formal analysis, and contributed to drafting the article. NS drafted the protocol, developed the prototype, assisted pilots during their training, handled data curation and formal analysis, and co-drafted the article. FE and EU drafted the protocol, assisted pilots during their training and handled data curation. EG contributed to developing the protocol and reviewed the article. FM was responsible for conceptualizing the project, securing funding, pilots' recruitment, overseeing project administration and supervision, and reviewing the article. MT was responsible for conceptualizing the project, securing funding, overseeing project supervision and reviewing the article. AP was responsible for conceptualizing the project, securing funding, overseeing project administration and supervision, and reviewing the article. SF was responsible for conceptualizing the project, securing funding, and reviewing the article. EA was responsible for conceptualizing the project, team coordination, drafting the protocol, securing funding, overseeing project administration and supervision, and reviewing the article.

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Data availability
The datasets analyzed in the current study are available in the Zenodo repository: https://zenodo.org/records/18599582.

Declarations

Ethics approval and consent to participate
All participants provided written informed consent. The study was approved by the ethics committee of Politecnico di Milano in December 2023 (approval number: 50/2023).

Consent for publication
The participant signed a consent form for publication.

Competing interests
The authors declare no competing interests.

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