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Participation to the first Cybathlon: an overview of the FREEWHEELS team FES-cycling solution

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Abstract

This article is a contribution to a special issue aiming at collecting data and documenting the different specificities of the teams which participated into Cybathlon 2016 FES-bike discipline. Our team prepared one paraplegic pilot over one year and developed a FES-cycling device based on existing commercial products. Our pilot (47 y.o, spinal cord lesion T3 AIS A since year 1995) was qualified for the final race and finished in 6th position over 12 participants in the discipline, covering a total distance of 750m at an average speed of 5.71km/h, propelled by his own quadriceps and hamstrings muscles.

Key Words: FES cycling, spinal cord injuries, Cybathlon

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In 2016 an academic research team (CAMIN, INRIA, Montpellier, France) and a rehabilitation center team (COS DIVIO, Dijon, France) have participated into Cybathlon competition, in the FES-bike discipline under the name of FreeWheels team.¹ Despite more than 14 years investigating on Functional Electrical Stimulation (FES) applications and more broadly in the field of Neuroprostheses,²⁻⁶ using FES for cycling was a first for the research team. The FES-bike discipline consisted of a series of races between two spinal cord injured (SCI) participants propelling a cycling device by means of their lower limbs muscular contractions elicited by FES. The participants had to cover a 750 meters distance in less than 8 minutes, starting from a 10° descending ramp. Mobile and stationary cycling using FES have been widely investigated since the 1980s through many studies.⁷⁻¹³ It has been shown that FES-cycling of subjects with SCI results in physiological and psychological positive effects such as cardiovascular training, decrease in pressure sores occurrence and self-esteem improvements.¹⁴⁻¹⁶ However, the use of this technology has often remained restricted to indoor and stationary ergometers in clinical contexts, partly due to the small amount (10–25 W) of power produced,^{17,18} the requirement of experimented users and the lack of commonly available affordable FES outdoor bikes. Cybathlon FES-bike challenge motivated considerable efforts in technical developments to allow the coverage of a significant distance at a suitable speed.

This event promoted the activity as recreational with potential mobility applications. In the following we

describe the different characteristics of our pilot and device.

Material and Methods

This study was conducted in accordance with the principles of the Declaration of Helsinki and approved by the local Ethics Committee (CPP Dijon, ID RCB: 2016-A00279-42), including the participant selection, physical preparation, training and participation into Cybathlon. One subject was included, the so-called pilot.

Inclusion and exclusion criteria

The Cybathlon competition rules constrained the participant to present an ASIA A or B spinal cord injury, with a complete loss of motor function. We have furthermore defined the following inclusion criteria: age ≥ 18 years and < 65 years, complete traumatic lesion > 12 months, neurological level T2 to T12, stable medical status, stimuable sublesional muscles and passive joint movement in the lower limbs. Exclusion criteria were defined as follows: body mass index ≥ 30 , pressure ulcer, thrombophlebitis, neurogenic paraosteoarthropathy, cardiovascular disease, muscle disease, DXA T-score < -2.5 , hip or knee arthroplasty, epilepsy, hypotension, lower limb fracture within the past 12 months, a pacemaker or other implant, and pregnancy. No beta-blocker treatment was authorized during the experiment.

Pilot profile

The pilot was selected in respect with the inclusion criteria listed in the previous paragraph. He was 47 years

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Fig 1. The two trikes used (left) during the initial training program, the Berkelbike Pro® and (right) for the final training program and at the competition, the FreeWheels trike

old (1m78, 74kg) at the time of inclusion and presented a spinal cord lesion T3 (AIS A) since 1995.

Tricycle description

Two distinct cycling devices were used during the study (Fig. 1).

- A the Berkelbike Pro®, a commercial tricycle designed for persons with physical limitations.
- B the FreeWheels trike, an instrumented recumbent cycle adapted from a commercial device, the ICE

Trike Adventure® designed for non disabled individuals.

The Berkelbike Pro® was chosen to allow the pilot to train before the FreeWheels competition device was finalized (3 months before the competition). No modification was done on the device. The choice of the competition tricycle was based on several considerations. The first requirement concerned accessibility allowing for safe wheelchair/trike transfers (retractable handles,



Fig 2. FreeWheels pilot during the Cybathlon final race. Photos credits : geschützt

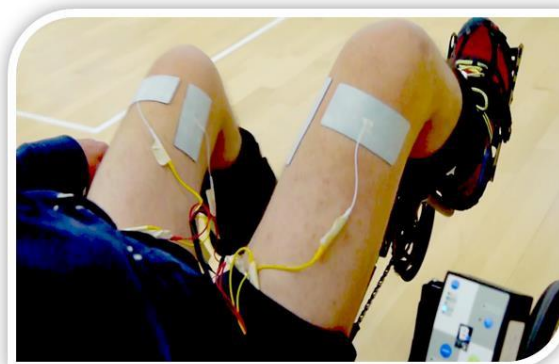
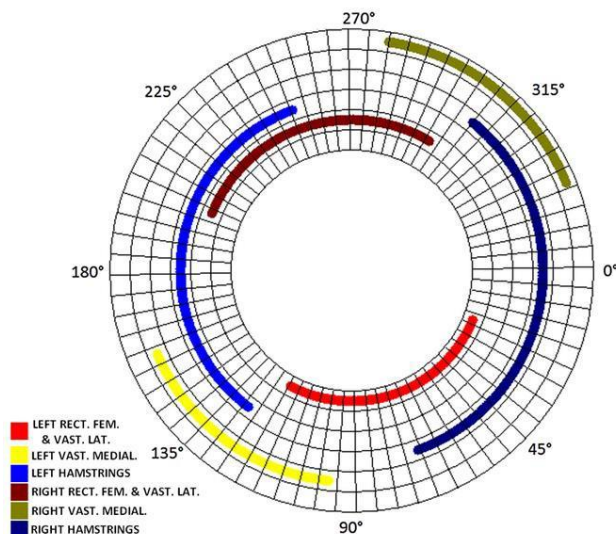


Fig 3. Stimulation pattern designed with individualized quadriceps and hamstrings. On each leg, one channel is dedicated to the rectus femori/vastus lateralis muscles, a second channel to the vastus medialis and a third one to the hamstrings

low height, high stability, etc ...). In order to later facilitate diffusion of the approach we also wanted the device to be affordable, foldable and sufficiently light for transportation. We have selected the ICE Adventure 26

model (cost € 3000, foldable steel frame, overall weight of 17.5Kg and 2m length). This product has a mesh seat, designed to provide an optimum back support and comfort. The tension in the back could be adjusted. The cover features is made on a breathable fabrics to maximise airflow. A VICAIR®-type pressure relief cushion was chosen by the team occupational and physiotherapists and then fixed on the seat to avoid sliding. Hase® pedals with calf support were adapted to ensure a sufficient lateral locking of the legs while holding the ankle joint at 90°. The ICE trike was initially equipped with a 26" rear wheel, we changed for a 24" one to tilt the bike and elevate the crank relatively to the pilot's position (Fig. 2). Low rolling resistance tires (Schwalbe® Kojak 24 x 1.35") were also mounted instead of the original tires.

A few weeks before Cybathlon competition we decided

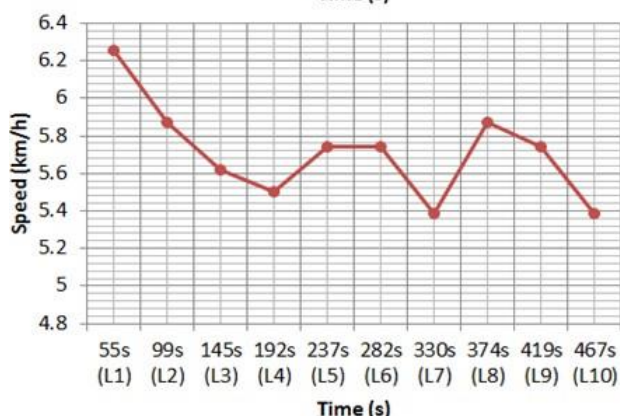
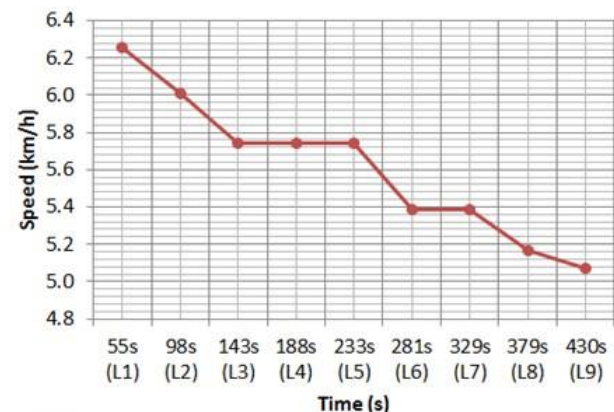


Fig 4. Average speed (km/h) computed on each lap (from L1 to L10) during the Cybathlon qualification (top) and final (bottom) races

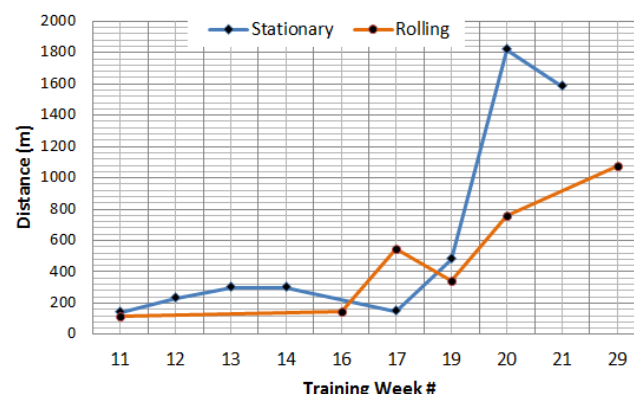


Fig 5. Maximum covered distance during the training sessions, from M9 to M13 (from week 11th to week 29th of the FES-cycling program)

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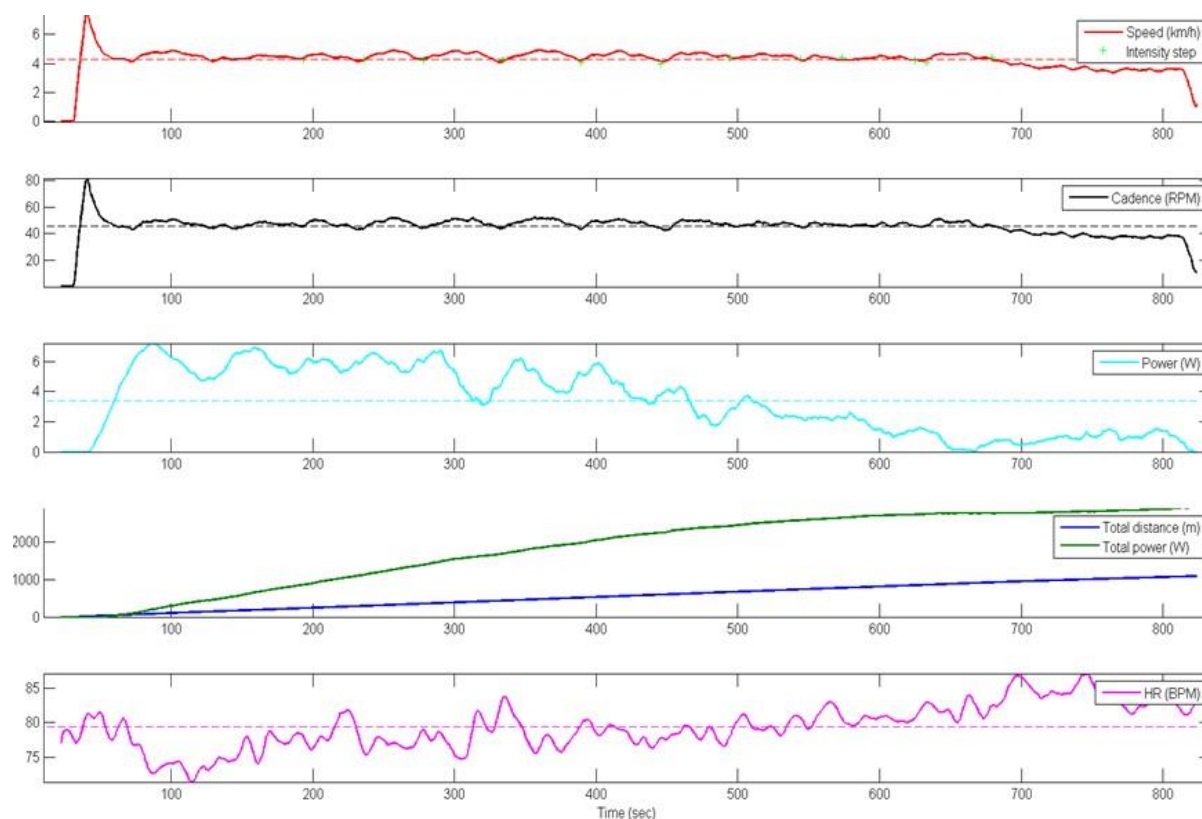


Fig 6. Data overview collected during a final evaluation race at M13.

to modify the rear wheel transmission, initially a freewheel, to a fixed-gear. This decision was made in consequences of difficulties to pass the “dead points” during cycling phase (0° and 180° , full extension/full flexion). Our pilot could not succeed to complete the pedaling cycle once fatigue appeared and sometimes from the beginning of training. Furthermore, the co-contraction balance between hamstrings and quadriceps muscle activations has a critical influence at these particular dead points and with time the equilibrium initially tuned is becoming less optimal (fatigue, movements on the seat...). The fixed-gear wheel was also supported by Szecei 2007 et al.¹⁹ results, where the forces smoothing introduced by the use of a fixed-gear improved endurance. The gear ratio was set to be equal to 1.22 (number of rear wheel spins for one complete crank spin, or ratio between the chainring and the rear sprocket). Calculated with the 24” rear wheel, we chose this ratio in order to best match between the optimal literature cadence,¹⁹ and the speed needed to reach 750 meters in 8 minutes, i.e. about 47 RPM (5.6km/h). The classical approach of FES-cycling is to predefine muscular activation patterns regarding the crank angle needed for the timing of the stimulation. The Berkelbike Pro® is equipped with such a crank sensor that can be connected to a stimulator commercialized by the company. A similar crank angle encoder (Baumer MDFK08) has been adapted on the crank axis of the FreeWheels trike in order to provide pedaling angle as

an input to the stimulator. In addition, we have instrumented the device with different kind of sensors used to monitor the performances. Two speedometers were set, one with the screen oriented towards the pilot and a second one oriented to be visible to a person walking aside the trike. Finally, we added an ANT+ cardiac strap monitor to follow heart rate in response to effort.

Stimulation Parameters

During this study, we used the Berkelbike® FES-Box stimulator, an 8-channels battery powered stimulator. In cycling mode, a pre-programmed pattern based on crank angle, triggers the stimulation on and off cycles. Electrical stimulation was delivered on each leg via three stimulation channels composed each one of two platinum stimulating electrodes, size 4.5x10cm, respectively located along the rectus femori/vastus lateralis muscles, the vastus medialis and the hamstrings (Fig. 3). A musculocutaneous flap was taken from the gluteus maximus as a treatment of a sacral pressure ulcer which prevented us to consider this muscle group as a candidate to electrical stimulation. Stimulation pattern was designed with individualized quadriceps. On each leg, the first channel dedicated to the rectus femori/vastus lateralis muscles was set to be effective during the pushing phase (full flexion to vertical crank), meanwhile the second channel was meant to later activate the vastus medialis, from the time where the



Fig 7. Power is computed via force pedals, cadence and speed are monitored via two inertial sensors (on the crank and rear wheel)

pedal was vertical to the full extension position. Hamstrings were respectively activated just before full extension and until the dead point was passed. Each training sessions were initiated with a warm-up phase, either set on a home trainer or rolling on a flat surface, before proceeding to the endurance race. During the warm-up phase, stimulation frequency was set to a lower level (20Hz) than during the race (30Hz). In both cases, we used a rectangular charge-balanced biphasic pulse stimulation with a pulsewidth of 400 μ S per phase, an interpulse of 200 μ S and a maximum intensity set to 150mA. The pilot controlled the stimulation intensity based on the speedometer information in order to fit the desired cadence of 47RPM. By pressing a button on the stimulator, he could gradually increase the level of stimulation on all the channels by 4.5mA steps when the speed tended to go below 5.6km/h.

Training information

A one year (12 mo.) training program was designed, divided into two stages:

1. from months M1 to M6: home based, two to three times a week, stimulation program of the lower limb muscles (quadriceps / hamstrings) during 30 minutes of isometric training using CEFAR® Physio 4 stimulator and the following stimulation parameters: rectangular charge-balanced biphasic pulse stimulation with a pulsewidth of 300 μ S per phase and a ramp up, sent at 30Hz during 10s followed by 3s of rest. At the start of each month, a mapping determined the intensity of stimulation needed to

obtain contraction of the electrostimulated muscle and the intensity needed to reach a 4/5 score on the MRC (Medical Research Council) scale.

2. from M7 to M11: FES-cycling training program, two to three times a week, on an instrumented trike. Either set on a home trainer or rolling outdoor and indoor on a flat surface. Stimulations parameters were modulated on the basis of progress.

From the beginning of the training, psychological and functional variables were also continuously monitored (self esteem, life quality, etc...).

Results

Performances

FES-bike race was divided into two main steps, a qualification race and a final race. Our pilot was successfully qualified after a first race (670m in 430s, Fig.4) and could take part in the final race. The average speed during the final race was of 5.71 km/h where he reached a maximal speed of 6.26km/h. He finished 6th out of 12, accomplishing the whole race in 467 sec. Our cyclist reached his best performance one week before Cybathlon when he succeeded to achieve a distance of 1820m on the ICE trike in stationary mode and 760m rolling outdoor on a flat surface (Fig.5). Overcoming some technical issues, the functional performances dramatically and continuously increased from M11 (Fig. 5). Speed and endurance goals were successfully reached at M12 and kept evolving at M13 (1080m in 14min, Fig. 6).

Feasibility

The total cost of the device including the tricycle and the stimulator is estimated to 7650€ (4500€ for the stimulator, 3000 euros for the tricycle, and the rest for mechanical adaptations). The solution has the advantage to be easily duplicated. The choices made on its adaptation were driven by the Cybathlon objective: to cover 750m in less than 8min. The system should be adapted and optimized to allow better performances based on the acquired knowledge. The stimulation patterns are designed through an individual manual tuning, with no general rule, making the procedure, at this stage, hardly feasible by an uninitiated user outside of a clinical environment

Discussion

Our participation into this human adventure was a team success. Despite numerous practical issues the initial goal was reached. We have not yet been able to objectivize and quantify all the technical choices and their consequences made to reach the Cybathlon goals. During the development phase we equipped the tricycle with inertial sensors (one on the crank and a second one on the rear wheel) and pedal power meters (Powertap P1, Fig. 7), using ANT+ wireless communication protocol and a specifically developed software. The

original idea was to modulate stimulation parameters and patterns regarding pedaling cycle and produced forces. However, the feature which was supposed to give us a real time access to the stimulator parameters had not been ready on time before Cybathlon competition. Moreover, the pedal power meters were not sensitive enough to ensure an accurate measurement of the weak produced forces and to be usable as input to close loop control. Meanwhile, the different figures monitoring speed during training and races (Fig. 4 and Fig. 6) show the manual control of intensity level regarding cycling speed was really close to the initially automated considered one (consign of average speed set at 5.6 km/h, average recorded speed during final race of 5.71 km/h). The covering surface of the track also represented an important factor which drastically affected the obtained performances all along training and race sessions and could not have been quantified. The pilot training was part of a research protocol in which a longitudinal observation was achieved. The aim was to follow the evolution of performances as well as physiological and psychological parameters. Our pilot demonstrated a global acceptance of the participation into this 1 year protocol and an improvement along the experience of psychological variables such as life quality and self-esteem could be observed. Taking part in a competition as the final aim of the training program demonstrated a real benefit on training constraints tolerance.²⁰⁻²⁷ This experience and the interactions with other teams breaks new grounds to innovative and generic FES-cycling based training programs for an important range of SCI subjects. However, the constraints and the reality behind people with SCI daily lives are far from the Cybathlon FES bike context and require numerous improvements such as further investigations to enable a safe recreational use in complete autonomy of this activity.

List of acronyms

AIS - Abbreviated Injury Scale.
CAMIN – Control of Artificial Movement & Intuitive Neuroprosthesis
COS - Centre d'Orientation Sociale
CPP - Comité de Protection des Personnes
DXA - Dual Energy X-Ray Absorptiometry
FES - Functional Electrical Stimulation
ICE - Inspired-Cycle-Engineering
INRIA - Institut National de Recherche en Informatique et Automatique
MRC - Medical Research Council
RCB - Recherche et Collection Biologique
RPM - Revolutions Per Minute
SCI - Spinal Cord Injuries

Author's contributions

BS is the principle author and responsible for the technical integration and software design of the FreeWheels project. CF and AD were responsible for

the clinical protocol, pilot training and follow up. CA was the leader of the team. All the authors read and approved the final version of the manuscript.

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Conflict of Interest

The authors declare no potential conflict of interests.

Ethical Publication Statement

We confirm that we have read the Journal's position on issues involved in ethical publication and affirm that this report is consistent with those guidelines.

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