

# Strategies and performances of Functional Electrical Stimulation Cycling using the BerkelBike with Spinal Cord Injury in a competition context (CYBATHLON)

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### Abstract

The functional electrical stimulation (FES) bicycle race was an event at the Cybathlon, held in Zurich October 2016. BerkelBike BV (The Netherlands) in collaboration with Imperial College London entered a spinal cord injury pilot who had tetraplegia to compete in this event. The BerkelBike Pro is a commercially available FES capable recumbent which is normally driven by the arm- and leg power. The arm cranking part was disabled. Now the tricycle must be driven using the pilots own lower limb muscles through stimulation in accordance with race rules. The bike used during the race was also adapted with a fixed gear for improved efficiency. The pilot who represented this team come second place overall in the event and attained the fastest race time of all pilots who utilised surface electrode FES. Steps can be taken to increase the race efficiency of the BerkelBikes and its FES capabilities even further.

**Key Words:** FES, FES ycling, Cybathlon, SCI, Tetraplegia

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The Cybathlon was an event that took place in Zurich, October 2016. This event was organised by ETH Zurich and involved six events with the aim of including individuals who were living with physical and neurological restrictions. International teams recruited ‘pilots’ to compete in these events, and included scientists and engineers from both academic and commercial enterprises. One of the events held at the Cybathlon was the functional electrical stimulation (FES) bike race. A pilot from the UK was entered into the FES bike race using a BerkelBike, this team was a collaboration between BerkelBike BV with support from academics at the Imperial College London (ICL).

### FES bike race

This event involved two pilots riding around a 750 m flat track. The time taken for the pilots to reach the finish line were recorded in a first round of races which determined the pilot pairings for the finals.<sup>1</sup> The pilots involved had spinal cord injuries (SCI) and were to move around the track using only the power from their legs, stimulated by FES. No additional pedalling assistance was allowed, this included hand cranks and pedal assist motors and drives.<sup>1</sup> Due to no additional pedalling assistance being allowed the FES pilots needed a running start. This came in the form of a

‘stumpy gate’ which held the pilots and their bikes on a declining slope. Once the race started the gates opened and allowed the pilots to start rolling forward.<sup>1</sup>

### Pilot inclusion criteria

The pilots for the FES bike race had to fit certain criteria<sup>1</sup>:

- Spinal cord injured pilots who have a lesion which has caused leg paralysis.
- ASIA A or B, with a complete loss of motor function.
- The lower motor neuron must be intact; thus, the lesion must be spastic (not atonic).
- Pilots must have sufficient voluntary control of their trunk, arms, and neck to steer the bike and stabilise the upper body while riding down a ramp and turning curves.

The BerkelBike and ICL team 3 potential pilots to choose from, all of whom were already riding a BerkelBike. A BerkelBike is an arm and leg driven tricycle.<sup>2</sup> The candidate was selected on their ability to cycle around a test track using only power from the legs while being stimulated with FES. They suffered from a weakness in both hands, but the right hand was sufficiently weak that it had to be safely strapped to the handle bars during training and racing to ensure it stayed

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in place. The pilot chosen for the event was the candidate who could cycle the furthest using FES with legs alone. This pilot had a C5 SCI and was tetraplegic.

### Pilot information

- Lesion level – C4/C5
- Age at injury – 16
- Current age – 22
- Pilot weight – 62 kg
- Pilot height – 178 cm

### Muscles stimulated during the race:

- Quadriceps
- Hamstrings
- Gluteal muscles

### Stimulation Parameters

- The stimulation program was controlled by the onboard computer.
- An encoder uses the position of the pedals to determine which muscles to stimulate
- During the race, the pilot could control the intensity of stimulations.

### Technology inclusion criteria

The technology used for the race had to comply with the following criteria:

- Only passive cycling devices without actuation are allowed. The propulsion force must come from the FES activated lower limbs of the pilot.
- The FES stimulator can be commercially available or custom made. If it is custom made, it must fulfil the standard rules for electrical safety, including the latest IEC standards 606011 and 606012-10 (or similar rules applied in other countries), which describe requirements for the basic safety and essential performance of transcutaneous nerve and muscle stimulators.
- Any control strategy or stimulation pattern can be used for stimulating lower extremity muscles such as quadriceps, hamstrings, gluteal, and calf muscle groups. It is not necessary to stimulate all these muscles.
- FES stimulation intensity can be adjusted by the cycling athletes during the race so that they can apply their own strategy to minimize muscle fatigue effects.
- Surface and implanted stimulation technologies are allowed. The implantations must be medically stable for at least six months and free of complications (e.g. infections) prior to the competition
- Any number of stimulation channels are allowed.
- The FES stimulators can apply closed-loop control strategies using sensors applied to the pilots or the bike.
- The cycling device structure and functioning can be optimized for better mechanical efficiency.
- Any number and any size of wheels are allowed.

- Maximum width of the cycling device is limited to 900 mm to enable proper use on the ramps and in the lanes.

Cycling devices must be able to turn curves with a radius of approximately 13 m. During the Cybathlon the pilot from BerkelBike and ICL was riding an EasyLegs Pro,<sup>2</sup> which allows propulsion from the legs only. The frame is made from Aluminium, and the weight is 19 kg, measuring approximately 170 by 78 by 100 cm in dimensions.<sup>2</sup> The EasyLegs Pro is a recumbent tricycle with a gear hub used at the front wheel.<sup>2</sup> A fixed gear was fitted for this event to improve pedalling efficiency. The BerkelBike Pro is a delta recumbent configuration tricycle with the pedals situated directly above the driving wheel. The seat can be changed in position relative to the longitude of the frame and in this case, was positioned slightly forward of the rear axle which has two wheels. The FES control box was situated in the centre of the handlebars of the BerkelBike and could be controlled by the pilot using buttons on this box. The FES control strategy was open-loop and the intensity of the stimulation was controlled by the pilot.

### FES parameters:

- Output current range – 0 to 150 mA.
- During the race, the pilot started at a stimulation level of 60 mA then worked up to the maximum of 150 mA.
- The stimulation had a frequency of 35 Hz.

Electrical stimulation using two electrodes per muscle was applied to the quadriceps, hamstrings and gluteal muscles of both legs of the pilot. The duration and timing of the pulses was determined by the position of the crank and the intensity was controlled by the pilot using plus and minus buttons on the stimulator attached to the steering bar in an open loop system. No further instrumentation was required during the race. The FES stimulation was applied using surface adhesive electrodes so was non-invasive.<sup>3-12</sup>

### Physical preparation of the pilot

Training for the event included outdoor cycling on the BerkelBike almost every day. The pilot had been in possession of a BerkelBike for 3,5 years prior to the Cybathlon, so they were already an active user of this technology. The BerkelBike that the pilot was already in possession of was an arm and leg system, so to prepare for the Cybathlon his training included sessions in which he was restricted from using his arms. This was to let the pilot get accustomed to leg cycling only. Physiotherapist sessions were used to help manage the SCI. A track was used to periodically measure the time taken to cycle 750 m as a performance indicator during the training phase. The pilots diet was examined and a higher protein intake and breakfast were recommended, as these were missing previously

## Performance at the Cybathlon

The pilot obtained a silver medal during the Cybathlon, achieving the best result of all the pilots utilising adhesive surface electrodes. During the first race at the event a track time of around 4:14 minutes was obtained, whilst in training the time was regularly around 7 minutes.

## Discussion

The increase in performance on the day of the event can be attributed to the conversion to a fixed gear system and updated FES protocols. During training a hub gear system was used. The limitations in cycling power output were determined by the capacity of the muscles of the pilot. A second pilot was considered for the Cybathlon who could produce much more force in his leg muscles therefore cycling faster, but he fatigued more quickly and was unable to cycle the required 750 m without reducing speed. The pilot was very active before his injury and thus was very motivated to become active again and find new ways of exercising, he had been using the BerkelBike for 3.5 years prior to the Cybathlon. He built up good fatigue resistance during these years and has had no injuries during training or use. As a tetraplegic, his right hand has no useful function so was strapped to the handlebars throughout the race, his left hand was used to push the buttons to control the stimulation intensity. During the final race, a bump in the track caused the pilot to be shifted in his seat, unable to shift himself back meant that performance was affected. The pilot had a faster start which dropped after the bump, the result was a time of 4:08 minutes. Improvements can be made to the seat or frame of the bike to ensure pilots are more secure in place in the future. Collaboration with other teams present at the first Cybathlon FES Cycling competition and beyond will provide further hints and tips.<sup>13-20</sup>

## List of acronyms

FES - functional electrical stimulation  
SCI - spinal cord injuries

## Author's contributions

RB and BV equally participated in experimental design, data collection, writing and revision of the manuscript.

## Acknowledgments

We would like to thank Dr. Aldo Faisal and Dr Ian Radcliffe from Imperial College London for their help in organising the team and for the support during the Cybathlon. Special thanks to Paul Moore at Active Linx in also helping to prepare for the event and to Johnny Beer for participating in the race.

## Conflict of Interest

The authors have no conflicts 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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