informatics mathematics

Activity Report 2018

Team CAMIN

Control of Artificial Movement & Intuitive Neuroprosthesis

Inria teams are typically groups of researchers working on the definition of a common project, and objectives, with the goal to arrive at the creation of a project-team. Such project-teams may include other partners (universities or research institutions).

RESEARCH CENTER
Sophia Antipolis - Méditerranée

THEME
Computational Neuroscience and Medicine

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Team CAMIN

Creation of the Team: 2016 January 01

Keywords:

Computer Science and Digital Science:

A1.2.6. - Sensor networks
A1.3. - Distributed Systems
A2.3. - Embedded and cyber-physical systems
A2.5.2. - Component-based Design
A4.4. - Security of equipment and software
A4.5. - Formal methods for security
A5.1.4. - Brain-computer interfaces, physiological computing
A6.1.1. - Continuous Modeling (PDE, ODE)
A6.3.2. - Data assimilation
A6.4.1. - Deterministic control

Other Research Topics and Application Domains:

B1.2.1. - Understanding and simulation of the brain and the nervous system
B2.2.1. - Cardiovascular and respiratory diseases
B2.2.2. - Nervous system and endocrinology
B2.2.6. - Neurodegenerative diseases
B2.5.1. - Sensorimotor disabilities
B2.5.3. - Assistance for elderly

1. Team, Visitors, External Collaborators

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2. Overall Objectives

2.1. Overall Objectives

CAMIN research team is dedicated to the **design and development of realistic neuroprosthetic solutions for sensorimotor deficiencies** in collaboration with clinical partners. Our efforts are focused on clinical impact: improving the functional evaluation and/or quality of life of patients. Movement is at the center of our investigative activity, and the **exploration and understanding of the origins and control of movement** are one of our two main research priorities. Indeed, optimizing the neuroprosthetic solutions depends on a deeper understanding of the roles of the central and peripheral nervous systems in motion control. The second research priority is **movement assistance and/or restoration**. Based on the results from our first research focus, neuroprosthetic approaches are deployed (Figure 1).

Electrical stimulation (ES) is used to activate muscle contractions by recruiting muscle fibers, just as the action potentials initiated in motoneurons would normally do. When a nerve is stimulated, both afferent (sensitive) and efferent (motor) pathways are excited. ES can be applied externally using surface electrodes positioned on the skin over the nerves/muscles intended to be activated or by implantation with electrodes positioned at the contact with the nerves/muscles or neural structures (brain and spinal cord). ES is the only way to restore movement in many situations.

Yet although this technique has been known for decades, substantial challenges remain, including: (i) detecting and reducing the increased early fatigue induced by artificial recruitment, (ii) finding solutions to nonselective stimulation, which may elicit undesired effects, and (iii) allowing for complex amplitude and time modulations of ES in order to produce complex system responses (synergies, coordinated movements, meaningful sensory feedback, high-level autonomic function control).

We investigate functional restoration, as either a **neurological rehabilitation solution** (incomplete SCI, hemiplegia) or for **permanent assistance** (complete SCI). Each of these contexts imposed its own set of constraints on the development of solutions.

Functional ES (FES) rehabilitation mainly involves external FES, with the objective to increase neurological recuperation by activating muscle contractions and stimulating both efferent and afferent pathways. Our work in this area naturally led us to take an increasing interest in brain organization and plasticity, as well as central nervous system (brain, spinal cord) responses to ES. When the objective of FES is a permanent assistive aid, invasive solutions can be deployed. We pilot several animal studies to investigate neurophysiological responses to ES and validate models. We also apply some of our technological developments in the context of human per-operative surgery, including motor and sensory ES.
CAMIN research will be focused on **exploring and understanding human movement** in order to propose neuroprosthetic solutions in sensorimotor deficiency situations to **assist or restore movement**. Exploration and understanding of human movement will allow us to propose assessment approaches and tools for diagnosis and evaluation purposes, as well as to improve FES-based solutions for functional assistance.

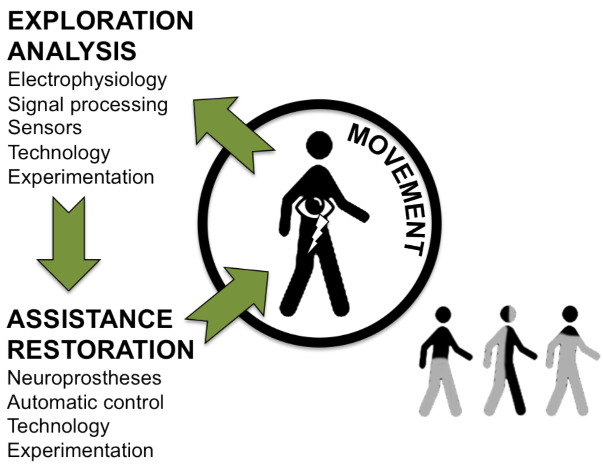


Figure 1. Overview of CAMIN *general scientific approach.*

The expertise and skills of our individual team members will be combined to design and develop solutions to restore movement functions.
We have chosen not to restrict our investigation spectrum to specific applications but rather to deploy our general approach to a variety of clinical applications in collaboration with our medical partners. **Our motivation and ambition is to have an effective clinical impact**.

3. Research Program

3.1. Exploration and understanding of the origins and control of movement

One of CAMIN's areas of expertise is **motion measurement, observation and modeling** in the context of **sensorimotor deficiencies**. The team has the capacity to design advanced protocols to explore motor control mechanisms in more or less invasive conditions in both animal and human.
Human movement can be assessed by several noninvasive means, from motion observation (MOCAP, IMU) to electrophysiological measurements (afferent ENG, EMG, see below). Our general approach is to develop solutions that are realistic in terms of clinical or home use by clinical staff and/or patients for diagnosis and assessment purposes. In doing so, we try to gain a better understanding of motor control mechanisms, including deficient ones, which in turn will give us greater insight into the basics of human motor control. Our ultimate goal is to optimally match a neuroprosthesis to the targeted sensorimotor deficiency.

The team is involved in research projects including:

- Peripheral nervous system (PNS) exploration, modeling and electrophysiology techniques
  Electroneurography (ENG) and electromyography (EMG) signals inform about neural and muscular activities. The team investigates both natural and evoked ENG/EMG through advanced and dedicated signal processing methods. Evoked responses to ES are very precious information for understanding neurophysiological mechanisms, as both the input (ES) and the output (evoked EMG/ENG) are controlled. CAMIN has the expertise to perform animal experiments (rabbits, rats, earthworms and big animals with partners), design hardware and software setups to stimulate and record in harsh conditions, process signals, analyze results and develop models of the observed mechanisms. Experimental surgery is mandatory in our research prior to invasive interventions in humans. It allows us to validate our protocols from theoretical, practical and technical aspects.
- Central nervous system (CNS) exploration
  Stimulating the CNS directly instead of nerves allows activation of the neural networks responsible for generating functions. Once again, if selectivity is achieved the number of implanted electrodes and cables would be reduced, as would the energy demand. We have investigated **spinal electrical stimulation** in animals (pigs) for urinary track and lower limb function management. This work is very important in terms of both future applications and the increase in knowledge about spinal circuitry. The challenges are technical, experimental and theoretical, and the preliminary results have enabled us to test some selectivity modalities through matrix electrode stimulation. This research area will be further intensified in the future as one of ways to improve neuroprosthetic solutions.
  We intend to gain a better understanding of the electrophysiological effects of DES through electroencephalographic (EEG) and electrocorticographic (ECoG) recordings in order to optimize anatomo-functional brain mapping, better understand brain dynamics and plasticity, and improve surgical planning, rehabilitation, and the quality of life of patients.
- Muscle models and fatigue exploration
  Muscle fatigue is one of the major limitations in all FES studies. Simply, the muscle torque varies over time even when the same stimulation pattern is applied. As there is also muscle recovery when there is a rest between stimulations, modeling the fatigue is almost an impossible task. Therefore, it is essential to monitor the muscle state and assess the expected muscle response by FES to improve the current FES system in the direction of greater adaptive force/torque control in the presence of muscle fatigue.
- Movement interpretation
  We intend to develop ambulatory solutions to allow ecological observation. We have extensively investigated the possibility of using inertial measurement units (IMUs) within body area networks to observe movement and assess posture and gait variables. We have also proposed extracting gait parameters like stride length and foot-ground clearance for evaluation and diagnosis purposes.

3.2. Movement assistance and/or restoration

The challenges in movement restoration are: (i) improving nerve/muscle stimulation modalities and efficiency and (ii) global management of the function that is being restored in interaction with the rest of the body under voluntary control. For this, both local (muscle) and global (function) controls have to be considered.
Online modulation of ES parameters in the context of lower limb functional assistance requires the availability of information about the ongoing movement. Different levels of complexity can be considered, going from simple open-loop to complex control laws (Figure 2).

Real-time adaptation of the stimulation patterns is an important challenge in most of the clinical applications we consider. The modulation of ES parameters to adapt to the occurrence of muscular fatigue or to environement changes needs for advanced adaptive controllers based on sensory information. A special care in minimizing the number of sensors and their impact on patient motion should be taken.

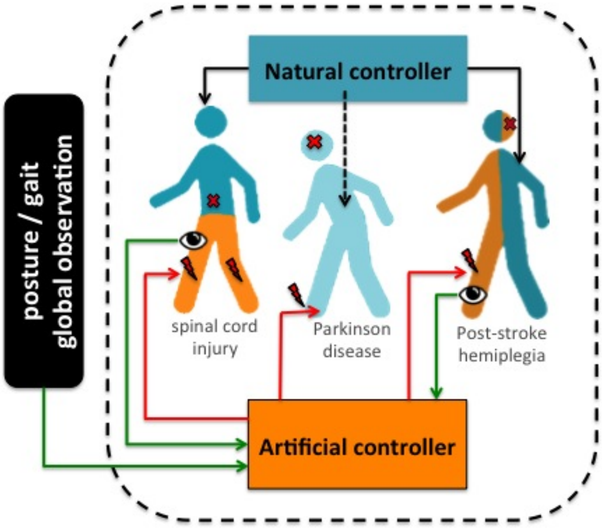


Figure 2. FES assistance should take into account the coexistence of artificial and natural controllers. Artificial controllers should integrate both global (posture/gait) and local (limb/joint) observations.

4. Highlights of the Year

4.1. Highlights of the Year

- The startup NEURINNOV was created in November 2018, David Andreu and David Guiraud will leave CAMIN team to join the company. A first research collaboration was established between CAMIN and Neurinnov as part of the Isite MUSE, through the Spin Stim project. The Spin Stim project focuses on severe impairments of vesico-sphincteric functions. It is a deep partnership based on the implementation of Neurinnov staff directly in the research unit.
- François Bonnetblanc was laureat of the French Scholars Lecture Series 2018 – Peter Wall Institute of Advanced Studies - University of British Columbia / Embassy of France in Canada, (https://pwias.ubc.ca/program/french-scholars-lecture-series) and laureat of the TOR Program 2018 between France and Sweden, (https://www.institutfrancais-suede.com/tout-sur-tor/).
- Benoît Sijobert was finalist of the Handitech Trophy (https://www.lahanditech.fr/), presenting a project related to his Phd work in CAMIN team, among 156 projects awarding inclusive technologies.
- Wafa Tigra got the 2017 IFRATH [1] PhD thesis price on October 2018.
- Ana Claudia Lopes (UnB, Brazil) presented the paper « Quadriceps electrical stimulation to assist sitting pivot transfer by a person with paraplegia » at IFESS conference 2018 and won the Vodovnik Award student paper competition (2nd position). This work was done within the context of CACAO associate team.

5. New Software and Platforms

5.1. RT_Stim

Real-Time simulation for functional electrical Stimulation

[1] Institut Fédératif de Recherche sur les Aides Techniques pour les personnes Handicapées

KEYWORDS: Real time - Biomechanics - Control - Co-simulation
FUNCTIONAL DESCRIPTION: Hybrid simulation architecture gathering in a single framework and consistent time scales both the numerical integration of the continuous model of a bio-mechanical system (bones, joints and muscles) and a model of the hardware and software control architecture, including control tasks, communication protocols and real-time schedulers. Simulation run in real-time when possible, and otherwise consistent time scales are generated. The framework is intended to seamlessly evolve from purely software models to hardware-in-the-loop simulation.

- Contact: Daniel Simon

5.2. Platforms

5.2.1. Modular embedded architecture for real time control of a FES system

Participants: Christine Azevedo Coste, Benoît Sijobert, Ronan Le Guillou.

The results presented in section 6.2 and 6.3 have led to the development of a new hardware and software architecture embedding a network of sensors and actuators interfaced to a controller, as part of Benoît Sijobert's PhD work and ADT STIMBIO (Ronan Le Guillou). In order to solve numerous issues and constraints observed during experiments, a new hardware and software architecture has been elaborated. The decision was made to decentralize the controller (i.e. the computer) directly on the participant, thereby relocating the essential wireless links around the user. For this purpose, a mini low-cost single board computer (Raspberry Pi3) was embedded in a 3D-printed case strapped around the waist of the subject. Using wireless inertial sensors connected as a WBAN, the sink node gets the data from all the IMUs, therefore highly decreasing the data flow when multiple IMUs were transmitting inside the network. To get rid of this limitation and guarantee an overall 100 Hz sampling rate no matter the number of IMUs, the wireless inertial sensors can be replaced by wired ones, low-cost with a high speed ARM Cortex-M0 based processor and a Kalman Filter directly providing quaternion estimation at 100 Hz for each IMU. The use of a multiplexer connected through an I2C interface (Inter Integrated Circuit) enabled to keep a 100 Hz rate using 4 IMUs.

The stimulator used in the experiments was a wireless programmable and controllable device. Latency issues and communication losses were observed when the computer sending the command to the stimulator was too far or if an obstacle was present between the computer and the participant wearing the stimulator. Taking advantage of the FES controller located on the subject to control the stimulator nearby has enabled us to solve this issue.

In this configuration, this autonomous FES controller is able to acquire the data, process them, execute control algorithms and send the appropriate stimulation command to the stimulator. For safety reasons, in order to access to the FES controller and to enable a remote access to the stimulation from a computer, an ad-hoc Wi-Fi network is automatically provided by the Raspberry on start-up. The ad-hoc network enables to be independent of a network infrastructure where the connection is not always possible (e.g. Wi-Fi network from the hospital).

This scalable architecture (Figure 3), developed as a modular system, now allows us to implement various new commands laws for Real Time closed loop control as well as giving us the ability to switch sensors and stimulators to meet the needs of specific applications. As part of making this system available for future projects in the team, the ability to easily change stimulators depending of the requirements was needed. To achieve this and in order for the FES architecture to directly control them, Application Programming Interfaces (APIs) were developed for 3 main commercial stimulators in the team. They each corresponds to a specific need and use case. The Vivaltis Phoenix Stimulator allows for low-weight embedding, wireless network control, but only 2 stimulation channels by pod, while being scalable. The BerkelBike Stimulator v2.0 presents a cumbersome but extended control compromise with 8 independent stimulation channels, which is an ideal solution for recumbent FES-assisted cycling. And finally the Hasomed Rehastim v1.0 allowing fine control but isn't battery powered in its commercial version and is not produced anymore.

This new architecture is currently used in clinical experiments and will continue to evolve with a goal of being easy to use, even by untrained clinicians. A funding (EDF Foundation) has been obtained by our clinical partner "CRF La Châtaigneraie" to perform a clinical protocol including 6 patients from which one will participate in the Cybathlon 2020 using this hardware and software architecture. The inclusions will begin in January 2019.

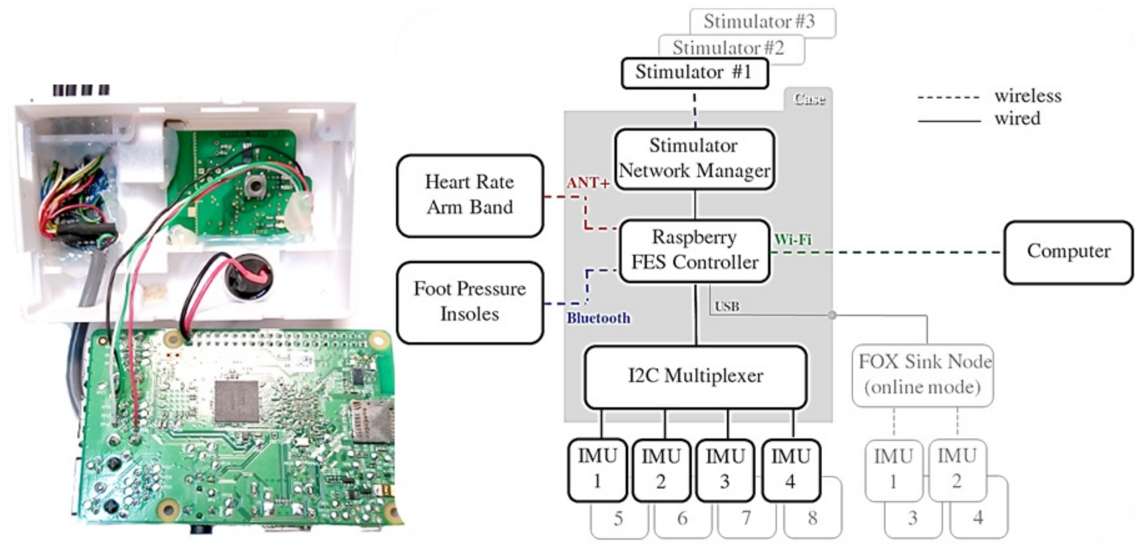


Figure 3. Experimental protocols have led to the development of a scalable hardware architecture decentralized on the subject.

5.2.2. Tremor monitoring system based on acceleration detection in Parkinson's Disease

Participants: Christine Azevedo Coste, Ronan Le Guillou.

As part of a preliminary study on the effects of Mindfulness meditation for patients with Parkinson's Disease (PD), an application was developed to monitor the accelerometer of a wrist worn device. The hypothesis being that reducing the cognitive load of a PD patient might reduce the severity of the tremors. We investigated a few devices that might correspond to our requirements : smartwatches, Myo armbands, Inertial Measurement Units,...Having already a Thalmic Myo Armband (Figure 4) we developed a program acquiring the accelerometer data in Real Time and logging it, as well as doing pre-processing and displaying it on the screen of the clinician to allow him to monitor the session. While this system was ready and already tested, we had to search for another solution due to the termination of the commercial product. We then selected the smartwatch Samsung Gear S3 as a possible alternative and the dedicated application is currently under development.

6. New Results

6.1. A sensor fusion approach for inertial sensors based 3D kinematics and pathological gait assessments

Participants: Benoît Sijobert, Christine Azevedo, Jérôme Froger, Francois Feuvrier.

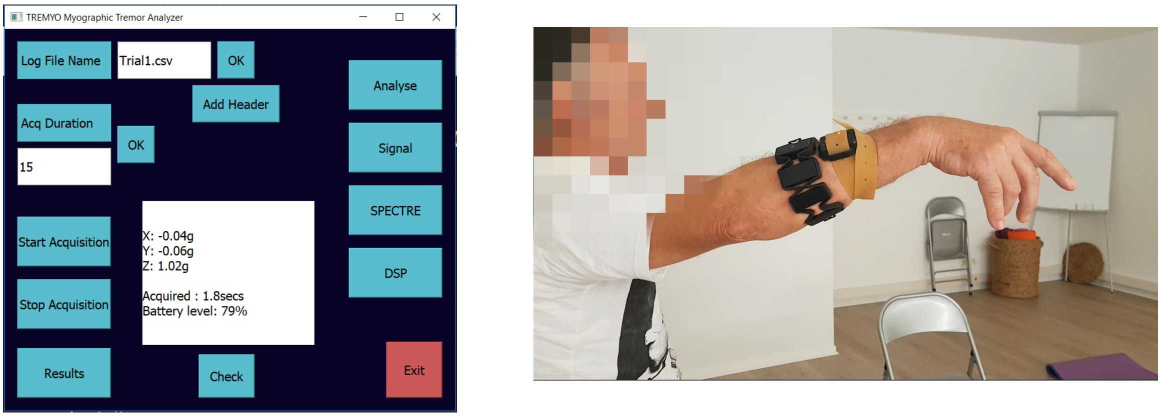


Figure 4. i) Graphical User Interface of the TREMYO Armband monitoring application during acquisition ii) Baseline test with straight extended arm for temporal comparison of the tremors severity.

Pathological gait assessment and assistive control based on functional electrical stimulation (FES) in post-stroke individuals, brings out a common need to robustly quantify kinematics facing multiple constraints.

Through an experimental study(Figure 5), we proposed a novel approach using inertial sensors to compute dorsiflexion angles and spatio-temporal parameters, in order to be later used as inputs for online close-loop control of FES. 26 post-stroke subjects were asked to walk on a pressure mat (GaitRite®) equipped with inertial measurement units (IMU) and passive reflective markers (Vicon®). A total of 930 strides were individually analyzed and results between IMU-based algorithms and reference systems compared. The novel methods integrated two aspects: 1) robust stance phase detection based on acceleration and angular rate combination and 2) estimation of joint angles based on an Attitude and Heading Reference System (non linear observer) algorithm and gravity cancellation for reconstructing 3D trajectory of individual steps. Mean absolute (MA) errors of dorsiflexion angles were found to be less than 4°, while stride lengths were robustly segmented and estimated with a MA error less than 10 cm [30]. These results open new doors to rehabilitation using adaptive FES closed-loop control strategies.

6.2. FES-based online closed-loop control of knee joint to reduce stance phase asymmetry in post-stroke gait

Participants: Benoît Sijobert, Christine Azevedo, Charles Fattal.

Numerous stimulation strategies have been investigated over the past thirty years to assist or restore gait (Figure 6). The studies using FES to restore gait have been mostly conducted in post-stroke individuals and focused on correcting the drop foot syndrome by supplementing the absence of dorsiflexion. The state-of-the-art reflects a real lack of interest in using FES to improve the paretic knee rehabilitation, which however plays a key role in post-stroke gait recovery.
An experimental protocol (#RCB 2017-A03611-52, CRF La Chataigneraie, Menucourt, France) was designed with the main purpose of proposing a novel approach using a FES-based control of knee joint to reduce stance phase asymmetry and study the feasibility of using such FES systems in clinical rehabilitation, compared to classical knee orthosis. Secondary objectives aimed at improving gait quality, walking range and comfortable speed using the same modality. The main hypothesis was to determine if using FES to real-time control the paretic knee angle could reduce the time needed to recover a normal balance while providing a secure stance phase. To monitor weight bearing and stance time asymmetry the participants were equipped with

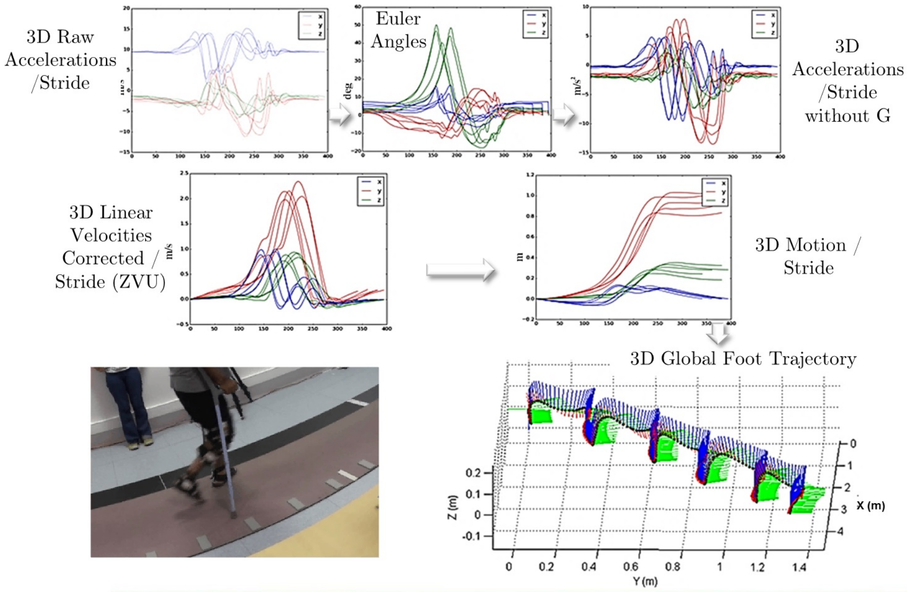


Figure 5. Illustration of the global approach needed to obtain gait trajectories from raw magneto-inertial data of a foot-mounted Inertial Measurement Unit to assess a circumduction gait.

instrumented insoles. The subjects were also equipped with 2 inertial measurement units located on the thigh and the tibia, wired to a Raspberry Pi3. Each IMU embedded a high speed based processor and a Kalman Filter directly providing quaternion estimation needed to compute knee angles. One IMU was installed in the back of the participants at the second sacral vertebra level to estimate vertical trunk displacement. Stimulation was sent via a two-channel wireless stimulator to the quadriceps and hamstrings via surface electrodes. A specific hardware architecture has been developed for this protocol. When required and depending on the participant's gait pattern, a "pre-stance" stimulation could be triggered either via an online detection of peak knee flexion or when the sagittal angular speed recorded via the gyroscope crossed zero. In stance phase, stimulation was triggered either to quadriceps or hamstrings, depending on the paretic knee angle (PKA) estimation relatively to the knee angle setpoint (KAS) defined by the practitioner as the optimal flexion during stance phase (around 5^{o}). A proportional (P) controller adjusted the pulse width depending on the error ϵ between PKA and KAS. Equipped with their usual technical aids (cane, ankle foot orthosis...) participants were asked to perform a 10m-path walking at a self-selected pace. An oral instruction was given at the beginning of each trial to encourage the participants to transfer their weight onto the paretic leg. This experiment is an ongoing experiment but preliminary tests have already validated the technical feasibility of the approach.

6.3. IMU-based FES cycling in individuals with SCI

Participants: Benoît Sijobert, Christine Azevedo, Ronan Le Guillou, Charles Fattal, Emerson Fachin Martin, Henrique Resende.

It has been shown that FES-cycling of subjects with Spinal Cord Injuries (SCI) results in physiological and psychological positive effects such as cardiovascular training, decrease in pressure sores occurrence and self-esteem improvements. 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 and the requirement of experimented users to finely tuned the stimulation patterns needed to stimulate lower limb muscles with an adequate modality. In order to promote the research around this topic and more broadly the

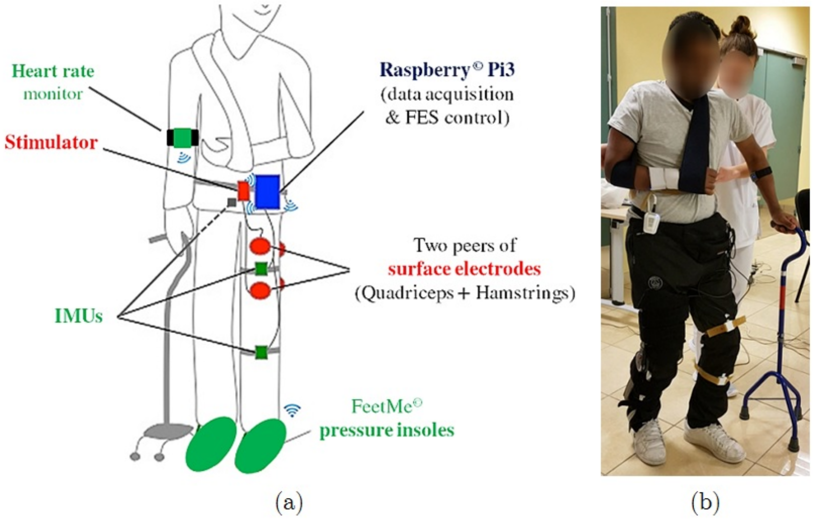


Figure 6. Experimental setup diagram (a) and picture (b). The participants are equipped with Bluetooth pressure insoles, 2 wired IMU on the leg and 1 wireless IMU in the back. A Raspberry records and processes the sensors data to send an appropriate command to a wireless stimulator to stimulate the quadriceps and hamstrings via surface electrodes

development of assistive technology for people with physical disabilities, we participated to the first Cybathlon in October 2016 (FreeWheels project), using a stimulation pattern based on crank angle. Taking part to this event highlighted the need for a simpler automated stimulation pattern generator, able to adapt the stimulation to the environment, to the muscle fatigue or to the individual (e.g. position on the bike, number of stimulable muscles, etc…). In order to further investigate control solutions, we first needed to be able to accurately quantify the influence of each parameter preliminarily used (stimulation pattern, stimulation parameters, fixed-wheel or free-wheel, individualized quadriceps, pilot position, etc…) on power produced and endurance and observe if other variables could be used as an input instead of the crank angle. The decision was made to develop an instrumented home trainer specifically designed to record a weak power (<200 W) while ensuring a minimum accuracy of 0.5 %: a rotating torquemeter (Scaime TSR 2300) was installed between the rear wheel and a flywheel thanks to a mechanical assembly built in collaboration with the National Engineering School of Saint-Étienne (ENISE, Loire, France)(Figure 7). The software part was developed as part of ADT STIMBIO.

Instead of using the crank angle, undergoing researches have also investigated the ability of using inertial sensors to automatically design a stimulation pattern on the bike depending on the knee angles. Based on the joint angle computation presented in section 6.1 and experimentally validated, a similar control modality have been studied and implemented. Using the online peak knee flexion algorithm developed in the study presented in section 6.2 to continuously detect this event, we developed a novel approach in order to trigger the quadriceps stimulation at the beginning of the pushing phase. This would enable to take into account a possible sliding in seat position without requiring an accurate placement of the IMUs or a geometrical model of the individual. A study has been initiated with the University of Brasilia (UnB, District Federal, Brazil) as part of the CACAO collaboration, to explore advanced control approaches [31]. Experimental data have been recorded and are investigated in order to compare the different control approaches (Figure 8).

6.4. Respiratory detection and monitoring

Figure 7. Experimental setup using IMUs to record joint angles and a specifically designed home trainer to monitor power output.

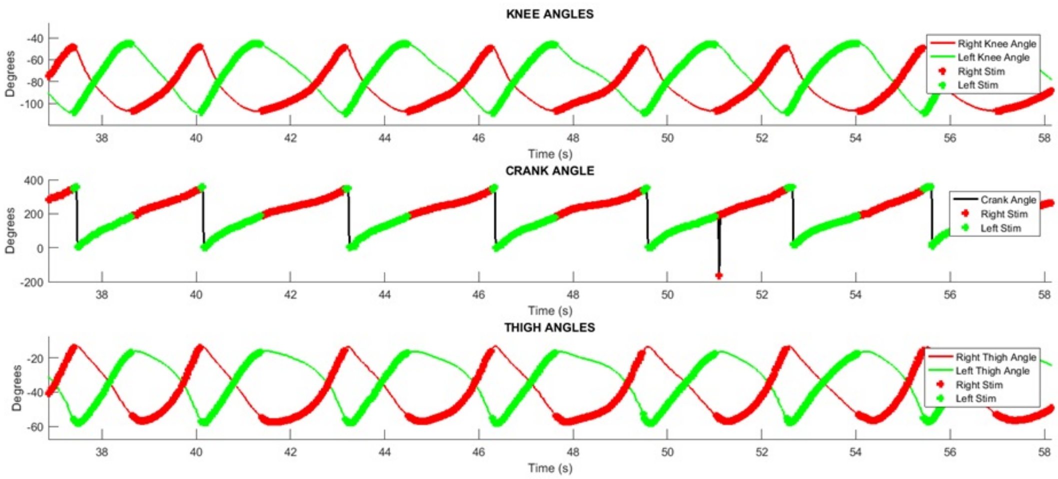
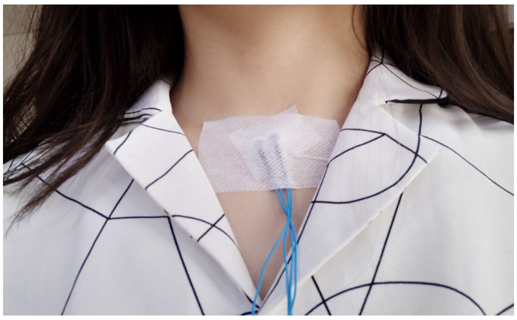


Figure 8. Comparison of stimulation patterns between crank angle and joint angle based triggering method.

Participants: Xinyue Lu, Christine Azevedo, David Guiraud, Serge Renaux [Neuroresp], Thomas Similowski [Groupe Hospitalier Pitié-Salpêtrière].

This work is conducted within a CIFRE phd thesis. The general subject is the respiration induced by implanted stimulation for the tetraplegic and syndrome of Ondine. In France, every year, there is approximately 90 new spinal cord injuries who have a ventilatory dependence due to a high cervical involvement. The prevalence of syndrome of Ondine (central sleep apnea) would be 25.5 per million inhabitants. Because of many disadvantages of mechanical ventilation, the technique of implanted electrical stimulation to restore the respiratory function of the patients can be proposed. But existing systems are based on open-loop controllers, ie the phrenic nerve is stimulated with the same intensity, at the same frequency for the whole time, even when the patients can breathe spontaneously. The principle aim of the work is to develop a respiratory detection/monitoring module in this context.

A solution based on tracheal sounds analysis has been developed. Tracheal sounds are recorded by microphone which is inserted into a support and stuck on the neck of subject like showed in Figure 9.i. All the materials are showed in Figure 9.ii: microphones (yellow), analog ampli-filtering card (red), the acquisition machine POWERLAB (green), the numeric development card NUCLEO (blue).



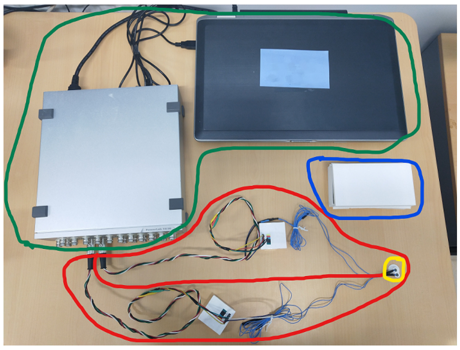


Figure 9. i)The placement of microphone ii)Recording materials

The signal is processed in its envelop (temporal domain) and frequency power (frequency domain). A threshold detection applied to detect respiration. An example of detection result is illustrated in Figure 10. Heart beating sounds can also be extracted to calculate cardiac rhythm.

Preliminary recordings on healthy individuals have been performed. Recordings on patients are in planning. Publications for conferences and journals are in preparation. The variation of cardiac amplitude will also be analyzed to give a secondary breathing detection. Advance signal processing techniques are now under study.

6.5. Attenuation and delay of remote potentials evoked by direct electrical stimulation during brain surgery.

Participants: Anthony Boyer, Sofiane Ramdani [LIRMM], Hugues Duffau [CHU Montpellier], David Guiraud, François Bonnetblanc.

Direct electrical stimulation (DES) is used during awake brain surgery for functional mapping as it generates transient behavioural disturbances, allowing the identification of both cortical areas and subcortical white matter pathways which are essential to the function. However, the electrophysiological effects of DES remain by far unknown. DES may be coupled with the measurement of Evoked Potentials (EPs) to study the conductive and integrative properties of activated neural ensembles and probe the spatiotemporal dynamics

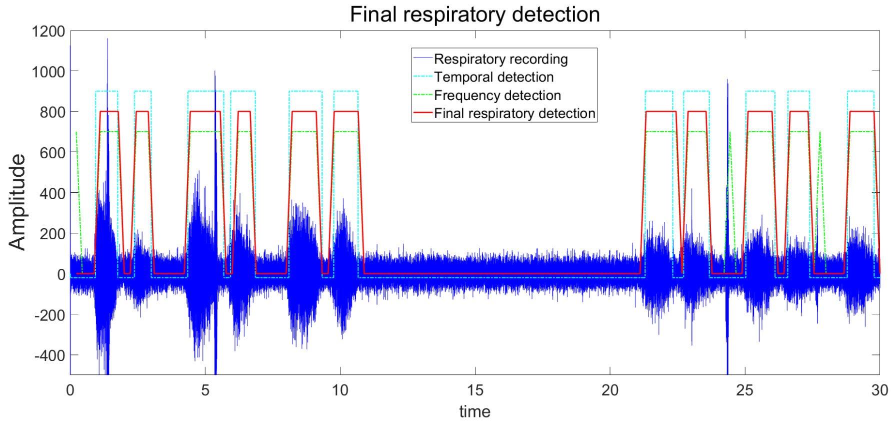


Figure 10. The detection result

of short- and long- range networks. We recorded ECoG signals on two patients undergoing awake brain surgery and measured EPs on functional sites after cortical stimulations, using combinations of stimulation parameters (Figure 11). We were more particularly interested in the generation of evoked potentials (EPs) triggered by both close and remote stimulations. Obtained EPs were very similar in shape, suggesting a stereotyped electrophysiological response, but delayed in time and attenuated in amplitude when elicited from a different gyrus or remotely from the recording site. We were also able to observe the bidirectional nature of the arcuate fasciculus triggering EPs on 2 anatomically connected sites. We propose different activation and electrophysiological propagation mechanisms following DES based on recruited neural elements. The variations in amplitude and delay of EPs are most likely due to different propagation mechanisms, which can be intra- or sub- cortical, and correspond to commonly described DCRs and CCEPs.

6.6. High Frequency stimulation used for efficient and fiber type selective stimulation

Participants: David Guiraud, Mélissa Dali, Olivier Rossel, Thomas Guiho, Pawel Maciejasz.

In neural electrical stimulation, limiting the charge delivered during a stimulus pulse is essential to avoid nerve tissue damage and to save power. Previous experimental and modeling studies indicated that waveforms such as nonrectangular continuous pulses or rectangular chopped pulse were able to improve stimulation efficiency. The goal of this study is to evaluate if non-rectangular chopped pulses such as quarter sine and ramp are more charge efficient than rectangular chopped pulse. We performed in vivo study on 17 lumbricus terrestris and compared the charge per stimulating phase needed to activate lateral giant fibers (LGF) and medial giant fiber (MGF) using chopped non-rectangular pulses and rectangular pulse, varying stimulation duration parameters. Results indicated that non rectangular chopped pulses activated MGF and LGF with less charge than rectangular chopped pulses. For MGF (respectively LGF), the gain of charge was up to 33.9% (resp. 17.8%) using chopped ramp, and up to 22.8% (resp. 18.1%) using chopped quarter sine.

6.7. Early detection of stroke during the accute phase

Participants: Victor Vagné, David Guiraud, Vincent Costalat, Emmanuelle Le Bars, Stéphane Perrey.

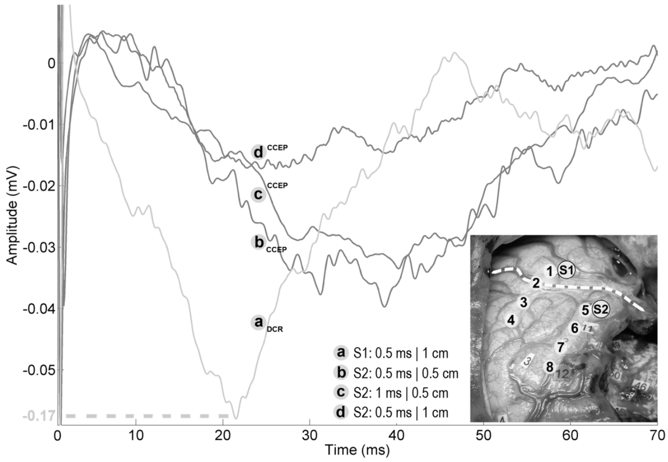


Figure 11. Differential recordings between electrodes 2 and 3 while stimulating S1 and S2. The picture illustrates the stimulation sites (S1, S2) and ECoG positioning with respect to the initial 60 Hz cortical brain mapping. Experimental DES was applied on: (1) the Wernicke's area (S1), associated with complete anomia; (2) the ventral premotor cortex (S2), which led to movement and counting interruptions. Tumor was about 164 cm3. The Sylvian fissure is highlighted by a thick dashed line.

Cerebral infarctions can now be treated with new techniques using intravenous thrombolysis and thrombectomy. Their proven efficacy is directly correlated to the time lapse between the start of symptoms and the initiation of treatment. Currently, a definitive diagnosis can only be made once the patient has performed a radiological imaging (CT scan or MRI) on a medical center equipped with these expensive devices, thus enabling the medical team to initiate the appropriate treatment. Transit times during the pre-hospitalization phase before diagnosis are therefore often longer and have the greatest negative impact on the patient's prognosis. In collaboration with the interventional neuroradiology department of Gui de Chauliac Hospital, I2FH and Euromov, the EleVANT project is aiming to prospectively evaluate new techniques to assess a diagnosis of acute cerebral ischaemia. This low cost technology could be used in a mobile way for the very early diagnosis of cerebral infarction and thus reduce treatment delays, opening the way to a new generation of diagnostic tools. The concept consist on evaluating the cerebral near-infrared spectroscopy (NIRS) response to different stimulus, and to evaluate its lateralization. Recently, we tested our device on healthy volunteers. Method: Left and right hemisphere reactivity index are recorded by NIRS and normalized (Figure 12). Result: The experiments present a suitable feasibility and repeatability. In healthy subjects, a good response to the stimulus is recorded, and no significant differences between hemispheres are observed. The confidence level is acceptable since the amplitude response in above the standard deviation level.

Discussion: The approach reveal interesting results on healthy subject group. We expect a discriminant difference between hemispheric signals in acute cerebral ischemia.

6.8. Real-time simulation of stimulation systems

Participant: Daniel Simon.

RT-STIM (Real-time FES simulation) is a C/C++ framework able to carry out realistic simulations of a fully featured functional electro-stimulation system. It allows for the temporally consistent co-simulation of both the continuous model of skeletal joints and muscles on one hand, and of numerical resources such as control tasks, schedulers and communication protocols on the other hand (Figure 13). Initial software-in-the-loop

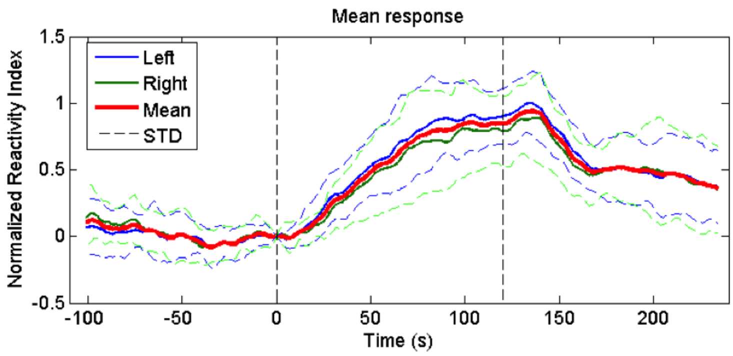


Figure 12. NIRS reactivity Index in response to a stimulus (bounded by the dashed lines)

simulations can be seamlessly extended towards hardware-in-the-loop simulation by a progressive integration of real components such as a Raspberry portable control board or gateways towards Vivaltis stimulators and HiKoB sensors.

It is intended to be a support for the design and implementation of safe stimulation feedback controllers in the team. Hence, the simulation software is designed around the bio-mechanical models of joints and muscles excited using electro-stimulation developed in the Demar and Camin teams during the past years. To cope with the objectives of the team which targets the restoration of grasping for tetraplegia, a model of a human hand, currently using 23 joints and 23 muscles, has been integrated. It is expected to be a central tool for the Agilis project starting in 2019.

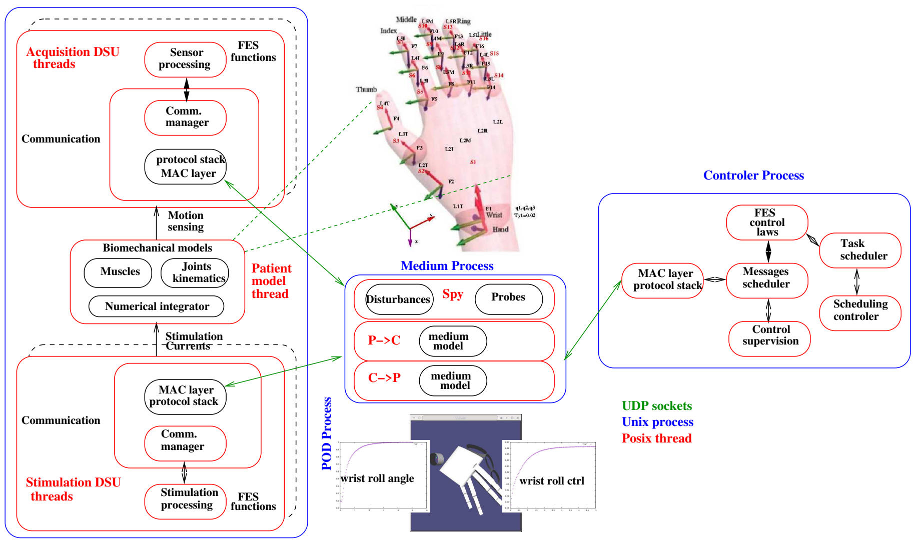


Figure 13. Simulation of a hand under FES

6.9. Real-time control for distributed stimulation systems

Participants: Daniel Simon, Ashwini Patil, Ronan Le Guillou.

Feedback control is needed to control complex movement, such as precise grasping, involving several muscles and nerves. Moreover, the components of the control loops (i.e., sensors, electrodes and micro-controllers) are distributed over communication links which induce data delivery scheduling, delays, and occasional data loss. A new approach gathering control and computation related design and implementation constraints was developed during the past years. From the feedback provided by experiments in real-time robot control,

Considering the non-linear and time varying models, simple controllers cannot provide reliable and robust solutions. the approach is developed along two main directions, control aware computing, e.g., using feedback schedulers, and real-time aware control, e.g. using feedback controllers designed to be robust and/or adaptive w.r.t. timing deviations [32].

Beyond simple control loops, a Model Predictive Control approach for FES using an adaptive horizon is under evaluation. Even if no conclusion about the control approach can be currently carried out, it was an occasion to positively evaluate the Julia programming language as an alternative to others high level languages for control design and real-time implementation.

A software control structure, primarily implemented and evaluated on a portable Rasperry3 micro-controller, is currently documented to become the root of a generic real-time control software template, usable even by non-specialists in the Camin team.

7. Bilateral Contracts and Grants with Industry

7.1. Bilateral Contracts with Industry

- collaboration contract with FEETME (http://www.feetme.fr) company.
- collaboration contract with Innopsys (https://www.innopsys.com/en) company.
- collaboration contract with ISIDU (https://isidu.eu/) company.
- collaboration contract with Berkelbike (https://berkelbike.com) company.

7.2. Bilateral Grants with Industry

- collaboration contract with NEURORESP (http://neuroresp.com/) company (CIFRE PhD thesis).
- collaboration contract with SubseaTech (https://www.subsea-tech.com/) company, CIFRE PhD thesis about the on-the-fly optimization of actuators steering for underwater vehicles.

8. Partnerships and Cooperations

8.1. Regional Initiatives

We have obtained a financial support from Occitanie Region for the CIFRE PhD thesis (Xynue Lu) with NEURORESP Company "PILE CIFRE" BREATHLOOP.

8.2. National Initiatives

- Inria ADT STIMBIO

  Participants : Christine Azevedo, Daniel Simon, Ronan Le Guillou, Benoît Sijobert.

  A 1-year engineer (R. LeGuillou) was funded by Inria ADT on the development of an architecture dedicated to FES-cycling platform.

- I-SITE MUSE COMPANIES AND CAMPUS grant

  Collaboration with academic local partners (CHU, IES) and NEURINNOV company on the spinal stimulation for bladder and bowel functions restoration. This is linked to an ongoing collaboration with Oslo University (Norway).

- LABEX NUMEV MEDITAPARK

  Collaboration with Montpellier Hospital (Neurology service) and the Montpellier Mindfulness Center to analyze the impact of meditation on upper limb tremor.

- EDF Foundation

  Collaboration with La Châtaigneraie Hospital on FES-assisted cycling. Financial support for a study on FES-cycling training method and performance otimization on individuals with complete spinal cord injury.

- I-SITE MUSE - EXPLORE

  Support for the visit of Henrique Resende (UFMG, Brazil) and Emersion Fachin (UNB, Brazil) as guest researchers from December to February 2019. Completed with a LIRMM laboratory financial aid.

8.3. European Initiatives

Program: EIT Health

Project acronym: Agilis

Project title: Restoration of Hand Functions in Tetraplegia through Selective Neural Electrical Stimulation

Duration: Jan. 2019 - June 2020

Coordinator: Camin Inria

Other partners: APHP, Univ. Heidelberg, CRF La Châtaigneraie, Neurinnov.

Abstract: Complete tetraplegia leads to inability to move, thus use, both hands. To date, there is no solution to restore this absolutely needed function for very common daily activities such as social interactions, washing, eating or self catheterizing. We aim at an innovative implanted stimulation of only two nerves associated with an intuitive interface. It will provide functional grasping without a third person and thus will drastically increase the autonomy of such people for the rest of their life.

8.4. International Initiatives

8.4.1. Inria Associate Teams Not Involved in an Inria International Labs

8.4.1.1. CACAO

Title: Lower limb electrical stimulation for function restoration

International Partner (Institution - Laboratory - Researcher):

> UNB Brasilia (Brazil), Physiotherapy department, Emerson Fachin Martins.

Start year: 2016

See also: https://team.inria.fr/cacao/

Electrical stimulation (ES) can activate paralyzed muscles to support rehabilitation. ES applied to fully or partially paralyzed muscles artificially induces muscle contraction substituting or completing the normal volitional control. In CACAO team we join our efforts and specific expertise to develop approaches of lower limb function restoration in spinal cord injured individuals. Two main applications have been addressed: 1) Functional Electrical Stimulation (FES) to assist SCI individuals to perform pivot transfers and 2) FES-assisted cycling. We aim at proposing solutions that can have an effect on patients' quality of life, thus our choices intend to be realistic form a practical point of view.

8.4.1.2. Informal International Partners

CAMIN collaborates with Dr JL Boulland (Norwegian Center for Stem Cell Research at Oslo University Hospital in Norway) on FES-assisted bladder and bowel functions restoration.

8.5. International Research Visitors

Henrique Resende (UFMG, Brazil) and Emerson Fachin (UNB, Brazil) will spend 3 months in CAMIN team from December 2018 to February 2019 to work on FES-cycling project.

9. Dissemination

9.1. Promoting Scientific Activities

9.1.1. General Chair, Scientific Chair

Christine Azevedo organized a special session "Application of FES for lower limbs movement assistance" at ICNR conference (Pisa, Italy) on October 2018.

9.1.2. Member of the Conference Program Committees

- David Guiraud was Co-editor of the theme 6 at IEEE EMBC conference
- Daniel Simon is member of the ICINCO conference program committee
- David Andreu was member of the ERTS2 conference program committee

9.1.3. Reviewer

- Christine Azevedo was reviewer for IEEE EMBC, IROS, ICNR conferences
- David Guiraud was reviewer for IEEE EMBC and IEEE NER
- François Bonnetblanc was reviewer for IEEE EMBC
- Daniel Simon was reviewer for the IFAC CAMS, IFAC ICINCO, ECC and IEEE CCTA conferences
- David Andreu was reviewer for the ERTS2 conference

9.1.4. Member of the Editorial Boards

- Christine Azevedo is member if ERCIM News' Editorial Board as Inria representant.
- David Guiraud is Associate Editor of Journal of Neural Engineering and Medical and Biological Engineering and Computing.

9.1.5. Reviewer - Reviewing Activities

- David Guiraud is reviewer of several journals among which IEEE TNSRE, IEEE ACCESS, IEEE TCST, JNE, J. Of Neuroscience Method, Computer in Biology and Medicine, Science Advances (AAAS)...
- Daniel Simon was reviewer for IEEE Control Systems Technology and Real Time Systems.
- David Andreu was reviewer for Journal of Neural Engineering.

9.1.6. Invited Talks

François Bonnetblanc: University of British Columbia and Peter Wall Institute of Advanced Studies. “Awake Brain Surgery: the naked brain”, 4 octobre 2018.

François Bonnetblanc : Karolinska Institute (Programme TOR). Neurosurgery Department, “Awake Neurosurgery and electrophysiology”). 5-9 novembre 2018.
Christine Azevedo was invited to give a lecture at Inria Rennes center "Pédalage assisté par stimulation électrique de muscles paralysés.".

9.1.7. Leadership within the Scientific Community

Christine Azevedo is member of the board of directors of International Functional Electrical Stimulation Society (IFESS).

9.1.8. Scientific Expertise

David Guiraud was reviewer for the ERC program (Starting and Advanced) in 2018
Christine Azevedo was examiner for APHP Delegation Clinical research and Innovation call for proposals for detached positions.

9.1.9. Research Administration

Christine Azevedo is member of Inria Evaluation Committee (CE). She participated in the competitive examinations for junior researcher recruitment in Inria Lille Center (April 2018) and Inria Grenoble Center (May 2018). She was also in the examination committee of CHRC and DR0 promotions as well as detachments.
Christine Azevedo is member of Inria Ethical Committee (COERLE).

9.2. Teaching - Supervision - Juries

9.2.1. Teaching

- Master SMH : David Guiraud, "Stimulation Electrique Fonctionnelle", 16h, M2, Université de Montpellier, France
- Master Neuroprothèses : Daniel Simon, "Control basics", 6.5h, M2, Université de Montpellier, France
- Master Neuroprothèses : Christine Azevedo, "Ethical considerations", 3h, M2, Université de Montpellier, France
- Master Neuroprothèses : François Bonnetblanc, "Motor Control", "Neuroplasticity", "Electrophysiology in Neurosurgery", 16h, M1, Université de Montpellier, France
- Master Mechanics and its Interactions : François Bonnetblanc, "Motor Control", 4,5h, M2, Université de Montpellier, Polytech, France
- DU Functional electrical stimulation : François Bonnetblanc, "Motor Control", "Neuroplasticity", "Electrophysiology in Neurosurgery", 12h, Université de Montpellier, France
- DU Functional electrical stimulation : David Andreu, "Neuroprosthesis: from functions to active medical implanted devices" , 6h, Université de Montpellier, France
- DU Functional electrical stimulation : David Guiraud, "Electrophysiology", "Biophysics", "Neuroprothesis", 6,5h, Université de Montpellier, France
- DU Functional electrical stimulation : Christine Azevedo, "Electrophysiology", "Functional Electrical Stimulation", "Clinical Applications", 7h, Université de Montpellier, France
- DU Functional electrical stimulation : Charles Fattal, "Functional Electrical Stimulation and Clinical Applications", 5h, Université de Montpellier, France

François Bonnetblanc is responsible for a DU about "Functional Electrical Stimulation"
D. Andreu teaches software engineering, real time OS, discrete event systems, control architectures, networks, neuro-prosthesis, 200 h, master and engineers degrees, Polytech Montpellier, France.

9.2.2. Supervision

- PhD: Benoît Sijobert, Assistive Control of Motion in SensoriMotor Impairments based on Functional Electrical Stimulation, Montpellier University, September 28th 2018, Christine Azevedo, David Andreu and Charles Fattal.
- PhD: Ibrahim Merzoug, Validation formelle des systèmes numériques critiques : génération d'espace d'états de réseaux de Petri exécutés en synchrone, Montpellier University, January 15th 2018, David Andreu and Karen Godary.
- PhD in progress: Antony Boyer, Neuroplasticity and recovery in remote (sub)cortical structures following wide-awake surgery of infiltrative low-grade gliomas: investigation of fMRI and EEG signals, 01/09/2016, François Bonnetblanc and Sofiane Ramdani.
- PhD in progress: Maxence Blond, Commande et modélisation d'un véhicule sous-marin, 18/01/2016, Daniel Simon, Vincent Creuze (LIRMM) and Ahmed Chemori (LIRMM).
- PhD in progress: Victor Vagne, "Couplage de la Spectroscopie en proche infrarouge et de la stimulation Transcrânienne (NIRS-tDCS) à courant continu dans l'Evaluation diagnostique de l'ischémie cérébrale lors d'un AVC", Oct. 2016, M. Hayashibe, D. Guiraud, Vincent Costalat (CHU Montpellier) and Emmanuelle Le Bars (CHU Montpellier)
- PhD in progress: XinYue Lu, Respiratory detection and monitoring Since March 2017, C. Azevedo Coste, T Similowski (Groupe Hospitalier Pitié-Salpêtrière), S Renaux (NEURORESP)
- PhD in progress (co-financing UM / Occitanie region): Vincent Iampietro, Contribution des méthodes formelles à la fiabilité des systèmes numériques complexes critiques : application aux dispositifs médicaux implantables innovants, since october 2018, D. Andreu, D. Delahaye (LIRMM).

9.2.3. Juries

Christine Azevedo was reviewer for the PhD thesis of Solenne Page (ISIR, UPMC University, Paris, France) "Control of a robotized walker based on postural characterization and application to obstacle avoidance." (May 2018).
Christine Azevedo was examiner in the defense committee of Mathilde Couraud (Bordeaux University, France) "Study of the sensori-motor control in a simplified artificial context with the aim to improve the control of myoelectric prostheses." (December 2018).
Christine Azevedo was examiner in the defense committee of Firas Kaddachi (Montpellier University, France) "Technological approach of early and non intrusive of health modification to better adapt services to elderly persons." (December 2018).
David Andreu was reviewer of the PhD thesis of T. Sotiropoulos (LAAS, Univ. Toulouse 3, France), "Test aléatoire de la navigation de robots dans des mondes virtuels." (May 2018).

9.3. Popularization

9.3.1. Education

Christine Azevedo Coste is mentor (2018-2019) for one Savanturiers project with Saussan school (CM1/CM2 level) https://les-savanturiers.cri-paris.org/
Christine Azevedo organized initiation sessions to informatics using Thymio robot at École Calendreta La Cardonilha (Mèze, France) in CP/CE1 level, 3 sessions of 2 hours (April 2018) .
Christine Azevedo organized initiation sessions to informatics using Thymio robot at École Valfalis (Montbazin, France) in CM1/CM2 level, 4 sessions of 2 hours (May-June 2018) .
As a COERLE member Christine Azevedo Coste was involved in one session on Ethics for phd students in Inria IRISA center (Rennes, france) (November 2018).

9.3.2. Interventions

- François Bonnetblanc : Pint of Science 16 mai 2018, François Bonnetblanc, Montpellier

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Major publications by the team in recent years

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