INRIA

INSTITUT NATIONAL DE RECHERCHE EN INFORMATIQUE ET EN AUTOMATIQUE

Project-Team DEMAR

Artificial movement and gait restoration

Sophia Antipolis - Méditerranée

Theme : Computational Medicine and Neurosciences

Activity Report

2009

Table of contents

1. Team

Research Scientist

David Guiraud [Team leader, Research Director (DR) Inria, HdR]
Christine Azevedo-Coste [Research Associate (CR) Inria]
Mitsuhiro Hayashibe [Research Associate (CR) Inria]

Faculty Member

David Andreu [Assistant Professor]
Guy Cathébras [Professor, half-time, site: LIRMM (Montpellier), HdR]
Philippe Fraisse [Professor, half-time, site: LIRMM (Montpellier), HdR]
Philippe Poignet [Professor, half-time, site: LIRMM (Montpellier), HdR]

External Collaborator

Fabien Soulier [Assistant Professor]
Bernard Espiau [Research Scientist, site: BIPOP (UR Grenoble)]
Nacim Ramdani [Research Scientist]
Serge Bernard [Research Scientist, site: LIRMM (Montpellier)]
Charles Fattal [Medical Doctor, PhD, site: Centre Mutualiste Propara (Montpellier)]
Martine Eckert [site: IMERIR (Perpignan)]
Alain Varray [Professor, University Montpellier I, site: UFR STAPS (Montpellier)]
Ken Yoshida [Assistant Professor, site: IUPUI (Indianapolis, USA)]

Technical Staff

Bernard Gilbert [Assistant Engineer, half-time, University Montpellier I, site: LIRMM (Montpellier)]
Robin Passama [Expert engineer from october 2007]
Loic Bourguine [Expert engineer from december 2007]
Gregory Angles [Associate engineer]
Laurent De Knyff [Hardware Technician]

PhD Student

Antonio Bo
Mourad Benoussaad
Jean-Charles Ceccato [site: MAC (Bordeaux)]
Jovana Jovic
Fanny Le Floch
Jérémy Laforet
Sébastien Lengagne
Christophe Michel [site: INM (Montpellier)]
Maria Papaiordanidou
Maud Pasquier [site: INRIA (Montbonnot)]
Olivier Rossel
Guillaume Souquet
Mickael Toussaint [site: Vivaltis (Montpellier)]
Qin Zhang

Post-Doctoral Fellow

Jean-François Pineau

Administrative Assistant

Annie Aliaga [Secretary (SAR) Inria]

2. Overall Objectives

2.1. Introduction

Functional Electrical Stimulation (FES) has been used for about 30 years in order to restore deficient physiological functions. At the beginning, only surface stimulation was possible and thus only used in a clinical context due to the low reliability of electrode placements. In the early eighties, implanted FES appeared through well-known applications: pacemaker, Brindley bladder control, cochlear implant, and more recently deep brain stimulation (DBS).

Currently, FES is the only way to restore motor function even though biological solutions are studied, but not yet successfully tested on humans. Few teams carry out researches on implanted FES and the functional results remain poor. Nevertheless, the technique has proved to be useable and needs enhancements that we partly address in DEMAR. Regarding technology, complex electrode geometries associated with complex stimulus waveforms provide a way to perform fibre type selectivity and spatial localisation of the stimuli in the nerves. These features are not yet implemented and demand new hardware and software architectures. Several teams Denmark (SMI U. Aalborg), Germany (IBMT Franhaufer Institute), England (U. College of London), Belgium (U. Catholique de Louvain), United States (Cleveland FES centre), and Canada (Ecole Polytechnique de Montréal), work on multi-polar neural stimulation but mainly on electrode aspect, except Polytsim Lab of Montréal.

Such a complex system needs advanced control theory tools coupled with a deep understanding of the underlying neurophysiological processes. This major area of research will be also an important part of the DEMAR objectives.

Besides, experiments are necessary to: improve neurophysiology knowledge, validate and identify models, evaluate control strategies or test neuroprostheses. Our experiments are carried on valid and non-valid individuals in clinical environment, but also on animals. They are particularly difficult to manage and highly time demanding to prepare, realize and analuyze data. Nevertheless, it really worth the effort in order to bring theory to useable systems.

Finally, industrial transfer is mandatory since we aim at proposing effective solutions to patients. Thus we try to prototype all our findings in order to validate and transfer efficiently our concepts. To be useable in clinical or private environments by the patients themselves, systems need to be certified as an industrial Medical Device.

DEMAR research is organized as follows:

1. modelling and identification of the human sensory-motor system.
2. Synthesis and control of functions.
3. Interfacing artificial and natural parts through neuroprosthetic devices: both stimulation and recording.

The main applied research fields are then:

- Quantitative characterization of the human sensory-motor system firstly for motor disorders diagnosis and objective quantification, and secondly in order to help the design and the control of neuroprosthetic devices.
- Restoring motor and sensitive functions through implanted FES and neural signals sensing such as lower limb movement synthesis and control for spinal cord injured patients, synergetic control of the deficient limb for hemiplegic patients, bladder control, pain relief...
- Improving surface stimulation for therapy such as active verticalization of paraplegic patients, reduction of tremor, reeducation of hemiplegic post-stroke patients...

2.2. Highlights

- Finalist Robocup Best Paper Award, IEEE IROS'2009: S. Lengagne, N. Ramdani, P. Fraisse, Planning and Fast Re-Planning of Safe Motions for Humanoid Robots: Application to a Kicking Motion, IEEE/RSJ International Conference on Intelligent Robots and Systems, IROS 2009, October 11-15th, Saint Louis, USA.
- INPG phd thesis award 2009: Rodolphe Héliot ""Functional rehabilitation of posture and walking: Coordination of healthy and deficient limbs".

3. Scientific Foundations

3.1. modelling and identification of the sensory-motor system

Participants: Mitsuhiro Hayashibe, Christine Azevedo Coste, David Guiraud, Philippe Poignet.

The literature on muscle modelling is vast, but most of research works focus separately on the microscopic and on the macroscopic muscle's functional behaviours. The most widely used microscopic model of muscle contraction was proposed by Huxley in 1957. The Hill-Maxwell macroscopic model was derived from the original model introduced by A.V. Hill in 1938. We may mention the most recent developments including the works of Zahalak introducing the distribution moment model that represents a formal mathematical approximation at the sarcomere level of the Huxley cross-bridges model and the works of Bestel and Sorine (2001) who proposed an explanation of the beating of the cardiac muscle by a chemical control input connected to the calcium dynamics in the muscle cells, that stimulates the contractile elements of the model. With respect to this literature, our contributions are mostly linked with the model of the contractile element, through the introduction of the recruitment at the fibre scale: the link between the parameters of the FES stimulator and the recruitment on one hand, and the Calcium signal path on the other hand, thus introduce a controlled model that can be used for FES application. The resulting model is able to reproduce both short term (twitch) and long term (tetanus) responses. It also matches with some of the main properties of the dynamic behaviour of muscles, such as the Hill force-velocity relationship or the instantaneous stiffness of the Mirsky-Parmley model. About integrated functions modelling such as spinal cord reflex loops or central pattern generator, much less groups work on this topic compared to the ones working on brain functions. Mainly neurophysiologists work on this subject and our originality is to combine physiology studies with mathematical modelling and experimental validation using our own neuroprostheses. The same analysis could be drawn with sensory feedback modelling. In this domain, our work is based on the recording and analysis of nerve activity through electro-neurography (ENG). We are interested in interpreting ENG in terms of muscle state in order to feedback useful information for FES controllers and to evaluate the stimulation effect. We believe that this knowledge should help to improve the design and programming of neuroprostheses. We try to investigate risky but promising way such as intrafascicular recordings, area on which only few teams in North America (Canada and USA), and Denmark really work on. Very few teams in France, and none at INRIA work on the peripheral nervous system modelling, together with experimental protocols that need neuroprostheses. Most of our INRIA collaborators work on the central nervous system, except the spinal cord, (ODYSSEE for instance), or other biological functions (SISYPHE for instance). Our contribution concern the following aspects:

- Muscle modelling,
- Sensory organ modelling,
- Electrode nerve interface,
- High level motor function modelling,
- Identification.

We contribute both to the design of reliable and accurate experiments with a well-controlled environment, to the fitting and implementation of efficient computational methods derived for instance from Sigma Point Kalman Filtering.

3.2. Synthesis and Control of Human Functions

Participants: Christine Azevedo Coste, Philippe Fraisse, Philippe Poignet, David Andreu.

We aim at developping realistic solutions for real clinical problems expressed by patients and medical staff. Different approaches and specifications are developped to answer to those issues in short, mid or long terms. This research axis is therefore obviously strongly related to clinical application objectives. Even though applications can appear very different, the problematic and constraints are usually similar in the context of electrical stimulation: trajectory tracking not possible, need for a good robustness to disturbances, limitation of possible observation of the system, interaction between body parts under voluntary control of the patient and under artificial control. Finally, this axis relies on modelling and identification results obtained in the first axis and on the technological solutions and approaches developped in the third axis (Neuroprostheses). The robotics framework involved in DEMAR work is close to the tools used and developped by BIPOP team in the context of bipedal robotics. There is no national teams working on those aspects. Within international community, several colleagues carry out researches on the synthesis and control of human functions, most of them belong to the International Functional Electrical Stimulation Society (IFESS) community. In the following we present two sub-objectives. Concerning spinal cord injuries (SCI) context not so many team are now involved in such researches around the world. Our force is to have technological solutions adapted to our theoretical developments. Concerning post-stroke context, several teams in Europe and North America are involved in drop-foot correction using FES. Our team specificity is to have access to the different expertises needed to develop new theoretical and technical solutions: medical expertise, experimental facilities, automatic control expertise, technological developments, industrial partner. These expertises are available in the team and through strong external collaborations.

3.3. Neuroprostheses

Participants: David Andreu, David Guiraud, Guy Cathébras, Fabien Soulier, Serge Bernard.

The main drawbacks of existing implanted FES systems are well known and include insufficient reliability, the complexity of the surgery, limited stimulation selectivity and efficiency, the non-physiological recruitment of motor units and muscle control. In order to develop viable implanted neuroprostheses as palliative solutions for motor control disabilities, objective 3 of the project-team aims at tackling four main challenges: (i) a more physiologically based approach to muscle activation and control, (ii) a fibres' type and localization selective technique and associated technology (iii) a neural prosthesis allowing to make use of automatic control theory and consequently real-time control of stimulation parameters, and (iv) small, reliable, safe and easy-to-implant devices.

Accurate neural stimulation supposes the ability to discriminate fibres' type and localization in nerve and propagation pathway; we thus jointly considered multipolar electrode geometry, complex stimulation profile generation and neuroprosthesis architecture. To face stimulation selectivity issues, the analogue output stage of our stimulus generator responds to the following specifications: i) temporal controllability in order to generate current shapes allowing fibres' type and propagation pathway selectivity, ii) spatial controllability of the current applied through multipolar cuff electrodes for fibres' recruitment purposes. We have therefore proposed and patented an original architecture of output current splitter between active poles of a multipolar electrode. The output stage also includes a monotonic DAC (Digital to Analog Converter) by design. However, multipolar electrodes lead to an increasing number of wires between the stimulus generator and the electrode contacts (poles); several research laboratories have proposed complex and selective stimulation strategies involving multipolar electrodes, but they cannot be implanted if we consider multisite stimulation (i.e. stimulating on several nerves to perform a human function as a standing for instance). In contrast, all the solutions tested on humans have been based on centralized implants from which the wires output to only monopolar or bipolar electrodes, since multipolar ones induce to many wires. The only solution is to consider a distributed FES architecture based on communicating controllable implants. Two projects can be cited: Bion technology (main competitor to date), where bipolar stimulation is provided by injectable autonomous units, and the LARSI project, which aimed at multipolar stimulation localized to the sacral roots. In both cases, there was no application breakthrough for reliable standing or walking for paraplegics. The power source, square stimulation shape and bipolar electrode limited the Bion technology, whereas the insufficient selection accuracy of the LARSI implant disqualified it from reliable use.

Keeping the electronics close to the electrode appears to be a good, if not the unique, solution for a complex FES system; this is the concept according to which we direct our neuroprosthesis design and development, in close relationship with other objectives of our project-team (control for instance) but also in close collaboration with medical and industrial partners.

Even if we focus on implanted FES system, since it is the most restrictive domain, we also work on surface FES architecture and stimulators; external FES system benefits from our concepts and advancements in implantable neuroprostheses.

4. Application Domains

4.1. Objective quantification and understanding of movement disorders

One main advantage of developping a model based on a physical description of the system is that the parapeters are meaningful. Therefore, these parameters when identified on a given individual, give objective and quantitative data that characterize the system and thus can be used for diagnosis purposes.

Modelling provides a way to simulate movements for a given patient and therefore based on an identification procedure it becomes possible to analyse and then understand his pathology. In order to describe complex pathology such as spasticity that appears on paraplegic patients, you need not only to model the biomechanics parts - including muscles -, but also parts of the peripheral nervous system - including natural sensors - to assess reflex problems. One important application is then to explore deficiencies globally due to both muscles and peripheral neural nets disorders.

4.2. Palliative solutions for movement deficiencies

Functional electrical stimulation is one possibility to restore or control motor functions in an evolutive and reversible way. Pacemaker, cochlear implants, deep brain stimulation (DBS) are successful examples. DEMAR focuses on movement disorder restoration in paraplegic and quadriplegic patients, enhancements in hemiplegic patients, and some other motor disorders such as bladder and bowel control. Nevertheless, since some advances in neuroprosthetic devices can be exploited for the next generation of cochlear implants, the team also contributes to technological and scientific improvements in this domain.

The possibility to interface the sensory motor system, both activating neural structure with implanted FES, and sensing through implanted neural signal recordings open a wide application area:

- Restoring motor function such as grasping for quadriplegic patient, standing and walking for paraplegic patient, foot drop for hemiplegic patients. These applications can be firstly used in a clinical environment to provide to physiotherapist a new efficient FES based therapy (using mainly surface electrodes) in the rehabilitation process. Secondly, with a more sophisticated technology such as implanted neuroprostheses, systems can be used at home by the patient himself without a clinical staff.
- Modulating motor function such as tremors in Parkinsonian patient using DBS. Techniques are very similar but for the moment, modelling is not achieved because it implies the central nervous system modelling in which we are not implied.

- Sensing the afferent pathways such as muscle's spindles, will be used to provide a closed loop control of FES through natural sensing and then a complete implanted solution. Sensing the neural system is a necessity in some complex motor controls such as the bladder control. Indeed, antagonist muscle's contractions, and sensory feedbacks interfere with FES when applied directly on the sacral root nerve concerned. Thus, enhanced activation waveforms and sensing feedback or feedforward signals are needed to perform a highly selective stimulation.

To achieve such objectives, experimentations in animals and humans are necessary. This research takes therefore a long time in order to go from theoretical results to real applications. This process is a key issue in biomedical research and is based on: i) design of complex experimental protocols and setups both for animals and humans, ii) ethical attitude both for humans and animals, with ethical committee approval for human experiments iii) volunteers and selected, both disabled and healthy, persons to perform experiments with the adequate medical staff.

5. Software

5.1. Software

5.1.1. RdP to VHDL tool

Participants: David Andreu, Grégory Angles.

Our SENIS (Stimulation Electrique Neurale dIStribuee) based FES architecture relies on distributed stimulation units (DSU) which are interconnected by means of a 2-wire based network. A DSU is a complex digital system since its embeds among others a dedicated processor (micro-machine with a specific reduced instruction set), a monitoring module and a 3-layer protocol stack. To face the complexity of the unit's digital part and to ease its prototyping on programmable digital devices (e.g. FPGA), we developed an approach for high level hardware component programming (HILECOP). To support the modularity and the reusability of sub-parts of complex hardware systems, the HILECOP methodology is based on components. An HILECOP component has: a Petri Net (PN) based behavior, a set of functions whose execution is controlled by the PN, and a set of variables and signals. Its interface contains places and transitions from which its PN model can be inter-connected as well as signals it exports or imports. The interconnection of those components, from a behavioral point out view, consists in the interconnection of places and/or transitions according to well-defined mechanisms: interconnection by means of oriented arcs or by means of the "merging" operator (existing for both places and transitions). We started, through an INRIA ODL (Opération de Développement Logiciel), the development of an Eclipse-based version of HILECOP with the aim at making it accessible to the academic community.

5.1.2. SENISManager

Participants: David Andreu, Grégory Angles, Robin Passama.

We developed a specific software environment called SENISManager allowing to remotely manage and control a network of DSUs, i.e. the distributed FES architecture. SENISManager performs self-detection of the architecture being deployed (Fig. 1; left). This environment also allows the manipulation of micro-programs from their edition to their remote control (Fig. 1; right).

5.1.3. STIMWare

Participants: David Andreu, Robin Passama.

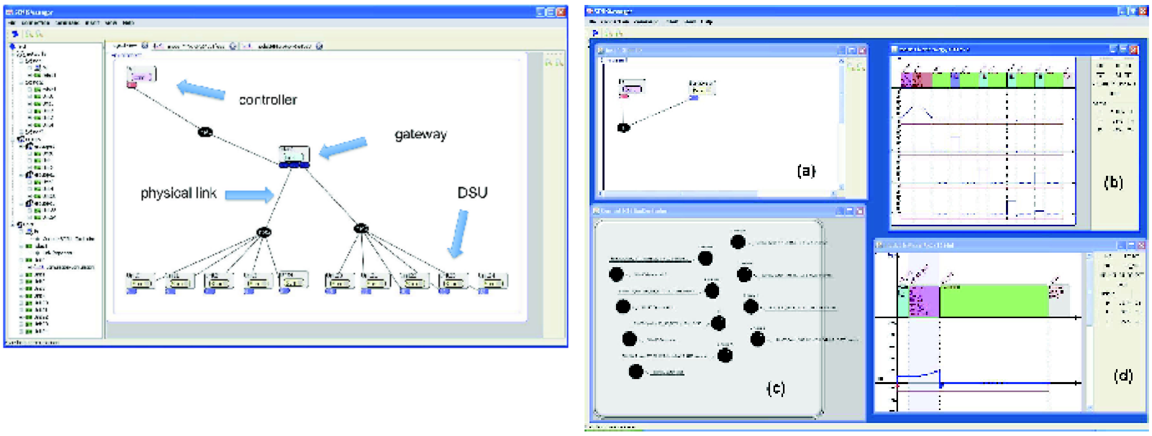


Figure 1. Left) Example of SENIS Architecture managed through SENIS Manager. Right) Some windows available on SENISManager: (a) FES architecture management, (b) graphical editing of micro-programs, (c) console for remote control of the execution of micro-programs of which parameter values are displayed in real-time (d).

We designed and partially developed a software environment allowing the management and control of a heterogeneous technology based external FES architecture. This software environment eases the configuration and exploitation of the external FES platform since it ensures the interoperability of the heterogeneous entities implied within the platform. It is based on a middleware and a set of modules organized according to two-layer software architecture: the interaction layer and the control layer. The interaction layer directly pilots stimulators and sensors used in the platform, ensuring the communication with these entities according to their specific protocol-stacks. Its middleware contains a scheduler in charge of the scheduling, the activation and the monitoring of the corresponding modules. The control layer supports the development of control strategies, potentially based on a set of heterogeneous entities (stimulators and sensors), like closed-loop controllers and/or supervisory controllers. This software is already tested with stimulators used on patient under ethical comitee approval.

A graphical interface will allow the end-user to manipulate the FES architecture (software entities and their associated hardware), at greater abstraction level.

5.1.4. gOM2N

Participants: Jérémy Laforêt, David Guiraud.

The software tool chain we set up to simulate the electrode-nerve interface is efficient but complex to use. It involves two different software (OpenMEEG and Neuron) and three ways of interaction: command line, Python scripts, and editing makefiles. To enable the use of this tool-chain by non specialist we designed a graphical interface managing the simulations. It is based only on free software technologies : Python, gtk and glade. It enables the user to define the model parameters and run the simulations. It takes into account the intermediate steps and thus can resume previous simulations or use part of them as basis for new ones.

5.1.5. Planning and Fast Re-Planning of safe motions

Participants: Sébastien Lengagne, Philippe Fraisse, Nacim Ramdani.

This algorithm allowing to generate optimal safe motion in term of balance is based on interval analysis. It can be downloaded at: http://safemotions.sourceforge.net/.

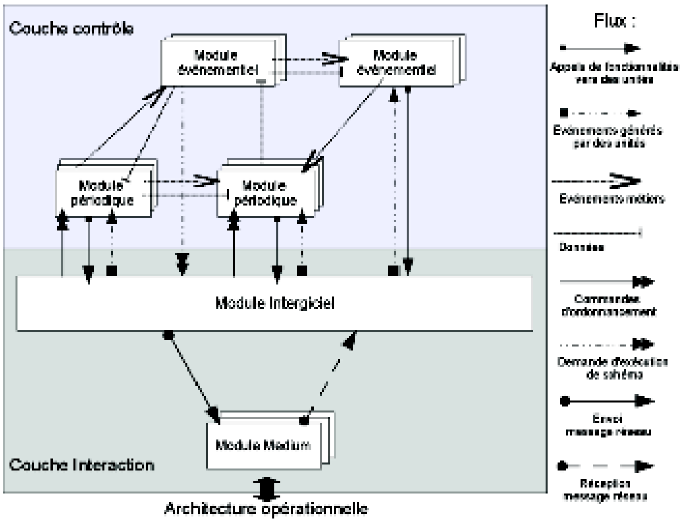


Figure 2. Schematic description of the software environment allowing the deployment of control strategies based on heterogeneous entities

6. New Results

6.1. modelling and Identification

6.1.1. Force assessment based on evoked EMG in intermittent stimulation

Participants: Qin Zhang, Mitsuhiro Hayashibe, Maria Papaiordanidou, Philippe Fraisse, Charles Fattal.

Muscle fatigue phenomenon and the inadequacy of force sensors limit the application of FES technology. It is essential to monitor muscle state and assess the generated force to compensate the fatigue and achieve the desired trajectory. It is also important to cease the stimulation depending on muscle fatigue to prevent serious muscle damages. Our final purpose is the on-line monitoring of muscle state and assessment of the muscle force to get a more accurate FES control. Evoked EMG signal offers a way of studying the myoelectric features of the neuromuscular activation associated with muscle contraction. This work was concentrated on the development of EMG-torque model to predict force more accurately. In this case, two spinal cord injured (SCI) subjects participated in the experiment for two sessions, recruitment and fatigue session. Tibialis anterior muscle was stimulated with intermittent stimulation, which can reduce muscle fatigue during rest duration, however, this complicated the EMG-torque relationship due to different recovery velocity of EMG and torque. Force assessment in intermittent stimulation is more difficult than the one in continuous stimulation.

With surface EMG acquisition and suppression of stimulation artifact, time domain EMG parameters, peak-to-peak (PTP) amplitude and second phase area (SPA), represent high correlation to the ankle torque. When the muscle is non-fatigued, PTP shows positive correlation with torque when increasing the stimulation level. When the muscle is fatigued PTP shows correlation with intermittent stimulation. SPA is negatively correlated with the torque at constant stimulation level. PTP and SPA can therefore be combined to build an EMG-torque model which can estimate the torque even when the muscle is fatigued. For each subject, the pooled data from both recruitment and fatigue session were used for model inference. Fig.3 illustrates the result obtained from one of the subjects using cross validation [35].

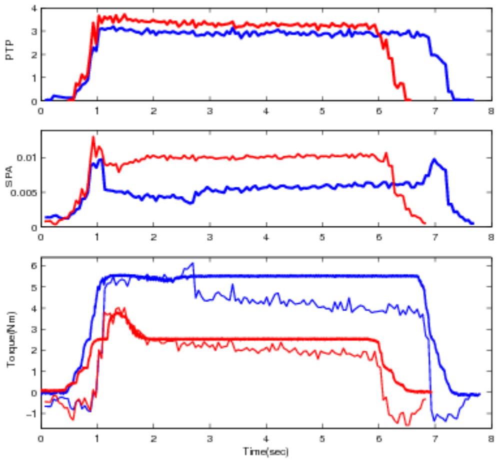


Figure 3. Non-fatigued (blue) and fatigued (red) PTP, SPA and torque in the same stimulation amplitude. The measured (smoothed line) and estimated (unsmoothed line) torque obtained using EMG-torque model (bottom). The estimation was based on the data which were not used to identify the model.

6.1.2. *Force assessment and muscle fatigue detection in implanted subject*

Participants: Mitsuhiro Hayashibe, Qin Zhang, David Guiraud, Christine Azevedo-Coste.

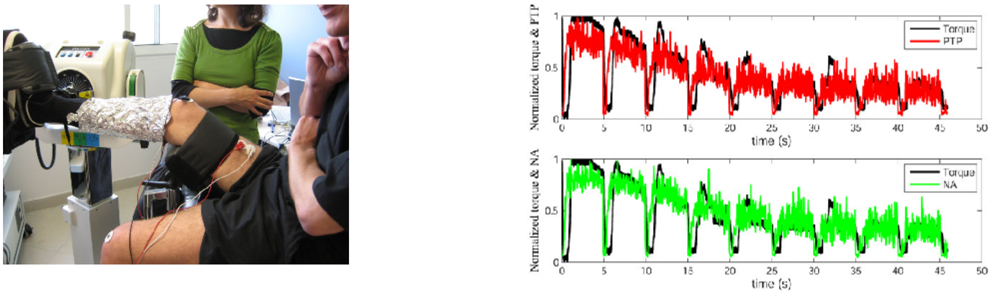
For SCI patients, muscle fatigue under FES is an insensible information. In fact, muscle fatigue is difficult to avoid in prolonged movement restoration even with the use of intermittent stimulation. Both for FES control and security of patient, it is essential to observe the time-varying muscle state especially for fatigue and recovery conditions. Implanted FES systems already provide the mobility to be used in private environments, similarly, muscle fatigue should be captured with sensors which have such mobility. EMG requires small electrodes and amplifiers and some wireless EMG systems are commercially available. Evoked EMG can be one of the solutions to detect the time-varying muscle conditions.

In this experiment, a fully implanted SCI subject participated in three sessions. Stimulation patterns were prepared for the recruitment with amplitude modulation, random amplitude modulation and fatigue session with prolonged stimulation. In this initial trial, continuous electrical stimulation was applied to peroneal branch of sciatic nerve by implanted stimulator. The experimental set-up is shown as in Fig.4a. PTP, root mean square (RMS), mean absolute value (MAV) and net area of the ellicited M-wave allow to track efficiently the changes in the joint torque during muscle fatigue. Fig.4b illustrates part of the results. The obtained EMG-torque model will be helpful to achieve more accurate FES control corresponding to muscle fatigue in future work. We are now working on on-line data processing of EMG for real-time assessment of muscle fatigue condition in FES.

6.1.3. *Kinetics of neuromuscular changes during low-frequency electrical stimulation of the abductor pollicis brevis*

Participants: Maria Papaiordanidou, Alain Varray, David Guiraud.

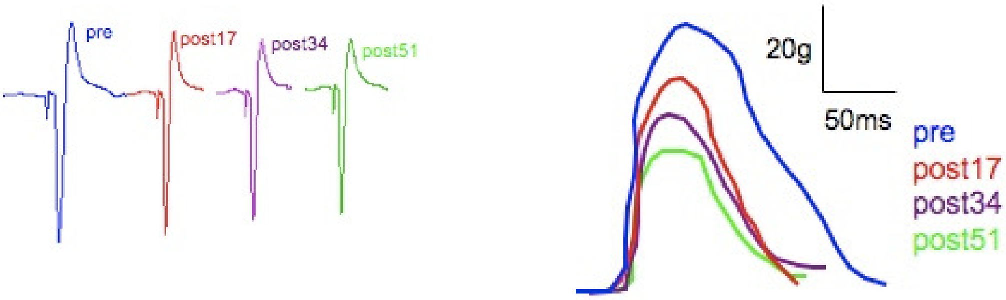
The aim of the present study was to examine the time evolution of fatigue components during electrically induced fatigue of the abductor pollicis brevis muscle (APB). Three series of 17 trains (30 Hz, 450μs, 4 s on - 6 s off, at the maximal tolerated intensity) were used to fatigue the muscle. Neuromuscular tests, consisting of electrically evoked and voluntary contractions, were performed before and after every 17-train series. Maximal voluntary force generation capacity and force induced by the trains of stimulation significantly decreased throughout the protocol (-20% and -27% respectively at the end of the protocol, $P < 0.001$). This decrease



(a) (b)

Figure 4. (a)Experimental set-up. (b)Upper graphics shows measured torque (black) and PTP of M-wave in measured EMG (red). Bottom graphics shows measured torque (black) and net area of M-wave in measured EMG (green).

was accompanied by significant impairment in the muscle contractile properties ($P < 0.05$), as assessed by the muscle mechanical response (Pt), as well as by failure in muscle excitability ($P < 0.01$), studied with the muscle compound action potential (M-wave or Mmax). Central fatigue indices (level of activation, RMS/Mmax and H reflex) were not significantly changed at any point of the protocol, giving evidence of optimal motor command reaching the motoneurons and preserving spinal excitability, ensuring fully central activation of the muscle. The results indicate that a low-frequency stimulation protocol when applied to a fast-fatigable muscle entails peripheral fatigue development, while central fatigue components are not implicated. The nature of the studied muscle (fast-fatigable or fatigue resistant) seems to be an important determinant of the fatigue component development, since, in an earlier study from our laboratory, the same protocol applied to the plantar flexors (fatigue resistant muscles) provoked central activation failure (fig.5).



(a) (b)

Figure 5. (a) Mwave evolution throughout the ES protocol. (b) Muscle mechanical response during the ES protocol.

6.1.4. A computational model of Inner Hair Cell ribbon synapse of the cochlea

Participants: Christophe Michel, Jérôme Bourien, Jean-Luc Puel, Christine Azevedo-Coste.

modelling the Inner Hair Cell (IHC) ribbon synapse is an interesting alternative to evaluate in silico hypothesis which are difficult (or impossible) to investigate in vitro and in vivo. Existing models are generally constituted of a cascade of five stages: i) stapes motion, ii) basilar membrane motion, iii) IHC depolarisation, iv) neurotransmitter release (glutamate) in the synaptic cleft, v) action potentials firing in auditory nerve fibers. In physiological conditions, these models provide a good agreement with both pre- and post-synaptic data recorded in vitro (patch clamp) and in vivo (Compound Action potential, Peri-Stimulus Time Histogram). These models are incomplete at the post-synaptic compartment. This lack does not permit to study pathologies like tinnitus which affect the firing of auditory nerve fibers. The aim of this work is to develop a computational model of the neurotransmission process from the IHC to auditory nerve fibers (fig.6). At the post-synaptic level, the release of glutamate vesicles in the synaptic cleft triggers action potential firing through a two-stage model (fig.7). Our preliminary results show that the activation of second receptor type which is inactive in normal conditions, leads to a drastic increase of the action potentials firing. This result reinforces previous data which reveal a firing increase of 250% in animals which experienced tinnitus. Beyond this work, we will develop a computational model of the pre-synaptic compartment in order to study in silico the neurotransmission diseases of this ribbon synapse like deafness and tinnitus.

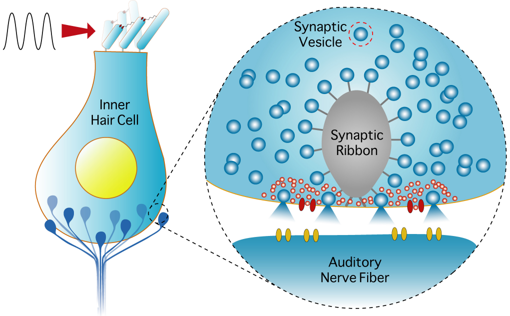


Figure 6. The neurotransmission process from the IHC to auditory nerve fibers. A sound stimulation causes: a cilia motion, a depolarisation of the IHC membrane, an opening of calcium channels, an exocytosis of glutamate vesicles into the synaptic cleft. AMPA receptors (yellow) detect and trigger action potential firing into the auditory nerve fibers

6.1.5. modelling trunk CPG in locomotion

Participants: Jean-Charles Ceccato, Christine Azevedo-Coste, Jean-René Cazalets.

We developped a new model of human locomotion based on a central pattern generator (CPG) mechanism. The CPG is represented by an oscillator network especially dedicated to reproduce trunk rhythmic activities during locomotion, as we have observed in vivo (see previous activity reorts). The model comprises an external input, which allows driving the behavior according to gait context or environment changes (fig.8). The model is able to reproduce walking, running and jumping behaviors. We also demonstrated how the model can be applied to observe the gait of an individual walking. In this case, the external input is a signal from an accelerometer sensor placed on the trunk of the subject. The model output is therefore synchronized with the subject and automatically adapts to changes of his gait pattern. Experimental results show a good synchronization between real and model based simulation behaviors. [20], [22]

6.1.6. Bladder function modelling

Participants: Jérémy Laforet, David Guiraud, Christine Azevedo-Coste, David Andreu, Maureen Clerc.

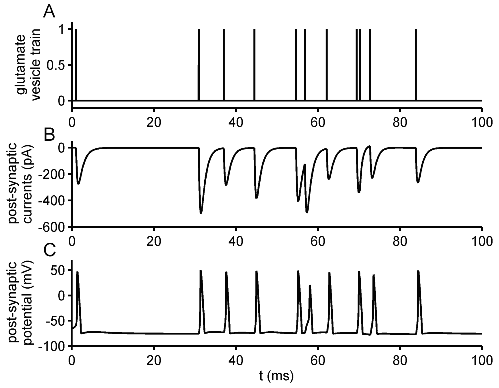


Figure 7. Two-stage post-synaptic model. A. Vesicle exocytosis times are assimilated to an impulse train. B. Each impulse generates through an IIR filter an excitatory post-synaptic current (EPSC). C. EPSCs drive an adapted Hodgkin-Huxley model which generates action potentials firing.

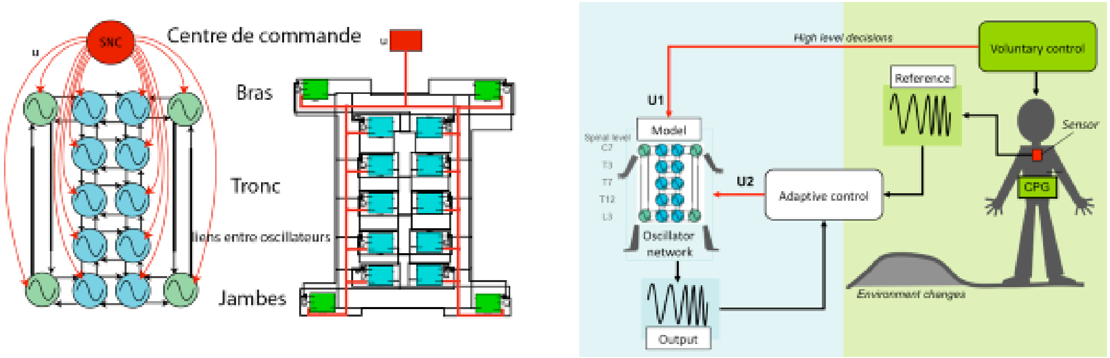


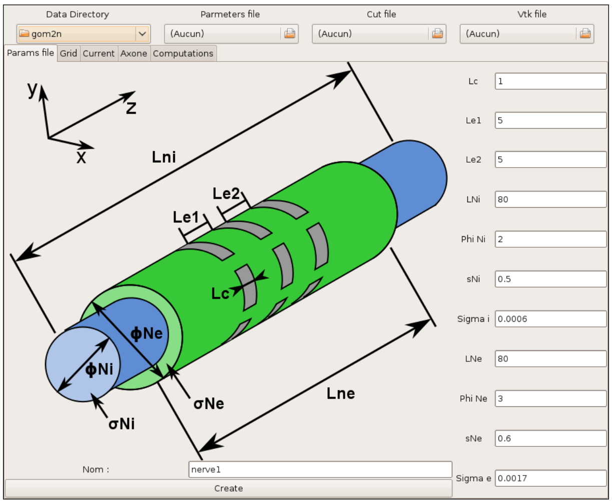
Figure 8. CPG-based trunk modelling and application to locomotion observation

We present a bladder model including detrusor and sphincter dynamics. The model focuses on artificially controlled bladder contractions under electrical stimulation. A numeric study of parameter sensitivity shows which ones are required for accurate estimation in order to achieve reasonable patient's dependent simulation. We finally demonstrate the interest of using such models in order to optimize the stimulation profile. Indeed, the choice of On-Off duty cycle influences the efficiency of the bladder voiding and the maximum intravesical pressure. Fine tuning of this duty cycle leads to enhanced urine outflow while maximal pressure is lowered (figure 10).

When contracting a muscle using NFES (Neural Functional Electrical Stimulation), the stimulus always activates first the axons of greater diameter. Also selective activation of a given fascicle inside a nerve is not possible with classical cuff electrode as the recruitment is performed uniformly around the nerve. These limits lead to poorly selective muscle recruitment, inducing fatigue and possible pain. To overcome this, selective stimulation strategies can be used. We propose a tool chain to investigate, simulate and tune selective stimulation strategies. It consists of:

- a conduction volume model to compute the electric field generated in the nerve by a cuff electrode surrounding it (work in collaboration with Odyssée project);
- an axon model to predict the effect of the field on the nerve fibre – the generation, propagation and possible block of action potentials;
- and an interface script that links the two models and generates the code of the input function for the nerve fibre model.

This tool-chain can be managed using a graphical interface to make the simulations easier to define and run (figure 9).



Data Directory: gom2n
Parmeters file: (Aucun)
Cut file: (Aucun)
Vtk file: (Aucun)

Lc: 1
Le1: 5
Le2: 5
LNi: 80
Phi Ni: 2
sNi: 0.5
Sigma i: 0.0006
LNe: 80
Phi Ne: 3
sNe: 0.6
Sigma e: 0.0017
Nom : nerve1

Figure 9. Screen-shot of the graphical interface developed to manage the simulation tool chain.

6.2. Function control and synthesis

6.2.1. Correction of drop-foot

Participants: Christine Azevedo Coste, Roger Pissard-Gibollet (SED INRIA), David Andreu, Bernard Espiau (INRIA RA), Jérôme Froger (Rehab. Centre, Grau du Roi, CHU Nîmes).

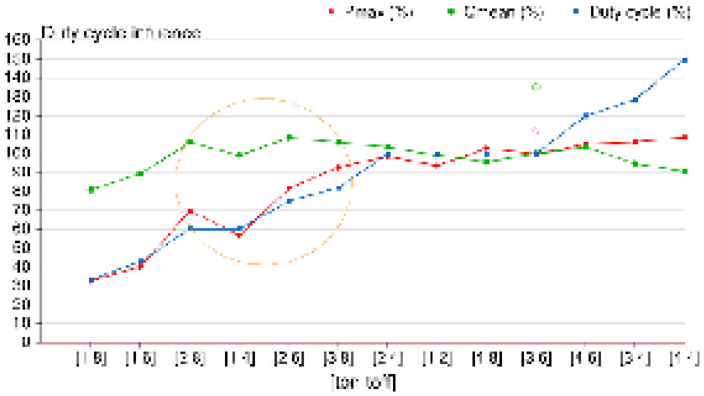


Figure 10. Summary of the numerical study results on the influence of the duty cycle of intermittent command for bladder voiding under FES.

Hemiplegia is a condition where one side of the body is paretic or paralyzed; it is usually the consequence of a cerebro-vascular accident. One of the main consequences of hemiplegia is the drop-foot syndrome. Due to lack of controllability of muscles involved in flexing the ankle and toes, the foot drops downward and impede the normal walking motion. Today, there are commercially available assistive systems that use surface electrodes to stimulate Tibialis Anterior (TA) muscle and prevent drop-foot. The efficiency of drop-foot stimulators depends on the timing of stimulation and functionality of dorsiflexion motion. Classically, available stimulators use footswitches to detect foot on/off events. These discrete events allow only for triggering the stimulation and/or playing with the duration of the stimulation pattern, but does not allow for precise online modification of the pattern itself. We have developed algorithms to monitor the ongoing walking cycle by observing the valid limb movements. In order to ensure legs coordination during walking, the CPG (Central Pattern Generator) concept was introduced, and we proposed a robust phase estimation method based on the observer of a nonlinear oscillator. Based on these preliminar results we have validated the phase estimation algorithm on hemiplegic subjects data. We have modified a commercial stimulator, ODSTOCK, in order to be able to trigger it using our own wireless sensors and algorithms (Fig. 11). The experiments on real-time triggering of drop-foot stimulator will started as soon as ethical comittee will give us the agreement to run tests on patients.

This work is related to the technological developements presented in this report on external device development.

6.2.2. Planning and Fast Re-Planning of Safe Motions for biped systems

Participants: Philippe Fraisse, Sébastien Lengagne, Nacim Ramdani.

Optimal motions are usually used as joint reference trajectories for repetitive or complex motions. In the case of soccer robots, the kicking motion is usually a benchmark motion, computed off-line, without taking into account the current position of the robot or the direction of the goal. Moreover, robots must react quickly to any situation, even if not expected, and cannot spend time to generate a new optimal motion by the classical way. Therefore, we propose a new method for fast motion re-planning based on an off-line computation of a feasible sub-set of the motion parameters, using Interval Analysis (figure 12).

6.2.3. Simulation of whole body motion under FES using HuMAnS Toolbox

Participants: Martine Eckert, David Guiraud, Mitsuhiro Hayashibe.

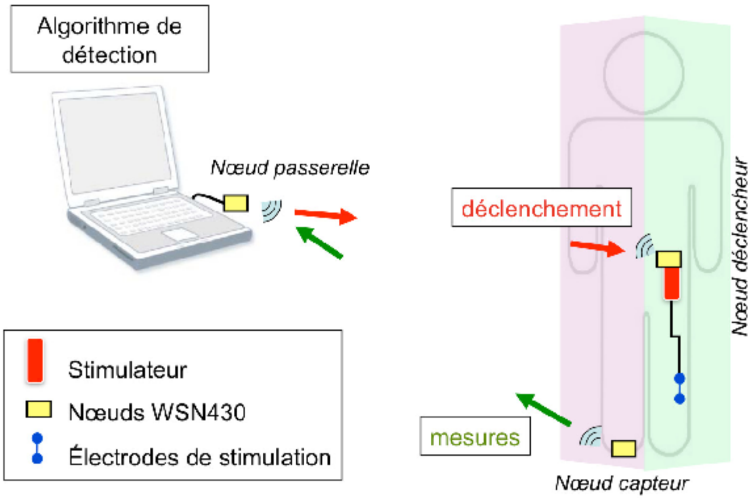
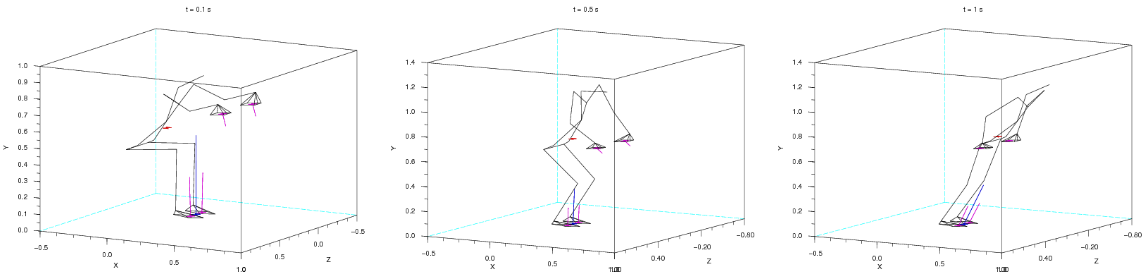


Figure 11. Principle of MASEA approach of drop foot correction using FES

Figure 12. new method for fast motion re-planning based on an off-line computation of a feasible sub-set of the motion parameters, using Interval Analysis

Mathematical models of the skeletal muscle can support the development of neuroprotheses to restore functional movements in individuals with motor deficiencies by the means of Functional Electrical Stimulation (FES). Since many years, numerous skeletal muscle models have been proposed to express the relationship between muscle activation and generated force. DEMAR model integrates the Hill model and the physiological one based on Huxley work allowing the muscle activation especially under FES. This musle model is implemented in a 3D biomechanical model of HuMAnS toolbox. Initially, only 4 muscles had been introduced in the human 36 model: the quadriceps and the hamstrings for knee joint actuation. Recently, we have introduced 10 other muscles: 6 muscles for the ankle and 4 muscles for the hip (right and left legs). For the ankle, we have modelled the tibialis anterior, the soleus and the two head of gastrocnemius and for the hip the iliopsoas and the gluteus maximus.

In future, the aim of this work is to simulate a patient standing up under FES and to compare the obtained results with experimental data in order to contribute for FES stimulation sequence generation by solving inverse dynamics problem. Simulation of standing up motion in HuMAnS toolbox is shown as in Figure 13. The required torques can be computed for certain task and it would be helpful to estimate the required combination of FES activations in muscles which were recently introduced for hip, knee and ankle joint actuations.



(a) (b) (c)

Figure 13. Simulation of standing up motion. The required torques can be computed for certain task and it would be helpful to estimate the required combination of muscle activations in FES.

6.2.4. Online tremor characterization and FES-based stiffness control

Participants: Antonio P. L. Bo, Philippe Poignet.

The main goal of the TREMOR Project is to evaluate the use of surface FES in the active compensation of pathological tremor. It is the most common movement disorder found in human pathology and its incidence is higher on the upper limbs.

In this scenario, algorithms previously proposed to perform online tremor characterization from inertial measurements were expanded to concurrently filter voluntary motion components also measured by these sensors. Tests were conducted in patients with different pathologies and the results have been compared with other solutions proposed in the literature [18]. The EKF-based algorithm was implemented in real-time and it was used to characterize tremor measured by different sensors, such as inertial sensors and a digitizing tablet.

Another research effort was directed to the development of a musculoskeletal model of the wrist joint actuated by flexor and extensor muscles. So far within the project, this Hill-based model, that describes joint motion dynamics under natural and artificial stimulation, has served different purposes.

In order to study the different effects the neural system may cause in tremor dynamics, a simulation study was conducted [8]. Effects of different levels were considered within the study, from changes on the dynamics of the reflex loops to interaction with higher levels of the neural system, represented by a central oscillator.

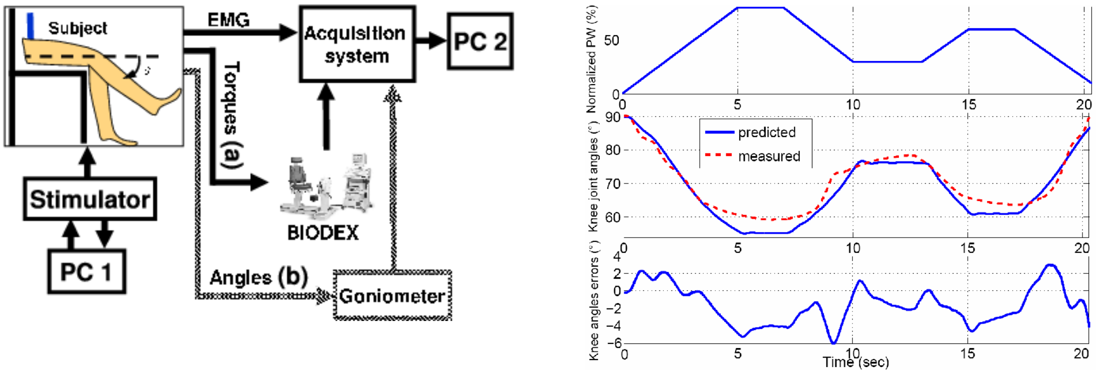
The model was also used in the development of new FES-based tremor compensation strategies. In [19], a strategy based on FES-controlled co-contraction of the antagonist muscles that act on the trembling joint was presented. In particular, the model was used to predict the stimulation pairs that do not interfere with the wrist joint, but allow modulation of the active stiffness that is provided to the wrist.

6.2.5. Identification protocol and validation of quadriceps-shank system: experimental results

Participants: Mourad Benoussaad, Philippe Poignet, David Guiraud, Mitsuhiro Hayashibe, Charles Fattal.

The knowledge and prediction of the behavior of electrically activated musculoskeletal muscles are important prerequisites for the synthesis and control of function by FES. The parameter identification of a physiological musculoskeletal model under FES is investigated in these works [14] [12]. The model represents the knee and its associated quadriceps muscle. The identification protocol is noninvasive and based on the in-vivo experiments on 10 spinal cord injured subjects. The measurements were obtained by stimulating the quadriceps muscles through surface electrodes. The torques were measured in isometric conditions through the Biodex system (Fig. 14-(a)- part (a)) and the joint angles were recorded in dynamical condition through an electrogoniometer (Fig. 14-(a)- part (b)).

The identification procedure consists of several steps, in order to identify: the geometrical parameters, the joint mechanical parameters, the force-length relationship, the recruitment function and the mechanical parameters of quadriceps. To perform this experiment, an authorization from the ethical review board and an agreement from each subject were obtained.



(a) (b)

Figure 14. Identification protocol and experimental validation. (a) The experimental setup in isometric condition (part a) and dynamic condition (part b). (b) The experimental cross validation.

A cross validation has been carried out using dynamical data set that has not been used for the identification. The results obtained for one subject is shown on figure 14-(b) and highlights a good prediction of the leg motion such as Normalized RMS Errors is about 3.5%.

6.3. Neuroprostheses

6.3.1. Activating the natural parts through neuroprosthetic devices

6.3.1.1. Distributed Stimulation Unit (DSU)

Participants: Guillaume Souquet, David Andreu, David Guiraud.

We designed and prototype a 12-pole stimulator according to the same concepts than those of the Stim'3D stimulator generation: a distributed stimulation unit [1]. This 12-pole stimulator, called Stim'nD, embeds the same modules as Stim'3D which are: a micro-machine for stimulation profile execution, a 3-layer procotocol-stack based communication module and a reference models based monitoring module. However, the micro-machine is based on another instruction set which allows to control the discharge phase, and the monitoring module is based on different reference models. These reference models monitor the quantity of charge which has been injected, instead of monitoring the stimulus duration.

We developed a specific software environment called SENISManager that allows to remotely manage and control a network of DSUs (see section 5.1.2). This environment has been extended in order to allow for controlling the new Stim'nD stimulator. SENISManager has been registered as a new software application at the french APP agency (IDDN.FR.001.320011.000.-S.P.2009.000.31500). It is already used by partners of the TIME project, taking advantage of our technology (both Stim'3D and Stim'nD stimulators): UAB Barcelone (SP), AAU-SMI Aalborg (DK), IUPUI Indianapolis (USA), MXM Sophia-Antipolis (FR). This software and the stimulator are used to study spatial fascicular and sub-fascicular selectivity, using an intrafascicular multichannel electrode (Fig. 15). Acute in-vivo measurements are performed on rat sciatic nerves [17].

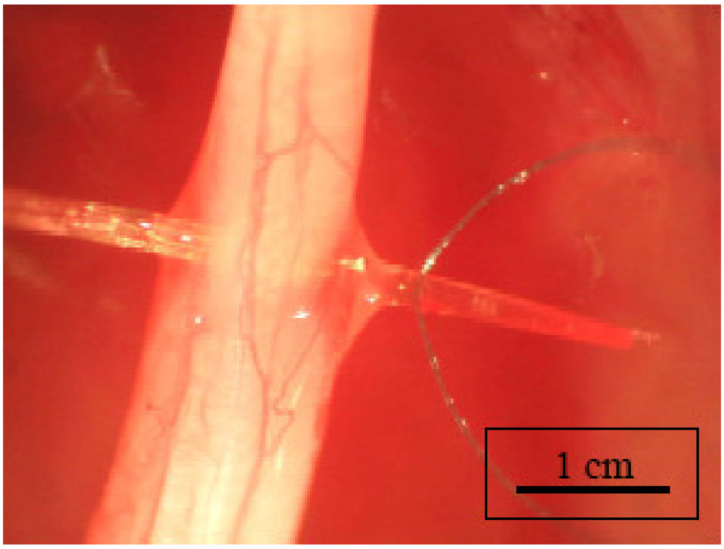


Figure 15. Rat sciatic nerve with a TIME device transversally implanted (X. Navarro, UAB).

6.3.1.2. Design and prototyping methodology

Participants: Guillaume Souquet, David Andreu.

Prototyping the digital architecture of distributed stimulation units (DSU) is performed on programmable digital electronic components (FPGA). In order to realize and characterize a dedicated circuit, we designed an ASIC version of the digital architecture of a DSU (its layout is shown in Fig. 16). The layout of such a complex multi-clock system has been difficult and presents the drawback of not being evolutive. We thus decide to realize the DSU using recent FPGA technology. This technology is flash-based and ultra-low power; corresponding small size dies are available and should comply with small volume and low power active medical implants. This work has been carried out within the NEUROCOM project.

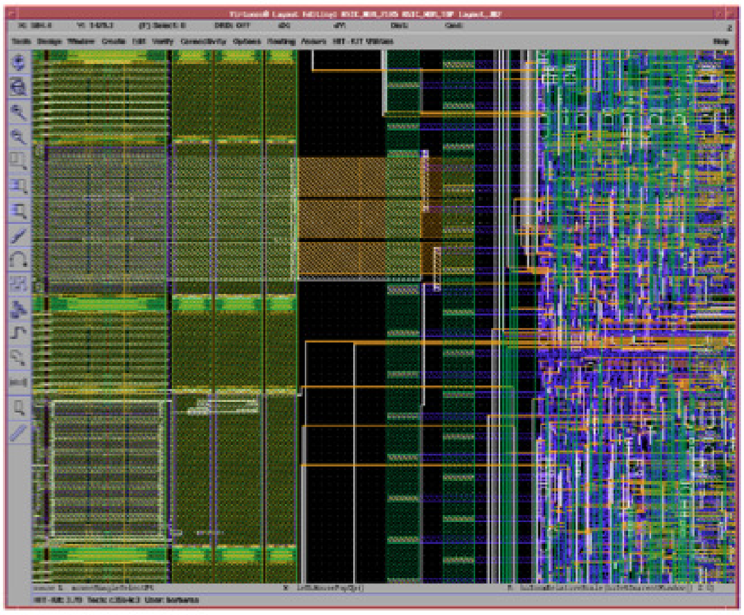


Figure 16. Layout of the DSU ASIC

6.3.1.3. Analog part of the micro-stimulator

Participants: Laurent De Knyff, Loïc Bourguine, Olivier Potin, Guy Cathébras, Serge Bernard, Fabien Soulier.

The analog part of the micro-stimulator consists of three main blocks:

- a digital-to-analog converter (DAC) for the conversion of the digital signal of the required stimulation wave-form into the effective electrical current,
- an output stage which amplifies and distributes the current from the DAC to the different poles of the electrode,
- a voltage measurement unit which allows us
    1. to check the right generation of the stimulation current,
    2. to detect potential partial or complete open or short between wires or poles,
    3. to assess the inevitable evolution of the nerve-electrode interface in order to adapt the stimulation current properties.

Since the begining of the DEMAR project, several versions of the analog part of the micro-stimulator have been realized. During this last year, we focussed on the characterization of these micro-stimulators and on the design of a new voltage measurement unit.

Concerning the characterization, we developed for the DAC and the output stage, different test boards. These boards allow:

- the measurement of the static parameters: integral and differential non-linearity (INL, DNL), offset and gain of the DAC,
- the dynamic parameters: signal-to-noise ratio (SNR), total harmonic distortion (THD)...
- an evaluation of the quality of the amplification (linearity) and the current distribution to the different electrode poles.

As an illustration, fig. 17 shows the Differential Non-Linearity of one of the DAC. Fig. 18 shows a conceptual view of the stability of the virtual electrode defined by the different current ratios between cathodes and anodes of the used multipolar electrode.

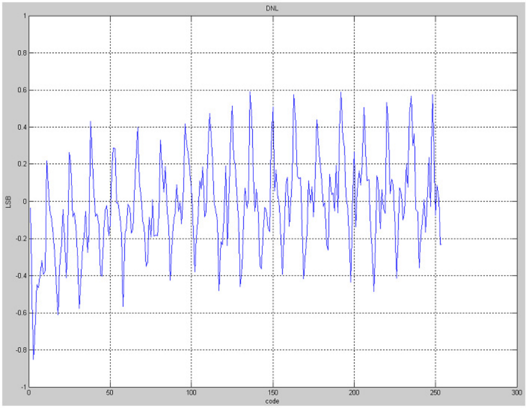


Figure 17. DNL *of a fabricated 8-bit* DAC.

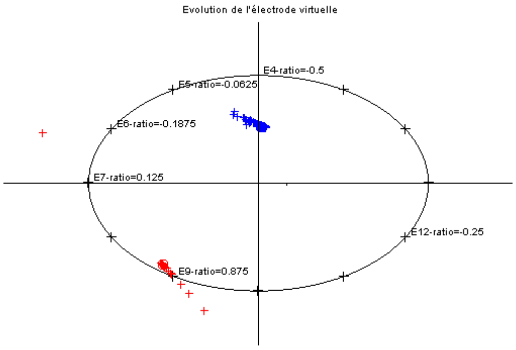


Figure 18. Stability of the virtual electrode (anode is blue and cathode is red).

Concerning the voltage measurement unit, we designed a new architecture running on various modes according to the objectives of the measurement. Indeed, for simple checking of the real generated current and for estimating the electrode-nerve interface the constraints are completely different in terms of accuracy and power consumption. The final version will be fabricated at the end of November and first validations are planned to 2010. Moreover, the proposed solution allows isolation and conversion to low voltage (3.3 V) of the measured nodes. Because of the nerve-electrode impedance value (1-4 kΩ) and the expected stimulation current (5 mA maximum) the pole voltages might be higher than 20 volts and the design of an ADC (analog-to-digital converter) at this high voltage supply would involve unacceptable silicon area overhead and significant power consumption. Fig. 19) gives the overview of the developed system for a sequential measurement on several poles (24 in this example) with only one ADC. This work has been carried out within the NEUROCOM project.

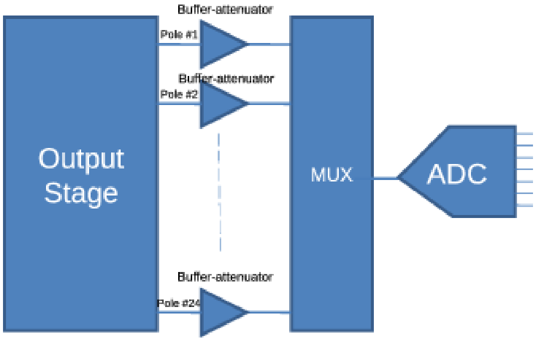


Figure 19. Overview of the voltage measurement unit.

6.3.2. External wireless FES system dedicated to clinical rehabilitation

Participants: Mickael Toussaint, David Andreu, Philippe Fraisse.

Even if we focus on implanted FES system, since it is the most restrictive domain, we also work on surface FES architecture and stimulators; external FES system benefits from our concepts and advancements in implantable neuroprostheses. Regarding surface FES architecture, we particularly developed wireless surface stimulation and/or bio-feedback units with our industrial partner Vivaltis. Using this technology, we aim at proposing an adequate solution for Drop Foot Stimulation (DFS) to face remote controllabilty, mobility and comfort issues (see section 6.2.1).

The first prototype of wireless surface stimulator that has been manufactured by Vivaltis is shown Fig. 20. It can provide 2 channels for stimulation or for bio-feedback.

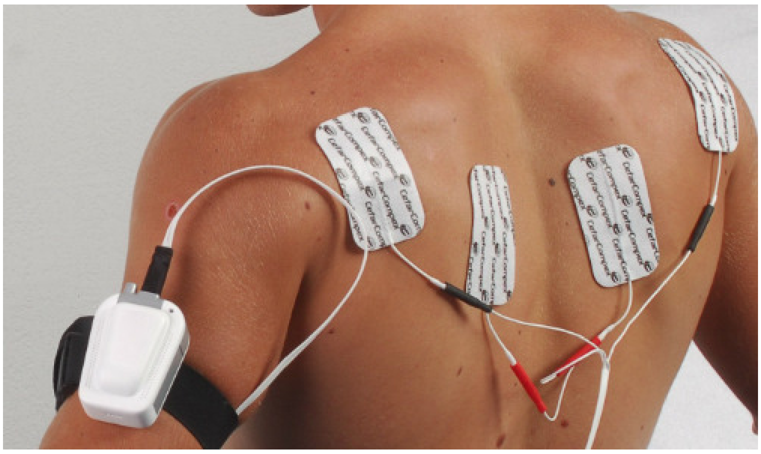


Figure 20. The wireless surface stimulator

6.3.3. Recording from the natural parts through neuroprosthetic devices

6.3.3.1. ENG electrode design

Participants: Olivier Rossel, Guy Cathébras, Fabien Soulier, Serge Bernard, Christine Azevedo Coste.

The motivation of this work is sensory information extraction from the peripheral nerves in chronic experiment. The propagation of afferent action potentials (AP) along the axons can be recorded via the electrical activity of the nerve (electroneurogramm, ENG). Unfortunately, this signal appears to be of very low level and even often below the micro-volt.

Moreover, bioelectrical activity makes the *in-vivo* environment very noisy, the worst noise being the signal generated by muscle activity (electromyogram, or EMG). In the particular case of peripheral nerve sensing, the EMG can exceed the ENG by order of magnitude of three at least. This parasitic signal will inevitably saturate the high gain amplifier needed to raise the ENG to a sufficient level for acquisition. Analog pre-processing must therefore be carried out in order to reject EMG-type noise.

Figure 21. Overview of the nerve signal acquisition system.

Based on a previous prototype [10], we carried out a system-oriented development of an implantable system for ENG recording (fig. 21). In order to facilitate the specification of this system, a single axon model have been used to simulate extracellular potential thanks to the *Neuron* software (fig. 22). Then, frequency analysis of simulated signal shows how to use spatial filtering techniques to extract the useful signal before amplification (fig.23). Based on simulation results, we have proposed solutions for signal preprocessing and electrode design [34].

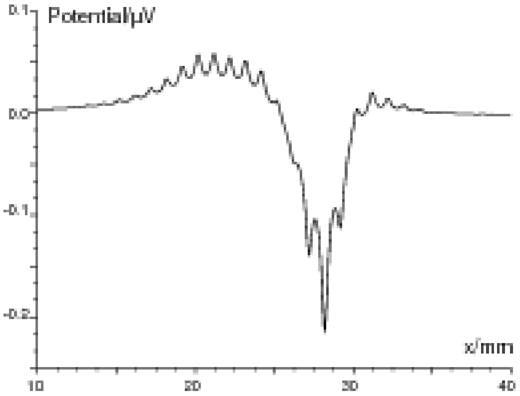


Figure 22. Extracellular potential along a single axon.

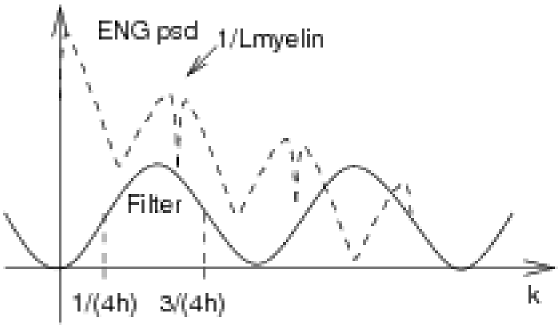


Figure 23. ENG spectrum and spatial filter response.

These simulations have shown that the optimal distance between the poles for this type of electrode is about $375\,\mu\mathrm{m}$. This inter-pole distance is much less than the classical distance between rings in multipolar cuff electrodes. This proposed design have been compared to state-of-art electrodes. The first results show better performance in terms of selectivity [31], [33].

6.3.4. Implant dependability

Participants: Fanny Le Floch, Guy Cathébras, Serge Bernard, Fabien Soulier.

The FES implanted system may be hazardous for patient and the reliability and dependability of the system must be maximal. Unfortunately, the associated systems are more and more complex and the fact that their development needs very cross-disciplinary experts is not favorable to safety. Moreover, the direct adaptation of the existing dependability techniques from domains such as space or automotive is not suitable. Therefore, we have developed a strategy for risk management at system level for FES medical implant. The idea is to give a uniform framework where all possible hazards are highlighted and associated consequences are minimized.

In particular, we focused on one of the most critical part of the FES system: analog micro-circuit which generates the electrical signal to the electrode. As this micro-circuit is the closest to the human tissue, any failure might involve very critical consequences for the patient. For instance, the level shifter has been pointed out as a high sensitive part of the output circuit and has proven sensitivity to voltage variations [32]. We have proposed a detection system as a simple down shifter (fig. 24) able to send a warning to the logic control for the implant to switch in a fail-soft mode.

6.4. Contrats

An industrial technological transfer contract is ongoing with the MXM company that develops cochlear implant and artificial lens implant. MXM can perform also Ethylene Oxyde sterilization necessary for all our experimental setups used during surgery. Two DSU prototypes (named Stim'3D and Stim'nD, cf. section 6.3.1.1) and the associated programming environment (SENIS Manager, cf. section 5.1.2) have been developed within this frame.
A contract has been signed with Vivaltis company that is specialized in the development of external stimulators. We commonly aim at new advanced external FES system dedicated to clinical rehabilitation; a first wireless external stimulator (cf. section 6.3.2) has been manufactured.

6.5. International Initiatives

6.5.1. National Medical Reasearch Council - Nayang Technological University

Participant: Philippe Poignet.

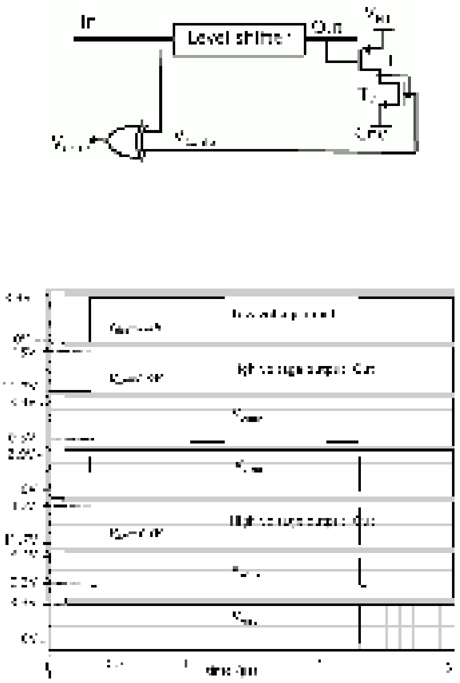


Figure 24. Level shifter error detection module.

Project on Pathological tremor. LIRMM scientific leader: P. Poignet. Funding for exchange (Oct. 2006 - Oct. 2009)

6.5.2. *Merlion program*

Participant: Philippe Poignet.

LIRMM scientific leader for Merlion program with NTU, Singapore. Junior and senior Researcher exchange (2009-2010).

6.6. National Initiatives

6.6.1. *PsiRob ANR*

Participant: Philippe Poignet.

Project TREMOR on pathological tremor compensation using FES, 243 kE. Partners: MXM, Propara, CHU Montpellier (Oct. 2006 - Oct. 2009). This project is jointly conducted with the DEXTER team at LIRMM.

6.6.2. *DGE Neurocom*

Participants: David Guiraud, David Andreu, Fabien Soulier, Serge Bernard, Guy Cathébras.

DGE Neurocom, (2007-2010). 475keuros, '*Implant Cochléaire 'tout implanté' pour la restauration des surdités sévères et profondes*'. Partners : MXM-Neurelec, ELA-Sorin group, APHM Hopitaux de Marseille, CHU Montpellier.

6.6.3. *COLOR INRIA MASEA*

Participants: Christine Azevedo, David Andreu, Roger Pissard-Gibollet, Jérôme Froger.

Drop foot correction using electrical stimulation.

6.7. Actions Funded by the EC

6.7.1. *European project Time*

Participants: David Guiraud, David Andreu, Fabien Soulier.

(2008-2012). 375keuros, "*Transverse, Intrafascicular Multichannel Electrode system for induction of sensation and treatment of phantom limb pain in amputees*". Partners : AAU (Aalborg, Denmark), MXM (Vallauris, France), SSSA (Pisa, Italy), IMTEK (Freiburg, Germany), UAB (Barcelona, Spain), UCBM (Roma, Italy), IUPUI (Indianapolis, USA).

6.8. Animation de la Communauté scientifique

- D. Guiraud
    1. Member of the scientific comittee of LIRMM
    2. Associate editor at EMBC 09
    3. Member of steering comittee of INSERM Institut des Technologies pour la Santé (ITS)
- C. Azevedo-Coste
    1. Associate Editor of Paladyn Behavioral Robotics Journal
- Mitsuhiro Hayashibe
    1. EMBC'09 Mitsuhiro Hayashibe was organizer and co-chair of the session Orthopaedic and Musculoskeletal Biomechanics, 31st Annual International Conference of the IEEE Engineering in Medicine and Biology Society, September, 2-6, 2009, Minneapolis, USA.
- D. Andreu:

1. D. Andreu was member of the Program Comittee of CAR'09

- P. Fraisse:
  1. Co-leader of the french working group on Humanoid Robotics of the GdR Robotique
  2. Head of Robotic Department (LIRMM)
  3. Program Committee Member of IEEE Humanoid 2009
- P. Poignet:
  1. Co-organizer of the french working group on Medical Robotics of the GdR Robotique (http://www.gdr-robotique.fr/index.php)
  2. Member of the IFAC T2.3 technical committee on Nonlinear Control Systems
  3. Member of the CNU 61 (2008-2012)
  4. Member of the evaluation comittee of ANR TECSAN
  5. Responsible for the 'Spécialité Doctorale' in Micro-electronics and Control System (about 80 PhD students) - (http://www.edi2s.univ-montp2.fr/)
  6. Responsible for the Licence Professionnelle par Apprentissage - Métiers de la Mesure et de l'Instrumention
  7. Member of the scientific comittee of the LIRMM
  8. Associate editor of JESA

6.9. Teaching

- David Guiraud, Master SMH, electrophysiology of striated muscles, modelling and control of electrically stimulated muscles
- David Andreu, Assistant Professor, 200h/y, Engineering school Polytech Montpellier and Master degree, Software engineering, real time OS, Petri Net.
- Guy Cathébras, Professor at Polytech'Montpellier (Electronics, Robotics and Industrial Informatics (ERII) Department), teaches: Mathematics and Signal theory for 3rd year ERII students; Analog integrated circuits: "An introduction to electronics: designing with Bipolar transistors", for 3rd year ERII students; "CMOS Analog integrated circuits design" CAD practical works for 4th year ERII students; "CMOS standard cells design" CAD practical works for 4th year ERII students. item Philippe Poignet Professor at IUT Montpellier Applied Physics teaching automatic control and signal processing.
- Philippe Fraisse, Professor at Polytech'Montpellier (ERII) teaching automatic control and networks.
- Fabien Soulier, assistant professor at Polytech'Montpellier (ERII) teaching electronics and signal processing.

6.10. Organization of seminars

- Katja Mombaur (LAAS) was invited to present her research topics on " Optimization & Human Movement ", on November 13th.

6.11. Participation in seminars and workshops

- Christine Azevedo-Coste
    1. Invited talk in Humanoïds 2009, workshop on modelling, Simulation and Optimization of Bipedal Walking.
- Mitsuhiro Hayashibe
    1. Invited talk in RIKEN Brain Science Institute-TOYOTA Collaboration Center, "Quantified description of the human sensory motor system based on functional electrical stimulation", July 2009 http://www.brain.riken.jp/en/events/bsiforum/2009/20090730_02.html
- David Guiraud
    1. David Guiraud was invited to present the work of DEMAR team around Neuroprostheses uses at "Fondation de la Recherche Médicale" Workshop dedicated to brain machine interfaces in the context of severe sensory motor deficiencies.

6.12. Theses and Internships

6.12.1. Thesis Defenses

1. **Jean-Charles Ceccato** co-supervised by Christine Azevedo-Coste and J.-R. Cazalets (UMR 5543-Bordeaux), *Le tronc de la locomotion à la commande*, Thesis BDI DGA-CNRS, 2006-2009, defended on: December 10th 2009.
2. **Guillaume Souquet** co-supervised by David Guiraud and David Andreu, *Architecture de stimulation électro-fonctionnelle implantable : des concepts aux applications*, Thesis CIFRE MXM, 2006-2009, defended on: December 11th 2009.
3. **Jérémy Laforêt** co-supervised by David Guiraud, David Andreu and Christine Azevedo-Coste, *Modélisation du recrutement sélectif en neurostimulation multipolaire multiphasique, application à la stimulation neuromotrice sélective*, Thesis LIRMM MENRT, 2006-2009, defended on: December 9th 2009.
4. **Sébastien Lengagne** co-supervised by Philippe Fraisse and Nacim Ramdani, *Planification et re-planification de mouvements sûrs pour les robots humanoïdes*, Thesis BDI INRIA / Région LR, 2006-2009, defended on: October 21st, 2009.
5. **Mourad Benoussaad** co-supervised by Philippe Poignet and David Guiraud, *Synthèse de séquences de stimulation optimales pour la déambulation de patients paraplégiques*, Thesis BDI INRIA / Région LR, 2006-2009, defended on: December 16th, 2009.
6. **David Andreu**, *Architectures de contrôle en Robotique et en Stimulation Electro-Fonctionnelle : une contribution à la croisée des disciplines*, HDR, defended on: December 17th, 2009.

6.12.2. Ongoing theses

1. David Andreu and Philippe Fraisse co-supervise **Mickael Toussaint**, *Conception et réalisation d'une architecture de stimulation musculaire externe distribuée et sans-fil : Application au contrôle de mouvement d'une articulation*, Thesis CIFRE VIVALTIS, 2008-2011.
2. Philippe Poignet supervises **Antônio Bo**, *Compensation active du tremblement pathologique du membre supérieur via la stimulation électrique fonctionnelle.*", Thèse CIFRE MXM ? Neuromedics 2007-2010
3. David Guiraud and Alain Varray supervise **Maria Papaiordanidou**,*Nature périphérique et centrale de la fatigue musculaire.*
4. Serge Bernard, Guy Cathébras co-supervise **Fanny Le Floch**, *Sûreté de fonctionnement des circuits implantables dans le corps humain.*, MENRT.

5. Guy Cathébras Fabien Soulier co-supervise **Olivier Rossel**, *Circuits intégrés de recueil et d'interprétation des signaux nerveux*, Axa fundation.
6. Jérôme Bourien (INM, Montpellier) and Christine Azevedo-Coste, co-supervise **Christophe Michel**, *Modélisation de l'efférence latérale du système auditif périphérique*, CIFRE MXM.
7. Christine Azevedo-Coste and Bernard Espiau co-supervise **Maud Pasquier**, *Observation et contrôle de mouvements non cycliques des membres inférieurs et supérieurs en assistance fonctionnelle.*, ANM.
8. Mitsuhiro Hayashibe and Philippe Fraisse co-supervise **Qin Zhang**, *FES modelling and control with on-line update of time-varying muscular property based on Evoked EMG.*, Oversea PhD Study Scholarship, awarded by China Scholarship Council in Ministry of Education.
9. Christine Azevedo-Coste, Philippe Fraisse and Charles Fattal co-supervise **Jovana Jovic**, *Maintien prolongé de la station debout équilibrée fonctionnelle chez le patient paraplégique*, BDI Région-INRIA.

6.12.3. PostDoc

- David Andreu supervises Jean-François Pineau, "Ordonnancement dans un système de stimulation électro-fonctionnelle" (1 year contract, Neurocom project), 2009-2010.

6.12.4. Internships

- Christine Azevedo supervised Philippe Dussaud, "Validation et optimisation d'un programme de suivi du mouvement pour le contrôle du déclenchement d'un stimulateur dans le cadre du syndrôme de pied tombant", Engineer intermediary internship, École des Mines (Nantes) from February 2008 to June 2008.
- David Andreu supervised Jérôme Barbaras, "Prototyping of a the embedded digital architecture of a 12-pole stimulator", Engineer final internship, from February 2009 to June 2009.
- Mickael Toussaint and David Andreu supervised Anthony Lihard, "Development of the embedded software of a wireless external stimulator", Engineer final internship, from February 2009 to June 2009.

6.12.5. Contract Engineers

- David Andreu supervised Robin Passama on "Configuration, programmation et contrôle à distance d'une unité de stimulation ; aspects logiciels", Computer Science Engineer (1 year contract, TIME financial support).
- David Andreu supervises Grégory Angles. "Conception et réalisation d'un environnement logiciel, basé sur Eclipse, pour le prototypage rapide sur composants électroniques programmables (HILECOP)". Computer Science Engineer, INRIA ODL contract (2 years contract, INRIA financial support).
- David Andreu supervised Abdellah El Jalaoui on "Contrôle à distance d'une unité de stimulation distribuée : communication et sécurité", Industrial Informatics Engineer (6-month contract, TIME financial support).
- Serge Bernard and Fabien Soulier co-supervise Loic Bourguine 'Micorelectronics design'. (2 year contract, NEUROCOM financial support)

7. Bibliography

Year Publications

Articles in International Peer-Reviewed Journal

[1] D. Andreu, D. Guiraud, G. Souquet. *A Distributed Architecture for Activating the Peripheral Nervous System*, in "Jounal of Neural Engineering", vol. 6, 2009, p. 001-018, http://hal-lirmm.ccsd.cnrs.fr/lirmm-00361686/en/.

[2] J.-C. Ceccato, M. De Sèze, J.-R. Cazalets, C. Azevedo-Coste. *Comparison of trunk activity during gait initiation and walking in humans*, in "PlosOne", vol. in press, 2009.

[3] S. Cotton, A. Murray, P. Fraisse. *Estimation of the Center of Mass: From Humanoid Robots to Human Beings*, in "IEEE/ASME Transactions on Mechatronics", vol. N/A, 2009, N/A, http://hal-lirmm.ccsd.cnrs.fr/lirmm-00413022/en/US.

[4] M. Djilas, C. Azevedo-Coste, D. Guiraud, K. Yoshida. *Interpretation of muscle spindle afferent nerve response to passive muscle stretch recorded with thin-film longitudinal intrafascicular electrodes*, in "IEEE TNSRE", vol. 17-5, 2009, p. 445-453, http://hal-lirmm.ccsd.cnrs.fr/lirmm-00411814/en/DKUS.

[5] N. Fourty, D. Guiraud, P. Fraisse, G. Perolle, I. Etxeberria, T. Val. *Embedded System used for Classifying Motor Activities of Elderly and Disabled People*, in "Computers & Industrial Engineering / Computers and Industrial Engineering", vol. 56, 2009, p. 1-14, http://hal-lirmm.ccsd.cnrs.fr/lirmm-00370444/en/ES.

[6] G. Pages, N. Ramdani, P. Fraisse, D. Guiraud. *A Method for Paraplegic Upper-Body Posture Estimation during Standing: a Pilot Study for Rehabilitation Purposes*, in "Medical & Biological Engineering & Computing / Medical and Biological Engineering and Computing", vol. 47, 2009, p. 625-633, http://hal-lirmm.ccsd.cnrs.fr/lirmm-00384983/en/FR.

[7] M. Papaiordanidou, D. Guiraud, A. Varray. *Kinetics of Neuromuscular Changes during Low-Frequency Electrical Stimulation*, in "Muscle and Nerve", vol. A paraitre, 2009, N/A, http://hal-lirmm.ccsd.cnrs.fr/lirmm-00405225/en/FR.

[8] D. Zhang, P. Poignet, A. P. L. Bó, W. Ang. *Exploring Peripheral Mechanism of Tremor on Neuromusculoskeletal Model: A General Simulation Study*, in "IEEE Transactions on Biomedical Engineering", vol. 56, n^{o} 10, 2009, p. 2359–2369 FR .

Articles in National Peer-Reviewed Journal

[9] C. Azevedo-Coste, D. Guiraud, D. Andreu, S. Bernard. *Principe de la stimulation électrique fonctionnelle. Exemples d'application thérapeuthique.*, in "Techniques de l'Ingénieur", vol. RE127, 2009, 12, http://hal-lirmm.ccsd.cnrs.fr/lirmm-00395562/en/FR.

[10] L. Gouyet, G. Cathébras, S. Bernard, F. Soulier, D. Guiraud, Y. Bertrand. *Amplificateur faible-bruit dédié à l'enregistrement d'ENG à partir d'une électrode cuff hexagonale*, in "REE : revue de l'électricité et de l'électronique", vol. 06-07 2009, 2009, http://hal-lirmm.ccsd.cnrs.fr/lirmm-00406532/en/FR.

Invited Conferences

[11] C. Azevedo-Coste, C. Heliot and. *Rôle du tronc dans les transferts assis-debout : Application chez le paraplégique*, in "Journée Nationale de Rééducation de Hauteville - "Le Complexe Lombo-Pelvi-Fémoral & Rééducation", France", 2009, http://hal-lirmm.ccsd.cnrs.fr/lirmm-00376055/en/FR.

[12] M. Benoussaad, M. Hayashibe, C. Fattal, P. Poignet, D. Guiraud. *Identification and Validation of FES Physiological Musculoskeletal Model in Paraplegic Subjects*, in "EMBC'09: Engeneering in Medicine and Biology Society, États-Unis d'Amérique Hilton Minneapolis, Minnesota", IEEE, 2009, http://hal-lirmm.ccsd.cnrs.fr/lirmm-00413465/en/FR.

International Peer-Reviewed Conference/Proceedings

[13] C. Azevedo-Coste, J.-Y. Hogrel, L. Viollet. *Low Frequency Electrical Stimulation in Spinal Muscular Atrophy: a Case Study Report*, in "IFESS'09: International Functional Electrical Stimulation Society", 2009, 2, http://hal-lirmm.ccsd.cnrs.fr/lirmm-00405360/en/FR.

[14] M. Benoussaad, D. Guiraud, P. Poignet. *Physiological Musculoskeletal Model Identification for the Lower Limbs Control of Paraplegic Under Implanted FES*, in "IROS 2009: The 2009 IEEE/RSJ International Conference on Intelligent RObots and Systems, St. L., MO, USA", 2009, 6, http://hal-lirmm.ccsd.cnrs.fr/lirmm-00413447/en/FR.

[15] V. Bonnet, P. Fraisse, N. Ramdani, J. Lagarde, S. Ramdani, B. Bardy. *A closed loop musculoskeletal model of postural coordination dynamics*, in "IEEE Conference on Decision and Control, CDC'09, Shanghai (China)", December 2009 FR .

[16] V. Bonnet, P. Fraisse, N. Ramdani, J. Lagarde, S. Ramdani, B. Bardy. *A robotic closed-loop scheme to model human postural coordination*, in "IEEE/RSJ International Conference on Intelligent Robots and Systems, IROS, Sain-L. (UA)", October 2009 FR .

[17] T. Boretius, J. Badia, A. Pascual-Font, D. Andreu, C. Azevedo-Coste, J.-L. Divoux, T. Stieglitz, X. Navarro, K. Yoshida. *Transversal intrafascicular multichannel electrode (TIME) a interface to peripheral nerves: preliminary in-vivo results in rats*, in "IFESS'09: International Functional Electrical Stimulation Society", 2009, 3, http://hal-lirmm.ccsd.cnrs.fr/lirmm-00408213/en/DEUSES.

[18] A. P. L. Bó, P. Poignet, C. Geny. *Filtering Voluntary Motion for Pathological Tremor Compensation*, in "IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS 2009)", 2009 FR .

[19] A. P. L. Bó, P. Poignet, D. Zhang, W. Ang. *FES-controlled Co-contraction Strategies for Pathological Tremor Compensation*, in "IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS 2009)", 2009 FR .

[20] J.-C. Ceccato, C. Azevedo-Coste, J.-R. Cazalets. *Real Time Control of a CPG Based Model of Human Trunk Activity in Different Walking Conditions*, in "EMBS'09: 31th Annual International Conference of the IEEE Engineering in Medicine and Biology Society", IEEE, 2009, 1, http://hal-lirmm.ccsd.cnrs.fr/lirmm-00407771/en/FR.

[21] J.-C. Ceccato, C. Azevedo-Coste, J.-R. Cazalets. *Using the trunk acceleration to detect gait initiation*, in "IFESS'09: International Functional Electrical Stimulation Society", 2009, 3, http://hal-lirmm.ccsd.cnrs.fr/lirmm-00407768/en/FR.

[22] J.-C. CECCATO, M. DE SÈZE, C. AZEVEDO-COSTE, J.-R. CAZALETS. *Trunk Activity in Human, from Posture to Locomotion*, in "ISPGR'09: International Society for Posture and Gait Research Conference, Bologne, Italie", 2009, A paraître, http://hal-lirmm.ccsd.cnrs.fr/lirmm-00375306/en/FR.

[23] D. GUIRAUD, C. AZEVEDO-COSTE, C. FATTAL. *Functional Electrical Stimulation for Spinal Cord Injured Patients*, in "Approche pluridisciplinaire de la motricité humaine, Lyon", Collet et al., 10 2009, p. 313-314, http://hal-lirmm.ccsd.cnrs.fr/lirmm-00429407/en/FR.

[24] D. GUIRAUD. *Neuroprothèses et déficiences sensori motrices, alternative et synergie thérapeutiques*, in "Workshop Brain Machine Interface, Paris", Fondation pour la Recherche Médicale / IRME / ICM, 11 2009, p. 34-35 FR .

[25] M. HAYASHIBE, D. GUIRAUD, P. POIGNET. *EMG-Based Neuromuscular Modeling with Full Physiological Dynamics and Its Comparison with Modified Hill Model*, in "EMBC'09: 31st Annual International Conference of the IEEE Engeneering in Medicine and Biology Society, Hilton Minneapolis, Minnesota USA", September 2009, p. 6530–6533 FR .

[26] M. HAYASHIBE, D. GUIRAUD, P. POIGNET. *EMG-to-force estimation with full-scale physiology based muscle model*, in "IROS'09: The 2009 IEEE/RSJ International Conference on Intelligent RObots and Systems", October 2009, p. 1621-1626 FR .

[27] D. LAFORÊT, M. CLERC. *A toolchain to simulate and investigate selective stimulation strategies for FES*, in "EMBC'09: IEEE Engineering in Medicine and Biology Conference", 2009, 1, http://hal-lirmm.ccsd.cnrs.fr/lirmm-00412305/en/FR.

[28] S. LENGAGNE, N. RAMDANI, P. FRAISSE. *Planning and Fast Re-Planning of Safe Motions for Humanoid Robots: Application to a Kicking Motion*, in "IROS'09: Intelligent Robots and Systems", 2009, N/A, http://hal-lirmm.ccsd.cnrs.fr/lirmm-00405359/en/FR.

[29] S. LENGAGNE, N. RAMDANI, P. FRAISSE. *Safe Motion Planning Computation for Databasing Balanced Movement of Humanoid Robots*, in "ICRA'09: IEEE International Conference on Robotics and Automation, Kobe, Japan", IEEE, 2009, p. 1669-1674, http://hal-lirmm.ccsd.cnrs.fr/lirmm-00385625/en/FR.

[30] M. PAPAIORDANIDOU, A. VARRAY. *What is known about fatigue sites under neuromuscular electrical stimulation?*, in "Approche Pluridisciplinaire de la motricité humaine, Lyon", Collet et al., 10 2009, p. 309-310, http://hal-lirmm.ccsd.cnrs.fr/lirmm-00429410/en/FR.

[31] O. ROSSEL, F. SOULIER, S. BERNARD, G. CATHÉBRAS. *New Electrode Layout for Internal Selectivity of Nerves*, in "EMBC'09: 31st Annual International Conference of the IEEE Engineering in Medicine and Biology Society", 2009 FR .

[32] F. SOULIER, F. LE FLOCH, S. BERNARD, G. CATHÉBRAS. *New Dependability Approach for Implanted Medical Devices*, in "ICM'09: International Conference on Microelectronics, Marrakech (Morocco)", december 2009 FR .

[33] F. SOULIER, O. ROSSEL, S. BERNARD, G. CATHÉBRAS, D. GUIRAUD. *An optimized layout for multipolar neural recording electrode*, in "IFESS'09: International Functional Electrical Stimulation Society, Seoul (Korea)", September 2009 FR .

[34] F. SOULIER, O. ROSSEL, S. BERNARD, G. CATHÉBRAS, D. GUIRAUD. *Design of Nerve Signal Biosensor*, in "NEWCAS-TAISA'09: North-East Workshop on Circuits and Systems, Traitement Analogique de l'Information, du Signal et ses Applications, Toulouse (France)", july 2009, p. 400-403 FR .

[35] Q. ZHANG, M. HAYASHIBE, M. PAPAIORDANIDOU, P. FRAISSE, C. FATTAL, D. GUIRAUD. *Torque assessment based on evoked EMG for FES-induced muscle contractions in SCI patients*, in "IFESS'09: Annual Conference of the International FES Society, Seoul, South Korea", 2009, 001, http://hal-lirmm.ccsd.cnrs.fr/lirmm-00413442/en/FR.

Scientific Books (or Scientific Book chapters)

[36] J. FROGER, C. AZEVEDO-COSTE, J. PELISSIER. *Modifications musculaires après lésion neurologique centrale*, in "Neuro-Orthopédie des Membres après Cérébrolésion Grave", Masson, 2009, N/A, http://hal-lirmm.ccsd.cnrs.fr/lirmm-00363937/en/FR.