INSTITUT NATIONAL DE RECHERCHE EN INFORMATIQUE ET EN AUTOMATIQUE

# *Project-Team DEMAR*

# *DEambulation et Mouvement ARtificiel*

*Sophia Antipolis*

THEME BIO

Activity Report

2005

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# 2. Overall Objectives

## 2.1. Overall Objectives

Functional Electrical Stimulation (FES) has been used for about 30 years in order to restore movements. 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 bowel control, cochlear implant, and more recently Deep Brain Stimulation). The complexity of the system for movement restoration is such that no commercial application really arise. Even though the original idea of FES is still the same, activating the moto-neurone axons with impulse current generator, the stimulus waveform and its parameters have drastically evolved and the electrode placements became various: epimysial stimulation at the muscle's motor point, neural stimulation on the nerve, Sacral roots stimulation near the spinal cord. These changes came from fundamental research, not yet achieved, in neurophysiology. This knowledge can efficiently be included in the next implanted neuroprosthetic devices allowing a wide variety of features. Moreover, currently, FES is the only way to restore motor function even though biological solutions are studied, because the research are not yet successfully tested on humans. Few teams carry out researches on implanted FES (http://www.ifess.org) and the functional results remain poor. Nevertheless, the technique has proved to be useable and needs enhancements that will be addressed by DEMAR (Deambulation Et Mouvement ARtificiel). In particular, 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. Some teams in Denmark (Thomas Sinkjaer, SMI U. Aalborg), Germany (Klaus Peter Koch, IBMT Franhaufer Institute), England (Nick Donaldson, U. College of London), Belgium (Claude Veraart, U. Catholique de Louvain), United States (Thomas Mortimer, Cleveland FES centre), and Canada (Mohammad Sawan, Ecole Polytechnique de Montréal), work on multi-polar neural stimulation but mainly on the electrode aspect.

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. Very few teams (for instance Robert Riener, ETH in Zurich, Switzerland) work on this topic because it needs a great amount of interactions between completely different disciplines such as neurophysiology, biomechanics, automatic control theory, and advanced signal processing. Besides, animal experiments performed in order to validate and identify models are particularly difficult to manage. Control schemes on such a complex non linear, under-actuated system, not completely observed and perturbed by the voluntary movements of the patient are quite difficult to study due to the lack of precise simulations platforms (for practical evaluation before experimentation) and the lack of theoretical results on such systems.

DEMAR (DEambulation et Mouvement ARtificiel) is a joint project between INRIA, CNRS, Universities of Montpellier I and II. DEMAR is located at LIRMM (joint CNRS and University laboratory working on Computer sciences, Micro electronics, and Robotics) in Montpellier. DEMAR works in close relationship with rehabilitation centres among them the Centre Bouffard Vercelli in Cerbère and Propara in Montpellier. International collaborations exist since 2003 with the Sensory Motor Interaction Lab at the University of Aalborg in Denmark (Professors Thomas Sinkjaer, Dejan Popovic, Ken Yoshida). DEMAR research interests are centered on the human sensory motor system, including muscles, sensory feedbacks, and neural motor networks. Indeed, DEMAR focuses on two global axes of research:

- Modelling and controlling the human sensory motor system.
- Interfacing artificial and natural parts through implanted neuroprosthetic devices.

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 of neuroprosthetic devices.
- Restoring motor and sensitive functions through implanted functional electrical stimulation (FES) and neural signals sensing.

# 3. Scientific Foundations

## 3.1. Modelling and controlling the human sensory-motor system

Our global approach is based on the theoretical tools of the automatic control theory.

### 3.1.1. Modelling

Designing efficient control schemes and performing realistic simulations need for modelling. The scientific approach is to develop multi scale models based on the physiological microscopic reality up to a macroscopic behavior of the main parts of the sensory motor system: muscles, natural sensors and neural structures. We also aim at describing multi scale time models to determine impulse synchronized responses that occur in a reflex or with FES, up to a long term fatigue phenomenon. All these models have a control input that allows them to be linked as different blocks of the sensory motor system.

Besides, we have to deal with problems related to the identification protocols. Identification is then based on the observation of signals such as EMG, output forces, and movement kinematics, while medical imaging gives the geometrical parameters and mass distributions. The success of the identification process is highly sensitive to the quality of the experimental protocols on animals and humans.

### 3.1.2. Synthesis & simulation

Simulation platforms have been largely developed for biped systems, including advanced impact models (using non regular equation, work carried out in collaboration with BIPOP). Given that kinematics and dynamics are described using Denavit-Hartenberg parameters and the Lagrangian formulae, such tools can be used. Nevertheless, important differences rely on the actuators and their associated model. Thus, based on this platform, a new one can be developed including the complex muscle dynamics. In particular, muscle dynamics contain discontinuous switching modes (contraction - relaxation, extension - shortening), strong non linearities, length and shortening speed dependencies that imply complex numerical resolutions.

As regards synthesis, generating a useful and efficient movement means that criteria can be defined and evaluated through an accurate numeric simulation. Optimization methods are then used to process the data in order to obtain stimulation patterns for a given movement. Two problems occur, firstly the complexity of the models may provoke the failure of the optimization process, secondly the criteria that have to be optimized are not always known. For instance, we have to define what is a "normal" gait for a paraplegic patient under FES; are the global energy, the joint torques, the estimated fatigue for each muscle the appropriate criteria ?

### 3.1.3. Closed loop control

Some tasks cannot be performed using open loop strategies. Keeping standing position with a balance control can be improved as regard the fatigue effect using ankle / knee / hip angle sensors feedback. Muscle’s contraction is then controlled to ensure the minimum of fatigue with the maximum stability. Cycling, walking on long distance pathways, need some control to be achieved with a higher level of performance. Modelling and simulation will be used to design control strategies while theoretical studies of performances (robustness, stability, accuracy) will be carried out. The system is highly non linear and not completely observable. New problems arise so that new strategies have to be designed. Finally a compromise between complexity, efficiency, robustness, and easy usage of the system has to be found. Thus, the success of a control strategy design will be evaluated not only through its intrinsic performances but also regarding its ergonomic.

Advanced control strategy such as high order sliding modes for the low level control of the co-contraction will be studied because of its robustness towards model uncertainty. Trajectory free predictive control will be also investigated for a movement phase such as swing phase during gait, because the movement can be described as intuitive constraints such as the center of mass need not to fall. Finally high level hybrid approaches based on continuous control and event triggered commutation of strategies will be studied using a formal representation of the architecture.

## 3.2. Interfacing artificial and natural parts through neuroprosthetic devices

To overcome the limitations of the present FES centralized architecture, a new FES architecture was proposed according to the SENIS (Stimulation Electrique Neurale dIStribuée) concept: the distribution of i) the stimulation unit with its control near its activator, i.e. its associated neural electrode ii) the implanted sensor with its embedded signal processing.
FES will be thus performed by means of distributed small stimulation units which are driven by an external controller in charge of the coordination of stimulation sequences. Each stimulation unit (called DSU, Distributed Stimulation Unit) will be in charge of the execution of the stimulation pattern, applied to the muscle by means of a neural multipolar electrode. A DSU is composed of analogue and digital parts (§6.2.1).
The SENIS architecture therefore relies on a set of DSU which communicates with an external controller. We therefore studied the communication architecture and defined an adequate protocol, assuming firstly that the communication should be performed on a wireless medium and secondly that this architecture can also contain distributed measurement units (DMU for sensors).

### *3.2.1. Stimulators*

We mainly focus on implanted devices interfaced with neural structures. Both the knowledge about how to accurately activate neural structures (neurophysiology), and technology including both electrode manufacturing and micro electronics will be studied. Complex electrode geometries, complex stimulus waveforms, and the multiplicity of the implantation sites are the subjects we deal with in order to obtain a selective, progressive and flexible activation of neural structures. Our theoretical approaches are based on:

- Design and test in micro electronics with ASIC developments.
- Formal Petri Nets representation of the numeric control parts.
- 3D electrostatic theory to model interactions between electrodes and neural structures.
- Electrophysiology modelling such as Hodgkin-Huxley model.

### *3.2.2. Sensors*

The development of a closed-loop controller implies the use of sensors whose choice and number are highly constrained by practical, psychological and cosmetic considerations: the stimulation system has to be implanted in order to simplify its use by the patient; it is therefore not possible to cover the person with various external apparatuses. An alternative to artificial sensors is the use of natural sensors already present, which are intact and active below the lesion in the spinal cord of the injured patients. DEMAR is then interested in implanted sensors in order to design complete implanted solutions (stimulation and sensing). As regards sensing, two kinds of sensors will be studied:

- Physical sensors such as micro attitude centrals.
- Natural sensors that means interfacing with afferent nerves and ENG recordings. The same theoretical tools and technology as for implanted stimulators could be used.

In both cases, advanced signal processing applied to biosignals is needed to extract relevant pieces of information.

#### 3.2.3. Patient interface

The patient interacts with the system in three ways:

- He decides which movement he wants to achieve and informs the system.
- He performs voluntary movements in a cooperative way, to turn right or left for instance, but he could also disturb the system when a closed loop control is running.
- Passive actions like arm supports through the walker for the paraplegic patient are used to control balance and posture.

It's not trivial to integrate all these events in the system. This field of research can learn from tele-operation and Human Machine Interfaces research fields. The patient needs also to get pieces of information of the current state of the system. Sensory feedback have to be implemented in the system such as screen, sound, tactile vibrations, electrical stimulation,... Choosing meaningful pieces of information such as heel contact, and the way to encode it, will be addressed.

#### 3.2.4. Supervision & networking

Activating the system through stimulators, sensors, and analysing patient behaviors need multiple devices that communicate and demand energy. Interfacing natural and artificial parts imply to address problems such as networking, data transfer, energy storage and transfer through wireless links. On such a complex system, supervision is necessary to ensure security at the different involved levels. Fault tolerance and reflex behavior of the system will be studied to improve system reliability particularly when the patient uses it at home without any medical person support. The theoretical approach is based on Petri Nets to design and then analyse the behavior of the entire distributed system. More technological aspects related to RF transmission will be studied.

# 4. Application Domains

## 4.1. Objective quantification and understanding of movement disorders

Modelling based on a physical description of the system lets appear meaningful parameters that, when identified on a person, give objective and quantitative data that characterize the system. Thus, they can be used for diagnosis.
Modelling provides a way to simulate movements for a given patient so that through an identification process it becomes possible to analyse and then understand his pathology. But 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 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.
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 - mainly surface - based therapy 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 (Deep Brain Stimulation). 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.

In any case, experimentations on animals and humans are necessary so that this research needs a long time to go from theoretical results to applications. This process is a key issue in biomedical research, it needs : i) design of complex experimental setups both for animals and humans, ii) 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. RdP to VHDL tool

**Participant:** David Andreu.

The architectural design underlying the SENIS concept leads to embed a complex system within each distributed FES unit (§6.2.1); a DSU (Distributed Stimulation Unit) embeds for instance a micro-machine, a RAM manager, reference models, a protocol interpreter, the analogue subsystem and its interface with the digital part. For the design of the digital part of this complex system with a relatively high level of abstraction, we use Petri nets. Its formalism and associated tools ease the description and verification (analysis) phases; we thus designed a tool allowing the implementation to be directly performed from this model. In this purpose, we proposed an approach based on components for the automatic translation into VHDL, of interpreted Petri nets with time. We thus developed a prototype (beta version) allowing this automatic VHDL code generation (producing a VHDL synchronous component) from a graphical description of a Petri net based model.

# 6. New Results

## 6.1. Modelling and controlling the human sensory-motor system

We continue to try using automatic control theory tools to obtain models and controls strategies schemes [20], [18].

### *6.1.1. Modelling and Identification of the Skeletal Muscle under Functional Electrical Stimulation*

**Participants:** Hassan El Makssoud, David Guiraud, Philippe Poignet.

The objectives of this study were both the modelling of skeletal muscles under FES and the identification of the associated parameters [8].

1. **Muscle modeling**

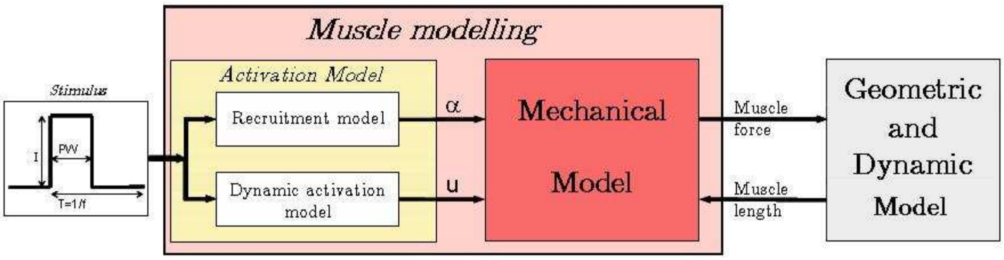



*Figure 1. Skeletal muscle model*

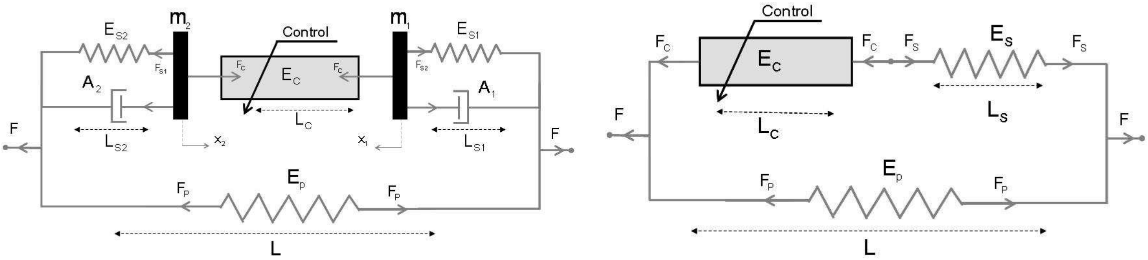



*Figure 2. Muscle model without and with muscle masses*

There are two main goals for muscle modelling: 1) the simulation and the synthesis of the movement in order to evaluate *a priori* the system performance, and 2) the design of advanced control schemes based on reference model. The input of the muscle model is an electrical signal provided by electrical stimulator such as the "PROSTIM" offering the possibility of tuning the amplitude, the pulse width and the frequency of the electrical signal of stimulation, and the outputs are the muscle force and stiffness. The muscle model we developed is composed of three blocks (fig.1):

- *Mechanical model:* an original multi-scale model (from sarcomere up to the whole muscle) was developed and presented in the state space with a set of differential equations. This model integrates both macroscopic (muscle scale) and microscopic (fibre scale) dynamical behavior of the muscle. Two control inputs are involved: a "static" input associated to the rate of fibers recruitment and a "chemical" input for the dynamical activation model. Two models were developed depending on their final use. One includes muscle masses in order to be accurate enough in isometric contraction i.e. without any link movement; the other one is much simpler without masses and dampers to be used in a complex musculoskeletal model (fig.2). In this case, dampers and masses are transferred respectively to the joint and the segments.
- *Recruitment model:* It represents the transfer function between the stimulus parameters (intensity and pulse width) and the percentage of activated muscle fibres. This model is static with a sigmoid like transfer function.
- *Dynamic activation model:* The calcium dynamics that appears between the neural signal action potential activation and the muscle fibers activation is modeled through a linear second order low pass filter followed by a threshold on off activation so that mainly the stimulus frequency (that triggers this dynamics) is involved.

The two last items may evolve because they are actually not based on micro-scale physiological phenomena.

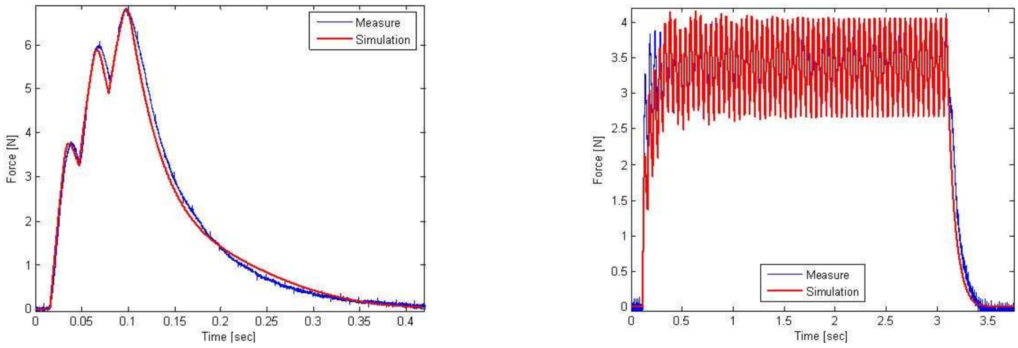



*Figure 3. Simulated (with estimated parameter) and measured isometric muscle force on Gastrocnemius animal muscle.*

2. **Identification**
   The parameters of the muscle model were identified experimentally in isometric mode on animal with classical techniques of identification such as Levenberg-Marquardt and the Extended Kalman Filter. The cross validations illustrate the pertinence of the model and the quality of the estimate (fig.3).

### *6.1.2. Closed loop control: Co-contraction case study*

**Participants:** Samer Mohammed, Philippe Fraisse, David Guiraud, Philippe Poignet.

Few studies have treated the human muscle as an entire physiological element in a closed loop system. Known by their robustness against unknown perturbation and their accuracy, we used the sliding mode control. Because of the nonlinearity and the presence of a 2 relative degree order system, we have adopted , a 2-order sliding mode controller, which seems necessary to ensure robust control and safer movement of the lower extremities. This latter was applied to a new multi-scale model developed within the $DEMAR$ project. We were able to control two antagonist muscles quadriceps and hamstrings alternatively and simultaneously (the so called co-contraction effect) with the same control vector, increasing the joint stiffness and forcing dynamically the system to behave as a first order one. Satisfactory stability and tracking error were achieved after a finite time delay. The performance of the closed loop system was assessed in the presence of an external force perturbations. The controller showed great accuracy and robustness against these perturbations.
The patient is supposed to be laying supine where only the shank is free to move around the knee joint (Fig.4).

The main goal concerns the computation of the needed stimulation patterns in order to ensure a safe and stiff movement through co-contraction of antagonist muscles for a given desired task, and to defer the muscular fatigue as much as possible. Thus we will compensate most of the non linear effects of the muscle model taking into account the time dependent parameters. Muscles and knee joint models can be rewritten as a non-linear state space function:

$$\dot{\mathbf{X}} = \mathbf{f}(\mathbf{x}, \mathbf{t}, \mathbf{U})$$

Where $X$ represents the state space vector of the forces and stiffness generated by the muscles as well as the knee joint angle and knee angular velocity and $U$ represent the control vector input gathering the recruitment variables and the chemical control inputs of both muscles. The controller was mathematically computed and showed satisfactory stability and position-tracking performance (Fig.5) [21].

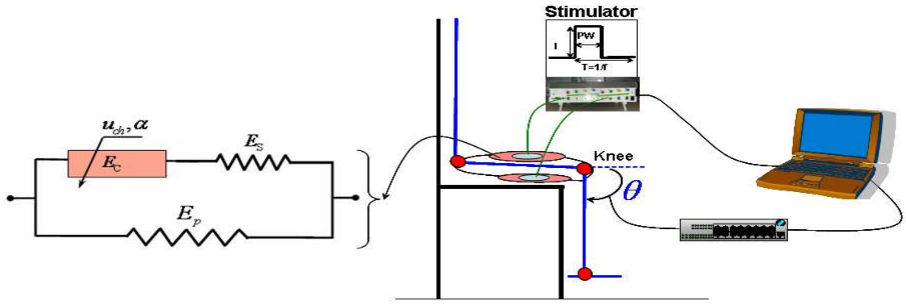



*Figure 4. Muscle model with the stimulation procedure*

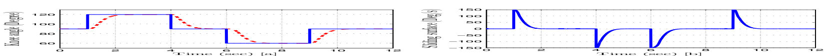


*Figure 5. Knee position tracking (a) and sliding surface (b)*

Co-contraction can be defined as the simultaneous activation of the antagonist muscles crossing the same joint.

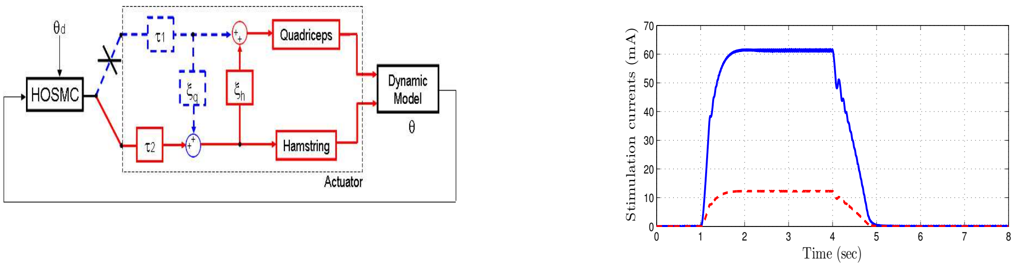


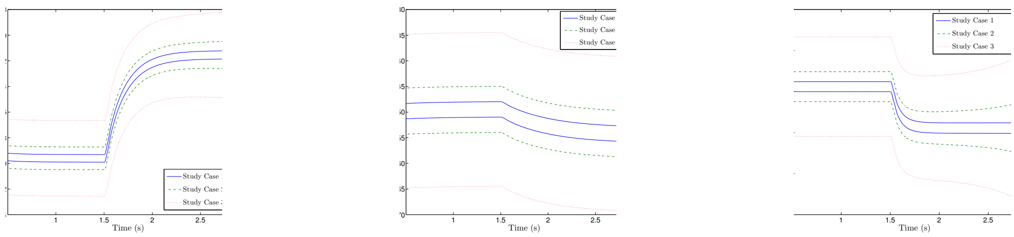

*Figure 6. Co-contraction of agonist (blue) and antagonist (red) muscles*

Since the number of actuator (muscles) is greater than the number of joints (knee), we have a redundancy problem. The force-sharing problem or the stimulation distribution between antagonist muscles was solved based on the optimization of the sum of muscular activities in the antagonist muscles [22]. Figure 6 shows the control schemes as well the resulted stimulation currents of the antagonist muscles.

### *6.1.3. Posture estimation and modelling*

**Participants:** Gaël Pages, Nacim Ramdani, Philippe Fraisse, David Guiraud.

A new approach aiming posture estimation by only measuring forces exerted on a walker's handles is outlined. The behavior of the system is modeled by an ordinary differential equation (ODE) which includes parameters whose value is uncertain. Since insufficiency in precision while solving ODEs may affect safe decision making, the method proposed is based on the numerical integration of a kinematic and dynamic model of the human body, where force measurements are considered as inputs to the model. In order to guarantee reliability in computation for safe posture estimation, and prevent cases like falling, the numerical methodology to use must be fail-safe from numerical errors introduced by the integration schemes. It must also account for any uncertainties in either initial posture values or with the anthropometric parameters which act in the biomechanical model.




a) Joint position $q_1$ b) Joint position $q_2$ c) Joint position $q_3$

*Figure 7. Joint position estimation of a 3-DOF manipulator using Taylor numerical integration scheme and error propagation based on interval arithmetics.*

A validated integration method via interval analysis is under investigation. The evaluation of the approach on simulation runs from a three degrees of freedom planar manipulator model and gives promising results (fig.7) [23].

### 6.1.4. Early detection of postural modifications and motion monitoring using micro attitude sensors

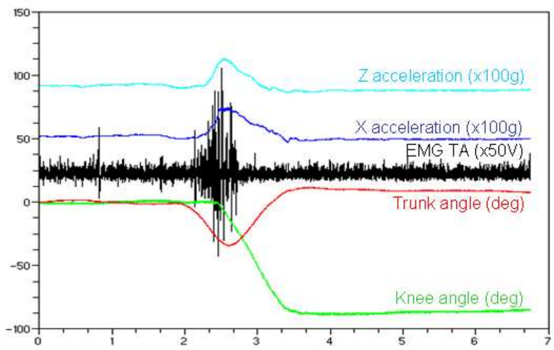
**Participants:** Rodolphe Héliot (INRIA/CEA-LETI), Christine Azevedo, Dominique David (CEA-LETI), Bernard Espiau (INRIA RA).

This work is based on a collaboration with CEA-LETI (Grenoble, France) and INRIA-Rhône-Alpes around R. Héliot PhD thesis.

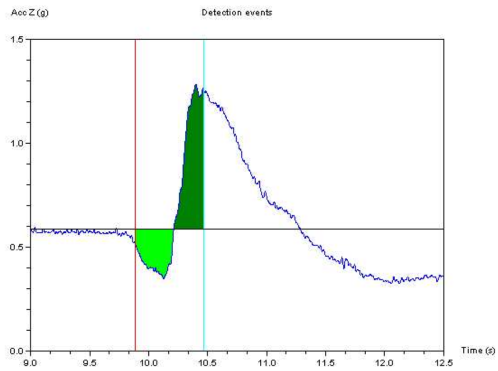
When controlling postural movements through artificial prosthetic limbs or muscle Functional Electrical Stimulation (FES), an important issue is the enhancement of the interaction of the patient with the artificial system through his valid limb motions. We believe that a clever observation of valid limbs could improve the global postural task by giving to the patient an active role in the control of his deficient limbs. We developed an approach to identify a postural task by observing one limb [11], [15]. Our objectives are to: 1) detect and identify subject voluntary actions as early as possible after a movement decision is taken, and 2) to monitor the current motion in order to estimate the task state variables. We employed a set of micro sensors (CEA-LETI TRIDENT system) providing us with accelerations and absolute 3D orientations, then implemented specific signal processing methods. Two axes have already been investigated:

1. Early detection of Sit-to-stand. Trunk sensor acceleration information allows us to detect task initiation 500ms before legs started moving in 10 healthy subjects. This delay is sufficient to envision using this detection in order to control a leg FES system in paraplegic patients. To do this, we employed abrupt change detection methods, which rely on SLR (Sequential Likelihood Ratio) estimates, and reveal to be a powerful tool for such applications [12], [19] (fig.8).

2. Gait phase identification in a steady-state walk by observing one leg with two sensors placed unilaterally at the thigh and shank levels during a walking task. 8 healthy subjects and 7 stroke patients have been involved in experiments carried out in Bronderslev rehabilitation center (Denmark). We were able to define a list of events associated to gait cycle phases which could be robustly detected. These results will find application in stroke patient rehabilitation, as part as early therapy, by triggering pre-computed stimulation sequences of deficient leg by observing valid leg. This study has been carried out in collaboration with D. Popovic (SMI, Aalborg, Denmark) during a 3 month stay of R. Héliot in SMI supported by a Marie-Curie grant.




a) Organization of measured signals




b) Detection of sit to stand using trunk anteroposterior acceleration

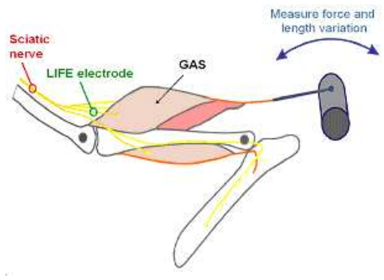
*Figure 8. Early recognition of sit to stand transfer through trunk observation*

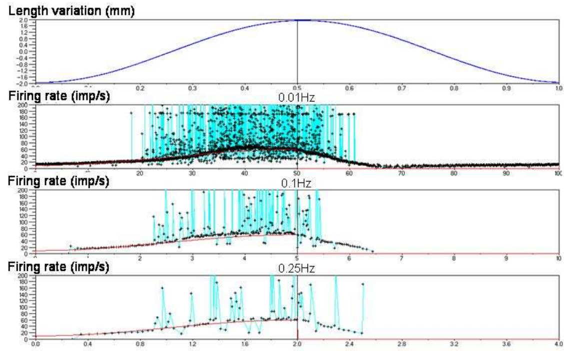
### *6.1.5. Towards a model-based estimator of muscle length and force using muscle afferent signals for real time FES control*

**Participants:** Christine Azevedo, Ken Yoshida (SMI).

This work is given in the context of motor function rehabilitation via implanted Functional Electro-Stimulation (FES) and is based on a collaboration with SMI (Aalborg, Denmark) started in 2004.
Our ultimate objective is to use natural muscle sensitive fiber information as feedback for the FES artificial controller. This implies online extraction of information from neural activity in a form usable by a closed-loop controller.
In this study, the in-vivo viscoelastic responses of the rabbit skeletal muscle Medial Gastrocnemius (MG) were investigated (fig.9-a). 6 anesthetized New Zealand white rabbits were surgically exposed and tested under in-vivo conditions during experiments we ran at Aalborg Hospital, Department of Pathology. A Longitudinal Intrafascicular Electrode (LIFE) was implanted in the tibial branch innervating MG muscle. Muscle state (length variation and force) as well as electroneurogram (ENG) from LIFEs were recorded while applying external mechanical stretches to the muscle. A series of sinusoidal stretch profiles ranging in rate from $0.01$ up to $1Hz$ were imposed on the muscle. Up to now 2 rabbit set of data were analyzed. Mechanical properties were expressed through a viscoelastic model and ENG signals were analyzed in terms of the single unit responses using simple threshold detection (fig.9-b). This approach has the advantage of being a fast and easy method for unit separation that could be implemented for online application [16].

Note: *This work is supported by an EADS foundation contract with INRIA for M. Djilas PhD thesis (October 2005-September 2008). A EURON financial support starting in November 2005 has also been obtained for this project involving DEMAR and SMI.*




a) Muscle stretching protocol b) Spike classification

*Figure 9. Towards a model-based estimator of muscle length and force using muscle afferent signals for real time FES control*

### *6.1.6. Contribution of afferent feedback to posture and gait control*

**Participants:** Christine Azevedo, Michael Grey (SMI), Thomas Sinkjaer (SMI).

The understanding of human postural reflexes and more precisely defining the contributions of afferent information to posture and locomotion control could be of high importance in FES context. Indeed, this knowledge could be integrated in both the design of control architectures and the modeling of muscle. This research axis is investigated through a collaboration with SMI (Aalborg, Denmark) started in 2003.

- **Positive afferent feedback to the human soleus muscle during quiet standing** [13]
  The ankle plantar flexors of a quietly standing person must produce a certain level of contraction in order to maintain an upright posture. We found evidence that a significant part of this background contraction in the soleus muscle may be due to ongoing force sensitive feedback. Valid subjects were asked to stand quietly on a moveable platform with arms crossed and eyes open, while the platform was, in random intervals, either moved forward, accelerated downwards, or rotated around the ankle joint (dorsiflexion). The downward acceleration of the platform caused a near instantaneous reduction in body weight, proportional to the acceleration, and a drop in averaged rectified EMG of the ankle plantarflexors was found at a short latency. The size of the EMG drop increased monotonically with the amount of downward acceleration from 0.2g to 0.8g, suggesting a gradual feedback from force sensitive receptors. Ischaemia at the level of the thigh abolished or reduced the drop in EMG, suggesting a peripheral origin, whereas ischaemic nerve block applied above the ankle joint had no reducing effect on the short latency reflex or the drop in EMG. Muscle tendon vibration applied at the Achilles' tendon had a decreasing effect on the amplitude of SOL responses, suggesting that group Ia afferent may be involved. Our results suggested that the short-latency drop in EMG in the soleus muscle, as was seen in the downward perturbation, might be due to a decrease in positive afferent feedback due to the sudden decrease in bodyweight. This implies the existence of an ongoing afferent feedback loop towards the soleus motoneuronal pool from force sensitive

receptors. Our findings suggested that both Ia and Ib afferents play a role in the responses observed for downward perturbations.

- **Loss of ground support produces a decrement in SOL EMG during human walking** [17]
  Sensory feedback from proprioceptive afferents is known to contribute to the enhancement of extensor locomotor muscle activity in cat and human walking. The soleus muscle (SOL) EMG is transiently depressed after a rapid plantar flexion perturbation during human treadmill walking. The objective of the present study was to investigate if a similar decrease in the SOL EMG is observed following a sudden loss in ground support. 8 volunteers walked at a self-selected speed such that the right foot struck a custom-made robotic platform positioned in the middle of the walkway. On random trials the ground support was rapidly removed by accelerating the platform downward at $7.85m.s^{-2}$ $(0.8g)$ for $8cm$. The perturbations were presented during the right foot stance phase with approximately 1 perturbation for every 8 control steps. The perturbations were delivered at early, mid, or late stance phase, and timed by the heel strike. Control step and perturbed step records were collected until approximately 15 perturbations were obtained for each of the 3 phases of stance. The removal of the support surface resulted in a transient drop in the SOL EMG by approximately $20\%$ with respect to the control step EMG irrespective of the stance phase time. The EMG decline had a mean onset latency of $41ms$ with respect to the removal of the support surface and was preceded $20ms$ earlier by a slow ankle plantar flexion. The head tilted forward with a mean onset latency of $14ms$ (i.e. $27ms$ prior to the decline in SOL EMG). The short delays between the onset of the ankle/head movement and the onset of the EMG decline suggests that spindle afferents from the ankle and neck are not responsible for this response. We suggest that the removal of feedback from group Ib receptors may be implicated in this response; however, a vestibular response cannot be ruled out with the present experimental paradigm [17].

### *6.1.7. Bipedal Locomotion: Towards Unified Concepts in Robotics and Neuroscience*

**Participants:** Christine Azevedo, Bernard Espiau (INRIA RA), Bernard Amblard (DPA, Marseille), Christine Assaiante (DPA, Marseille).

This research axis is investigated through a collaboration with Développement et Pathologie de l'Action (DPA) group (Marseille) started in 2002.
We carry out a joint discussion on the functional bases of bipedal locomotion and how could they be controlled? The originality of this work is to synthesize two approaches: automatic/control and neurosciences, in order to take advantage of the knowledge concerning the adaptability and reactivity performances of humans, and of the rich tools and formal concepts available in biped robotics. Indeed, we claim that the theoretical framework of robotics can benefit human postural control description by formally expressing the experimental concepts used in neuroscience. Inversely, biological knowledge of the human posture and gait can inspire biped robot design and control. We attempted to provide common theoretical framework to formally express concepts in gait and posture control. This unification of definitions would be useful not only for the furtherment of human movement analysis, but also for the transfer of knowledge from neuroscience to robotics and vice-versa. [10]. We also believe that these concepts will find application in FES context for the development of controller architectures.

## 6.2. Interfacing artificial and natural parts through neuroprosthetic devices

### *6.2.1. Activating the neural system*

**Participants:** Jean-Denis Techer, Guy Cathebras, Serge Bernard, David Guiraud, David Andreu.

This work has been developed in the context of the technological transfer we have began in 2005, with MXM.
A first prototype of external stimulator has been built: it corresponds to a DSU (Distributed Stimulation Unit) of our distributed stimulation architecture. This prototype is based on two ASIC (analog part of the DSU) and

one FPGA (numerical part of the DSU). The numerical part contains the micro-machine (which executes the micro-program corresponding to the stimulus waveform to be generated) and the interface with the stimulus generator designed by the DEMAR team using HILECOP software [14]. As it embeds two ASIC, it allows to simultaneously control two quadrapolar electrodes.
A DSU programming environment (MedStim) has also been developed; it allows to graphically describe and to directly download stimulation sequences (pattern of stimulation) into the DSU component (FPGA part). Then the stimulation, executed on the prototype, can be programmed/started/stopped from the environment.
This prototype will be used for the experimentations to be performed in the "GENESYS" project. Security aspects, based on reference models, are currently studied in this project and will then be embedded in the DSU. We also work on the extension of the instruction set (micro-machine evolution) in order to generate more complex stimulus waveforms. Furthermore, based on the experimental results obtained on rabbits with the first ASIC, we have designed a modified enhanced version of the analogue part in 0.35 High Voltage CMOS technology. The circuit is currently under fabrication and will be tested in 2006.

### 6.2.2. Communicating between units

**Participants:** David Andreu, Jérome Galy.

The protocol stack embedded in a DSU, including MAC (patented in 2004) and application levels, has been implemented on FPGA devices. A test platform is under development, based on a set of FPGA devices (DSUs) connected by means of an ethernet bus (that will later be replaced by a wireless medium). As the prototype of external stimulator (external DSU) we developed (cf. section §6.2.1) can communicate on an ethernet bus, it will be integrated in the test platform which aims to study the global implanted architecture before developing specific hardware.

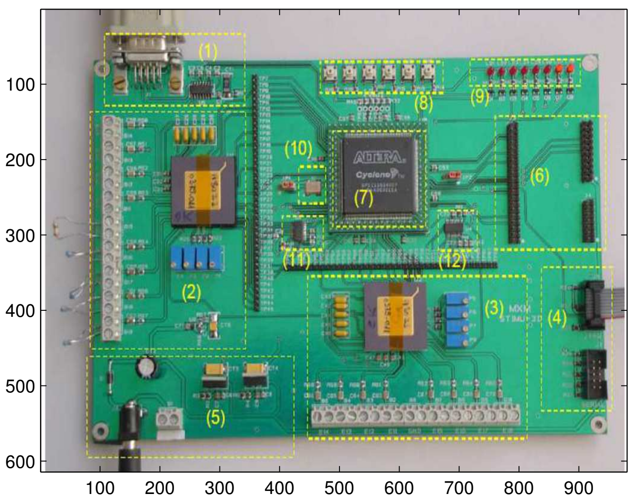



*Figure 10. Prototype board of a DSU based on the first version of the ASIC*

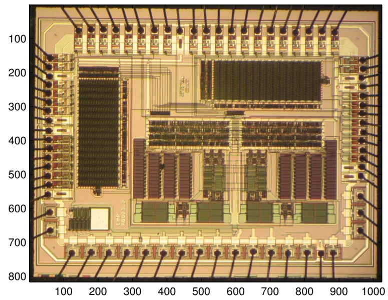



*Figure 11. First ASIC including analogue parts*

# 7. Contracts and Grants with Industry

## 7.1. Contracts and Grants with Industry

An industrial technological transfer contract has been signed with the MXM company that develop cochlear implant and artificial lens implant. MXM can perform also Ethylene Oxyde sterilization. A DSU prototype and programming environment (MedStim) has been developed then developed within this frame; it allows to graphically describe and to directly download stimulation sequences (pattern of stimulation) into the DSU component (FPGA). Then stimulation can be started/stopped from the environment.

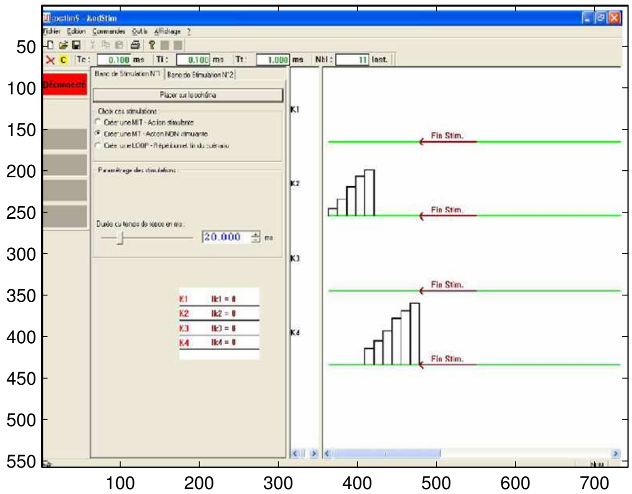



*Figure 12. MedStim screen Interface*

# 8. Other Grants and Activities

## 8.1. International grants

- EURON Prospective Research Project (European Research Network FP6-NOE-507728 sponsored by the CEC- IST Future and Emerging Technologies unit) (2005-2006) "*Lower-extremity movement restoration through muscle closed-loop FES control using natural sensor feedback*". 90 keuros. Consortium : INRIA SA and SMI Aalborg Denmark.

## 8.2. National grants

- STIC-Santé GENESYS, (2006-2007), 80 keuros, "*GEneric NEuroprosthetic SYStem*"the project focuses on: i) the modelling of electrode-nerve interaction for stimulation in order to provide model based design of electrode, ii) the integration of the first DSU, iii) animals experiments to validate the concept... Partners, ODYSSEE INRIA Sophia-Antipolis, MXM Company Sophia Antipolis, and St Therese Hosp. (Cologne, Germany).
- RNTS, MIMES project, (2004-2006), 60.4 keuros, the project focuses on the complete modeling of the body, developing dedicated simulation software tools, advanced external stimulators, and instrumented walker. Partners, BIPOP INRIA Rhône-Alpes, Centre de rééducation Bouffard Vercelli Cerbère, MXM Company Sophia Antipolis.
- ACI neurosciences intégratives et computationnelles (2004-2007), 15 keuros, "*Functional electrical stimulation: a specific model of neuro-artificial cooperation for vertical conquest in paraplegic patients*". Leader DPA (CNRS) Marseille.
- Grant from University Montpellier II to innovative projects of young researchers (2005) "*Exploitation des signaux neurophysiologiques pour le contrôle artificiel du mouvement.*" 2 keuros.
- EADS contract phd thesis grant support of M. Djilas (2005-2008) "*Natural sensor feedback on-line interpretation for skeletal muscle artificial control*". 105 keuros
- Marie-Curie Grant (April-June 2005) "*Improving post-stroke hemiplegic patients rehabilitation of walking using Functional Electrical Therapy (FET).*" R. Héliot 3 month stay at SMI (Aalborg Danemark).
- INRIA DREI support for collaboration with Denmark (2005). 2 keuros for travel expenses between SMI (Aalborg, Danemark) and DEMAR (C. Azevedo (SMI, May 2005), D. Popovic (LIRMM, September 2005), K. Yoshida (LIRMM, October 2005), M. Grey (LIRMM, December 2005)).

# 9. Dissemination

## 9.1. Services to scientific community

- Philippe Poignet, David Andreu and David Guiraud are members of the local scientific commission number 61.
- Philippe Fraisse is member of the national scientific commission CNU 61.
- Nacim Ramdani is member of the national scientific commission CNU 61.

## 9.2. Teaching

- David Andreu, associate professor at Polytech'Montpellier (Department of Micro-Electronics and Automation (MEA)), teaches:

  – Discrete Event Systems : "modelling and analysis with Petri nets" for 2nd year MEA students, "high level Petri nets" for 3rd year MEA students, "Hardware and software Implementation of Petri nets" for DEA SYAM students (corresponding to 2nd year SAEI Master students)

  – Network : "TCP/IP Model" and "Industrial local area networks" for 2nd year MEA students and 1rst year SAEI Master students.

  – Real-Time Systems : "Initiation to real-time systems " for 2nd year MEA students.

- Gaël Pages is in charge of the Matlab/Simulink teaching for 2nd year SAEI Master degree students (40h).
- Hassan El Makssoud is lecturer at University of Montpellier II, he teaches Signal Processing (32h tutorial) for 2nd year DEUG STPI EEA (Electrical, electronics and Automatic) at UFR Sciences and Automatic control system (48h practical works) for 2nd year MEA students at Polytech'Montpellier (Department of Micro-Electronics and Automation).
- Philippe Fraisse, assistant professor at IUT de Montpellier, department of Communication and Networking. He has given a lecture to master students (information theory and networked control systems).
- Guy Cathébras, associate professor at Polytech'Montpellier (Micro-Electronics and Automation (MEA) Department), teaches:

  – Signal theory (12h course and 12h tutorial) for 1st year MEA students (corresponding to third year SAEI Licence students).

  – Analog integrated circuits: "An introduction to electronics: designing with Bipolar and MOS transistors" 24h tutorial for 1st year MEA students (SAEI L3) ; "CMOS Analog integrated circuits design" 28h CAD practical works for 2nd year MEA students (SAEI M1); "CMOS standard cells design" 20h CAD practical works for 2nd year MEA students (SAEI M1).

  – Electronic systems: 40h practical works for 2nd year MEA students (SAEI M1).

- Philippe Poignet is a lecturer at IUT of Montpellier, Physic's Instrument Department. He co organised the Summer European University (2003) in Surgical Robotics and gave a talk on "Motion control and interaction control in medical robotics". He was invited for a tutorial "From mini-invasive surgery to endocavitary / endoluminal interventions. Part I : Research issues in endoscopic mini-invasive surgery" at the 7th Conference on Medical Image Computing and Computer Assisted Intervention (MICCAI04).

## 9.3. Organization of seminars

- M. Grey Center for Sensory-Motor Interaction SMI (Aalborg, Danemark). "Neuromuscular control and rehabilitation of human walking". December 7th 2005, LIRMM Montpellier.
- K. Yoshida Center for Sensory-Motor Interaction SMI (Aalborg, Danemark). "The tfLIFE - a potential high selectivity neural interface for the future". October 24th 2005, LIRMM Montpellier.
- D. Popovic Center for Sensory-Motor Interaction SMI (Aalborg, Danemark). "Part I- Neurorehabilitation of individuals with central nervous system injury. Part II- Control of assistive systems for walking". September 16th 2005, LIRMM Montpellier.
- R. Riener, Automatic Control Laboratory, ETH Zentrum, Zurich University (Switzerland). "Human-centered rehabilitation robotics", 1st december 2005, LIRMM Montpellier.
- M. Sawan, Polytechnique Montreal (Canada). "Wireless biomedical circuits and systems techniques dedicated to sensing and neurostimulation", 9th of november 2005, LIRMM Montpellier.

## 9.4. Research fellow visits

- V. Rajagopalan (thèse au SMI (Aalborg, Danemark) supervised by D. Popovic) 3-11 février 2005.
- K. Yoshida (Assistant Professor au SMI (Aalborg, Danemark)) du 24-30 Mars 2005.
- K. Yoshida (Assistant Professor au SMI (Aalborg, Danemark)) du 19-25 Octobre 2005.

## 9.5. Participation in seminars and workshops

- C. Azevedo was invited to present her works at the special session "Modeling and control for movement neural prostheses" of International Conference on "Computer as a tool" EUROCON, Belgrade, Serbia, 21st-24th November 2005.
- C. Azevedo gave a talk "*Des capteurs artificiels aux capteurs biologiques pour la réhabilitation du mouvement.*" GDR STIC SANTÉ, 17th November 2005.

## 9.6. Theses and Internships

### *9.6.1. Thesis Defenses*

- Jean-Denis Techer, co-supervised by Serge Bernard, Yves Bertrand, Guy Cathébras and David Guiraud, defended is PhD Thesis: “*Conception, vérification et test de circuits integrés analogiques pour application médicales*", on November 9th 2005 [9].
- Hassan El Makssoud (PhD Thesis LIRMM, 2002-2005), co-supervised by Philippe Poignet, David Guiraud, and Etienne Dombre defended is PhD Thesis: “*Modélisation et Identification des Muscles Squelettiques sous Stimulation Electrique Fonctionnelle*", on December 2nd 2005 [8].
- Guy Cathébras defended his HDR,“*Contributions aux architectures et méthodes de conception collaboratives des circuits intégrés réalisés en technologie CMOS*", on 12th December 2005 [7].

### *9.6.2. Ongoing thesis*

- Philippe Fraisse, and David Guiraud, co-supervise Gaël Pagès, “*Vers une estimation de posture fiable d’un sujet paraplégique en vue de la réhabilitation fonctionnelle des membres inférieurs pour la station debout.*", Thesis CIFRE MXM, 2004-2007.
- Philippe Fraisse, David Guiraud, co-supervise Samer Mohammed, “*Synthèse et simulation des séquences de stimulation pour la marche en boucle ouverte à partir de modèles biomécanique et physiologique du membre inférieur*",Thesis LIRMM, 2003-2006.
- Christine Azevedo co-supervises Rodolphe Héliot, “*Modélisation sensori-motrice du contrôle des membres inférieurs chez l’homme et son application à la réhabilitation fonctionnelle*", Thesis from INPG (Grenoble), in collaboration with Bernard Espiau (INRIA RA) and Dominique David (LETI/CEA), 2004-2007.
- Guy Cathébras and Christine Azevedo co-supervise Milan Djilas, “*Natural sensor feedback on-line interpretation for skeletal muscle artificial control*", Thesis INRIA/EADS, 2005-2008.
- Guy Cathébras and Serge Bernard co-supervise Lionel Gouyet, “*Traitements analogiques et numériques des signaux ENG*", Thesis LIRMM MENRT, 2005-2008.

### *9.6.3. Internships*

- **2004-2005**

  – David Andreu has tutored Guihlem Vavelin, "*Développement d’un prototype de stimulation externe et de son environnement logiciel de programmation*", Engineer final internship, from February 2005 to June 2005. This project was carried out within a technological transfer frame with MXM lab. Company. G. Vavelin has now a permanent engineer position in MXM lab.

  – David Andreu has supervised of Guihlem Vavelin, "*Développement d’une plateforme de test de l’architecture SENIS, basée ethernet et FPGAs*", Projet Intégré de Fin d’Etudes (MEA 3rd year), from September 2004 to January 2005.

  – David Andreu has supervised Guillaume Souquet, "*Implantation matérielle d’une méthode MAC déterministe pour réseau de stimulation intra-corporel*", Engineer internship (MEA 2nd year), from June 2005 to September 2005.

  – Christine Azevedo and David Andreu co-supervised Maryline Artaud "*Etude de l’architecture globale d’un système de stimulation électro-fonctionnelle"*, 1rst year Master STPI internship (University Montpellier II), from April to June 2005.

  – Christine Azevedo and David Andreu co-supervised Jéremy Laforêt "*Etude des applications de l’électro-stimulation fonctionnelle"*, 1rst year Master STPI internship (University Montpellier II), from July to September 2005.

  – Christine Azevedo and David Andreu co-supervised Maryline Artaud and Jéremy Laforêt "*Étude du sytsème nerveux pour la réhabilitation de la marche et de la posture*", 1rst year Master STPI Project (University Montpellier II), from February to April 2005.

  – Christine Azevedo supervised Z. Andriambololona "*Interprétation de signaux neurophysiologiques issus des récepteurs sensoriels musculaires*", 2nd year Master STPI (University Montpellier II), from February to June 2005.

  – Guy Cathébras and Serge Bernard supervised L. Gouyet "*Traitement du signal ENG*", 2nd year Master STPI (University Montpellier II), from February to June 2005.

- **2005-2006**
  - David Andreu has started the supervision of Guillaume Souquet, "*Réalisation d'une plateforme expérimentale, basée ethernet et FPGAs, pour le test de la pile protocolaire de l'architecture SENIS"*, Projet Intégré de Fin d'Etudes (MEA 3rd year), from September 2005 to January 2006.
  - Christine Azevedo, David Guiraud and David Andreu have started the co-supervision of Jéremy Laforêt "*Etude du contrôle de la vessie par stimulation neurale implantée"*, 2nd year Master STPI intenship (University Montpellier II), from November 2005 to June 2006.

# 10. Bibliography

## Major publications by the team in recent years

[1] C. AZEVEDO, P. POIGNET, B. ESPIAU. *Artificial Locomotion Control: from Human to Robots*, in "Robotics and Autonomous Systems (RAS) Elsevier", vol. 47/4, 2004, p. 203–223.

[2] C. AZEVEDO, J. USHIBA, J. VAN DOORNIK, T. SINKJAER. *Contribution of group Ia afferents to Soleus EMG after an imposed vertical acceleration during quiet standing*, in "Society For Neuroscience (SfN) Conference, San Diego, USA", October 2004.

[3] H. EL MAKSSOUD, D. GUIRAUD, P. POIGNET. *Enhancement of physiological and mechanical modelling of the skeletal muscle controlled by Functional Electrical Stimulation*, in "IFESS'04: International Functional Electrical Stimulation Society", 2004.

[4] H. EL MAKSSOUD, D. GUIRAUD, P. POIGNET. *Mathematical muscle model for Functional Electrical Stimulation control strategies*, in "International Conference on Robotics and Automation (ICRA)", 2004, p. 1282-1287.

[5] D. GUIRAUD, J. DIVOUX, P. RABISCHONG. *Identification of a First Order Model of Implanted Electrode on the First SUAW Patient*, in "IFESS'02: International Functional Electrical Stimulation Society, Ljubljana, Slovenia", June 2002.

[6] D. GUIRAUD, P. POIGNET, P. B. WIEBER, H. EL MAKSSOUD, F. PIERROT, B. BROGLIATO, P. FRAISSE, E. DOMBRE, J. L. DIVOUX, P. RABISCHONG. *Modelling of the human paralyzed lower limb under FES*, in "Proceedings of the International Conference on Robotics and Automation (ICRA), Special session on medical robotics", 2003.

## Doctoral dissertations and Habilitation theses

[7] G. CATHÉBRAS. *Contributions aux architectures et méthodes de conception collaboratives des circuits intégrés réalisés en technologie CMOS*, Ph. D. Thesis, Habilitation à diriger des Recherches, Université Montpellier II, December 2005.

[8] H. EL MAKSSOUD. *Modélisation et Identification des Muscles Squelettiques sous Stimulation Electrique Fonctionnelle*, Ph. D. Thesis, Thèse de doctorat, Université Montpellier II, December 2005.

[9] J. TECHER. *Conception, vérification et test de circuits integrés analogiques pour application médicales*, Ph. D. Thesis, Thèse de doctorat, Université Montpellier II, November 2005.

## Articles in refereed journals and book chapters

[10] C. AZEVEDO, B. ESPIAU, B. AMBLARD, C. ASSAIANTE. *Bipedal Locomotion: Towards Unified Concepts in Robotics and Neuroscience*, in "Biol. Cybernetics", submitted.

[11] C. AZEVEDO, R. HÉLIOT. *Rehabilitation of Functional Posture and Walking: Coordination of healthy and Impaired Limbs*, in "Journal of Automatic Control", vol. 15-Suppl., 2005, p. 11-15.

[12] R. HÉLIOT, C. AZEVEDO, D. DAVID. *Sensing Valid Limb Attitude to Improve Deficient Limb Artificial Control*, in "Gait and Posture", vol. 21-Suppl.1 (abstracts International Society of Posture and Gait Research Congress), 2005, S147.2.

[13] J. VAN DOORNIK, C. AZEVEDO, J. USHIBA, T. SINKJAER. *Positive afferent feedback to the human soleus muscle during quiet standing*, in "Experimental Brain Research", submitted.

## Publications in Conferences and Workshops

[14] D. ANDREU, J. TECHER, T. GIL, D. GUIRAUD. *Implantable Autonomous Stimulation Unit for FES*, in "IFESS'05: 10th Annual Conference of the International Functional Electrical Stimulation Society", 2005, p. 36-38.

[15] C. AZEVEDO, R. HÉLIOT. *Réhabilitation fonctionnelle de la posture et de la marche : vers une coordination des membres valides et déficients*, in "Journée Thématique de la Société de Biomécanique (JTSB). "Biomécanique du Mouvement et Handicap Moteur", Lyon, France", 2005.

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[23] G. PAGES, N. RAMDANI, P. FRAISSE. *Towards a reliable posture estimation for standing rehabilitation in paraplegia*, in "International Conference on Robotics and Automation (ICRA), Special session on Humanitarian Robotics", submitted.