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Project-Team DEMAR

Artificial movement and gait restoration

IN COLLABORATION WITH: Laboratoire d'informatique, de robotique et de microélectronique de Montpellier (LIRMM)

RESEARCH CENTER
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THEME
Computational Medicine and Neurosciences

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Project-Team DEMAR

Keywords: Automatic Control, Functional Electrical Stimulation, Human Assistance, Multi-scale Models, Sensors

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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 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 in 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 Polystim 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, identify and validate models, evaluate control strategies or test neuroprostheses. Our experiments are carried on valid and non-valid individuals in clinical environment, but also on animals. 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 signal 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

- The organization of NER 2015, IEEE/EMBS Conference on Neural Engineering by INRIA-LIRMM DEMAR project was officially annouced.

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 Zahalak's work introducing the distribution moment model that represents a formal mathematical approximation at the sarcomere level of the Huxley cross-bridges model and the works by 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 formalizing the link between FES parameters, recruitment and Calcium signal path. The resulting controlled model is able to reproduce both short term (twitch) and long term (tetanus) responses. It also matches 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 investigate risky but promising fields 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,
- Model parameters 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, Mitsuhiro Hayashibe, 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: classical desired trajectory tracking is not possible, robustness to disturbances is critical, possible observations of system are limited. Furthermore there is an interaction between body segments under voluntary control of the patient and body segments 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, the third axis "Neuroprostheses" of our 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 analog 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.

Our efforts are mainly directed to implanted FES system but we also work on surface FES architecture and stimulator; most of our concepts and advancements in implantable neuroprostheses are applicable somehow to external devices.

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 parameters are meaningful. Therefore, these parameters when identified on a given individual (valid or deficient), 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, compensating foot drop for hemiplegic patients. These applications can be firstly used in a clinical environment to provide physiotherapist with 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. FES muscle modeling in opensim framework

Participants: Mitsuhiro Hayashibe, Philippe Fraisse, Emel Demircan, Oussama Khatib (INRIA Equipe Associee, Stanford Univ.).

In FES, movement synthesis and control are still challenging tasks due to the complexity of whole body dynamics computation and the nonlinearity of stimulated muscle dynamics. An efficient movement synthesis means that criteria can be defined and evaluated through an accurate numeric simulation. We perform the implementation of muscle model representing the electrically stimulated muscle into the OpenSim framework which has whole body musculoskeletal geometry. We would like to develop the FES simulator using Stanford Operational Space Whole-Body Controller which allows the real-time motion generation with virtual FES and finally we aim at the development of motion correction controller to find the appropriate FES signals against a disabled motor function.

5.1.2. Further development of gom2n software - a toolchain to simulate and investigate selective stimulation strategies for FES

Participants: Guillaume Jourdain, Pawel Maciejasz, Jeremy Laforet, Christine Azevedo Coste, David Guiraud.

Concurrently with the experiments on selective stimulation of nerve fibres, performed on earthworms (see section 6.1.6), also the gom2n toolchain developed previously by our team was further developed. Main objective of this work was to be able to simulate similar behaviour of nerve fibres, as observed during electrical stimulation of the giant nerve fibres of earthworms, and therefore to be able to compare computational and experimental results. Main improvements which has been implemented in the new version of the gom2n toolchain are:

- improved and more intuitive users interface
- possibility to perform concurrently multiple simulations for various stimulation parameters, as well as various diameters and locations of nerve fibres within the nerve.

Further work is however still needed to adapt electrical properties of simulated fibres, since electrical properties of the earthworm's giant nerve fibres are different that properties of mammalian nerve fibres."

5.1.3. RdP to VHDL tool

Participants: Gregory Angles, David Andreu, Thierry Gil.

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).

The development of an Eclipse-based version of HILECOP has been achieved. This new version of HILECOP has been registered (new deposit) in september 2011, at the french Agence de Protection des Programmes (APP) with the IDDN.FR.001.380008.000.S.P.2011.000.31235.

It will be accessible to the academic community at the beginning of 2012.

5.1.4. SENISManager

Participants: Robin Passama, David Andreu.

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 allows the manipulation of micro-programs from their edition to their remote control (Fig. 1; right). It also allows the programming of control sequences executed by an external controller in charge of automatically piloting a stimulator.

This new version of SENIS Manager has been registered (updated deposit) in september 2011, at the french Agence de Protection des Programmes (APP), with the IDDN.FR.001.320011.001.S.P.2009.000.31500

6. New Results

6.1. Modelling and Identification

6.1.1. Multi-Dimensional Wrist Musculoskeletal Modeling for Tremor Simulation

Participants: Peng Yao, Mitsuhiro Hayashibe, Dingguo Zhang (Shanghai Jiao Tong Univ.).

In this work, we established multi-dimensional wrist musculoskeletal model to be used for suppressing the wrist joint's tremor by functional electrical stimulation. Often the wrist model for FES control is based on 1DOF biomechanical model for the simplicity and convenience to develop the controller. However, wrist motion is generated by complex interactions of multiple muscles spanning the wrist joint. Here, we have tried to have 3DOF wrist model considering main musles involved in flex-extension, radial-ulnar deviation, and pron-supination as in the left of Fig. 1 (opensim model). Inertia of 3DOF joint model was obtained based on the work of de Leva which modified Zatsiorsky parameters. Joint dynamics was formed by inertia, gravitational torque, and passive visco-elastisity. As for the mapping between torque and muscles, the moment arm matrix (3×4) was obtained from opensim software, thus anatomical information could be considered along with muscle parameters such as muscle-length, isometric maximal forces. For this first trial, 4 muscles were considered based on Hill-type model. In order to confirm the generated motion by muscle activation, we activated the ECRB (extensor carpi radialis brevis) and FCU (flexor carpi ulnaris) in antiphase, the corresponding 3DOF wrist angles were obtained as in Fig. 1. Qualitatively, we know that ECRB can generate negative flexion angle, negative deviation angle and positive pronation when it is activated; while FCU can produce positive flexion angle, positive deviation angle and positive pronation angle. When both ECRB and FCU are activated in order, the reasonable wrist angles could be generated. We will work on the development of tremor controller in the future work.

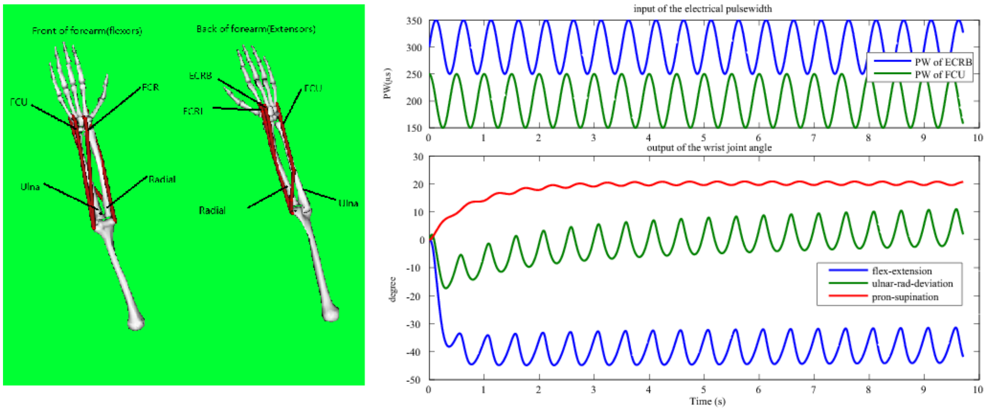

Figure 1. 3DOF Wrist Musculoskeletal Modeling. Anatomical layout of principle wrist muscles, moment arm matrix was obtained from opensim (left). 3DOF wrist angles were generated by tremor like activation in ECRB and FCU (right).

6.1.2. Multi-functional EMG classification for dynamic EMG-motion modeling

Participants: Lizhi Pan, Mitsuhiro Hayashibe, Dingguo Zhang, Xiangyang Zhu (Shanghai Jiao Tong Univ.).

EMG signal is widely used to control a limb protheses such as exoskeleton. It would be also useful to control prosthetic hand for upper-extremity amputees. Especially for upper limb control, hybrid control both for position and torque is required for dynamic motions. In this work, we aimed at establishing the EMG-joint angle model for dynamic motions, to effectively decode EMG signals to reproduce the corresponding motion in different velocity. In the experiment, the subject performed the wrist flextion-extension with different speeds along with EMG measurements on flexor and extensor muscles. ARX model, of which the parameters are adaptively identified by extended kalman filter, was applied to represent 1 DoF (degree of freedom) EMG-joint angle model. The result shows that the EMG-angle model could produce good angle tracking as shown in Fig. 2. We have observed that three principal parameters a1, a2, a3 for autoregressive term are almost constant at the same angular speed and different angular speeds correspond to different model parameters. With this regular pattern, SR (Switch Rregime) model would be possible to be used to switch the model to reproduce the motion in different conditions. In the further work, we work on creating a SR EMG-angle model using learning and classification technique to dynamicaly decode the EMG signals into the corresponding motions only based on EMG without angle information.

6.1.3. Real-time Volumetric Skeletal Muscle Deformation

Participants: Yacine Berranen, Mitsuhiro Hayashibe, Benjamin Gilles.

In this work, we explore skeletal muscle volumetric deformation. The current available simulation for musculoskeletal model is basically using wire-type muscle model which considers only principal longitudinal path of the muscle-tendon units. If we aim at the simulation of the interaction between muscles and objects like orthesis, exoskeleton keeping classical biomechanical property, wire-type modeling is not sufficient. In addition, muscle modeling in volumetric way gives another advantage to reflect microscopic muscle fiber direction and function. We have tried to implemente real-time volumetric skeletal muscle deformation as in Fig. 3 using the INRIA SOFA environment. The idea is making more realistic musculoskeletal simulation from the current approximation of muscle model as wire element to physically and functionally detailed simulation as volumetric element.

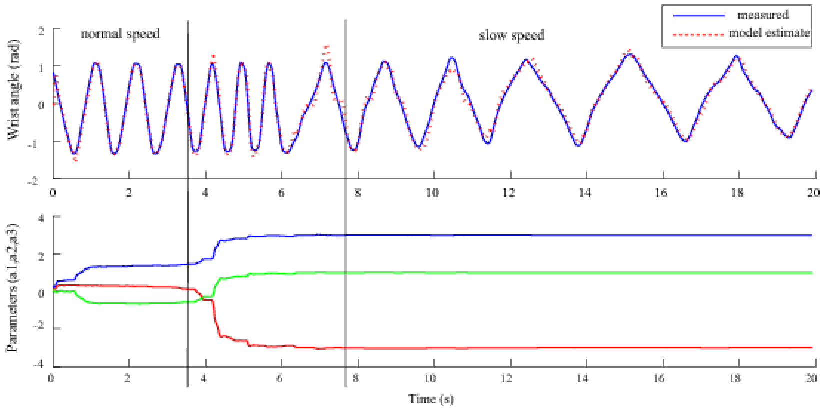

Figure 2. Dynamic EMG-motion modeling and identification. Subject performed the wrist flextion-extension with different speeds along with EMG measurements on flexor and extensor muscles. Adaptive identification was implemented with Kalman filtering. Model parameters and speed will be used for classification.

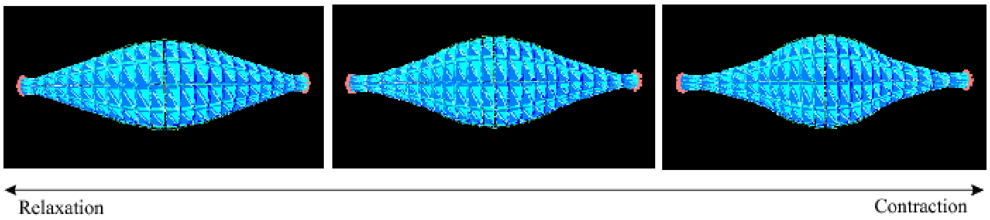

Figure 3. Real-time Volumetric Skeletal Muscle Deformation. Internal muscular force was generated along the muscle fiber direction in the contractile element.

6.1.4. Muscle Strength and Mass Distribution Identification in Musculoskeletal Modeling

Participants: Mitsuhiro Hayashibe, Gentiane Venture (Tokyo Univ. of Agriculture and Technology), Ko Ayusawa (Univ. of Tokyo), Yoshihiko Nakamura (Univ. of Tokyo).

In current biomechanics approach, the assumptions are commonly used in body-segment parameters and muscle strength parameters due to the difficulty in accessing those subject-specific values. Especially in the rehabilitation and sports science where each subject can easily have quite different anthropometry and muscle condition due to disease, age or training history, it would be important to identify those parameters to take benefits correctly from the recent advances in computational musculoskeletal modeling. In this paper, Mass Distribution Identification to improve the joint torque estimation and Muscle Strength Identification to improve the muscle force estimation were performed combined with previously proposed methods in muscle tension optimization. This first result highlights that the reliable muscle force estimation could be extracted after these identifications. Fig. 4 shows the estimated muscle forces of Rectus Femoris, Vastus Lateralis and Vastus Medialis with different speeds (first two series are normal speed, second two are slow and last two are fast). The corresponding visualizations of estimated muscle tensions at the indicated time instant are depicted in the bottom. The proposed framework toward subject-specific musculoskeletal modeling would contribute to a patient-oriented computational rehabilitation [22].

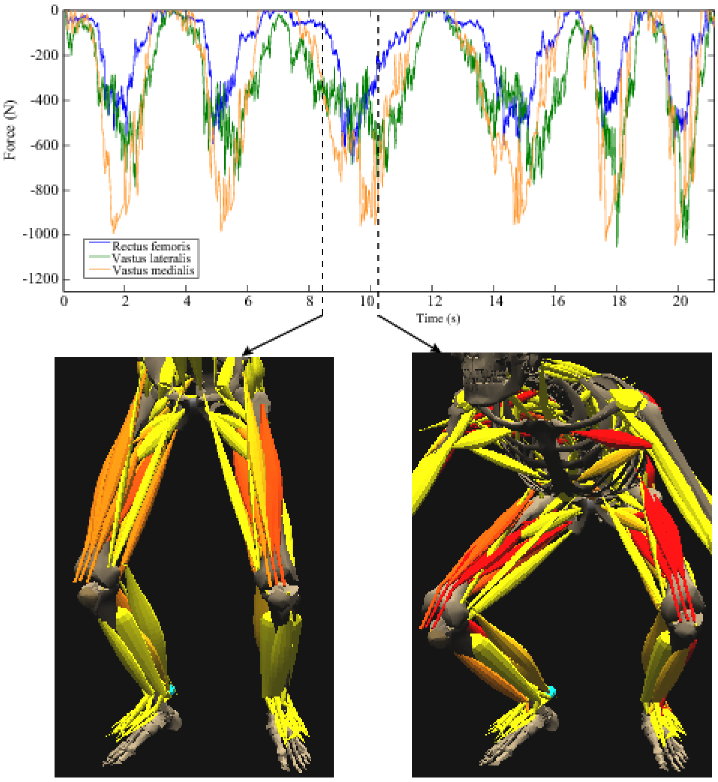

Figure 4. Estimated muscle forces of Rectus Femoris, Vastus Lateralis and Vastus Medialis using the identified model in squat motion with 4kg load with different speeds (first two series are normal speed, second two are slow and last two are fast) (up). The corresponding visualization of estimated muscle tensions at the indicated time instant (bottom).

6.1.5. Joint Angle Estimation with Inertial Sensors Calibrated by Kinect

Participants: Mitsuhiro Hayashibe, Antonio Padilha Lanari Bo (Univ. of Brasilia), Philippe Poignet.

In this work, we explore the combined use of inertial sensors and the Kinect for applications on rehabilitation robotics and assistive devices. In view of the deficiencies of each individual system, a new method based on Kalman Filtering was developed in order to perform online calibration of sensor errors automatically whenever measurements from Kinect are available. The method was evaluated on experi- ments involving healthy subjects performing multiple DOF tasks. Accelerometers and gyrometers are used to estimate joint angle, while the Kinect is used for initializing the inertial system and for enabling 3D visualization of the performed task as in Fig. 5 [32].

Figure 5. Angles estimated using inertial sensors in a sit-to-stand task.

6.1.6. Investigation of fibre size stimulation selectivity using earthworm model

Participants: Pawel Maciejasz, Christine Azevedo Coste, David Andreu, David Guiraud.

Fibre type and diameter selective stimulation may allow to restore various motor and sensory functions of human body that have been lost due to disease or injury. For example in people unable to voluntary empty the bladder, selective stimulation of small fibres within the ventral branch of the sacral nerve roots (S2-S4/5) would induce detrusor contraction and those cause bladder empting closest to normal physiology. Currently, it is not possible to perform it in such a way, because stimulation of sacral nerve roots activates also bigger fibres innervating the urethral sphincter, which closest the outlet of the bladder.

Already many stimulation techniques have been proposed for fibre type and diameter selective stimulation. They were verified performing computer simulations and in some cases also by in vivo experiments on mammalian models. However, results of computer simulations still need to be confirmed by in vivo experiments, whereas experiments on mammalian models, due to high number of fibres within stimulated nerve, can be very complex to perform and obtained results difficult to interpret. As a result, it is still unclear which stimulation parameters may allow for selective stimulation of only particular group of fibers.

Therefore we propose the earthworm (Lumbricus terrestris) as a model for selective stimulation. The earthworm has three giant nerve fibres, with two distinctly different conduction velocities and diameters. Therefore it is very easy to distinguish between fibres that are firing at the moment. As a consequence the selectivity of stimulation may be immediately verified without application of sophisticated signal processing and averaging techniques.

We have investigated influence of various pulse amplitudes and durations on the selectivity of stimulation. Using a simple experimental set-up [29] shown in the fig.6 A, we were able to achieve selective activation of small (fig. 6 C) and big (fig. 6 D) fibers, as well as concurrent activation of both fibers (fig. 6 B) [28]. For that purpose we have used so called "anodal block" technique.

Based on the results of the above experiments, the recommendations of the optimal parameters for selective stimulation of nerve fibres will be prepared. Afterwards we are going to verified these recommendations in mammalian models (rats).

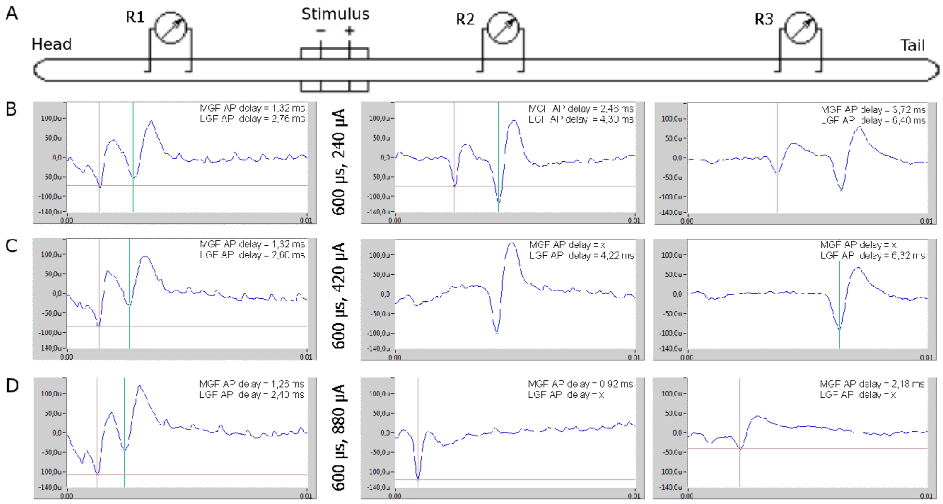

Figure 6. A. The schematic representation of the stimulation ("-" - cathode, "+" - anode) and recording (R1, R2 and R3) sites during experiments on earthworms; B, C and D - examples of nerve responses recorded for various pulse amplitudes. It may be observed that although all fibres are activated under cathode (R1 recording site, first plot in each line), on the anode side (R2 and R3 recording sites, second and third plot in each line respectively) activation of all (B), only small (C) and only big (D) fibres could be achieved.

6.1.7. Neural network based identification for time-variant dynamics

Participants: Zhan Li, Mitsuhiro Hayashibe, David Guiraud.

Due to high nonlinearity and time variance in muscle dynamics under FES, the identification of muscle model is complex task. The time-variance of muscle response may come from muscle fatigue, but also the electrode attachment condition. Along with such long-term time-variance, short term time-variance may be created by reflex effect. In addition, the characteristics of such variance even may change in time in an unpredicted way. Reinforcement learning framework may be applied to bring the robustness in adaptive identification. Current work is focused on the usage of discrete-time recurrent neural network for model identification.

6.2. Function control and synthesis

6.2.1. Correction of drop-foot in post-stroke hemiplegic patients

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

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, we propose a robust phase estimation method based on the observer of a nonlinear oscillator. We have modified a commercial stimulator, ODSTOCK, in order to be able to trigger it using our own wireless sensors and algorithms. Agreement from Nîmes CPP (ethical committee) was obtained in June 2010 to run tests on patients. The protocol comprises 1) the control algorithm triggering the stimulator based on signals issued from one wireless inertial sensor placed on healthy shank, 2) a sensor setup including inertial sensors placed on deficient shank and foot, one goniometer measuring deficient ankle angle, one EMG sensor placed on stimulated TA and one instrumented carpet (GAITRITE) (fig.7). Several patients have been included in the study and data is being processed [15][14].

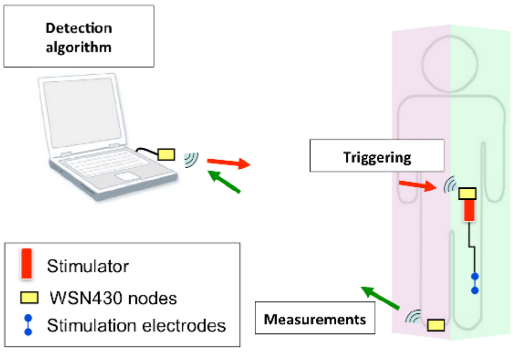

Figure 7. Stroke patient study protocol description.

6.2.2. eEMG Feedback Torque Control in FES

Participants: Mitsuhiro Hayashibe, Qin Zhang, Christine Azevedo Coste.

Electrical stimulation (ES) is one of the solutions for drop foot correction. Conventional ES systems deliver predefined stimulation pattern to the affected muscles. However, time-variant muscle response may influence the gait performance as they are difficult to be taken into account in advance. Therefore, closed-loop ES control is important to obtain desired gait in presence of muscle response variation. In this work, a dual predictive control, which consists of two nonlinear generalized predictive controllers, is proposed to track desired torque. The stimulated muscle dynamics are modeled by Hammerstein cascades, with one representing stimulation to activation, the other representing activation to torque. Ankle dorsiflexion torque and ES-evoked EMG of tibialis anterior were recorded experimentally for model identification. The control scheme is validated by following desired torque trajectories with the identified model. The results show that the stimulation pattern obtained from the dual predictive control can produce good torque tracking according to the current muscle condition as shown in Fig. 8. The updates of model parameters were switched off after certain instant for both the excitation and contraction model. Consequently, the model prediction in the control was only driven by the model input and the last model parameter estimates. The dual predictive controller can still generate suitable control signal to obtain desired torque trajectory [23].

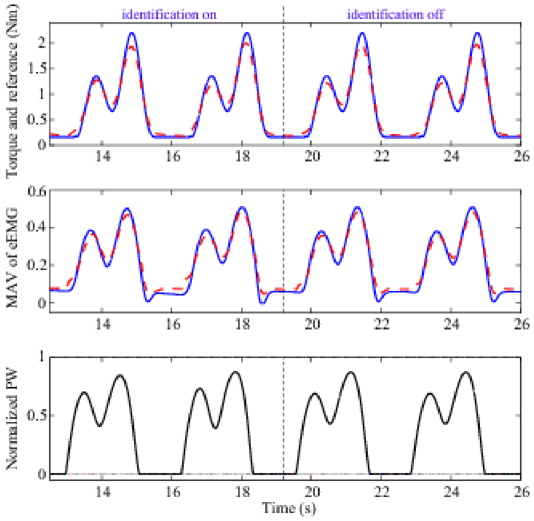

Figure 8. Torque reference (solid blue) and reproduced torque output by the proposed controller (dashed red). The updates of model parameters were switched off after 19.2s. Consequently, the model prediction in the control was only driven by the model input and the model parameter estimates at the time of 19.2s.

6.2.3. FES assisted Sit-to-Stand

Participants: Jovana Jovic, Christine Azevedo Coste, Philippe Fraisse, Charles Fattal.

Standing up is a common daily activity and a prerequisite to standing or walking. This frequently executed task is one of the most biomechanically demanding activities. The ability to rise from a sitting to a standing position is very important for individuals with paraplegia in order to achieve minimal mobility and has functional and therapeutic benefits related to bone loading, joint extension, cardio-circulatory stimulation, and pressure sore prevention.One method which has been widely investigated is functional electrical stimulation (FES) of the lower extremities. The sit-to-stand method, which is widely used in clinical practice, involves open-loop stimulation of knee extensors activated by hand switches. This technique works adequately in many cases, however, in applying this strategy, stimulation starts without referencespect to the upper body movement. Hence, the whole- body motion is not optimal and requires a high velocity of the joints and large upper limb forces during the rising motion, which may cause both damage of joint tissues and shoulder complications.

We propose a "patient-driven" FES method that would coordinate motion of the trunk, which is under voluntary control of the patient, and motion of the lower limbs, which are under FES control. The proposed approach is based on the observation of trunk movement during rising motion and a detection algorithm, which triggers a pre-programmed stimulation pattern.Trunk acceleration was acquired by a singleone-axis wireless accelerometer positioned on the subject's back. The detection algorithm consists of an online comparison of the movement acceleration of the ongoing motion with the reference pattern (a typical pattern characterizing the sit-to-stand transfer for each subject) using Pearson's correlation coefficients [25]. Experiments on paraplegic subjects are ongoing in refabilitation center PROPARA. The experimental setup and a paraplegic subject of the experiment are presented in Fig.9.

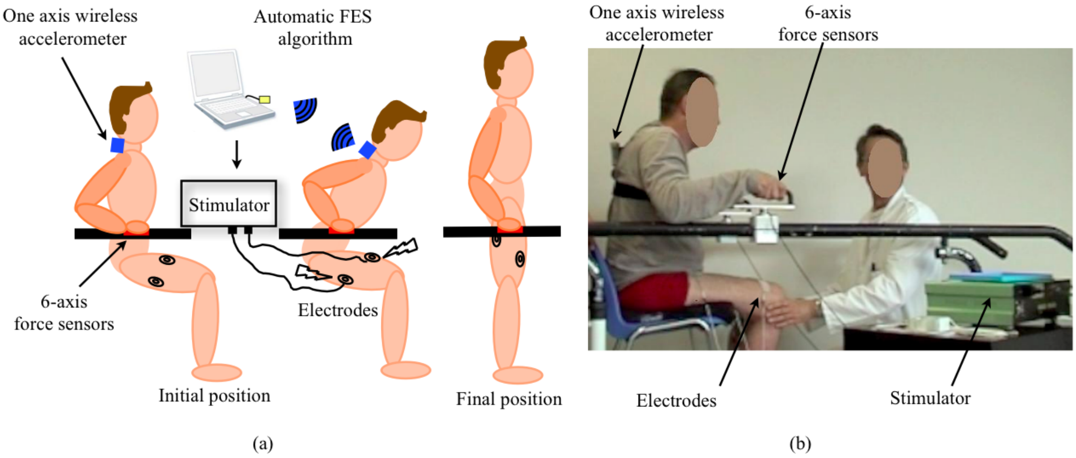

Figure 9. Experimental setup.

We have shown that in the cases where the acceleration and reference signal are similar, our algorithm is able to recognize sit-to-stand motion and to properly trigger leg stimulation at the desired instant. Also, we have showned that there is an influence of stimulation timing on applied hand forces during the motion. The best results were achieved for trials in which motion was similar to the one of the able bodied subjects in terms of trunk motion and the beginning of the leg motion with respect to the trunk acceleration signal.

We also investigated dynamic optimization as a tool to improve FES assisted sit tostand transfers of paraplegic subjects. The objective would be to find optimal strategy for voluntary trunk movement, which would minimize hip, knee and ankle torques and demand minimal upper limb participation during the motion. Our results suggest paraplegic patients should bend their body forward in order to use linear momentum of the trunk in sit off phase. Figure 10 shows optimal coordination of ankle, knee, and hip angles during sit-to-stand motion [26], [24].

6.2.4. *Signal-based segmentation of human locomotion using embedded sensor network*

Participants: Maud Pasquier, Christine Azevedo Coste, Bernard Espiau, Christian Geny (CHU Montpellier), Fabien Jammes.

Last year, we introduced a simple approach to segment in homogeneous phases a long-duration record of locomotion data consisting of body segment acceleration and foot pressure information. We used a system

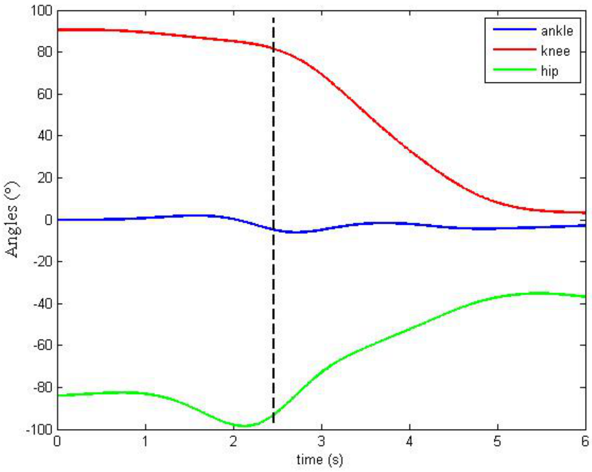

Figure 10. Optimization results for lower limb trajectories. Blue line is ankle angle, red line is knee angle and green line is hip angle. The dashed bar marks the beginning of sit off phase.

based on a network of wireless nodes embedding various types of sensors [3]. Two cases were considered: walk and run around an indoor running track [35] and outdoor marathon [34].

We now use this system as part of a study of mobility impairment caused by Parkinson's disease (fig.11). Freezing of gait (FOG) has been identified as one of the main contributors to gait disturbances in this disease. We introduce an ambulatory gait analysis method using body attached gyroscopes and accelerometers to detect the freezing of gait. One hand, we aim at proposing a FOG detection algorithm more robust because the existing algorithms were not able to detect the FOG without tremor. On the other hand, we would like to anticipate the freezing before ir is installed in order to reduce the risk of falling.

Before and during a FOG, a patient tends to walk slowly with short strides and fast rhythm. The detection of an increase of frequency is not enough, because there exists similar variations during the initiation of gait or a voluntary acceleration. The association of an increase of the gait rhythm together with a decrease of stride length allows us to detect a FOG. The computation of correlation coefficient in a moving window allows us to estimate the rhythm of strides. We are also working on different methods to estimate the stride length using one or two IMU (3-axis gyroscope and 3-axis accelerometer).

A time-frequency representation permits to show an increase of fundamental frequency and a duplication before a FOG, Fig.12. The variations of the fundamental frequency are already detected with the correlation. In the future works, we aim at characterizing these duplications and to propose an algorithm of automatic detection.

6.2.5. Awake surgery: How to optimize functional brain mapping by improving per-operatory testing?

Participants: Cheikh Niang, Pom Charras, Stephane Argon, Christine Azevedo, Hugues Duffau, David Guiraud, François Bonnetblanc.

It is now possible to perform resections of slowgrowing tumors in awake patients. Using direct electrical stimulation (DES), real-time functional mapping of the brain can be used to prevent the resection of essential areas near the tumor. For now, simple clinical tests are performed on conscious patients and combined with DES in order to discriminate functional and non-functional areas invaded by the tumors. In this work we try to

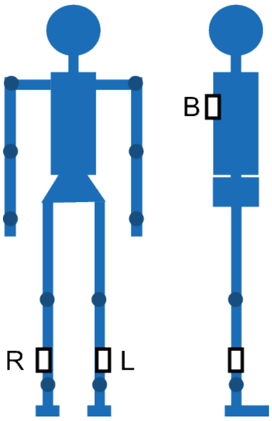

Figure 11. nodes disposition on the patient.

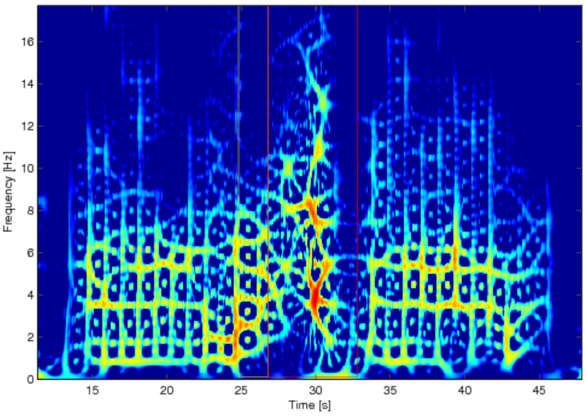

Figure 12. FOG: Smoothed pseudo Wigner-Ville time-frequency distribution with causal kernel.

develop a simple device based on a simple technology to better quantify the performances of the patients during the surgery itself and give a real-time feedback to the neurosurgeon that will help to further guide the surgery by improving the sensibility of the functional mapping. This procedure should also allow building a strong database that should serve retrospectively to improve the surgical procedure and reinforce the neurosurgeons' experience as well as to monitor the patients' performances all along their life.

6.2.6. Closed-loop CoM based posture control in FES

Participants: Alejandro González, Mitsuhiro Hayashibe, Philippe Fraisse.

Center of Mass control has been used in humanoid robotics to create stable standing postures and movements. By controlling the CoM position and acceleration, joint trajectories which respect to the ZMP stability criterion can be generated. FES may be used to drive joint torques in order to maintain a standing posture within a closed loop controller. Current work is focused on locating a human's CoM by creating a statically equivalent serial chain (SESC) model using widely accessible equipment, such as the Kinect camera and the Wii balance board.

6.3. Neuroprostheses

6.3.1. Stimulator calibration

Participants: Jérémie Salles, Fabien Soulier, Serge Bernard, Guy Cathébras.

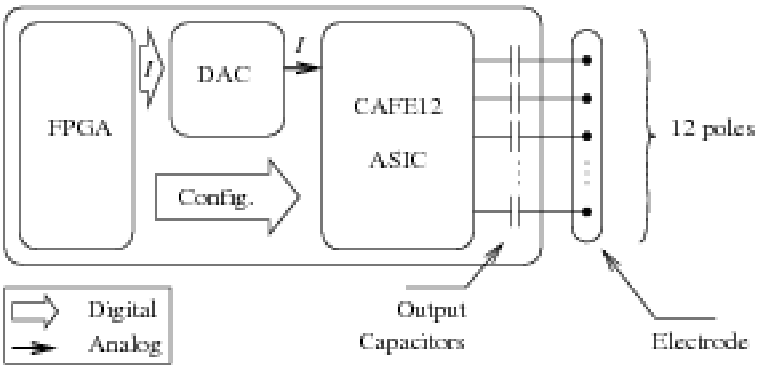

Figure 13. Stimulator architecture overview.

In the context of the TIME project, one CAFE12-based stimulator will be used for chronic experiment in human. During the validation of the stimulator, it appeared that we needed to improve both the linearity and the current matching of the 12 channels. We thus define a calibration process consisting in:

- PCB modification: To take advantage of the 10 bits of the DAC (only 8 were used before for compatibility reasons). The modification give the FPGA access to the two latter bits. Moreover, test points were added between the ASIC and the output capacitors that now can be removed for the calibration phase.
- Digital interface modification: To allow a 16^{th} current amplifying ratio (only 0-15 were enable). Improvements in the activation sequences of output current mirrors have also been carried on.
- Reference voltage and current tuning: The stimulator use several level of power supply and voltage references. Nominal values are:

$$\begin{aligned} V_{\text{hv}} &= 16.0\,\text{V}, & V_{\text{DD}} &= 3.3\,\text{V}, & V_{\text{hv}}2 &= 13.3\,\text{V}, \\ V_{\text{ref}}\,\text{P} &= 13.5\,\text{V}, & V_{\text{ref}}\,\text{N} &= 1.5\,\text{V}. \end{aligned}$$

The DAC current reference is set to get a $5.46\,\mathrm{mA}$ maximum current at the stimulator output for ratio of 15. We have enabled modification of the biasing resistor in order to fine-tune this current reference.

- Raw data acquisition: Measurement of the 12 output currents are carried on independently with the following configuration:
  - all outputs configured as cathodes,
  - all ratios set to 16.

  The measurement setup makes use of a characteristic analyzer (HP4156A) to maintain the voltage load to $7.5\,V$ for all the DAC current values.
- Correction: The linearity and matching correction is specific to the association of a particular ASIC with a particular DAC. For human experiment, the configuration will be limited to common anode/controlled cathodes. A first-order linear regression is applied to the 12 raw current measurements. This gives gain and offset adjustments for each channel that are applied by a linear digital correction block (fig. 14). The DAC initial value (8-bit) is multiplied by the correction gain and summed to the correction offset (both channel-dependant), resulting in a 10-bit corrected command. At last, respective correction values are chosen and quantified to lower impact of these modifications to the precision and dynamic range of the stimulator output (no “lost” bit). Concerning the implementation, since the 3 most significant bits of the correction gain appear to be constant, it is possible to use channel-independent bit-shifts and a substractor to perform the 8 to 10-bit multiplication.

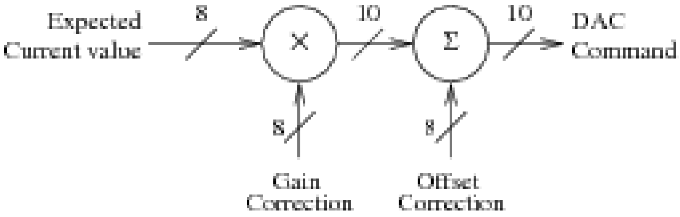

Figure 14. Linear digital correction principle.

The improvement in the matching of the 12 channels can be seen in figure 15. The results in terms of linearity are an integral non-linearity of $\pm 2.5\,\mathrm{LSB}$ and a differential non-linearity of $\pm 0.3\,\mathrm{LSB}$.

6.3.2. Nerve Modelling for ENG recording

Participants: Olivier Rossel, Jonathan Coulombe, Fabien Soulier, Serge Bernard, Guy Cathébras.

In the context of FES, neural recording is one of the main issues, as the control requires information carried on afferent peripheral nerves. Because specific information are carried in different fascicles, we propose to realize a non-invasive and spatial-selective electrode. Last year, based on investigation on the topic of extracellular Action Potentials (AP), we proposed a new tripole design, where the tripolar output signal is the image of the activity in the close vicinity of this tripole, providing high spatial selectivity.

We showed however, that this high spatial selectivity is achieved at the expense of signal amplitude. This first result jeopardizes the feasibility of this kind of electrode since the signal amplitude appears to be on the same range of the expected noise. First, we propose to estimate the performance of the proposed electrode with a quantitative study of the electrode selectivity. Then, to conclude on the feasibility of this electrode, the SNR has to be determined. So with a more accurate model, we studied the sensitivity of the proposed tripole, allowing to determine precisely the amplitude level of the expected signal. Thus, the SNR can be estimated knowing the expected noise.

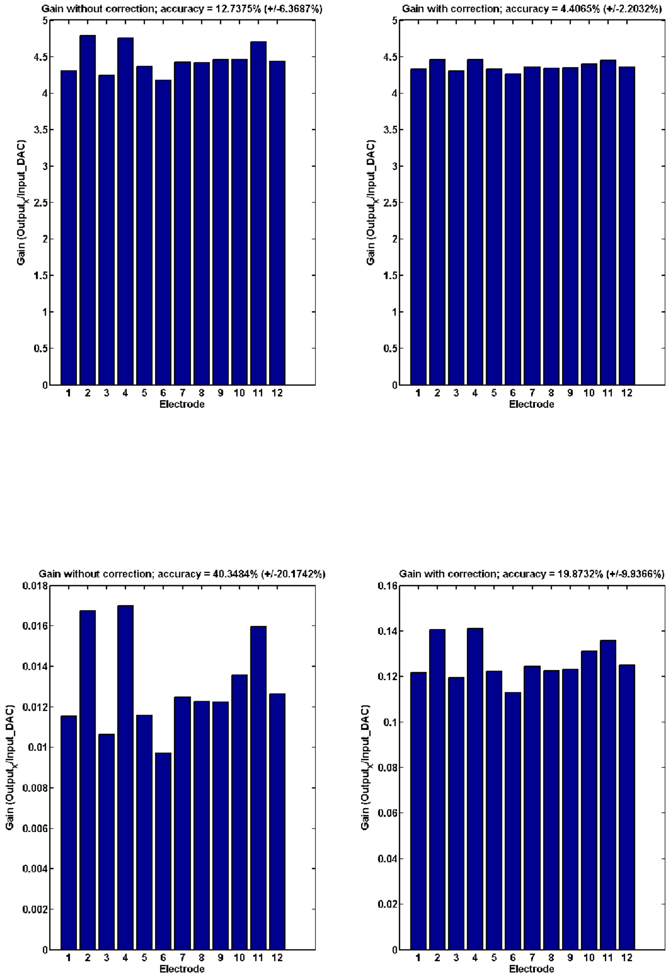

Figure 15. Mean gain (top) and worst case (bottom) before and after correction.

In short, the work of this year aims at characterizing the performances and evaluating the feasibility this new multi-contact cuff electrode.

6.3.2.1. Selectivity

We proposed an electrode configuration inspired from the FINE electrode (figure 16) designed for the same purpose. The electrode is composed of many tripoles, placed around the nerve. This disposition is used for two electrode, state-of-the-art electrode A and the proposed electrode B. The unique difference between both electrode resides on the longitudinal inter-pole distance (d_e), which is respectively $5\,\mathrm{mm}$ for the electrode A and $0.375\,\mathrm{mm}$ for the electrode B.

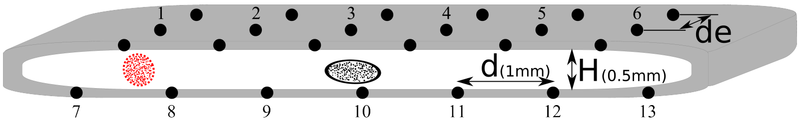

Figure 16. Electrodes A *and* B *have the same shape but differ on the longitudinal inter-pole distance (d_e). Two fascicles are represented.*

The electrodes performances are evaluated based on simulations using a model of a nerve comprising multiple fascicles [38]. The Selectivity Index (SI) quantifies the ability to record and distinguish between different active fascicles in such a manner that $\mathrm{SI} = 0$ corresponds to a case where an active fascicle yields identical signals at every recording site, while $\mathrm{SI} = 1$ occurs when one recorded signal is different from every other. This SI has to be presented according to the inter-fiber spacing.

The result of electrode selectivity are presented in the fig. 17. This figure shows that activity of two fascicles separated by as little as $1\,\mathrm{mm}$ can be distinguished for the proposed electrode (for this distance SI for electrode B ($\approx$ 0.9) is more than double that of electrode A (< 0.4). The proposed electrode thus appears to be much more selective than the reference electrode.

6.3.2.2. Sensitivity

Using a more realistic model (inhomogeneous and anisotropic), we investigate the spatial properties of extracellular AP and that of the filtering done by the proposed tripole [37]. This allows us to represent the tripolar sensitivity. It was realized for the proposed tripole B and compared to a state-of-the-art tripole A 18. This sensitivity represents the amplitude of the tripolar output signal for a single unit action potential.

This figure shows that the classical tripole radial sensitivity is huge compared to that of the proposed electrode. This confirms the high spatial sensibility of the proposed tripole. We can also determine the expected amplitude, where the signal can reach $6\,\mu$V. Considering this amplitude and knowing that in natural case there will be superposition of action potentials, we can conclude that the signal amplitude could be higher than the expected noise (around $1\,\mu$V). So we can conclude positively to the feasibility of this kind of electrode.

6.3.3. Low-noise, low-power ENG amplifier design

Participants: Jonathan Coulombe, Olivier Rossel, Fabien Soulier, Serge Bernard, Guy Cathébras.

This year we proposed a method for enhancing the noise-power tradeoff of front-end amplifiers in parallel recording applications of analog signals with respect to a common reference. One example of application is shown in the Fig. 19 for spatial-selectivity ENG recordings.

The circuit architecture is based on a Shared-Input Amplifier (SIA), composed by shared-input transconductance amplifiers and a differential stage. Averaging null signals and subtracting the result from every signal reduce the noise because the correlated noise between parallel outputs is attenuated. It results significant supply current savings without noise penalty. One example is shown in the Fig. 20 for the specific case of two average of two null signals.

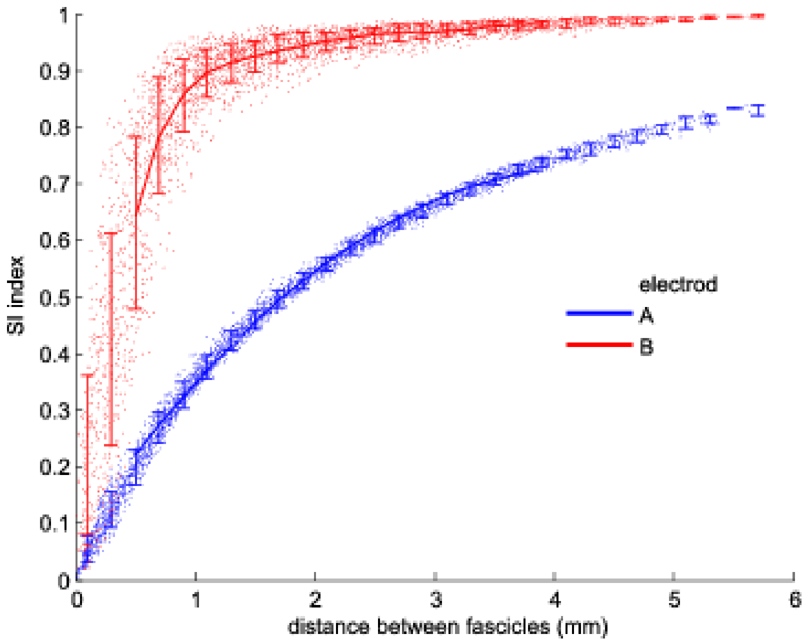

Figure 17. Selectivity index computed for random combinations of simulated fascicles, plotted as a function of the distance between each couple of fascicles.

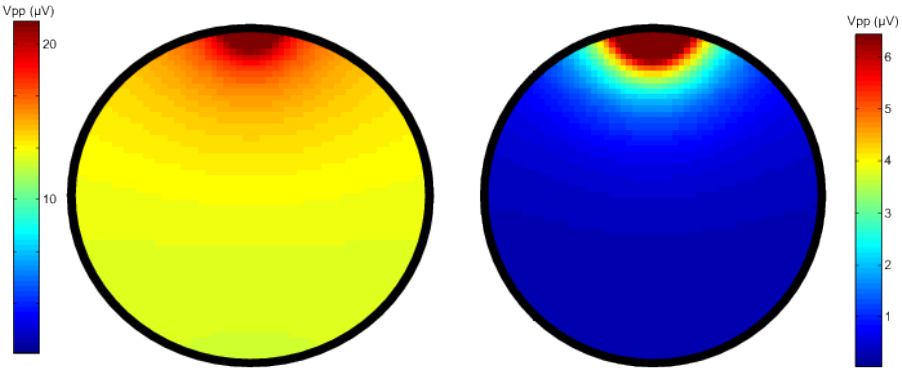

Figure 18. Comparison between classical and proposed tripole sensitivity. The peak-to-peak amplitude of a single unit action potential is represented, measured by a classical tripole on the left and by the proposed tripole on the right. The tripoles are placed on the surface of a nerve of $300\ \mu\mathrm{m}$ *radius.*

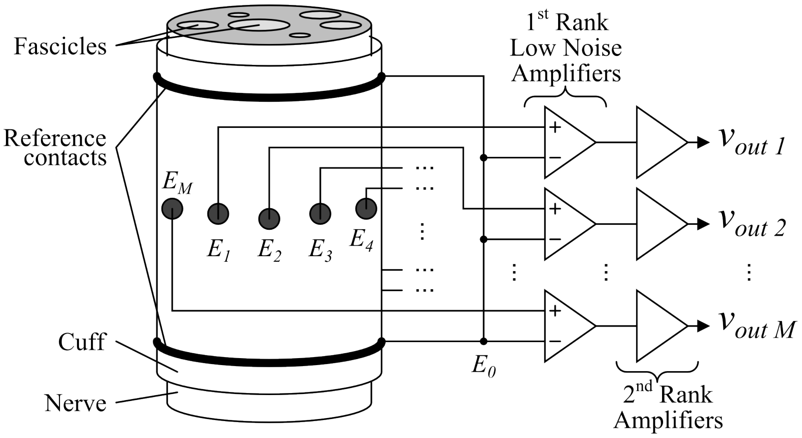

Figure 19. Conceptual representation of a selective ENG *recording system.*

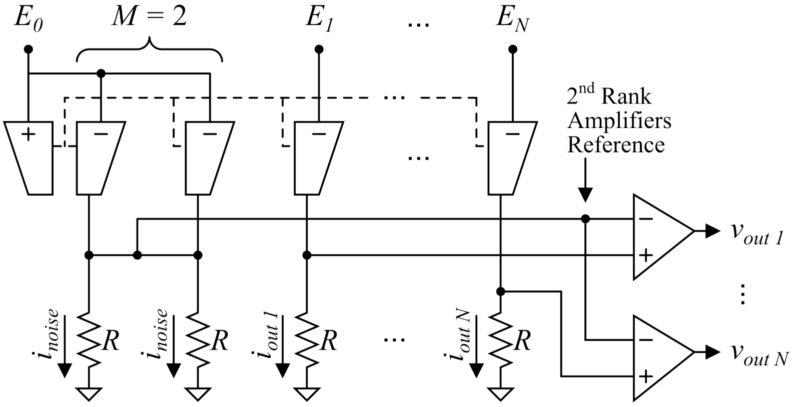

Figure 20. SIA modified for the use of transconductance amplifiers in open-loop configuration for ENG *recordings. And concept of parallel SIA with noise reduction using null output averaging and differential readout.*

Also, a method for reducing the remaining noise with little power penalty is possible. And it is possible to combine both methods, either noise level, total supply current, or both can be significantly reduced. The benefits of combining both methods and the related trade-offs was validated by simulations using models of a $0.35\,\mu\mathrm{m}$ BiCMOS process. So we have shown that the total supply current can be reduced by more than $50\,\%$ that of a comparable system using conventional differential amplifiers with equivalent output noise. Alternatively, the noise can be reduced by approximately $35\,\%$ with comparable power consumption.

This should enable low-noise recording of signals with significantly better efficiency than even the theoretical limit of any conventional differential amplifier. Future work will include circuit optimization and investigation of the impact of the architecture over other performances of the system, such as crosstalk, linearity, distortion, and channel mismatch. Implementation of the circuit for full characterization is expected to be completed in the near future.

7. Contracts and Grants with Industry

7.1. Contracts with Industry

- 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), one miniaturized DSU (named USR24*1000) and an external controler have been developed within this frame. The associated programming environment (SENIS Manager, cf. section 5.1.2) has also been developed in this context.
- The contract with Vivaltis company that is specialized in the development of external stimulators, has been completed. We jointly developed a new advanced external FES system dedicated to clinical rehabilitation; this first wireless external stimulation architecture is now marketed by Vivaltis.

8. Partnerships and Cooperations

8.1. Regional Initiatives

8.1.1. SANOFI (Montpellier financial support)

Participants: Christian Geny (CHU Montpellier), Christine Azevedo-Coste, René Zapata (LIRMM), Lionel Lapierre (LIRMM).

Project SANOFI on developing a robot carrying a video camera for gait analysis of patients with neurological disorders..

8.2. National Initiatives

8.2.1. DEMAR / MXM I-Lab project

Participants: David Guiraud, David Andreu.

INRIA I-Lab project (2011-2014). 1 engineer (3 y.), 20keuros, '*The aim of this INRIA's national initiative is to favor the scientific collaboration and technological transfer of the innovation between DEMAR and MXM. The aim of this project is to prototype concepts conjointly patented like stimulation unit 's embedded sequencer and implantable FES controller with its dedicated software environment"*'. Partner : MXM.

8.2.2. Cosinus ANR

Participants: David Guiraud, Mitsuhiro Hayashibe, Christine Azevedo-Coste, Benjamin Gilles.

Project SoHuSim on modeling muscle tissue during contraction in 3D movements using SOFA software and functional modeling of the organs. 150 kE. Partners: INRIA Evasion, Tecnalia, HPC, CHU Montpellier (Oct. 2010 - Oct. 2014).

8.2.3. ADT SENSAS - SENSBIO

Participants: Christine Azevedo-Coste, David Guiraud, David Andreu.

SENSAS is an INRIA ADT (Actions de Développement Technologique), implying several INRIA project teams on the “SENSor network ApplicationS” theme. SENSAS aims to propose applications based on wireless sensor and actuator network nodes provided from the work done around senslab and senstools preliminary projects. SENSAS is organized around the following work packages :

- SensRob : Robotics applications
- SensBio : Bio-Logging applications
- SensMGT : Wireless sensor/actuator network management/configuration applications
- SensBox : Wireless sensor/actuator network simulation applications and tools

Our team is mainly implied in the SensBio work package, in particular for the following applications: Spinal Cord Injured Patients FES-Assisted Sit to Stand, Post-Stroke Hemiplegic Patient FES-correction of drop foot, Gait analysis of parkinson freezing and Motion analysis of longterm race data.

8.2.4. Programme de recherche en qualité hospitaliere (PREQHOS)

Participants: Leader: Jean-Christophe LUCET (GH Bichat - Claude Bernard), Christine Azevedo-Coste, Eric Fleury (INRIA), Bruno Grandsebastien (CHRU Lille).

Project: Surgery room behaviour and impact on infectious risks (ARIBO : Attitudes et Risque Infectieux au Bloc Operatoire)

8.3. European Initiatives

8.3.1. 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).

8.3.2. Collaborations in European Programs, except FP7

- ÉGIDE, Partenariats Hubert Curien (PHC), Programme GALILEE (2011)
  Participants: Philippe Fraisse, Christine Azevedo Coste, Ahmed Chemori (LIRMM), Aurélio Capozzo (LABLAB, Roma, Italy), Claudia Mazza (LABLAB, Roma, Italy).

  Human locomotor and postural system mechanical parameter identification an dynamic and kinematic variables estimation.

8.4. International Initiatives

8.4.1. Japan-France Integrated Action Program "SAKURA and AYAME Junior"

Participant: Mitsuhiro Hayashibe.

"Modele Neuromusculaire du Corps Humain et ses Applications pour la Rehabilitation par la Stimulation Electrique Fonctionnelle", Funding for exchange supported by JSPS and INRIA 2010-2011.

8.4.2. INRIA Associate Teams

Title: @WALK(Artificial Walking)

INRIA principal investigator: Philippe Fraisse

International Partner:

  Institution: Stanford University (United States)

  Laboratory: Artifical Intelligence Lab

Duration: 2010 - 2012

See also: http://www.lirmm.fr/~fraisse/@WALK/

The motivation approach is the complementary research works of these teams. Indeed, a collaborative project should give an additional value to their research results. On one hand, the DEMAR Project Team has experience in Functional Electrical Stimulation to restore or modulate movements on spinal cord injured patients and post stroke patients. In both pathologies researches on assisted gait using FES (for paraplegics with a walker and hemiplegics) are carried out in the team. On the other hand, the Robotics research group (Stanford) carries out manipulation tasks with a humanoid robot under equilibrium constraints. Within the framework of the previous collaboration, the crossed visits and seminars last year led us to work on two different directions: - FES muscle modeling in Opensim framework - Control mechanisms underlying age-related changes in motor control strategies during Sit-To-Stand.

8.4.3. INRIA International Partners

- Collaborative Research agreement on Academic Co-operation (contrat sans financement) "Neuromuscular function analysis and identification for Rehabilitation" Partner: University of Tokyo (Prof. Yoshihiko Nakamura) Duration: 2011 - 2014

9. Dissemination

9.1. Animation of the scientific community

+ D. Guiraud
    1. Associate editor for Journal of Neural Eng. and EMBC'11 conference
    2. Member of the steering committee of "Institut des Technologies pour la Santé"
    3. Chair of the Labex Numev "Aide à la personne malade et déficiente" specific action

+ C. Azevedo-Coste
    1. Board member of IFESS society (international functional electrical stimulation society)
    2. Associate Editor of Paladyn Behavioral Robotics Journal
    3. Invited Editor of Paladyn Behavioral Robotics Journal for the special issue on Rehabilitation Robotics

+ M. Hayashibe
    1. ICIRA2011 Program committe
    2. Organizer for Workshop on Robotics for Neurology and Rehabilitation, IEEE IROS2011, San Francisco, California

+ D. Andreu
    1. Co-organizer of the french working group on Control Architectures of Robots of the french GdR Robotique
    2. assitant manager of the Robotic Department (LIRMM)
    3. member of the Program Comittee of CAR'11
    4. member of the Scientific Comittee of JNRR'11
+ F. Soulier
    1. Local coordinator of the Belem (BioElectronics for Medical Engineering) intensive programme for the University of Montpellier 2. Belem is funded by the European Community in the framework of the Erasmus programme.

9.2. Teaching

- David Guiraud, 16h/y in Master second year degree "Science du Mouvement Humain", 10h/year in Master TIC-Santé
- Christine Azevedo-Coste, "parcours TIC et Santé IT-Montpellier" and MASTER TIC-SANTé, neurophysiology, 4h/y.
- David Andreu, Associate Professor, 200h/y, Engineering school Polytech Montpellier and Master degree, Software engineering, real time OS, discrete event systems, networks, neuroprosthesis.
- Fabien Soulier, Associate professor at Polytech' Montpellier (ERII) teaching electronics and signal processing.

9.3. Participation in seminars and workshops

- Fabien Soulier was invited to give a talk about the DEMAR research at the workshop *TIC & Santé* organized by *MEITO* and the *CRITT Santé Bretagne*, Brest. Nov. 17th 2011. “Progrès de la stimulation électrique fonctionnelle pour la restauration du mouvement.”

9.4. Theses and Internships

9.4.1. Thesis Defenses

1. David Andreu and Philippe Fraisse supervise **Mickael Toussaint**, *Architecture de mesure et de stimulation électro-fonctionnelle Externe : des concepts aux applications.* defended on 9th December in Montpellier.
2. Mitsuhiro Hayashibe and Philippe Fraisse supervise **Qin Zhang**, *Evoked EMG-based torque prediction for muscle fatigue tracking and closed-loop torque control in FES.* defended on 13th December in Montpellier.

9.4.2. Ongoing theses

1. Serge Bernard and Guy Cathébras supervise **Fanny Le Floch**, *Sûreté de fonctionnement des circuits implantables dans le corps humain.*, MENRT.
2. Guy Cathébras and Fabien Soulier supervise **Olivier Rossel**, *Circuits intégrés de recueil et d'interprétation des signaux nerveux*, Axa fundation.
3. Jérôme Bourien (INM, Montpellier) and Christine Azevedo-Coste, supervise **Christophe Michel**, *Modélisation de l'efférence latérale du système auditif périphérique*, CIFRE MXM.

4. Christine Azevedo-Coste and Bernard Espiau supervise **Maud Pasquier**, *Observation et contrôle de mouvements non cycliques des membres inférieurs et supérieurs en assistance fonctionnelle.*, ANM.
5. Christine Azevedo-Coste, Philippe Fraisse and Charles Fattal supervise **Jovana Jovic**, *Maintien prolongé la station debout équilibrée fonctionnelle chez le patient paraplégique*, BDI Région-INRIA.
6. David Andreu supervises **Hélène Leroux**, *Abstraction et composition pour la conception formelle de neuroprothèses*, Thesis ENS, 2011-2014.
7. David Guiraud and David Andreu supervise **Guillaume Coppey**, *Unité implantable de mesure répartie pour suppléance fonctionnelle en boucle fermée*, Thesis CIFRE MXM, 2011-2014.
8. Mitsuhiro Hayashibe and Philippe Fraisse supervise **Alejandro González**, *Closed-loop whole body posture control and stability analysis in FES.*, European Comission:CORDIS, 2011-2014.
9. Mitsuhiro Hayashibe, Benjamin Gilles and David Guiraud supervise **Yacine Berranen**, *Volumetric musculoskeletal modeling and simulation.*, CNRS Handicap, 2011-2014.
10. Mitsuhiro Hayashibe and David Guiraud supervise **Zhan Li**, *Computational rehabilitation and neuromuscular control based on reinforcement learning.*, China Scholarship Council (CSC), 2011-2014.

9.4.3. PostDoc

- Christine Azevedo Coste, David Guiraud and David Andreu supervise Pawel Maciejasz, "Selective neural electo-stimulation" (1.5 year contract, TIME project), 2010-2011.
- Serge Bernard and Fabien Soulier supervise Guilherme Bontorin, "High level modeling for dependability of FES system" (1.5 year contract, TOETS project), 2010-2011.
- Serge Bernard, Fabien Soulier and Guy Cathébras supervise Jonathan Coulombe, "Programmable micro-amplifier for ENG recording" (1 year contract, Bourse postdoctorale du Conseil de Recherche en Sciences Naturelles et Génie (CRSNG) du Canada), 2010-2011.
- François Bonneblanc and Hugues Duffau supervise Pom Charras, "The validation on pre, post and intra-operative evaluations of patients during awake neurosurgeries of slow-growing tumors in the brain", contract Association pour la Recherche sur le Cancer (ARC-France) 'subvention-libre N°3184', post-doctoral fellowship, 2010-2011.

9.4.4. Internships

- David Andreu supervised Guillaume Magro, "Développement d'un séquenceur de SEF externe", Engineer final internship, from Mar. 2011 to Jul. 2011.
- David Guiraud and David Andreu supervised Guillaume Coppey, "Conception et prototypage d'une unité de mesure accélérométrique", Engineer final internship, from Apr. 2011 to Sep. 2011.
- David Andreu supervised Ronald Reboul and Jérémy Servoz, "Prototypage d'un séquenceur embarqué au sein d'un implant de stimulation", Projet Industriel de Fin d'Etudes (engineer final year), from Sep. 2011 to Jan. 2012.
- David Andreu supervised Jean-François Happe, "Etude de stratégies d'économie d'énergie pour implant de stimulation", Projet Industriel de Fin d'Etudes (engineer final year), from Sep. 2011 to Jan. 2012.
- Christine Azevedo Coste, Philippe Fraise and Vincent Bonnet (LABLAB, Roma, Italy) supervised Ugo Gouedard, Engineer project, "Center of Mass and Joint Angle estimation", Institut Telecom - Formation TIC et Santé Montpellier, from Mar. 2011 to Aug. 2011.
- Christine Azevedo Coste, Jeremy Laforet and Pawel Maciejasz supervised Guillaume Jourdain on "Computer simulation of the electrical stimulation of the nerve fibres", Master student project and afterwards 3 month training (TIME project financing), from Oct. 2010 to Jun. 2011.

- Mitsuhiro Hayashibe and Benjamin Gilles supervised Yacine Berranen on "Analyse des déformations de tissus mous actifs et passifs", Master student project and afterwards 3 month training (Sohusim project financing), from Mar. 2011 to Aug. 2011.
- Mitsuhiro Hayashibe supervised Lizhi Pan (Shanghai Jiao Tong Univ.) on "Multi-functional EMG classification for dynamic EMG-motion modeling", INRIA international internship program (EGIDE+ANR Sohusim), from Sep. 2011 to Nov. 2011.
- Mitsuhiro Hayashibe supervised Peng Yao (Shanghai Jiao Tong Univ.) on "Multi-Dimensional Wrist Musculoskeletal Modeling for Tremor Simulation", INRIA international internship program (EGIDE+ANR Sohusim), from Sep. 2011 to Nov. 2011.
- Mitsuhiro Hayashibe supervised Seiya Sakaguchi (Tokyo Univ. of Agriculture and Technology) on "Joint stiffness analysis under FES", Japan-France Integrated Action Program "SAKURA and AYAME Junior", Mar. 2011.
- David Guiraud and Pawel Maciejasz supervised Thomas Guiho on "Proposing and implementing the algorithm for automated detection and classification of the action potentials in signals recorded using a few channels", Master student project, from Oct. 2011 to Mar. 2012.
- David Guiraud and Guillaume Coopey supervises Edouard Lavaud and Majid Houtachj, Tis santé internship on "Data and energy transmission on a 2-wire implanted bus"
- Christine Azevedo Coste and Jovana Jovic supervise Camilla Pierella on "Assisting transfer in paraplegic subjects", MASTER student (ERASMUS financial support).

9.4.5. Contract Engineers

- 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, Babylone contract (3 years contract, INRIA).
- David Andreu supervises Guillaume Magro. "Spécification et prototypage d’un contrôleur de SEF implantable". Industrial Informatics Engineer, INRIA Expert Engineer contract (3 years contract, INRIA).
- Guy Cathébras, Serge Bernard and Fabien Soulier co-supervise Jérémy Salles "Correction de la version 2 et développement de la version 3 de l’ASIC de stimulation 12 pôles" Microelectronics Design Engineer (1 year contract, NEUROCOM financial support)

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Publications of the year

Articles in International Peer-Reviewed Journal

[1] J. BADIA, T. BORETIUS, D. ANDREU, C. AZEVEDO COSTE, T. STIEGLITZ, X. NAVARRO. *Comparative Analysis of Transverse Intrafascicular Multichannel Electrode (TIME), Longitudinal Intrafascicular Electrode (LIFE) and Multipolar Cuff Electrode for the Selective Stimulation of Nerve Fascicles*, in "Journal of Neural Engineering", 2011, vol. 8, n^{o} 3, 13, http://hal.inria.fr/lirmm-00588922/en.

[2] V. BONNET, S. RAMDANI, P. FRAISSE, N. RAMDANI, J. LAGARDE, B. BARDY. *A Structurally Optimal Control Model for Predicting and Analyzing Human Postural Coordination*, in "Journal of Biomechanics", July 2011, vol. 44, n^{o} 11, p. 2123-2128 [*DOI :* 10.1016/J.JBIOMECH.2011.05.027], http://hal.inria.fr/lirmm-00609097/en.

[3] G. CHELIUS, C. BRAILLON, M. PASQUIER, N. HORVAIS, R. PISSARD-GIBOLLET, B. ESPIAU, C. AZEVEDO COSTE. *A Wearable Sensor Network for Gait Analysis: A 6-Day Experiment of Running Through the Desert*, in "IEEE/ASME Transactions on Mechatronics", 2011, vol. 16, n^{o} 5, p. 878 - 883, http://hal.inria.fr/lirmm-00604988/en.

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[5] H. EL MAKSSOUD, D. GUIRAUD, P. POIGNET, M. HAYASHIBE, P.-B. WIEBER, K. YOSHIDA, C. AZEVEDO COSTE. *Multiscale modeling of skeletal muscle properties and experimental validations in isometric conditions*, in "Biological Cybernetics", July 2011, vol. 105, p. 121-138 [*DOI :* 10.1007/S00422-011-0445-7], http://hal.inria.fr/lirmm-00631528/en.

[6] M. HAYASHIBE, Q. ZHANG, D. GUIRAUD, C. FATTAL. *Evoked EMG-based torque prediction under muscle fatigue in implanted neural stimulation*, in "Journal of Neural Engineering", October 2011, vol. 8, n^{o} 6, 7 [*DOI :* 10.1088/1741-2560/8/6/064001], http://hal.inria.fr/lirmm-00630237/en.

[7] S. KRUT, C. AZEVEDO COSTE, P. CHABLOZ. *Secured Microprocessor-Controlled Prosthetic Leg for Elderly Amputees: Preliminary Results*, in "journal of Applied Bionics and Biomechanics", 2011, vol. Special Issue on Assistive and Rehabilitation Robotics, 8, in press, http://hal.inria.fr/lirmm-00502000/en.

[8] J. LAFORÊT, D. GUIRAUD, D. ANDREU, H. TAILLADES, C. AZEVEDO COSTE. *Smooth muscle modeling and experimental identification: application to bladder isometric contraction*, in "Journal of Neural Engineering", May 2011, vol. 8, n^{o} 3, 13 [*DOI :* 10.1088/1741-2560/8/3/036024], http://hal.inria.fr/lirmm-00597214/en.

[9] S. LENGAGNE, N. RAMDANI, P. FRAISSE. *Planning and Fast Replanning Safe Motions for Humanoid Robot*, in "IEEE Transactions on Robotics", September 2011, vol. 9, n^{o} 99, p. 1-12 [*DOI :* 10.1109/TRO.2011.2162998], http://hal.inria.fr/lirmm-00605551/en.

[10] J. VAN DOORNIK, C. AZEVEDO COSTE, J. USHIBA, T. SINKJAER. *Positive Afferent Feedback to the Human Soleus Muscle during Quiet Standing*, in "Muscle and Nerve", 2011, vol. 43, n^{o} 5, p. 726-732, http://hal.inria.fr/lirmm-00529289/en.

[11] Q. ZHANG, M. HAYASHIBE, P. FRAISSE, D. GUIRAUD. *FES-Induced Torque Prediction with Evoked EMG Sensing for Muscle Fatigue Tracking*, in "IEEE/ASME Transactions on Mechatronics", July 2011, vol. 16(5), p. 816 - 826 [*DOI :* 10.1109/TMECH.2011.2160809], http://hal.inria.fr/lirmm-00604670/en.

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Invited Conferences

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[15] C. AZEVEDO COSTE, J. FROGER. *Quelle place pour la SEF dans la rééducation de l'hémiplégie vasculaire ?*, in "Entretiens de Médecine Physique et de Réadaptation", France, March 2011, http://hal.inria.fr/lirmm-00588923/en.

[16] F. SOULIER, S. BERNARD, G. CATHÉBRAS, D. GUIRAUD. *Advances in Implanted Functional Electrical Stimulation*, in "DTIS'11: 6th IEEE International Conference on Design and Technology of Integrated Systems in Nanoscale Era", Athens, Greece, July 2011, p. 1-6 [*DOI :* 10.1109/DTIS.2011.5941417], http://hal.inria.fr/lirmm-00607832/en.

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[18] B. ADORNO, A. PADILHA LANARI BO, P. FRAISSE, P. POIGNET. *Towards a Cooperative Framework for Interactive Manipulation Involving a Human and a Humanoid*, in "ICRA'11: IEEE International Conference on Robotics and Automation", Shanghai, China, 2011, p. 3777-3783 [*DOI :* 10.1109/ICRA.2011.5979787], http://hal.inria.fr/lirmm-00641657/en.

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Patents and standards

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