RESEARCH CENTRE

Inria Branch at the University of Montpellier

2024
ACTIVITY REPORT

Project-Team
CAMIN

Control of Artificial Movement & Intuitive Neuroprosthesis

DOMAIN

Digital Health, Biology and Earth

THEME

Computational Neuroscience and Medicine

Contents

Project-Team CAMIN

Creation of the Project-Team: 2019 March 01

Keywords

Computer sciences and digital sciences

A1.2.6. – Sensor networks

A1.3. – Distributed Systems

A2.3. – Embedded and cyber-physical systems

A2.5.2. – Component-based Design

A4.4. – Security of equipment and software

A4.5. – Formal methods for security

A5.1.4. – Brain-computer interfaces, physiological computing

A5.9.2. – Estimation, modeling

A5.10.5. – Robot interaction (with the environment, humans, other robots)

A6.1.1. – Continuous Modeling (PDE, ODE)

A6.3.2. – Data assimilation

A6.4.1. – Deterministic control

A6.4.6. – Optimal control

Other research topics and application domains

B1.1.9. – Biomechanics and anatomy

B1.2.1. – Understanding and simulation of the brain and the nervous system

B2.2.1. – Cardiovascular and respiratory diseases

B2.2.2. – Nervous system and endocrinology

B2.2.6. – Neurodegenerative diseases

B2.5.1. – Sensorimotor disabilities

B2.5.3. – Assistance for elderly

1 Team members, visitors, external collaborators

Research Scientists

- Christine Azevedo Coste [Team leader, INRIA, Senior Researcher]
- François Bailly [INRIA, Researcher]
- François Bonnetblanc [INRIA, Researcher]
- Thomas Guiho [INRIA, ISFP]
- Olivier Rossel [INRIA, Researcher, from Oct 2024]

Post-Doctoral Fellows

- Tiago Coelho Magalhaes [INRIA, Post-Doctoral Fellow]
- Etienne Moullet [INRIA, Postdoc co-supervised WILLOW/CAMIN]
- Sabrina Otmani [INRIA, Post-Doctoral Fellow]
- Pierre Schegg [INRIA, Post-Doctoral Fellow, from Nov 2024]
- Lucie William [INRIA, Post-Doctoral Fellow, from May 2024 until Jul 2024]

PhD Students

- Paul Andre [INRIA, from Oct 2024]
- Jonathan Baum [INRIA]
- Laurence Colas [REEV SAS, CIFRE, until Feb 2024]
- Gabriel Graffagnino [INRIA]
- Charlotte Le Goff [Association APPROCHE, from Mar 2024]
- Valentin Maggioni [INRIA]
- Felix Schlosser-Perrin [UNIV MONTPELLIER]
- Clotilde Turpin [INRIA, CIFRE]

Technical Staff

- Jean De Gheldere [INRIA, Engineer, from Apr 2024]
- Baptiste Faraud [INRIA, Engineer, from Jul 2024]
- Ronan Le Guillou [INRIA, Engineer]
- Olivier Rossel [UNIV MONTPELLIER, Engineer, from Jul 2024 until Sep 2024]
- Olivier Rossel [INRIA, Engineer, until Jun 2024]

Interns and Apprentices

- Jordan Langlet [INRIA, Intern, from Jun 2024 until Jul 2024]
- Elisa Salanqueda [INRIA, Intern, from Jun 2024 until Aug 2024]

Administrative Assistant

- Claire-Marine Parodi [INRIA]

Visiting Scientists

- Ali Boukhsibi [UNIV MONTPELLIER, from Oct 2024]
- Riccardo Carpineto [EPFL LAUSANNE, from Jul 2024 until Aug 2024]

External Collaborators

- Charles Fattal [USSAP]
- David Guiraud [Neurinnov]
- Benoît Sijobert [INSTITUT ST-PIERRE]

2 Overall objectives

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

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

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

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

We have chosen not to restrict our investigation spectrum to specific applications but rather to deploy our general approach to a variety of clinical applications in collaboration with our medical partners. **Our motivation and ambition is to have an effective clinical impact**.

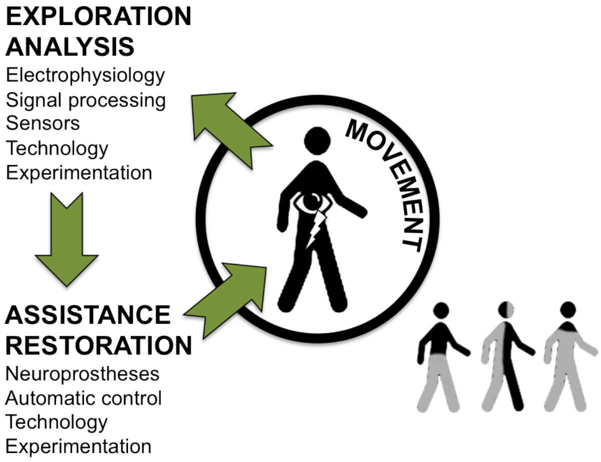


Figure 1: Overview of **CAMIN** general scientific approach.

3 Research program

3.1 Exploration and understanding of the origins and control of movement

One of CAMIN's areas of expertise is **motion measurement, observation and modeling** in the context of **sensorimotor deficiencies**. The team has the capacity to design advanced protocols to explore motor control mechanisms in more or less invasive conditions in both animal and human.

Human movement can be assessed by several noninvasive means, from motion observation (MOCAP, IMU) to electrophysiological measurements (afferent ENG, EMG, see below). Our general approach is to develop solutions that are realistic in terms of clinical or home use by clinical staff and/or patients for diagnosis and assessment purposes. In doing so, we try to gain a better understanding of motor control mechanisms, including deficient ones, which in turn will give us greater insight into the basics of human motor control. Our ultimate goal is to optimally match a neuroprosthesis to the targeted sensorimotor deficiency.

The team is involved in research projects including:

- Peripheral nervous system (PNS): modeling, exploration and electrophysiology
  Electroneurography (ENG) and electromyography (EMG) signals inform about neural and muscular activities. The team investigates both natural and evoked ENG/EMG through advanced and dedicated signal processing methods. Evoked responses to ES are very precious information for understanding neurophysiological mechanisms, as both the input (ES) and the output (evoked EMG/ENG) are controlled. CAMIN has the expertise to perform animal experiments (rabbits, rats, earthworms and big animals with partners), design hardware and software setups to stimulate and record in harsh conditions, process signals, analyze results and develop models of the observed mechanisms. Experimental surgery is mandatory in our research prior to invasive interventions in humans. It allows us to validate our protocols from theoretical, practical and technical aspects.

- Central nervous system (CNS) exploration
  Stimulating the CNS directly instead of nerves enables direct activation of the neural networks responsible for generating functions. Once again, if selectivity is achieved the number of implanted electrodes and cables would be reduced, as would the energy demand. We have investigated **spinal electrical stimulation** in animals (pigs) for urinary track and lower limb function management.

This work is very important in terms of both future applications and the increase in knowledge about spinal circuitry. The challenges are technical, experimental and theoretical, and the preliminary results have enabled us to test some selectivity modalities through matrix electrode stimulation. This research area will be further intensified in the future as one of the ways to improve neuroprosthetic solutions.

We intend to gain a better understanding of the electrophysiological effects of Direct Electrical Stimulation (DES) through electroencephalographic (EEG) and electrocorticographic (ECoG) recordings in order to optimize anatomo-functional brain mapping, to better understand brain dynamics and plasticity, and to improve surgical planning, rehabilitation, and the quality of life of patients.

- Muscle models and fatigue exploration
  Muscle fatigue is one of the major limitations in all FES studies. Simply, the muscle torque varies over time even when the same stimulation pattern is applied. As there is also muscle recovery when there is a rest between stimulations, modeling the fatigue is almost an impossible task. Therefore, it is essential to monitor the muscle state and assess the expected muscle response by FES to improve the current FES system in the direction of greater adaptive force/torque control in the presence of muscle fatigue.

- Movement interpretation
  We intend to develop ambulatory solutions to allow ecological observation. We have extensively investigated the possibility of using inertial measurement units (IMUs) within body area networks to observe movement and assess posture and gait variables. We have also proposed extracting gait parameters like stride length and foot-ground clearance for evaluation and diagnosis purposes.

3.2 Movement assistance and/or restoration

The challenges in movement restoration are: (i) improving nerve/muscle stimulation modalities and efficiency and (ii) global management of the function that is being restored in interaction with the rest of the body under voluntary control. For this, both local (muscle) and global (function) controls have to be considered.

Online modulation of ES parameters in the context of lower limb functional assistance requires the availability of information about the ongoing movement. Different levels of complexity can be considered, going from simple open-loop to complex control laws (Figure 2). Real-time adaptation of the stimulation patterns is an important challenge in most of the clinical applications we consider. The modulation of

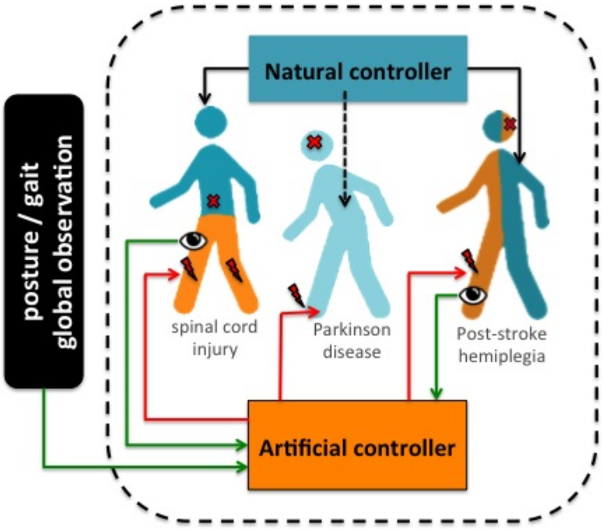


Figure 2: FES assistance should take into account the coexistence of artificial and natural controllers. Artificial controllers should integrate both global (posture/gait) and local (limb/joint) observations.

ES parameters requires more advanced adaptative controllers based on sensory information in order to adapt to muscle fatigue or environmental changes. A special care in minimizing the number of sensors and their impact on patient motion should be taken.

4 Application domains

4.1 Movement Assistance

CAMIN develops neuroprosthetic solutions dedicated to restore or assist movements of paralyzed limbs. Among the considered functions we can cite: pedalling, grasping or walking. Different users are considered: individuals with post-stroke hemiplegia, people with spinal cord lesions and persons with Parkinson disease.

We have also started to develop skills in orthosis design.

4.2 Movement Analysis

For the purpose of assisting movement, CAMIN has developped an important expertise in movement interpretation using a large range of sensors: inertial measurement units, MOCAP systems, encoders, goniometers... Various Classification methods are used depending on the objective.

This knowledge is applied in other applications than movement assistance, like in MEDITAPARK project where we developped an application (PARAKEET) embedded in a smartwatch to monitor hand tremor in persons with parkinson disease.

4.3 Evoked electrophysiology

CAMIN develops solutions to trigger, record and process electrophysiological signals evoked by electrical stimulation applied to various neural tissues. These evoked responses are used to control the activity of the excitable tissue, to probe its electrophysiological status for diagnostic purposes and to investigate the conductivity/connectivity between the stimulation and the recording sites (electrophysiological mapping).

These neural engineering procedures can be applied to muscle, nerve, spinal cord and brain, in animals and humans.

For instance, electrical stimulations can be applied externally and non-invasively on muscles to induce muscle contractions as well as invasively on the human brain in order to guide neurosurgeries.

5 Social and environmental responsibility

5.1 Impact of research results

CAMIN research is clearly dedicated to applications which intend to improve quality of life and/or self esteem of individuals with sensori-motor deficiencies.

Our activities are associated with an important working load on designing protocols and obtaining authorizations from ethical committees and/or health agencies. We list in the following the protocols that have obtained authorizations and were valid in 2024.

1. Measure of the Potential Evoked by Electric Stimulation (PE & CE). CHU Montpellier. Autorisation CPP RCB 2014-A00056-43. ClinicalTrials.gov Identifier: NCT02509442

2. Prehens-Stroke 2: Prospective multicenter study on the evaluation in clinical setting of a Grasp NeuroProsthesis and self-triggering control modalities for the restauration of paretic side prehension capabilities in post-stroke subjects. Study carried by the University Hospital (CHU) of Toulouse in collaboration with the Le Grau du Roi rehabilitation center from the University Hospital (CHU) of Nîmes (ClinicalTrial.gov ID: NCT04804384; Autorisation CPP ID-RCB: 2020-A01660-39).

3. Grasp-Again: Prospective monocentric, real-life, feasibility case series study on 2 months long usage of a wearable grasp neuroprosthesis, at home in autonomy by post-stroke participants. Study carried by the University Hospital (CHU) of Toulouse (ClinicalTrial.gov ID: NCT05625113; Autorisation CPP ID-RCB: 2022-A01202-41).

4. AI-Hand CT1 - Sensors: Evaluation of Non-Invasive Control Interfaces for Operating Assistive Devices for Individuals with Tetraplegia. Autorisation CPP ID-RCB: 2024-A01014-43 / Dispositif médical classe I

5. Freewheels: Impact of training a tetraplegic subject in pedaling a tricycle assisted by electrical simulation of sub-lesional muscles: A Pilot Study. Autorisation CPP ID-RCB: 2023-A02399-36

6. Exofinger: a tool for entering objects. COERLE (autorisation nº 2021-47 Exofinger)

7. SOFTMOCAP: Comparison of Three Methods for Analyzing Hand Movements in Healthy Subjects. COERLE (autorisation nº 2022-57 SOFTMOCAP)

8. CoCoS: Quantify the correlation between muscle co-activation in each agonist/antagonist muscle group of interest during the phases of the gait cycle and the spasticity assessment associated with each of these muscle groups. COERLE (autorisation nº 2024-44)

9. Opticycle: Study the impact of knee configuration (flexed or extended) on hip muscle torque during flexion-extension movements. COERLE (autorisation nº 2024-02)

10. i-grip: Evaluation of an Algorithm for Detecting Object Grasping Intent and Selecting an Appropriate Grip. COERLE (autorisation nº 2024-01)

11. AI-Hand - Animal studies: Experimentations in pigs to support the development of an implantatable stimulation device designed to eventually restore prehension in people with tetraplegia (Ethical agreement from the Ministry of Higher Education and Research nº #47593-2024021614231926 v2).

5.2 HLI: Handitechlab INRIA

Humanlabs are collaborative spaces for digital fabrication or repair of objects, open to people with disabilities to enable them to appropriate technology for their own use. In 2021, Christine Azevedo and Roger Pissard-Gibollet (SED INRIA Montbonnot) have launched the Inria's HumanLab intiative. This action was sustained by a decision of INRIA's management under the name of Handitechlab INRIA (HLI) and contributes to meeting the needs expressed by individuals with disabilities within the framework of the Humanlabs network or via clinical partners. Our action is part of a frugal and opensource innovation approach and aims to implement the scientific and technological know-how of Inria's staff to meet specific needs. www.inria.fr/en/hli

About ten team members participated in the 3-day hackathon FABRIKARIUM organized by the HumanLab Saint Pierre (LINK). Several of them have been involved in projects throughout the year.

- a'Grip project: Rime, 6 years old, has cerebral palsy. She uses a walker to move but often forgets to keep her left hand tightly around the handle (hemineglect). We installed a force sensor (FSR) to detect when the grip force falls below a threshold and trigger a vibration to remind Rime to regrip. The walker has been delivered and is being used both at home and at the physiotherapist's office.

- e-moulinet Project: This project aims to motorize a fishing reel to allow the user to reel in the line autonomously. Initial tests have been performed with the developed solution, and the system is being finalized for delivery in February 2025.

- BionicoHand Project: We collaborated with various partners in the development of a myoelectric hand prosthesis for Nicolas. We participated in the 2024 Cybathlon, where Nicolas finished in second place in his discipline. The hand was presented at the Humanoids conference in Nancy in November at INRIA's booth (LINK).

- Tactipix Project: We participated in a workshop to create two open-source Braille embosser machines: BRAILLERAP. With the capabilities of BRAILLERAP, we initiated a project with Florie, a visually impaired adult, to create tactile picture booklets for young children. These booklets will be accompanied by an audio description to guide the reading. (LINK).
- EASYSNAP Project: Maxime is tetraplegic and has an assistance dog. He lacks sufficient strength in his fingers to attach/detach the leash to the collar. We adapted a magnetic carabiner system that allows for easy manipulation. (LINK).
- CapParents Project: We are collaborating with the Parental Support Service for People with Disabilities (SAPPH) in Île-de-France. We are implementing solutions to emboss ultrasound images or tracking documents (such as weight and height curves) for visually impaired parents.
- e-nable Project: We joined the global e-nable movement, which brings together more than 15,000 volunteers with the goal of creating open-source assistive devices for disabilities.

6 Highlights of the year

- 10 team members attended a 2-day training on applying the requirements of ISO 14971 in the context of the development and market launch of Medical Devices, and
- 10 team members attended a 1-day training on applying the requirements of the IEC 62304 standard to the software life cycle.

7 New software, platforms, open data

7.1 New software

7.1.1 i-GRIP

Keywords: Handicap, Computer vision, Persons attendant, Exoskeleton, Detection

Scientific Description: Detection of object grasping intention and automatic selection of grasp type for shared control of (neuro)prostheses.

Functional Description: From a video stream of hands and objects, i-GRIP detects the intention to grasp one of them and identifies the grip the hand should adopt to appropriately seize it based on the approaching movement. i-GRIP will enable intuitive and low cognitive load control of hand movement assistive devices (exoskeletons, functional electrical stimulation, prosthetics).

URL: `https://gitlab.inria.fr/CAMIN/i-GRIP`

Publication: hal-04141469

Contact: Etienne Moullet

7.1.2 EMOK

Name: Easy MOtion Kapture

Keywords: Video analysis, Artificial intelligence, Health

Functional Description: Software that automates the capture of videos with multiple cameras simultaneously, and then allows them to be easily analyzed using Mediapipe and Deeplabcut algorithms.

URL: `https://gitlab.inria.fr/CAMIN/agilis-mocap/emok`

Contact: François Bailly

7.2 New platforms

Within AI-Hand project we have developed 3 experimental platforms.

7.2.1 AI-Hand platforms

Chronic and acute pig experimental platform

Participants: Christine Azevedo, Thomas Guiho, Jonathan Baum.

The AI-Hand project experiments support the development and validation of an implant for peripheral nerve stimulation, capable of restoring - at least partially - everyday wrist and finger functions. As this implies an innovative technology and a new surgical approach, it is necessary to validate and test the whole implanted system in its final version before the first permanent implantation in humans. 2 experimental procedures on large animals (30-50kg pigs) - one focused on acute studies and the other on chronic monitoring of the device - have therefore been planned (the first experimental session of each protocol took place in the second half of 2024):

- Acute studies i) individually test each brick of the implantable device and ii) provide the experimental data needed to develop a strategy for adjusting the stimulation parameters.
- Chronic studies assess the implant's efficacy and reliability over time (between 25 and 35 days).

To carry out these tests, an experimental platform enabling combination of stimulation (Fig. 3) and acquisition (Fig. 4) in the operating room (a very constrained and noisy environment) was developed within the team to enable:

- Refinement of the surgical procedure (placement of electrodes around the peripheral nerve and positioning of the casing of the implant)
- Placement of stimulation electrodes (around the nerve) and recording electrodes (intramuscular electrodes - manufactured in-house)
- Handling of stimulator settings and delivery of complex stimulations
- Synchronize acquisition of biological signals on the stimulator output
- Setting up and adjusting the acquisition system: Amplification, Filters, Sampling, Display and Recording.

AI-HAND first clinical trial (CT1) experimental platform to assess the capacity to modulate stimulation intensity to adjust grasping force

Participants: Christine Azevedo, François Bailly, Baptiste Faraud.

The content of this experimental platform consists in two main aspects : the control modalities (Fig. 5, up) and the Target-Track software in static mode (Fig. 5, bottom). Users included in CT1, with tetraplegia without functional electrical stimulation) can use several control modalities to adjust a virtual grasping force which is displayed through the Target-Track software. The force adjustment is performed thanks to two distinct control inputs, "+" and "-", respectively. The Target-Track software provides a visual feedback to the user (through the display of the current grasping force achieved through the control inputs) and a reference value (static or dynamic) to be tracked by the user. The overall objective is to evaluate the performances of the several control modalities to achieve force adjustments.

The Target-Track software has two modes: a static gauge (Fig. 5 bottom) and a dynamic serious game (Fig. 6).

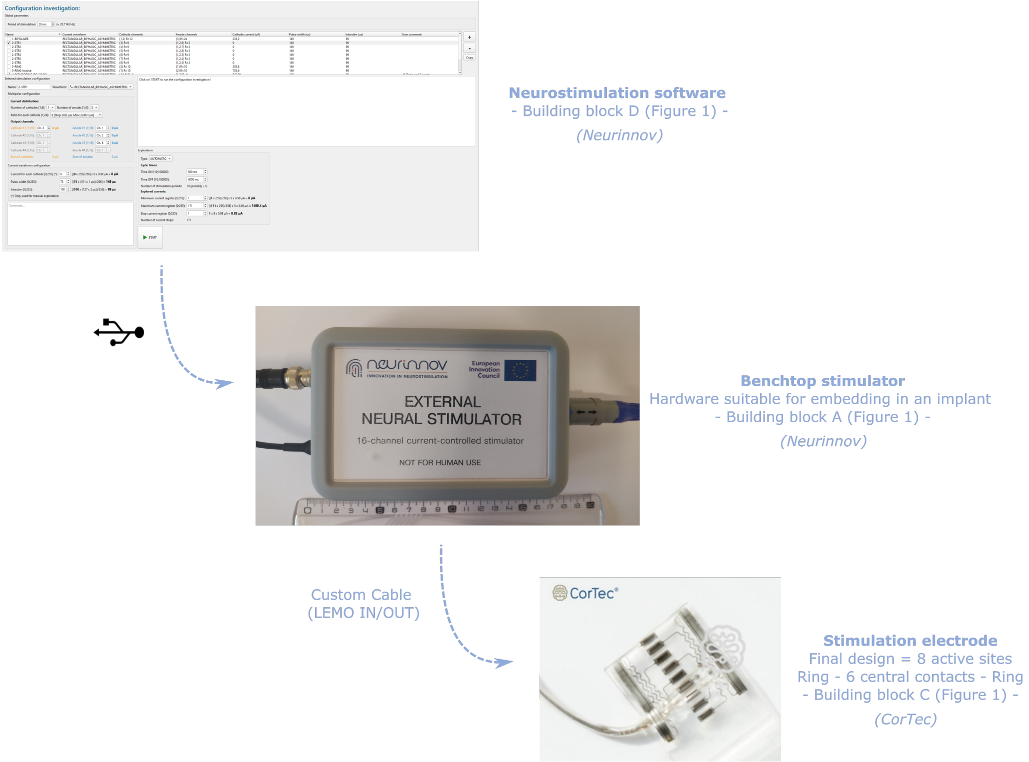


Figure 3: Stimulation setup for AI-Hand in vivo experiments

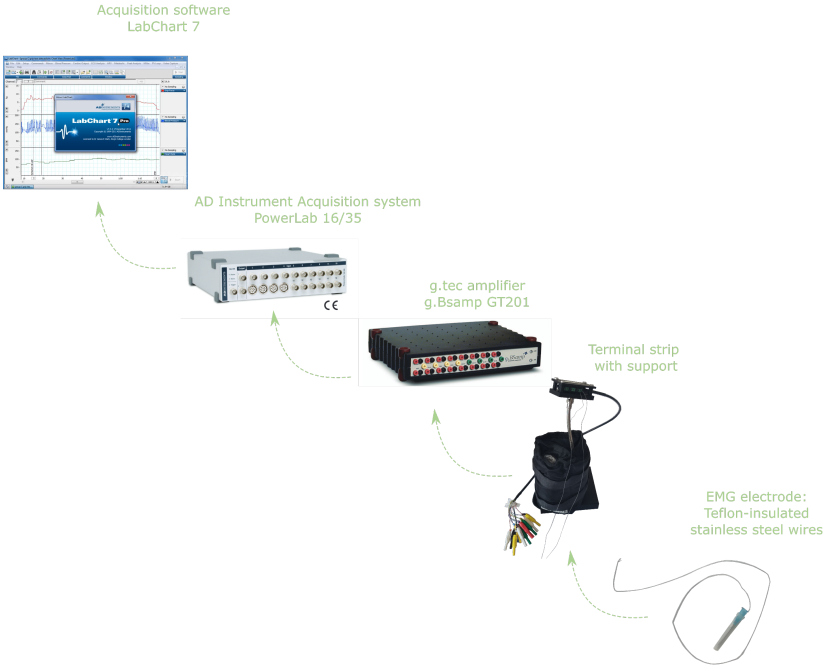
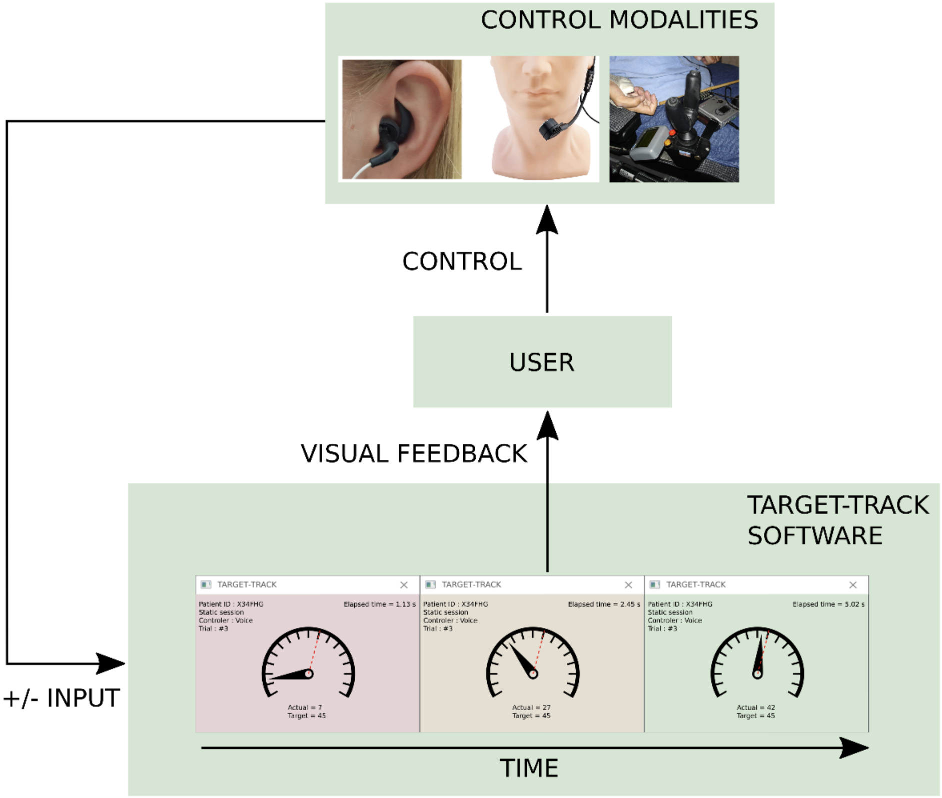


Figure 4: Acquisition setup for AI-Hand in vivo experiments

Force estimation



Patient ID : X34FHG
Static session
Controler : Voice
Trial : #3
Elapsed time = 1.13 s
Actual = 7
Target = 45

Patient ID : X34FHG
Static session
Controler : Voice
Trial : #3
Elapsed time = 2.45 s
Actual = 27
Target = 45

Patient ID : X34FHG
Static session
Controler : Voice
Trial : #3
Elapsed time = 5.02 s
Actual = 42
Target = 45

Figure 5: Experimental setup of CT1

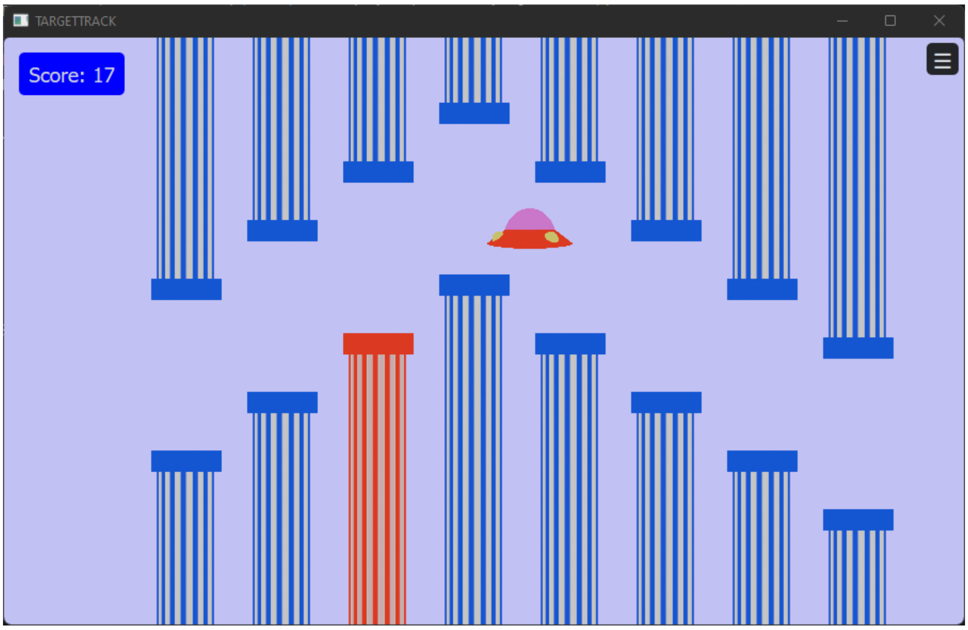


Figure 6: Target-Track software, in dynamic serious game mode

Participants: Christine Azevedo, François Bailly, Jean De Gheldere.

As part of the AI - HAND project, we are developing a technique for the indirect estimation of hand grasping forces. In order to correctly characterize and calibrate the identified technologies, we need to have means of direct measurements of the grasping force, in a variety of configurations and scenarios. We therefore developed a haptic feedback device capable of simulating different types of contact (soft, rigid) between the hand and a virtual object. This device is also capable of measuring the force generated by the hand during virtual contact, enabling us to calibrate the final technology. The system consists of two parts: a 'robot' part and an 'interface' part. The robot is an assembly of two torque-controlled axes, incorporating a capstan drive mechanism, enabling backlash-free transmission between the motor (current-controlled DCM) and the 'interface' subsystem (Fig. 7).

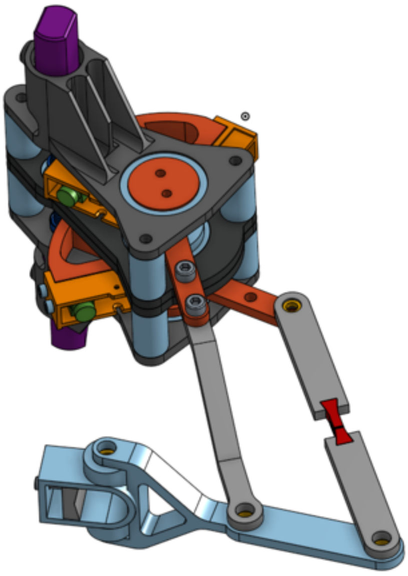


Figure 7: CAD design of the haptic feedback and force measurement device of a finger

The interface is a 4-bar mechanism, one bar of which contains a strain gauge force measurement cell. The system as a whole was partially prototyped in order to validate the technical choices of each sub-system.

7.3 Open data

Participants: Christine Azevedo, François Bailly, Valentin Maggioni.

2024 - "Experimental dataset of ecological hand and finger movements for the comparison of marker-less motion capture systems.", https://doi.org/10.57745/JQYAWK, Recherche Data Gouv, V1

8 New results

We have organized the results around 3 main subsections: 8.1) Brain Potentials Evoked by Direct Electrical Stimulation for on-line guidance of Neurosurgery, 8.2) Movement analysis, detection and modeling and 8.3) Motor functions assistance

8.1 Brain Potentials Evoked by Direct Electrical Stimulation for on-line guidance of Neurosurgery: a combined experimental and simulation approach

8.1.1 Conduction velocity in the Brain through the Evoked Potentials Method

Participants: Clotilde Turpin, Olivier Rossel, Félix Schlosser-Perrin, Mathilde Carrière *(CHU Montpellier)*, Riki Mastumoto *(Kyoto Hospital, Japan)*, Emmanuel Mandonnet *(APHP Paris)*, Hugues Duffau *(CHU Montpellier)*, Sam Ng *(CHU Montpellier)*, François Bonnetblanc.

Estimating conduction velocity within the brain involves analyzing the latencies between two evoked potentials (EP) following direct electrical stimulation during human brain surgery. This study aims to investigate the factors affecting this estimation, with a particular focus on the selection of temporal markers in EP and the estimation of the recording distance from the stimulation site. We examined the impact of different temporal markers and distance measurements for axono and cortico-cortical evoked potentials on conduction velocity estimation. The study was conducted during a rare brain surgery case involving a multifocal tumor, requiring extensive cortical exposure across a whole right human hemisphere. EPs recorded at a distance from the stimulation site showed similar components with a delay, reduced amplitude, and temporal expansion compared to those recorded near the site. Significant variability was observed depending on the temporal marker used for the conduction velocity estimation. The estimation of conduction velocity from EPs is highly variable due to the choice of temporal markers. The most reliable estimate gives a conduction velocity around 15 $m.s^{-1}$. This study underscores the potential sources of error in conduction velocity estimation during neurosurgical procedures, emphasizing the need for precise and consistent methodology in interpreting EPs (Fig. 8).

8.1.2 Simulation of the effects of direct cortical electrical stimulation from biophysical models of axons

Participants: Félix Schlosser-Perrin, Olivier Rossel, Clotilde Turpin, Riki Mastumoto *(Kyoto Hospital, Japan)*, Hugues Duffau *(CHU Montpellier)*, Emmanuel Mandonnet *(APHP Paris)*, François Bonnetblanc.

The objective of this study is to model the effects of Direct Electrical Stimulation (DES) parameters (intensity, monophasic or biphasic pulses, mono or bipolar electrodes) on the extent of recruitment of (simplified) pyramidal axons during cortical stimulation. Our work therefore aims to carry out coarse-grained modeling using biophysical models of axons alone to determine the effects of DES applied directly to the surface of the cortex and study the variation of different parameters in connection with different clinical practices for the study of intraoperative connectivity via measurement of Cortico-cortical Evoked Potential (CCEP). More specifically, in the context of tumor surgery, it is possible to measure CCEP by stimulating the cortex with a bipolar probe of 1 and 2 mm in diameter with an inter-electrode spacing of 5 mm for the Montpellier block electrodes and Paris respectively. The pulse lengths used are 1 ms and 0.5 ms for these different operating rooms, with a stimulation intensity ranging from 2 to 5 mA. In the case of epileptic patients chronically implanted with subdural ECoG grids, as is practiced by Professor Matsumoto's team, the DES is carried out bipolarly between two ECoG contacts (contact surface) of diameter 3 mm and inter-electrode distance 1 cm, with alternating cathodic and anodic pulses, a frequency of 1 Hz, a pulse length of 1 ms, and stimulation intensities ranging from 8 to 12 mA. The waveforms produced in the first 100 ms after the onset of the evoked potential remain generally identical (Matsumoto, Kunieda, and Nair 2017) but the observation of CCEPs remains significantly more reproducible in the case of epileptic patients. We therefore wish to better understand and interpret the differences in the effects of DES between types of clinical practices. We therefore hypothesize that the SED parameters used for epilepsy will activate a larger section of projection axons (Fig. 9).

8.1.3 Modeling and Optimizing Electrical Stimulation for Artifact Reduction

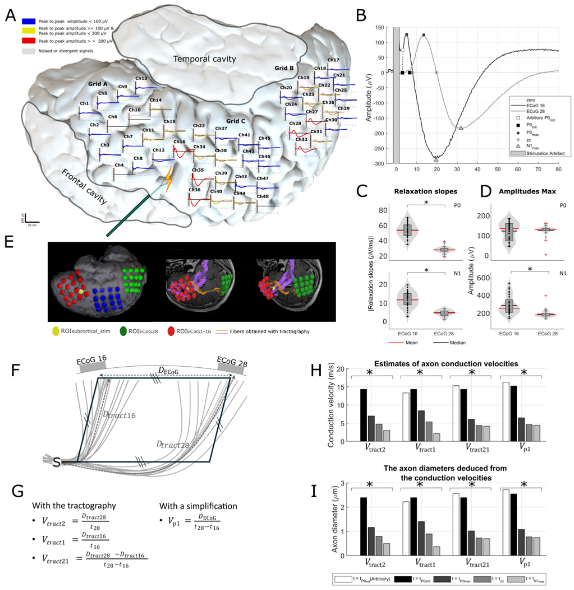


Figure 8: A) ECoG recordings for the 3 (4x4) grids and DES positioning in the 3D pre-operative brain, showing also the two resection sites. B) Averaged traces of a close and a distant ACEP (ECoG 16 an EcoG 28 respectively) with the different points (Arbitrary P0init, P0init, P0max, zc, N1max) where the temporal markers were measured (C) Boxplot and violin plot (in gray) of the regression slopes of P0 and N1 for ECoG 16 and ECoG 28, which follow a normal distribution D) Boxplot and violin plot (in gray) of the maximum amplitude of N1 and P0 for ECoG 16 and ECoG 28, which follow a non-normal distribution. E) Whole tractogram « cut » (removal of frontal branches seeded by the subcortical stimulation): remaining fibers reflect connections between subcortical stimulation site and channel 28 of the Grid B. Whole tractogram cut (removal of frontal branches seeded by the subcortical stimulation): remaining fibers reflect connections between subcortical stimulation site and channel 16 of the Grid A. F) and G) Various modes of calculation and estimation for the distances and geometrical scheme. H) and I) Barplots of estimated conduction velocities (upper) and estimated axons diameter (lower) for each method of distance calculation and each temporal marker.

Participants: Olivier Rossel, Emmanuel Mandonnet *(APHP Paris)*, Hugues Duffau *(CHU Montpellier)*, François Bonnetblanc.

The Correction of Long-lasting Evoked-potentials Artifacts for Neurodata (CLEAN) project aimed to develop models for understanding and mitigating long-lasting artifacts induced by electrical stimulation in electrophysiological recordings. Initial efforts focused on stimulus artifact modeling to improve signal interpretation and artifact suppression strategies.

An alternative approach was explored: triphasic stimulation, designed to minimize long-lasting artifacts. This method involves generating balanced stimulation waveforms to reduce artifact persistence while preserving the integrity of the electrophysiological data. A preliminary study proposed a simple and effective method for theoretical total artifact cancellation, relying on an appropriate balance between the first and third pulse amplitudes, defined in accordance with the system's time constant (Fig. 10).

8.2 Movement analysis, detection and modeling

Our team develops tools and methods to understand and model movement in order to improve function assistance.

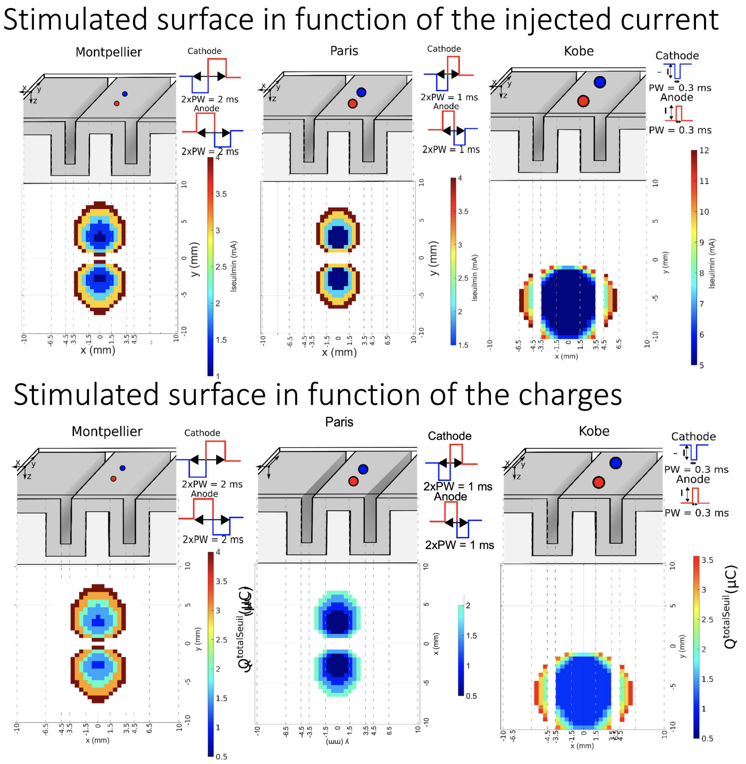


Figure 9: Surface of pyramidal axons directly activated by cortical electrical stimulation in 3 DES configurations used clinically in different centers in function of the injected current (upper panel) and quantity of charges (lower panel). The model does not currently allow absolute quantification of the section of pyramidal axons (i.e. white matter fascicle) activated by DES due to anatomical inaccuracies (the pyramidal axons will not all have a vertical orientation in the activated area; only one axon diameter is used so it is assumed here that the spatial distribution as a function of axon diameter is homogeneous). However, this type of model allows a relative comparison between the different centers and to correlate these simulation results with certain components of the EP, associated with the direct activation of these pyramidal axons and recorded in the vicinity of the DES to test and improve the reliability of the model and better interpret the differences between EP measured in these clinical centers.

8.2.1 Cycling

CAMIN developed expertise in FES-assisted cycling since 2015 and the participation in the first Cybathlon event in FES-bike discipline . Using electrodes at skin surface overling leg muscles it is possible to coordinate the activation of the different muscles contractions to induce a pedalling movement.

OPTICYCLE project: optimize bikes to improve cycling performances

Participants: Sabrina Otmani, Andrew Murray *(Dayton University, USA)*, Christine Azevedo, François Bailly.

In the opticycle project, we work on the improvement of FES assisted pedalling performance for people with spinal cord injury (SCI). Our approach is to maximize the power throughput at the crank at constant speed, by optimizing the bike design. The bike was optimized taking into account user's biomechanical data such as the height, weight, age, gender, limb lengths but also considering admissible hip and knee torque values obtained from the literature as an input of the optimization problem. This methodology was first studied on non-pathological subjects M1 and F1, a male and a female subject,

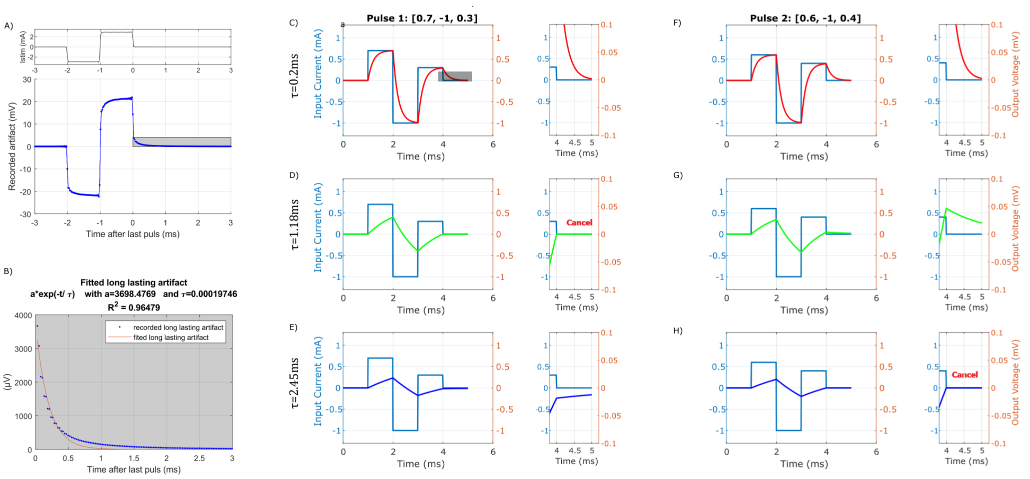


Figure 10: A) Simultaneous recording of the stimulation current 'Istim' (top left), stimulation artifact (bottom left). B) Zoom on the Long Lasting Artefact (LLA) component (bottom right); it can be noted that the decay of the LLA can partialy be expressed by a decaying exponential. The figure C) to H) displays the input currents and the corresponding theoretical output voltages for two distinct triphasic pulses simulated through an RC circuit. This circuit represents the component of the model responsible for the LLA. Two pulse shapes are exposed : Pulse 1: $[+0.7, -1.0, +0.3]$ mA in fig C, D and E and Pulse 2: $[+0.6, -1.0, +0.4]$ mA in fig F, G and H. Each pulse phase lasts 1 ms. The system response is analyzed for three time constants ($\tau = 0.2ms$, $1.18ms$, and $2,45ms$ fig C-F, D-G and E-H respectively). The left y-axis shows the input current waveform in mA. The right y-axis shows the output voltage response in mV. The x-axis represents time in ms. On the zoom part of figures D and H, the LLA is totally canceled, it appear for $\tau = 1.18$ for Pulse 1 and $\tau = 2.45$ for Pulse 2.

with very different anthropometries. Three bike architectures were studied from the simplest to the more complex one: the Traditional Recumbent Mechanism (TRM, corresponding to a classical bike design), the Crank-Rocker Mechanism (CRM) and the Coupler-Driver Mechanism (CDM) [30] (Fig. 11). Several constraints were considered regarding each architecture such as the Grashof criteria which ensures the kinematic feasibility of the pedaling cycle, but also the ranges of motion of the knee and hip to avoid non feasible kinematics. For both studied subjects, simulation results show the possibility of obtaining higher power throughput at the crank with the CRM and CDM compared to the same users riding a classical bike (TRM) [31]. These results suggest that accounting for biomechanical data in the bicycle design process could have a significant impact on the pedaling performance of individuals, from everyday users to athletes to those with motor impairments.

Additionally, as a direct product of this project, a novel crank-pedal mechanism was developed in simulation for the TRM architecture (Fig. 12). The power throughput at the crank obtained with this optimized crank-pedal mechanism was compared to the one obtained with a classical pedal. Alterations of the feet trajectories were observed with the novel crank pedal mechanism compared to the classical one (Fig. 13) leading to a 10% improvement of the power throughput. A patent was filled for this new mechanism (Registration number FR2409775). Future works will validate these simulation results experimentally.

Finally, we encountered the need to enhance the data used as an input to the bike architecture optimization (hip and knee torques). In the literature, hip torques were recorded with the knee fully extended which is typically irrelevant when studying cycling motions. Experimental acquisitions were thus performed on 14 subjects (7 males and 7 females) using an isokinetic dynamometer (the Biodex System 3). These acquisitions included passive movements, isometric and isokinetic contractions (both concentric and eccentric). Our acquisitions aim to demonstrate the impact of one joint configuration (hip or knee) on the performance of the other joint (knee or hip) while enhancing the data used in our simulations. To achieve this, each sub-acquisition performed on one joint was repeated three times,

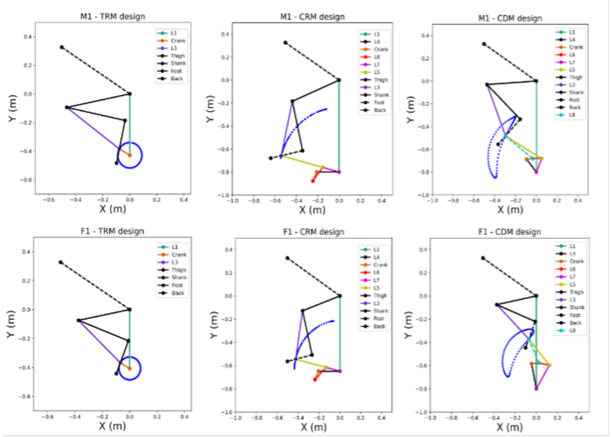


Figure 11: TRM, CDM and figures CRM bike designs optimized for M1 and F1

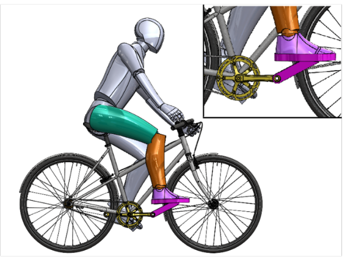


Figure 12: Novel crank-pedal mechanism applied on a classical bike

accounting for three different configurations of the other joint (Fig. 14).

Participation in Cybathlon 2024

Participants: Tiago Coelho Magalhaes, François Bailly, Christine Azevedo, Henrique Resende *(UFMG Brazil)*, Matheus Marcondes *(UFMG Brazil)*, Karina Boson *(UFMG Brazil)*.

In the context of our GOIABA associate team with Brazil, we continue training participants with spinal cord lesion. Our Brazilian partner prepared one pilot to participate in Cybathlon event in November in Zurich. The FES race was a stationary race in a virtual scenario in which several FES pilots compete against each other at the same time. The pilot who reaches the finish line first (1200m), or travels the furthest within 8 minutes, wins the race. The pilot and brazilian colleagues spent 2 weeks in CAMIN before the competition to finalize the technical adjustments of the tricycle. We participated in the event (Freewheels 2 team) and the pilot was able to pedal for 8 minutes (Fig. 15) (cybathlon webpage).

8.2.2 Numerical Optimal Control Compliant Physiology-Based Muscle Model for Electrically Stimulated Induced Contractions

Participants: Tiago Coelho Magalhaes, François Bailly, Christine Azevedo.

In this work, an existing physiological muscle model that predicts muscular force in response to electrical stimulation is adapted to be compatible with gradient-based optimization, in particular with numerical

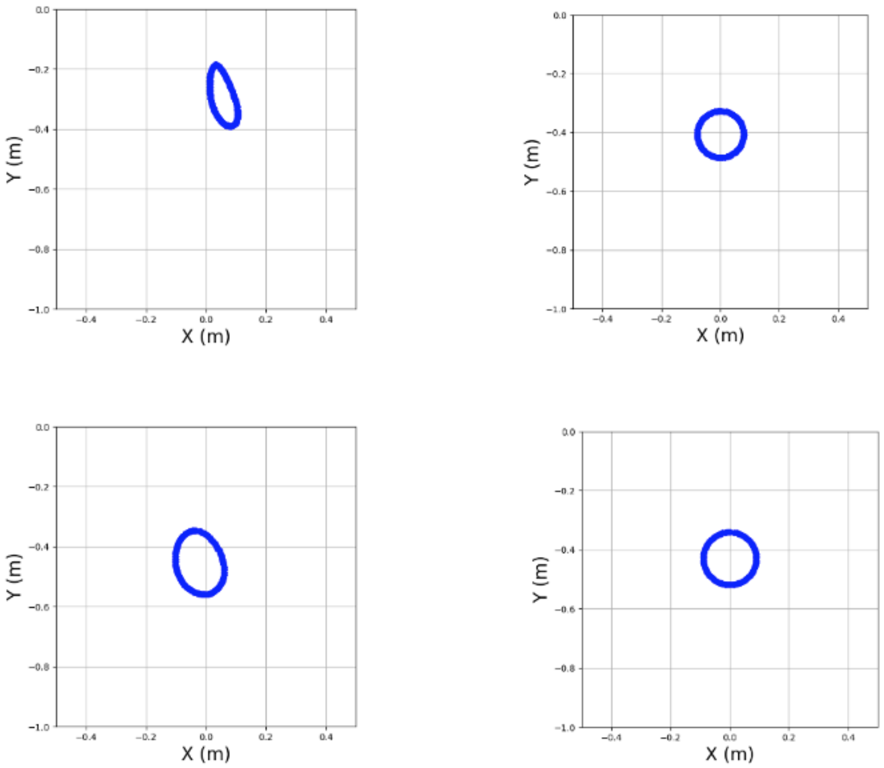


Figure 13: Foot trajectory for F1 (top) and M1 (bottom) with the novel crank pedal mechanism (left) and without (right)

optimal control/estimation problems. The physiological-based muscle model proposed in [26] consists of two coupled differential equations. They relate the dynamics of the rate-limiting step that leads to the formation of the Ca^{2+}-troponin complex (c_N; unitless) to the force development as a response to n consecutive electrical pulses delivered before time t. The objective is to integrate biomechanical models with those that correlate muscle force generation with electrical pulse patterns from a physiological perspective, with the aim of achieving optimal patterns in electrical stimulation-driven activities. To achieve this, the activation dynamics of the original model, initially constrained to a stimulation train of predefined and constant length, is reformulated to account for stimulation sequences that dynamically change over time. This is typically necessary to simulate complex motions, which would otherwise be impossible to achieve with the earliest formulation.

In this work, we reformulated the dynamics to account for the effect of a limited number of pulses p moving in time. We define $n(t) = \lfloor t/T \rfloor$ to represent the largest integer n, such that $n \le t/T$, where T represents a constant pulse period. Therefore, the activation dynamics is approximated by:

$$\frac{dc_N}{dt} = \frac{1}{\tau_c} \sum_{i=n_0}^{n(t)} \alpha_i R_i \exp\left(-\frac{t-t_i}{\tau_c}\right) - \frac{c_N(t)}{\tau_c}, \tag{1}$$

where $n_0 = max(1,\ n(t) - p)$ is within the truncated or window-sized train of pulses containing the history of the last $p \in \mathbb{N}^*$ pulses. The result of this approximated calcium dynamics is depicted in Fig.16 for several values of p.

To identify the model parameters, experimental torque data of 3 participants with spinal cord injury performing electrically evoked isometric quadriceps contractions at different knee angles are used. We then employ an optimal control framework to demonstrate the model's ability to predict knee torques and the possibility of achieving optimized stimulation patterns in simulation for controlling muscle force and reaching motions with the lower limb (Fig. 17).

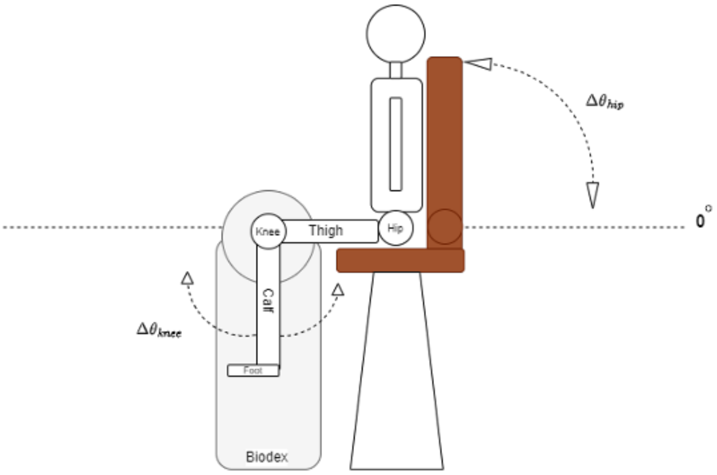


Figure 14: Experimental setup for knee data acquisitions. Study of the knee joint with variation of the hip configuration

Our results reveal that the identified model allows accurate prediction of knee torque and optimization of stimulation patterns while satisfying the system's dynamics at the skeletal and physiological muscle levels. This proof of concept is a first step towards physiological muscle model-based control of functional electrical stimulation to achieve movements that best exploit an individual's physiological and biomechanical characteristics. In this sense, our approach involves integrating biomechanics and optimal control techniques to optimize the stimulation patterns during the activity. The primary goal is to develop new control laws that adapt electrical stimulation parameters based on the subject's muscular state. We aim to address challenges associated with the reversed order of muscle fiber recruitment caused by electrically evoked contractions coupled to muscle atrophy and increased fatigue that hinders prolonged pedaling.

8.2.3 RESCUEGRAPH project: Functional stimulation system for rehabilitation of gait and driving neural plasticity after spinal cord injury using graphene based nerve electrodes in rodent

Participants: Christine Azevedo, François Bailly, Xavier Navarro *(UAB Barcelona, Spain)*.

This work was done in the context of FLAG ERA RESCUEGRAPH project.

The objective of CAMIN contribution was to develop a gait pattern controller that could drive complex patterns of electrical stimuli to the nerve fascicles innervating muscles implicated in locomotion by means of graphene electrodes. StimRG Rat Gait software was used in animal experiments to mimic normal gait by triggering the stimulator (Fig. 18). We have also set up the existing Motion Capture equipment available at UAB: an optoelectronic motion capture system made up of 6 infrared cameras and developed and shared Python scripts for our biologist colleagues to automatically extract joint angles from the motion capture files. The UAB team carried out two kinematic recordings on 26 rats before and 60 days after spinal cord injury.

8.2.4 SOFTMOCAP: Optimization and comparison of markerless and marker-based motion capture methods for hand and finger movement analysis

Participants: Valentin Maggioni, Christine Azevedo, François Bailly.

Figure 15: FREEWHEELS 2 pilot at Cybathlon competition on November 2024. ETH Zurich / Cybathlon / Nicola Pitaro

Ensuring an accurate tracking of hand and fingers movements is an ongoing challenge for upper limb rehabilitation assessment. The high number of degrees of freedom and segments in the limited volume of the hand makes this a difficult task, even for marker-based motion capture solutions, known for their precision but also for their frequent inadequacy with clinical use.

In this context, this work aims to find and develop an effective tool for accurate tracking of hand movements, for monitoring and improving patient progress in our current AI-HAND project, which aims to restore hand function in tetraplegics through selective electrical neural stimulation. More specifically, the objective of this study is to evaluate the performance of two markerless approaches (the Leap Motion Controller and the Google MediaPipe API) in comparison to a marker-based one. This work additionally aims to improve the precision of the markerless methods by introducing additional data processing algorithms by fusing multiple recording devices.

For the Leap Motion and MediaPipe solutions, three controllers and four webcams were respectively combined with dedicated algorithms to improve their accuracy. Fifteen healthy participants were instructed to perform five distinct hand movements while being recorded by the three motion capture methods simultaneously. The captured movement data from each device was analyzed using a skeletal model of the hand through the inverse kinematics method of the OpenSim software. Finally, the root mean square errors of the angles formed by each finger segment was calculated for the markerless and marker-based motion capture methods to compare their accuracy. A summary of the steps taken during this investigation from the experimental measurements to the comparison of the results is shown in Fig 19.

Our results indicate that the MediaPipe-based setup is both more accurate and versatile than the Leap Motion Controller-based one (average root mean square error of 10.9° versus 14.7°) (Fig. 20), showing promising results for the use of markerless-based methods in clinical applications. The developed motion capture method using MediaPipe was finally embedded within an easy-to-use software (EMOK), to allow for its future use within the AI-HAND project and any other project requiring the use of hand motion capture within the CAMIN team. We published the experimental data on recherche.data.gouv to make them available to the community.

To complete this study we now aim to use the developed method on the hand kinematic data measured during the AGILIS and AGILIStim projects to test its efficacy within a clinical setting with all of its associated constraints.

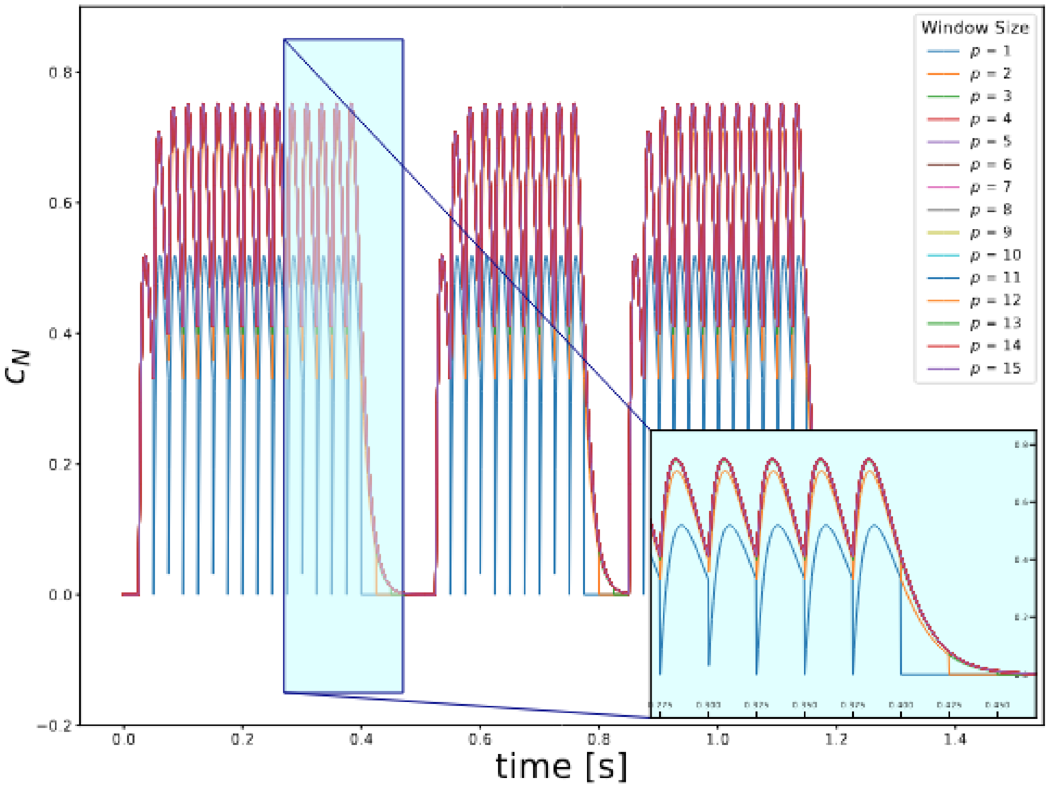


Figure 16: Effects of the different window sizes (p = 1 to 15) on the approximated response of the calcium dynamics for a 40Hz stimulation frequency

8.2.5 noCNN : No-brain-shift and Comprehensive Neurosurgical Navigation using computer vision

Participants: Paul André, François Bonnetblanc, François Bailly.

In this work, we focus on correcting brain shift during brain surgery, a phenomenon that can significantly impact the accuracy of image-guided neurosurgery. We focus only on camera-based methods rather than laser or ultrasound-based ones.

Our goal is to achieve a non-rigid registration between the pre-operative MRI and the operating scene captured using one or more cameras. In order to do this, we identified two differents approaches.

The first approach is to perform this registration by using a fixed marker present in the two images in order to perform an initial rigid registration aligning the two markers. Then, by taking two point clouds representing the two surfaces of the brain, we can run a non-rigid registration to quantify the brain-shift. The intra-operative brain surface can be reconstructed using stereo vision techniques or machine learning.

The second approach is based on the segmentation of specific anatomical landmarks, such as vessels or gyri, which would make it possible to obtain direct correspondences between the two surfaces, which is useful for alignment[27]. Such segmentation can be done using a Unet [32], a CNN model designed for image segmentation. This model is suitable for medical applications because it requires little training data to give good results. We have very preliminary segmentation results (the thesis began in October) on brain images to isolate the vessel network (Fig. 21).

The first approach is easier to implement. However, the second approach offers less constraints for the surgeon, as it eliminates the need for markers to be placed in the scene.

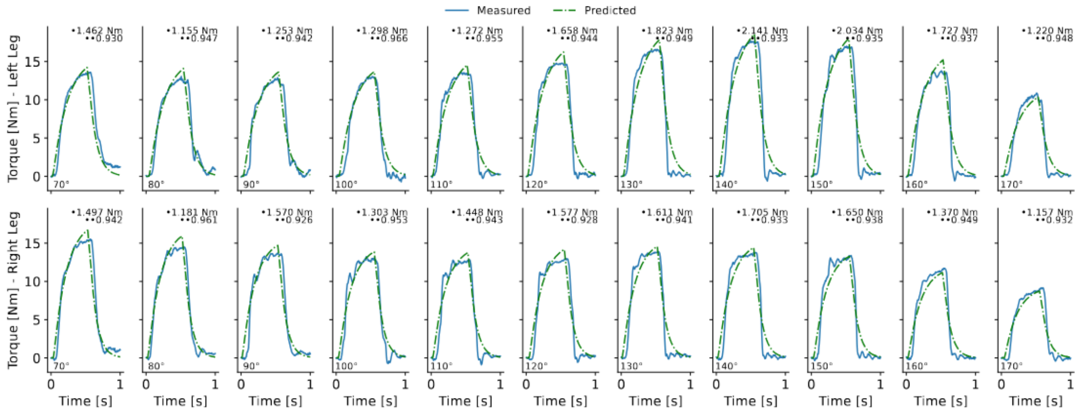


Figure 17: Measured and predicted torques for both legs of subject 1. Root mean square error RMSE (•) and R^2 (••) are shown for each knee angle.

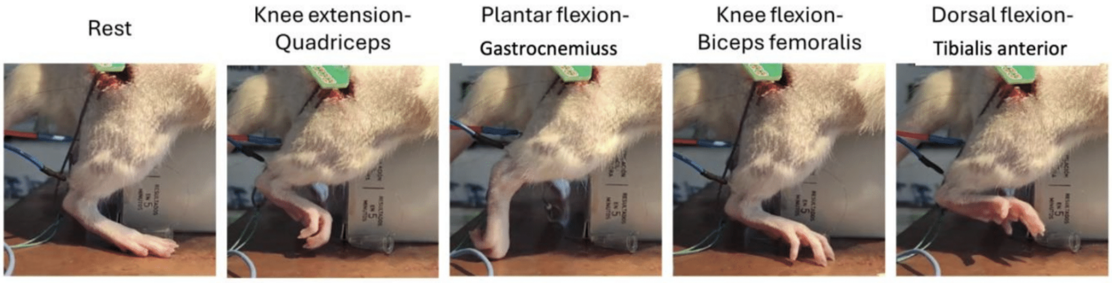


Figure 18: sequence of images starting from a resting position demonstrates how the selective activation of muscles induces flexion and extension movements of the ankle and knee

8.3 Motor functions assistance

8.3.1 AI-Hand project: Restoring upperlimb functions in individuals with tetraplegia

The AI-Hand European project (EIC pathfinder), focuses on the development of an implant for neural stimulation - supported by Neurinnov company - to restore wrist and hand function in individuals with tetraplegia. In this framework, the project is divided into two successive phases, a phase dedicated to the development/refinement of the approach that will immediately be followed by a clinical phase by 2026 (first implantation in people with tetraplegia). The CAMIN team, tasked with coordinating the project, focuses on several key aspects. The advancements for 2024 are:

- the design of a protocol and its acceptance by animal ethics committee and health agency to exlore different piloting interfaces modalities with participants with SCI;
- the design of a protocol and its acceptance by animal ethics committee to carry out experiments on pigs: acute experiments on 4 animals to investigate the electrophysiological evoked responses to advanced neural electrical stimulation using the new technology developed by NEURINNOV and chronic experiments on 2 animals (1 month follow up) to assess the stability and performances of NEURINNOV implant;
- the design and development of solutions to assess hand movements kinematics and grasping forces (see Softmocap project);
- the exploration of new piloting modalities to simplify the user interaction with the stimulator (see i-Grip project).

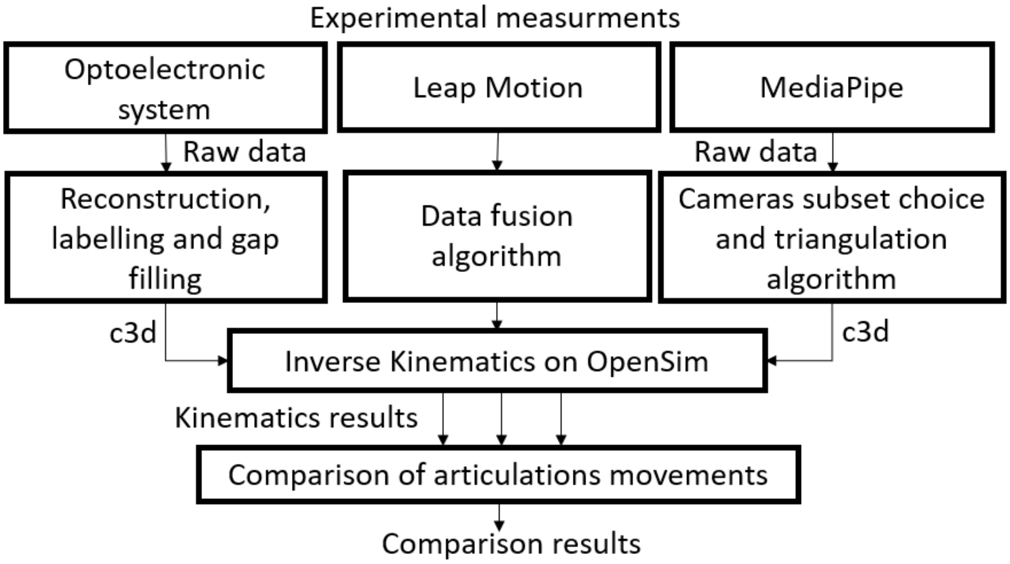


Figure 19: Summary of the steps of the study from the experimental measurements to the comparison of the results.

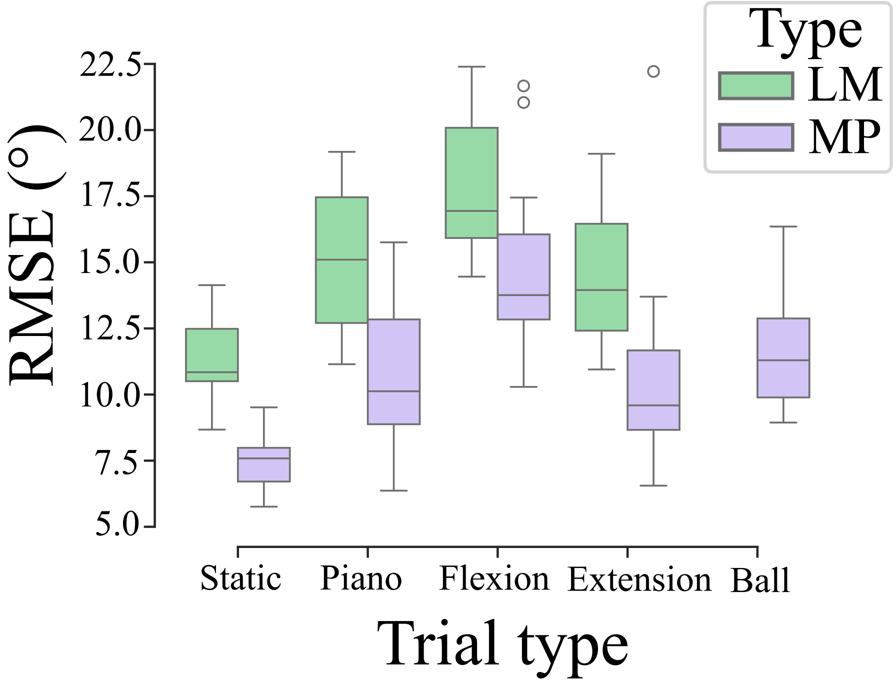


Figure 20: Boxplot of the root mean square error (RMSE) of the hand joints for the MediaPipe-based method (MP) in purple and the Leap Motion method (LM) in green, depending on the type of trial. The values in each box are the mean of the RMSE computed over each joint of the hand for a specific participant and a specific trial type. As such, each box contains 15 values (one per participant).

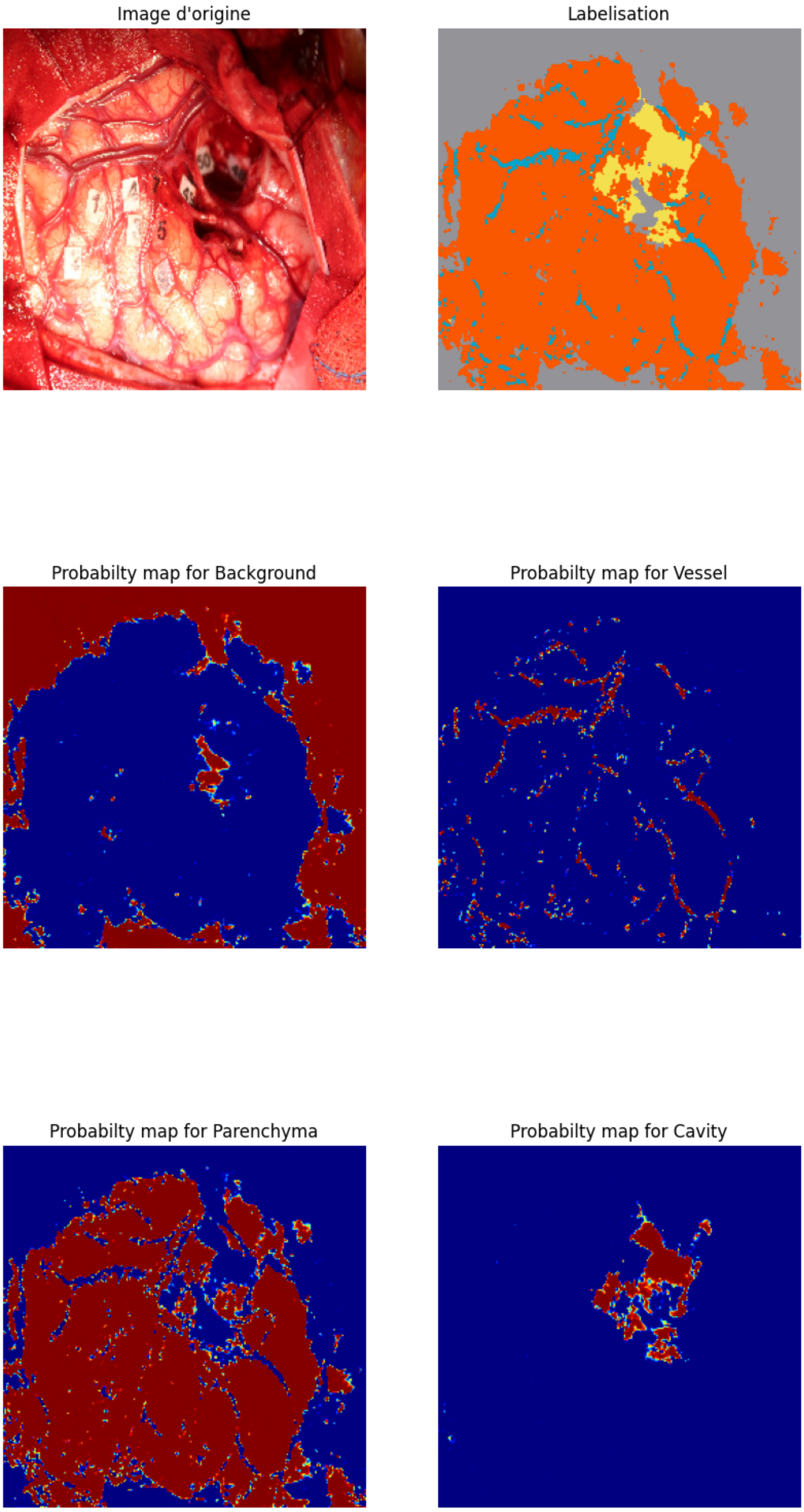


Figure 21: Preliminary segmentation results on a craniotomy picture to isolate the vessel network

In-vivo acute experiments - PLASTICISTIM project

Participants: Jonathan Baum, Thomas Guiho, Christine Azevedo, Riccardo Carpineto, Gabriel Graffagnino, David Guiraud *(NEURINNOV)*, Manon Chamot-Nonin *(NEURINNOV)*.

The PLASTICISTIM project is a complementary initiative to the AI-Hand project. It aims to study the benefits of combining peripheral nerve stimulation (PNS) - as investigated in AI-Hand - with spinal cord stimulation (SCS) for restoring motor function in spinal cord injured individuals. The aim of this combination is to potentiate the direct restoration of motor function enabled by PNS with a progressive refinement of movements due to SCS. Indeed, recent studies attest to the impact of SCS in facilitating the passage of degraded voluntary commands and also in the progressive restoration of motor functions (following long-term clinical trials combining SCS and physical rehabilitation exercise). The literature does not reference any study exploring this combination and the aim of the PLASTICISTIM project, which should be seen as a proof of concept, is to fill this gap in order to pave the way for a new therapeutic approach enabling the restoration of numerous functions in people with spinal cord injuries.
PLASTICISTIM started in December 2023. Following a literature review, the chosen approach investigated the effects of SCS through transcutaneous stimulation on pigs, which provide a convenient model close enough to the human nervous system to allow transferability. PNS was ensured by Neurinnov's bench top stimulator and CorTec's epineural cuff electrodes, while t-SCS was provided by Pajunk's Stim2go stimulator. Taking advantage of preclinical trials of AI-Hand project (from 19/06 to 03/07), three pigs were investigated with PNS paired with transcutaneous SCS (t-SCS) during acute experiments after ethical committee agreement. Effects of PNS itself and paired with t-SCS were assessed through muscle activation monitored with implanted custom EMG needles. EMG signals were recorded with a Gtec acquisition device and a PowerLab amplifier linked to Labchart signal recording software. Pigs were anesthetized before the first phase of PNS followed by paired stimulation, eventually controlled by a last phase of PNS alone. EMGs data concerning t-SCS investigations will be processed during the following year (Fig. 22).

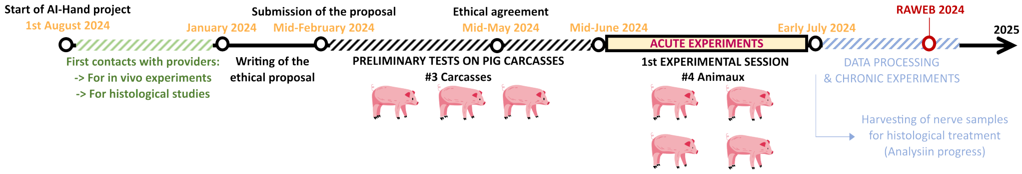


Figure 22: PLASTICISTIM's first phases timeline

On the other hand, some literature review has been done to identify histological targets linked to PLASTICISTIM's topic. Nerve tissue harvesting and staining protocols have been refined in cooperation with laboratories from Montpellier and specialized in histological studies (IRCM and IGMM histological facilities). Every stimulated nerve and some control nerves were harvested after animal euthanasia before fixation and staining by IRCM and IGMM. Samples are currently processed by IRCM and IGMM. When received, their results will be processed according to EMG signals to explore links between selective PNS, nerve architecture and muscle recruitment (Fig. 23).

In-vivo chronic experiments

Participants: Thomas Guiho, Christine Azevedo, Jonathan Baum, David Guiraud *(NEURINNOV)*, Manon Chamot-Nonin *(NEURINNOV)*, Matthieu Bechet *(NEURINNOV)*, Jacques Teissier *(Clinique Saint-Jean)*, Frank Hertel *(CHU Luxembourg)*, Benjamin Degeorge *(Clinique Saint-Jean)*.

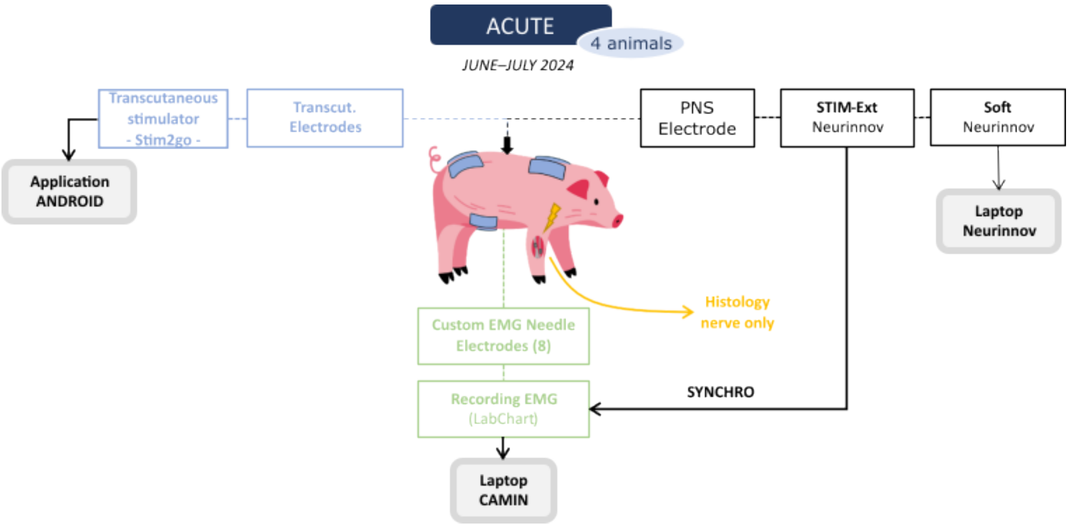


Figure 23: Experiment setup overview and stimulation/acquisition chains

In September 2024, two animals were implanted with the first fully implantable peripheral nerve stimulation device developed by Neurinnov. In each animal, 2 multi-channel electrodes were positioned around the nerves of the animals' arms and connected to a subcutaneous casing to evaluate both the efficacy and the reliability of the stimulation delivered by the implant over a 30-day period. Once a week, the animals were sedated to stimulate the peripheral nerves and evaluate the selectivity of the stimulation as well as the quality of the evoked physiological responses (electromyograms and motion capture). At the end of this one-month period, the devices were explanted, and various layers of biological tissue were biopsied for anatomopathological analysis to assess the integrity of tissues that had been in prolonged contact with the various implant components (skin, connective tissue - fibrosis, nerve) (see Fig. 24).

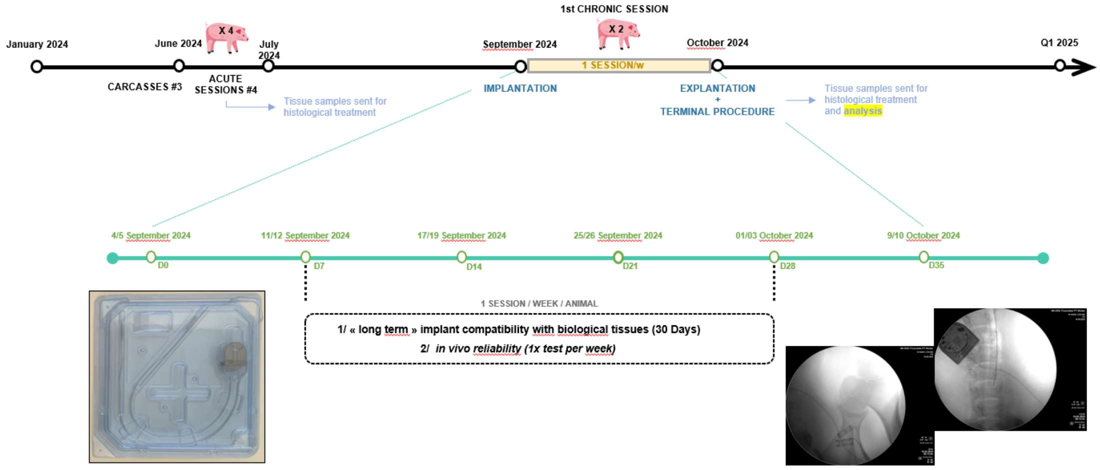


Figure 24: Overview of chronic experiments

i-GRIP: Towards intuitive upper-limb assistive devices, a vision-based interface for grasping intention detection and grip selection

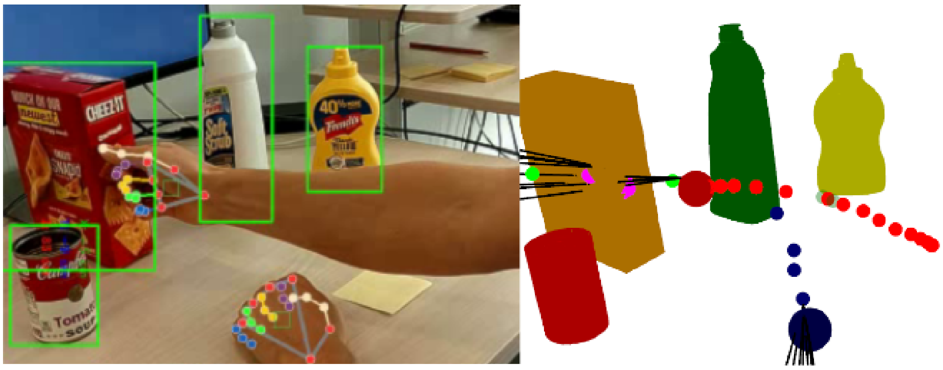

(a) (b)

Figure 25: Experimental setup and pre-processing: (a) - Example of a video frame captured during a trial overlaid with green rectangles marking the detected objects and multicolored landmarks marking hands keypoints. (b) - Corresponding 3D virtual scene: Orange, yellow, red, and green objects are the rendered meshes of the detected objects. Big blue and red spheres represent the 3D positions of, respectively, left and right hands. The middle-sized red and green spheres represent, respectively, the past and expected future trajectory of the right hand. The black lines are a cone of rays expanding from the expected future trajectory of the right hand, and whose impacts are the small magenta dots on the mesh.

Participants: Etienne Moullet, Christine Azevedo, François Bailly, Justin Carpentier *(INRIA WILLOW)*.

Various conditions - such as spinal cord injuries, stroke, or amputation - may hinder the grasping function, significantly impacting an individual's quality of life and autonomy. Various approaches and assistive devices aim to restore this function (functional electrical stimulation (FES), exoskeletons, prostheses) but often exert considerable cognitive loads on users and lack controllability and intuitiveness in daily life [25, 28]. In [20], we introduce i-GRIP, a novel movement intention estimator designed to facilitate the control of assistive devices for grasping tasks in individuals with upper limb impairments. Operating within a collaborative grasping control paradigm, the users naturally move their hand towards an object they wish to grasp and i-GRIP identifies the target of the movement and subsequently selects an appropriate grip for the assistive device to perform. In [21], we describe and evaluate i-GRIP in an experimental study involving 11 healthy participants. i-GRIP exhibited promising estimation performances and responsiveness, paving the way towards more intuitive control of grasping assistive device for individuals with upper limb impairments.

Integration in assitive solutions

From continuous observations of a *scene* (a human upper body and surrounding objects) i-GRIP gathers information about the initiation of a grasping movement by the user and transmits it to a dedicated, downstream process in charge of controlling an assistive device which terminates it autonomously. It is structured in a sequential manner, first identifying the target of the movement and then selecting an appropriate grip to grasp it. The data transmitted to the downstream process was chosen to embed not only the found grip, but also the identified target, for information such as its shape and size may be crucial to optimally prepare the configuration of the device during the approach movement.

Algorithm overview

I-GRIP is designed to work downstream of any scene observation process able to provide hands 3D position and objects 6D poses. In the experiment reported below, stereoscopic cameras (OAK-D S2, Luxonis) recorded RGB frames and depth maps, allowing to estimate Hands 3D positions using mediapipe [33] and to estimate objects 6D poses using CosyPose [29].

Detected hands and objects are represented in a virtual 3D duplicate scene (see Fig. 25). At each time step and new measurement, the algorithm performs a kinematic analysis of the hands' motions to predict their near-future trajectories. Then, for each hand-object pair, confidence scores are computed based on

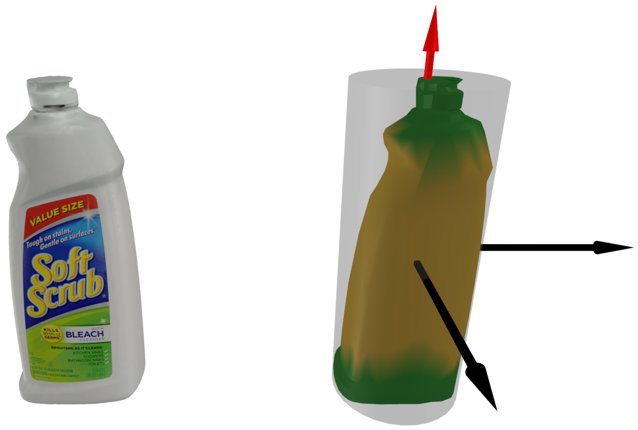


Figure 26: Bleach bottle (left) and a visualization of the corresponding grip selection process (right). Transparent gray volume is the bounding cylinder of the mesh. Red arrow figures the z-axis of the object's frame. The yellow zone illustrates the z-values corresponding to a palmar grip, while the green zone and outwards correspond to a pinch grip.

four metrics that describe the motion of a hand relatively to an object :

- **ray impacts:** the number of impacts onto the object's mesh from cones of rays, cast from near-future trajectory points in the direction of the local velocity vector,
- **distance derivative:** the time derivative of the distance between the hand's position and the position of the center of the object's mesh,
- **distance:** the distance between the hand's position and the object's mesh,
- **future distance:** the distance between the barycenter of near-future trajectory points and the object's mesh.

These 4 confidence scores are velocity-dependent weighted summed into a global confidence score, and the target of the hand's movement is identified as the observed object with the highest confidence score. Finally, the appropriate grip is determined by the hand's position relative to the identified target and its shape (see Fig. 26).

Experiment and results

An experimental study approved by INRIA ethical committee (COERLE Decision 2024-01) involving eleven healthy participants was conducted to evaluate i-GRIP's performance, allowing 1553 movements to be analyzed. I-GRIP successfully identified the target in 89.9% of the recorded movements and selected the correct grip in 94.8% of them. Targets were identified within a mean delay of 0.52s and grips within a mean delay of 0.39s, leaving mean temporal margins before the end of the movement of, respectively, 0.67s and 0.80s.

Links

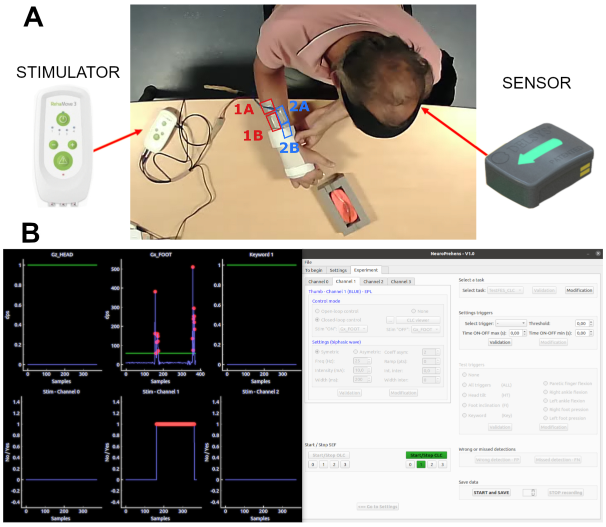
- BIL : https://bil.inria.fr/fr/software/view/4891/tab
- HAL Humanoids : https://inria.hal.science/hal-04706577v1
- HAL ICNR : https://inria.hal.science/hal-04706628v1

8.3.2 Post Stroke upper limb neuroprosthesis : Clinical evaluation (Project Prehens-Stroke 2)

Participants: Ronan Le Guillou *(SED, CAMIN, Inria)*, Christine Azevedo, David Gasq *(CHU Toulouse)*.

The improvement of grasping abilities remains a challenge in 50% of post-stroke subjects who have not recovered a functional grasp on their paretic side due to paralysis of the finger's extensor muscles. Following the Prehens-Stroke 1 (ePrehension-Stroke) study in 2019-2020 and its informative results, a new study was started in 2021-2024. The PHRCi Prehens-Stroke 2 project (ClinicalTrials.gov Identifier: NCT04804384) aims to evaluate the piloting modalities and the functional impact of a grasping neuroprosthesis in the vascular hemiparetic patient (Fig. 27). Head lateral inclination, foot motion and voice control are being investigated as self-triggering modalities for the user to perform FES induced paretic hand opening. As of the end of 2024, a total of 21 patients had been fully included in this protocol, notably through the opening of a second inclusion center in the medical rehabilitation center of the University Hospital of Nîmes in Le Grau-du-Roi, collaborating with the CHU of Toulouse on this study.

A scientific publication on the technical aspects of the Grasp Neuro-Prosthesis (GNP) used in both of these research protocols was accepted in the Journal of BioMedical Engineering OnLine in December 2024.



Stim "ON": Gx_FOOT
Stim "OFF": Gx_FOOT
○ Symetric ○ Asymetric
Coeff asym: 2
Freq (Hz): 25
Ramp (pts): 0
Intensity (mA): 10,0
Int. inter: 0,0
Width (ms): 200
Width inter: 0
Select task: TestFES_CLC
Select trigger: -
Threshold: 0,00
Time ON-OFF max (s): 0,00
Time ON-OFF min (s): 0,00
○ None
○ All triggers (ALL)
○ Head tilt (HT)
○ Foot inclination (FI)
○ Keyword (Key)
○ Paretic finger flexion
○ Right ankle flexion
○ Left ankle flexion
○ Right foot pression
○ Left foot pression

Figure 27: **Prehens-Stroke research protocol Grasp neuroprosthesis setup.** **A.** A participant using an IMU sensor to trigger electrical stimulation from a stimulator in order to induce hand openning. **B.** NeuroPrehens software interface and visual feedback for investigators and users allowing parametrization and usage of the system.

This article focused on the evaluation in ease-of-use and reliability of a panel of proposed control modalities, as well as the system's responsiveness during usage with these various control modalities. Furthermore, the functional improvements provided by the GNP on standardized tasks were also investigated to demonstrate clinical significance. The results regarding ease-of-use and reliability evaluations for all control modalities investigated fully as part of these protocols are shown in Fig. 28.

8.3.3 Post Stroke upper limb neuroprosthesis : Home-use investigation (Project Grasp-Again)

Participants: Ronan Le Guillou *(SED, CAMIN, Inria)*, Christine Azevedo, David Gasq *(CHU Toulouse)*.

Stroke is the leading cause of acquired motor deficiencies in adults. The restoration of prehension capabilities once in chronic stages of rehabilitation is particularly challenging due to the variability of the user's needs and the lack of devices available for practical use in daily-life conditions. In 2023 we investigated the 2-month-long use by 6 chronic stroke survivors in autonomy at home, of a wearable

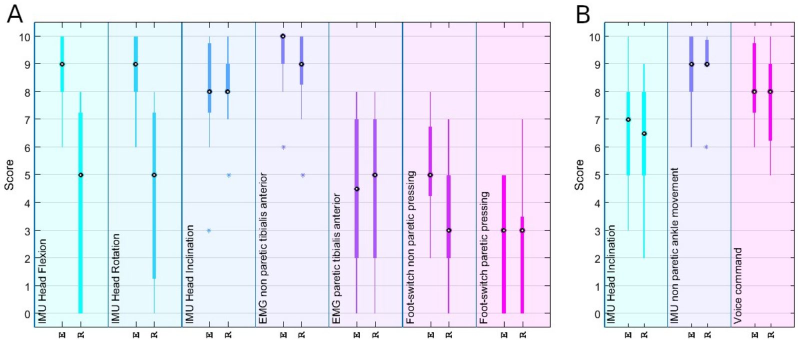


Figure 28: **Ease-of-use (E) and Reliability (R) evaluations for all control modalities. A.** Seven control modalities from the Prehens-Stroke 1 study (N=11). **B.** Three modalities from the Prehens-Stroke 2 study (N=11). Scores range from worst imaginable (0/10) to best imaginable (10/10).

Grasp Neuro-Prosthesis (wGNP). This wGNP allows for user-triggered Functional Electrical Stimulation (FES) of the paretic finger extensors muscles to achieve hand opening.

An embedded version of the Grasp Neuro-Prosthesis developed for the Prehens-Stroke studies, based on the CE marked FESIA Grasp upper-limb rehabilitation stimulator (Fig. 29) was designed, developed and tested throughout the year 2022. This embedded version was used in the Grasp-Again protocol (ClinicalTrial.gov ID: NCT05625113; ID-RCB: 2022-A01202-41), carried out in 2023 from January to July, with 6 post stroke participants, aiming to investigate the use of such a wearable grasp neuro-prosthesis in practical conditions, at home, in autonomy. We evaluated various aspects such as its functional impact on activities of daily living, its responsiveness to user commands and followed and described its use by the participants throughout the 2 months of usage in the protocol as can be seen in Table 1. This work was presented at the International Conference on NeuroRehabilitation (ICNR) 2024 and is published in the associated book of ICNR Conference proceeding by Springer Nature.

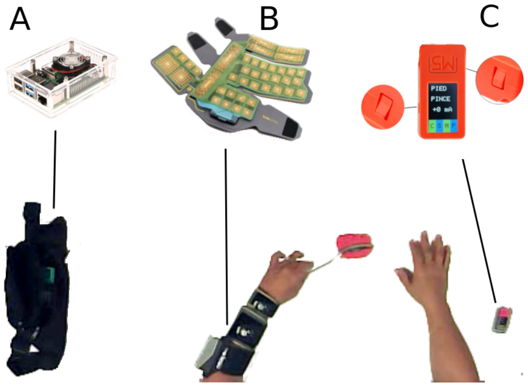


Figure 29: **Wearable neuroprothesis setup illustration while used for prehension task by a participant. A.** Onboard computer unit. **B.** FES sleeve garment. **C.** User interface module. Another M5StickC Plus module is strapped to the ankle of the user on the non-paretic side to allow for the triggering when the foot control modality is selected.

Users could switch at will between two types of grasp (key-pinch or palmar-grasp) and three control modalities (voice control, foot motion and button presses). The daily usage of the device was monitored (median daily usage of 188.4) and self-assessed (median accuracy 85.8%) as well as the preferred modality (Foot motion 4/6). Usage and satisfaction questionnaires were performed (QUEST median score 31/40 and CSQ-8 median score 25/32).

The software Inria BIL APPs for this platform can be found as the IMUSEF and NeuroPrehens projects, respectively with the BIL Ids: Software_3520 and Software_3559. The IMUSEF software was made Open-source in October 2023.

Table 1: Autonomous home-based wGNP usage per participant

Patient ID	Total use (n)	Days used (n)	Use (n) per day used	Self-log accuracy (%)	Preferred modality
1	7718	54	142.9	98.4	Button
2	51991	58	896.4	93.3	Foot
3	2745	21	130.7	60.9	Button
4	8299	40	207.5	78.7	Foot
5	22726	45	505	92.9	Foot
6	162	6*	27	0*	Foot
Median	8008.5	42.5	188.4	85.8	Foot

8.3.4 Assisting Gait in Children with Cerebral Palsy

Participants: Gabriel Graffagnino, Christine Azevedo, Benoît Sijobert *(Institut Saint Pierre, Palavas)*, Karine Patte *(Institut Saint Pierre, Palavas)*, David Gasq *(CHU Toulouse)*.

Gabriel's thesis, funded by an INRIA-INSERM grant, focuses on pathological gait in children with cerebral palsy (CP).

In the context of rehabilitation for children with cerebral palsy (CP), real-time gait-analysis tools provide extensive data, making it challenging to focus on specific metrics when evaluating the efficacy of a device in improving gait. To guide future studies on the impact of transcutaneous spinal cord neuromodulation on children's gait, we aimed to explore the connections between various recurrent variables assessed during gait rehabilitation in children.

To achieve this, we collected comprehensive gait analyses, including electromyographic data, kinetic and kinematic parameters, and spasticity levels of lower-limb muscles. We calculated the co-activation of each agonist/antagonist muscle pair and examined the correlation between muscle spasticity levels and co-activation. Our findings suggest that muscle co-activation and spasticity levels appear to be independent variables, and both should be evaluated separately when investigating the potential effects of an intervention.

Additionally, we analyzed the Gait Variable Score (GVS), which quantifies the deviation of kinematic variables from normal gait patterns. As anticipated, our results demonstrated weak correlations between GVS and spasticity, as well as between GVS and muscle co-activation (Fig. 30).

These analyses provide a roadmap for future experiments: it is crucial to compute and analyze all these variables—spasticity, muscle co-activation, and kinematic variability—to thoroughly assess the potential effects of an intervention on the gait of children with CP.

8.3.5 Analyzing needs and uses related to robotic assistance

Participants: Charlotte Le Goff, Christine Azevedo, Charles Fattal *(USSAP)*, Pauline Coignard *(Association Approche)*.

Charlotte's PhD thesis is done in the context of PEPR O2R Assistmov project. We have started to explore the needs and uses related to robotic assistance for human movements, with the ultimate goal of developing and clinically evaluating an exoskeleton for individuals with disabilities. The first phase involves a literature review and an inventory of existing devices, combined with semi-structured interviews to identify factors that facilitate or hinder their adoption. Subsequently, functional requirements and usage priorities will be defined in collaboration with users and technical partners, guiding the development of a breakthrough innovation tailored to their needs. Particular attention will be paid to perceived

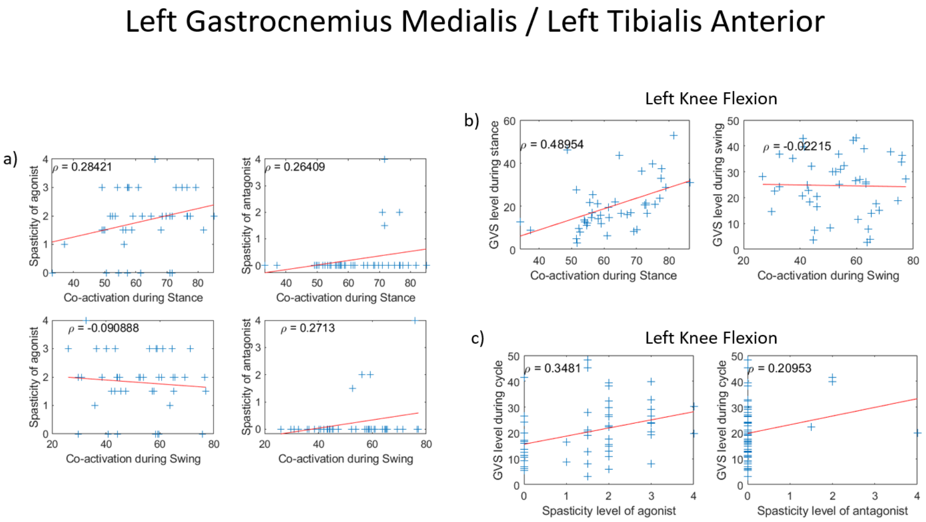


Figure 30: Agonist muscle = Left Gastrocnemius Medialis, Antagonist muscle = Left Tibialis Anterior / a) Correlation between Co-activation during stance and swing phases and level of spasticity of agonist/antagonist muscles b) Correlation between Co-activation of agonist/antagonist muscles and GVS level of the left knee flexion during stance and swing phases b) Correlation between spasticity level of agonist/antagonist muscles and GVS level of the left knee flexion across the gait cycle

utility, usability, and the psychosocial impact of this technology. Finally, clinical studies will evaluate the performance and socio-economic impacts of the prototype, with potential adjustments to optimize its adoption and effectiveness.

9 Bilateral contracts and grants with industry

9.1 Neurinnov

Participants: Jonathan Baum, Thomas Guiho, David Guiraud *(Neurinnov)*, Christine Azevedo.

NEURINNOV startup finances half of the PhD thesis salary of Jonathan Baum (from December 2023 - PLASTICISTIM Project).
A convention was signed with Neurinnov for David Guiraud to join the team as a collaborator.

10 Partnerships and cooperations

10.1 International initiatives

Participants: Christine Azevedo, François Bailly, François Bonnetblanc, Thomas Guiho, Ronan Le Guillou, Olivier Rossel.

10.1.1 Inria associate team not involved in an IIL or an international program

GOIABA

Title: Optimization of Hybrid Mechatronic Devices for Rehabilitation

Duration: 2023 -> 2025

Coordinator: Henrique Resende Martins (henriquerm@gmail.com)

Partners:

- Universidade Federal de Minas Gerais Belo Horizonte (Brésil)

Inria contact: Christine Azevedo Coste

Summary: Our teams are involved in research projects that combines mechatronic systems and functional electrical stimulation (FES). FES allows to restore muscle contraction in paralyzed limbs. The use of FES in interaction with an instrumented tricycle for instance allows people with spinal cord injuries to pedal. FES can also be combined with orthoses, in particular for the upper limb to take advantage of the 2 solutions. Our aim is to develop a collaboration to optimize the outcomes of hybrid mechatronic devices in the context of functional rehabilitation.

10.1.2 Participation in other International Programs

François Bonnetblanc was a recipient of the Asgard Program 2024 to visit Norvegian colleagues (Torbjorn Ness and Gaute Einvoll from Oslo University).

10.2 International research visitors

10.2.1 Horizon Europe

AI-HAND AI-HAND project on cordis.europa.eu

Title: Advanced Intelligent stimulation device: HAND movement restoration

Duration: From August 1, 2023 to January 31, 2027

Partners:

- INSTITUT NATIONAL DE RECHERCHE EN INFORMATIQUE ET AUTOMATIQUE (INRIA), France
- CORTEC GMBH (CORTEC), Germany
- ALBERT-LUDWIGS-UNIVERSITAET FREIBURG (ALU-FR), Germany
- NEURINNOV, France
- UNION SANITAIRE ET SOCIALE POUR L'ACCOMPAGNEMENT ET LA PREVENTION (USSAP), France
- CENTRE NATIONAL DE REEDUCATION FONCTIONNELLE ET DE READAPTATION, Luxembourg

Inria contact: Christine Azevedo

Coordinator: Christine Azevedo

Summary: Very advanced stimulation paradigms applied to peripheral nervous system (PNS) have been studied for years even decades among which the 3D current distribution through multi-contact epineural electrodes. Non rectangular stimulus waveforms are also of strong interest to provide more efficient or fibre type selective stimulation. However none were implemented in an Active Implanted Medical Device and thus almost none validated through clinical trials. One of the reasons is the high complexity of the needed analogue front end and its safe control by a microcontroller or a digital system. AI-HAND project aims at developing a breakthrough, ASIC basedtechnology, together with a specific self adapting epineural multi contact electrode to provide such an AIMD. The demonstration of the clinical relevance of such an approach will be achieved through a first-in-man proof of concept aiming at the restoration of hand movements in persons with complete quadriplegia. It means that a full innovative device should be developed and validated in animals, but the real added value will be supported by the clinical trial; indeed, no animal model exists while the clinical needs is clearly stated by clinicians and patients. Thus this project will innovate concerning both the technology and the therapeutic approach with a minimally invasive concept. Indeed, spatial selectivity allows to stimulate nerves selectively targeting muscles through 3D currents shaping instead of implanting one electrode per muscle. The technology clearly addresses generic issues so that the paradigms and the innovative technology can be further used to stimulate the central nervous system (spinal cord and brain) and, on a long term basis, may drastically open new therapeutics for medical needs that are still unmet.

10.3 National initiatives

INRIA-INSERM Phd thesis grant (2023-26)

Coordinator: Christine Azevedo (INRIA).

We obtained a grant to finance the PhD thesis of Gabriel Graffagnino between CAMIN and INSERM Tonic team in collaboration with Institut Saint Pierre (Palavas).

ANR Grasp-It (2019-24)

Coordinator: Univ. Lorraine. Local coordinator : Christine Azevedo (INRIA).

Design and evaluation of a tangible and haptic BCI for upper limb rehabilitation after stroke. The project aims to recover upper limb control improving the kinesthetic motor imagery (KMI) generation of post-stroke patients using a tangible and haptic interface within a gamified Brain-Computer Interface (BCI) training environment.

ARC FOUNDATION for Research Against Cancer (2022-2025)

Guiding brain tumor surgery in real time using electrophysiology (collaboration with Pr Hugues Duffau and Pr Emmanuel Mandonnet). Coordinator: François Bonnetblanc (INRIA).

During the resection of brain tumors, the neuro-surgeon has substantial imaging data allowing him/her to plan his/her gesture upstream. However, during the actual surgical gesture, in real time, this imaging becomes ineffective due to the deformation of the brain (so called brain shift). It is then possible to use direct electrical stimulation of the brain in an awake patient who cooperates with the neurosurgeon to determine the functional areas and those which are not. When patients are under general anesthesia this possibility no longer exists. We have planned to use the electrophysiology evoked by the DES of the brain during brain surgery to diagnose and determine the location the tumor and the anatomical connectivity on-line in order to guide the surgery in awake patients or under general anesthesia. This needs to go beyond the proof of concept, we have alrealdy performed, and necessitates to address and solve some methodological challenges. At a fundamental level, this will also help to better understand the electrophysiological effect of DES in order to optimize its use.

LabEx NUMEV - MEDITAPARK project (2021-2024)

Coordinator : Ronan Le Guillou (INRIA) and CHU Montpellier.

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

AEx noCNN (2024-27)

Coordinators : François Bailly and François Bonnetblanc (INRIA).

No-brain-shift and Comprehensive Neurosurgical Navigation using computer vision, funded by INRIA's Action Exploratoire program.

Human Lab Inria (HLI) (2021-24)

Local coordinator: Christine Azevedo (INRIA).

Exploratory Research Action.

ANR B-IRD (2024-28)

Coordinator: François Bailly (INRIA).

Biomechanically-Informed Rehabilitation Devices : Fast and reliable biomechanical methods dedicated to assistive technologies.

10.4 Regional initiatives

Défi clé robotique centrée sur l'humain de la région Occitanie (2023-25)

Coordinator : François Bailly (INRIA).

Postdoc fellowship of Sabrina Otmani for the opticycle project.

11 Dissemination

Participants: Christine Azevedo, François Bailly, Jonathan Baum, François Bonnetblanc, Charles Fattal, Gabriel Graffagnino, Thomas Guiho, David Guiraud, Ronan Le Guillou, Valentin Maggioni, Sabrina Otmani, Olivier Rossel, Felix Schlosser-Perrin, Benoit Sijobert, Clotilde Turpin.

We try to maintain a regular activity of our LinkedIn account.

11.1 Promoting scientific activities

11.1.1 Scientific events: organisation

- Christine Azevedo and François Bailly organized and hosted a 1-Day workshop with INRIA teams involved in Biomechanics Research (Montpellier May 31st)
- Christine Azevedo and Emilie Blottière organized and hosted AI-Hand Kick-Off meeting (Montpellier January 22-23th)
- François Bonnetblanc organized a second international 2-day workshop about brain evoked potentials to guide brain surgey with Japanese colleagues involved in the past France Inria-Japan Associate team and Swiss, German, Norwegian and Aamerican colleagues (Montpellier June 24-25th).

11.1.2 Journal

Member of the editorial boards

- Christine Azevedo is member of the International Functional Electrical Stimulation Society (IFESS) society board.
- Christine Azevedo is member of editorial boards of Frontiers in Neurology and Frontiers in Neuroscience and associate editor for Institute of Electrical and Electronics Engineers Robotics and Automation Letters (IEEE RA-L) and IEEE EMBC (Engineering in Medicine and Biology Society) (Theme 6).

Reviewer - reviewing activities

- Thomas Guiho was reviewer for Journal of Neural Engineering, IEEE TNSRE (Transactions on Neural Systems and Rehabilitation Engineering), Medical & Biological Engineering & Computing.
- François Bailly was reviewer for Robotics and Automation Letters, Scientific Data, IEEE-RAS International Conference on Humanoid Robots, IEEE Engineering in Medicine & Biology Society.
- Christine Azevedo was reviewer for IEEE TNSRE (Transactions on neural systems and rehabilitation engineering), SENSORS MDPI, Frontiers in Neurorobotics Frontiers in Neuroscience, Journal of NeuroEngineering and Rehabilitation.
- François Bonnetblanc was reviewer for Journal of Neural Engineering, Communications Biology, Clinical Neurophysiology, Journal of Neurology, Scientific Reports, Journal of Neurophysiology.
- Olivier Rossel was reviewer for Journal of Neural Engineering, Scientific Report, Biomedical Physics & Engineering Express, EMBC Annual Internationl Conference of the IEEE Engineering in Medicine and Biology Society.
- Ronan Le Guillou was reviewer for EMBC Annual Internationl Conference of the IEEE Engineering in Medicine and Biology Society (EMBC).

11.1.3 Invited talks

- François Bailly was invited to give a talk on human modeling for human-robot interaction at the Journées Nationales de la robotique humanoïde, held in Nancy, November 2024.
- Thomas Guiho was invited to give a talk reviewing recent researches in the field of spinal cord stimulation at the SOFMER conference (39th congress of the french society of physical and rehabilitation medicine).
- François Bonnetblanc was invited to give a 30 min talk on canonical waveforms for cortico-cortical evoked potentials at the International Society for Intra-operative Neuromonitoring (ISIN 2024, Barcelona, 7-9th November) (ISIN 2024).
- François Bonnetblanc was invited as a keynote speaker to give a 1h Master Class on Direct cortical responses, axono-cortical and cortico-cortical evoked potential to guide brain surgery at the g.tec BCI & NEUROTECHNOLOGY SPRING SCHOOL 2024 (April 22 – May 1st) (g.tec Spring School 2024).
- David Guiraud presented AGILIS project during the SOFMER conference (39th congress of the french society of physical and rehabilitation medicine).
- Christine Azevedo presented AGILIS project as keynote lecture at IEEE ICARSC conference in May 2024 (Portugal).
- Christine Azevedo presented HumanLab HLI actions during INRIA scientific Days "Handicap" in Paris (March 2024 and November 2024).
- Christine Azevedo presented the team research at the Conference on Disability, Sport, and Movement Sciences organized by Académie des Sciences (October 2024, Paris).

- Christine Azevedo and Ronan Le Guillou presented CAMIN research activities during INRIA scientific Days "Handicap" in Paris (March 2024 and November 2024).
- Christine Azevedo presented AGILIS project as keynote lecture at ICNR conference in November 2024 (Spain).

11.1.4 Scientific expertise

- Christine Azevedo is member of Program INRIA Quadrant (PIQ) expert committee.

11.1.5 Research administration

- Thomas Guiho is responsible for the “Neuroprostheses” teaching unit (Univeristé de Montpellier, Dpt EEA). This unit is an option common to all the masters of the Information and Communication Technologies (ICT) for health training package.
- Thomas Guiho participited to the reflection group on the homepage of the Université Côte d’Azur’s Inria center, as part of the development of the new Numin digital platform.
- François Bailly is a member of the NICE committee (postdoc selection).
- Christine Azevedo and Roger Pissard-Gibollet (SED Grenoble) coordinate the HanditechLab Inria (project.inria.fr/handitechlabinria).
- Christine Azevedo was a member of COERLE (Inria Comité d’éthique) until May 2024
- Christine Azevedo was a member of projects committee office (BCEP) until May 2024
- François Bonnetblanc co-supervised with Christophe Botella the local comittee for sustainable development. They organized an internship with support from inria in order to coordinate the policy for the whole campus in relation to the other institutes
- Olivier Rossel and Clotilde Turpin are members of the local committee for sustainable development.

11.2 Teaching - Supervision - Juries

11.2.1 Teaching

- Master ICT for Health, Neuroprotheses option: Charles Fattal, “Neuroprosthesis and motor support strategies after spinal cord injuries”, 3h, M1, Montpellier University, France
- Master ICT for Health, Neuroprotheses option: Jonathan Baum, “Neuroanatomy and Motor Control”, 6h, M1, Montpellier University, France
- Master ICT for Health, Neuroprotheses option: Clotilde Turpin, “Activating Function” and "Acquisition of biological signals and associated preprocessing", 13.5h, M1 and M2, Montpellier University, France
- Master ICT for Health, Neuroprotheses option: Olivier Rossel, “Modeling of the peripheral nervous system”, 6h, M1 and M2, Montpellier University, France

- Master ICT for Health, Neuroprotheses option: Sabrina Otmani, “Strategies of control”, 3h, M2, Montpellier University, France

- Master ICT for Health, Neuroprotheses option: Ronan Le Guillou, “Control basics and signal processing”, 3h, M2, Montpellier University, France

- Master ICT for Health, Neuroprotheses option: Valentin Maggioni, “Biomaterials and biocompatibility” and "Signal processing of neural signals", 9h, M2, Montpellier University, France

- Master ICT for Health, Neuroprotheses option: Gabriel Graffagnino, “Sensory supplementation: overview and prospects”, 1.5h, M2, Montpellier University, France

- Master Cognitive and integrated neuroscience, "Sensorimotor Deficiencies and palliative strategies teaching unit": Thomas Guiho, “Implantable neuroprosthesis for motor rehabilitation”, 4.5h, M2, Paul Sabatier University, Toulouse, France

- Master Health, "Integrated Pathophysiology": Charles Fattal, “Neuroprosthesis and Robots for motor replacement”, 1.5h, M2, Montpellier University, France

- Engineering degree, "Microelectronics and automation": Olivier Rossel, “Discrete event system”, 30h, 4th year, Polytech Engineering School, Montpellier, France

- Engineering degree, "Microelectronics and automation": Gabriel Graffagnino, “Introduction to electronic”, 12h, 3rd year, Polytech Engineering School, Montpellier, France
- Master ICT for Health, "Health device engineering": David Guiraud, “Medical device industrialisation: From fundamental to clinical research”, 9h, M1, Montpellier University, France

- Master in Pharmaceutical Sciences, "Neuroprosthesis": Félix Schlosser-Perrin, “Signal processing and basic electronics”, 64h, L1, Montpellier University, France

- Bachelor in Pharmaceutical Sciences, "Neuroprosthesis": Clotilde Turpin, “Basic electronics”, 63h, L1, Montpellier University, France
- State diploma of “hearing aid professional” : Jonathan Baum, “signal processing, office automation and prototyping on labview”, 64h, 1st year, audiocampus, Montpellier University, France

11.2.2 Supervision

- PhD defended on December 2024 : Félix Schlosser-Perrin, "Simulation des effets de la stimulation électrique directe cérébrale à partir de modèles biophysiques d’axones.", University of Montpellier, september 2021-september 2024, supervised by François Bonnetblanc and Emmanuel Mandonnet (PU-PH in Neurosurgery at APHP)[23].

- PhD in progress : Clotilde Turpin (2022-...), "Compréhension de l’électrogénèse des potentiels évoqués par la stimulation électrique du cerveau en neurochirurgie", Inria, supervised by François Bonnetblanc.

- PhD in progress : Gabriel Graffagnino (2023-...) , " Apport des nouvelles technologies numériques dans la rééducation pédiatrique : stimulation électrique fonctionnelle, réalité virtuelle et robotique d'assistance dans la rééducation de la marche chez l'enfant atteint de paralysie cérébrale", Inria-INSERM-Institut St Pierre, supervised by Christine Azevedo, Benoît Sijobert, Karinne Patte and David Gasq.

- PhD in progress : Valentin Maggioni (2023-...), "Développement d'un simulateur neuromusculosquelettique du membre supérieur sous stimulation électrique fonctionnelle", University of Montpellier-Inria, supervised by François Bailly and Christine Azevedo.

- PhD in progress : Jonathan Baum (2023-...), "Precise neural stimulation and underlying electrophysiological mechanisms", University of Montpellier-Inria-NEURINNOV, supervised by Thomas Guiho, David Guiraud and Christine Azevedo.

- PhD in progress : Paul André (October 2024-...), "Navigation neurochirurgicale exhaustive et sans décalage de cerveau grâce à la vision par ordinateur", Inria, supervised by François Bailly and François Bonnetblanc.

- PhD in progress : Charlotte Le Goff (2024-...) , "Étude des besoins et des usages pour l'assistance robotique aux mouvements humains, développement et mise en place d'un exosquelette pour les personnes en situation de handicap", PEPR O2R ASSiSTMOV, supervised by Charles Fattal, Christine Azevedo.

- Internship: Elisa Salanqueda, April 2024-August 2024,"Conception et Modélisation d'aides techniques pour les membres supérieurs et inférieurs", supervised by François Bailly and Christine Azevedo.

- Internship: Jordan Langlet, April 2024-July 2024,"Développement et centralisation d'outils informatiques de mesure du mouvement de la main.", supervised by François Bailly and Christine Azevedo.

- Internship: Riccardo Carpineto, July 2024-August 2024, "Étude de signaux électroneurogrammes dans le cadre d'une stimulation du nerf périphérique", supervised by Thomas Guiho.

- Internship: Ali Boukhsibi, October 2024-December 2024, "Matrix Factorization for Decomposition of Evoked Electromyographic Signals", supervised by Olivier Rossel.

11.2.3 Juries

- François Bailly was vice-president in the jury for the selection of a maître de conférence for the Université de Toulouse 3 (section 74) .

- Christine Azevedo participated in Junior Professor Chair competition jury for the Inria Saclay center.

- Christine Azevedo was member of the thesis committee of the PhD thesis defense of Alexis Poignant, "Voluntary control of an assistive robotic manipulator placed in the peripersonal space" ISIR Paris, October 15th 2024.

- Christine Azevedo was reviewer for the PhD thesis defense of Bianca Letto, "Biomimetic control of a prosthesis based on natural movements: database and reference frame transformation for a real-life scenario." Bordeaux University, October 3rd 2024.
- Christine Azevedo was reviewer for the general synthesis review of Kevin Co's thesis "Minimization of Muscle Fatigue Induced by Functional Electrical Stimulation During a Rehabilitative Arm Pedaling Task Using Optimal Control" Université de Montréal 27 June 2024.
- Christine Azevedo was reviewer of Ardit Dvorani thesis "On-demand gait-phase synchronous electrical cueing to reduce freezing of gait in Parkinson's disease". Technische Universität Berlin, May 22nd 2024.
- Christine Azevedo was member of Simão Pedro Fernandes Machado Dias Carvalho PhD thesis committee "Bio-inspired Control for a Lower Limb Neuroprosthesis towards Motor Reestablishment" Universidade do Minho Portugal, October 8th 2024.
- Clotilde Turpin and Gabriel Graffagnino were members of the jury assessing the work performed by ICT for health Master's students during their 2 months projects in immersion in public laboratories or private companies.

11.3 Popularization

11.3.1 Internal or external Inria responsibilities

- François Bailly is elected member of the AGOS committe of the Inria Centre at Université Côte d'Azur for the Inria branch of Montpellier University.

- Olivier Rossel is volunteer for the AGOS Montpellier's local committee.

- Thomas Guiho is the Montpellier referent for the "1 Chercheur, 1 Classe : Chiche!" programme.

- Thomas Guiho helped supply the prizes for the winners of the Olympiad in Mathematics.

11.3.2 Participation in Live events

- Christine Azevedo, Sabrina Otmani and François Bailly showcased 3 live demonstrations at the INRIA stand during the IEEE-RAS International Conference on Humanoid Robots, 22-24 November 2024, Nancy, France.

11.3.3 Others science outreach relevant activities

- Ten team members participated in the 3-day hackathon FABRIKARIUM organized by the Human-Lab Saint Pierre (LINK).
- Christine Azevedo followed up a research project about environement preservation using Thymio Robot for a total of 20 hours. COSTA BELLE elementary school (St Bauzille de la Sylve).
- Christine Azevedo gave introduction to programming interventions using Thymio Robot in Collège Léon Cordas (4 sessions of 1,5 hour).
- Christine Azevedo, Jonathan Baum and Gabriel Graffagnino spoke to students in 8 second-year classes at Lycée Philippe Lamour in Nîmes on April 26th, 2024 as part of the "1 Chercheur, 1 Classe : Chiche !" program.
- François Bailly spoke to students in 3 second-year classes at Lycée Jacques Prévert in Saint-Christol-lès-Alès on May 25th, 2024 as part of the "1 Chercheur, 1 Classe : Chiche !" program.

- Gabriel Graffagnino spoke to students in 5 second-year classes at Lycée Thierry Maulnier in Nice on Novembre 14th, 2024 as part of the “1 Chercheur, 1 Classe : Chiche !" program.
- François Bonnetblanc and Thomas Guiho spoke to students in 10 second-year classes at Lycée Déodat-de-Sévérac in Céret on March 3rd, 2024 as part of the “1 Chercheur, 1 Classe : Chiche !” program.
- Thomas Guiho, Valentin Maggioni and Sabrina Otmani spoke to students in 9 second-year classes at Lycée Jean Mermoz in Montpellier on April 4th, 2024 as part of the “1 Chercheur, 1 Classe : Chiche !” program.
- Thomas Guiho spoke to students in 2 second-year classes at Lycée Notre Dame de la Merci in Montpellier on May 23rd, 2024 as part of the “1 Chercheur, 1 Classe : Chiche !” program.
- Christine Azevedo presented her profession to four 8th and 9th-grade classes during a career forum organized by the school Collège Léon Cordas (Montpellier, November 26th 2024).
- CAMIN team welcomed 1 week internships of 2 school children this year (8th and 9th-grade) and 2 highschool students (10th-grade) for 2 weeks.

12 Scientific production

12.1 Major publications

[1] C. Azevedo Coste, L. William, L. Fonseca, A. Hiairrassary, D. Andreu, A. Geffrier, J. Teissier, C. Fattal and D. Guiraud. ‘Activating effective functional hand movements in individuals with complete tetraplegia through neural stimulation’. In: *Scientific Reports* 12.1 (Dec. 2022), p. 16189. DOI: `10.1038/s41598-022-19906-x`. URL: `https://hal.archives-ouvertes.fr/hal-03817189`.

[2] A. Boyer, J. Deverdun, H. Duffau, E. Le Bars, F. Molino, N. Menjot De Champfleur and F. Bonnetblanc. ‘Longitudinal Changes in Cerebellar and Thalamic Spontaneous Neuronal Activity After Wide-Awake Surgery of Brain Tumors: a Resting-State fMRI Study’. In: *Cerebellum* 15.4 (Aug. 2016), pp. 451–465. DOI: `10.1007/s12311-015-0709-1`. URL: `https://hal-lirmm.ccsd.cnrs.fr/lirmm-01348011`.

[3] A. Boyer, S. Ramdani, H. Duffau, M. Dali, M. Vincent, E. Mandonnet, D. Guiraud and F. Bonnetblanc. ‘Electrophysiological Mapping During Brain Tumor Surgery: Recording Cortical Potentials Evoked Locally, Subcortically and Remotely by Electrical Stimulation to Assess the Brain Connectivity On-line’. In: *Brain Topography: a Journal of Cerebral Function and Dynamics* (2020). DOI: `10.1007/s10548-020-00814-0`. URL: `https://hal.inria.fr/hal-03106388`.

[4] C. Fattal, B. Sijobert, A. Daubigney, E. Fachin-Martins, B. Lucas, J.-M. Casillas and C. Azevedo Coste. ‘Training with FES-assisted cycling in a subject with spinal cord injury: Psychological, physical and physiological considerations’. In: *Journal of Spinal Cord Medicine* (July 2018), pp. 1–12. DOI: `10.1080/10790268.2018.1490098`. URL: `https://hal.archives-ouvertes.fr/hal-01875806`.

[5] T. Guiho, C. Delleci, C. Azevedo Coste, C. Fattal, D. Guiraud, J.-R. Vignes and L. Bauchet. ‘Impact of direct epispinal stimulation on bladder and bowel functions in pigs: A feasibility study’. In: *Neurourology and Urodynamics* 37.1 (Jan. 2018), pp. 138–147. DOI: `10.1002/nau.23325`. URL: `https://hal-lirmm.ccsd.cnrs.fr/lirmm-01539038`.

[6] F. M. Petrini, M. Bumbasirevic, G. Valle, V. Ilic, P. Mijović, P. Ċvanċara, F. Barberi, N. Katic, D. Bortolotti, D. Andreu, K. Lechler, A. Lesic, S. Mazic, B. Mijović, D. Guiraud, T. Stieglitz, A. Alexandersson, S. Micera and S. Raspopovic. ‘Sensory feedback restoration in leg amputees improves walking speed, metabolic cost and phantom pain’. In: *Nature Medicine* 25.9 (Sept. 2019), pp. 1356–1363. DOI: `10.1038/s41591-019-0567-3`. URL: `https://hal-lirmm.ccsd.cnrs.fr/lirmm-02282558`.

[7] F. M. Petrini, G. Valle, M. Bumbasirevic, F. Barberi, D. Bortolotti, P. Cvancara, A. Hiairrassary, P. Mijovic, A. O. Sverrisson, A. Pedrocchi, J.-L. Divoux, I. Popovic, K. Lechler, B. Mijovic, D. Guiraud, T. Stieglitz, A. Alexandersson, S. Micera, A. Lesic and S. Raspopovic. 'Enhancing functional abilities and cognitive integration of the lower limb prosthesis'. In: *Science Translational Medicine* 11.512 (Oct. 2019). DOI: `10.1126/scitranslmed.aav8939`. URL: `https://hal-lirmm.ccsd.cnrs.fr/lirmm-02307824`.

[8] O. Rossel, F. Soulier, S. Bernard, D. Guiraud and G. Cathébras. 'A phantom axon setup for validating models of action potential recordings'. In: *Medical and Biological Engineering and Computing* 10.4 (2016), pp. 671–678. DOI: `10.1007/s11517-016-1463-3`. URL: `https://hal-lirmm.ccsd.cnrs.fr/lirmm-01347422`.

[9] W. Tigra, M. Dali, L. William, C. Fattal, A. Gélis, J.-L. Divoux, B. Coulet, J. Teissier, D. Guiraud and C. Azevedo Coste. 'Selective neural electrical stimulation restores hand and forearm movements in individuals with complete tetraplegia'. In: *Journal of NeuroEngineering and Rehabilitation* 17.1 (May 2020), pp. 66–78. DOI: `10.1186/s12984-020-00676-4`. URL: `https://hal-lirmm.ccsd.cnrs.fr/lirmm-02613474`.

[10] W. Tigra, B. Navarro, A. Cherubini, X. Gorron, A. Gélis, C. Fattal, D. Guiraud and C. Azevedo Coste. 'A novel EMG interface for individuals with tetraplegia to pilot robot hand grasping'. In: *IEEE Transactions on Neural Systems and Rehabilitation Engineering* 26.2 (2018), pp. 291–298. DOI: `10.1109/TNSRE.2016.2609478`. URL: `https://hal.archives-ouvertes.fr/lirmm-01373668`.

[11] H. M. R. Ugalde, D. Ojeda, V. Le Rolle, D. Andreu, D. Guiraud, J.-L. Bonnet, C. Henry, N. Karam, A. Hagege, P. Mabo, G. Carrault and A. I. Hernandez. 'Model-Based Design and Experimental Validation of Control Modules for Neuromodulation Devices'. In: *IEEE Transactions on Biomedical Engineering* 63.7 (June 2016), pp. 1551–1558. URL: `https://hal.archives-ouvertes.fr/hal-01337430`.

[12] M. Vincent, O. Rossel, B. Poulin-Charronnat, G. Herbet, M. Hayashibe, H. Duffau, D. Guiraud and F. Bonnetblanc. 'Case report: remote neuromodulation with direct electrical stimulation of the brain, as evidenced by intra-operative EEG recordings during wide-awake neurosurgery'. In: *Clinical Neurophysiology* (Nov. 2015). Letter to the editor, pp. 1752–1754. DOI: `10.1016/j.clinph.2015.11.005`. URL: `https://hal-lirmm.ccsd.cnrs.fr/lirmm-01237964`.

12.2 Publications of the year

International journals

[13] M. Chateaux, O. Rossel, O. Rossel, F. Vérité, C. Nicol, A. Touillet, J. Paysant, N. Jarrassé and J. B. de Graaf. 'New insights into muscle activity associated with phantom hand movements in transhumeral amputees'. In: *Frontiers in Human Neuroscience* 18 (2024), p. 1443833. DOI: `10.3389/fnhum.2024.1443833`. URL: `https://hal.science/hal-04709202`.

[14] R. Le Guillou, J. Froger, M. Morin, M. Couderc, C. Cormier, C. Azevedo Coste and D. Gasq. 'Specifications and functional impact of a self-triggered grasp neuroprosthesis developed to restore prehension in hemiparetic post-stroke subjects'. In: *BioMedical Engineering OnLine*. Biosystems & Biorobotics 23.1 (21st Dec. 2024), p. 129. DOI: `10.1186/s12938-024-01323-y`. URL: `https://hal.science/hal-04879755`.

[15] C. Trotobas, F. Ferreira, J. P. F. Bonfim, M. R. d. F. Moraes, A. M. V. N. V. Petten, H. R. Martins, C. Fattal and C. A. Coste. 'Combining Functional Electrical Stimulation (FES) to Elicit Hand Movements and a Mechanical Orthosis to Passively Maintain Wrist and Fingers Position in Individuals With Tetraplegia: A Feasibility Test'. In: *IEEE Transactions on Medical Robotics and Bionics* (2024), pp. 1–1. DOI: `10.1109/TMRB.2024.3421667`. URL: `https://inria.hal.science/hal-04660558`.

[16] C. Turpin, O. Rossel, F. Schlosser-Perrin, S. Ng, R. Matsumoto, E. Mandonnet, H. Duffau and F. Bonnetblanc. 'Shapes of direct cortical responses vs. short-range axono-cortical evoked potentials: The effects of direct electrical stimulation applied to the human brain'. In: *Clinical Neurophysiology* (Nov. 2024). DOI: `10.1016/j.clinph.2024.10.016`. URL: `https://inria.hal.science/hal-04795276`.

[17] D. N. Wright, M. Züchner, E. Annavini, M. J. Escalona, L. Hammerlund Teige, L. G. Whist Tvedt, A. Lervik, H. A. Haga, T. Guiho, I. Clausen, T. Glott and J.-L. Boulland. 'From wires to waves, a novel sensor system for in vivo pressure monitoring'. In: *Scientific Reports* 14.1 (30th Mar. 2024), p. 7570. DOI: `10.1038/s41598-024-58019-5`. URL: `https://inria.hal.science/hal-04533302`.

Invited conferences

[18] C. Azevedo Coste. 'Keynote lecture: Technical innovations for functional assistance of the upper limbs'. In: ICARSC 2024 - 24th IEEE International Conference on Autonomous Robot Systems and Competitions. Paredes de Coures, Portugal, 2nd May 2024. URL: `https://hal.science/hal-04700883`.

International peer-reviewed conferences

[19] T. Coelho-Magalhães, C. Azevedo Coste and F. Bailly. 'FES-induced musculoskeletal trajectory optimization with an adapted muscle model'. In: *Artificial Organs (abstract)*. IFESS 2024 - annual conference of the International Functional Electrical Stimulation Society. Bath (UK), United Kingdom, 1st Sept. 2024. URL: `https://hal.science/hal-04701752`.

[20] E. Moullet, J. Carpentier, C. Azevedo Coste and F. Bailly. 'A Grasping Movement Intention Estimator for Intuitive Control of Assistive Devices'. In: ICNR 2024 - International Conference on NeuroRehabilitation. La granja, Spain, 5th Nov. 2024. URL: `https://hal.science/hal-04706628` (cit. on p. 27).

[21] E. Moullet, J. Carpentier, C. Azevedo Coste and F. Bailly. 'i-GRIP, a Grasping Movement Intention Estimator for Intuitive Control of Assistive Devices'. In: *IEEE Xplore*. Humanoids 2024 - IEEE-RAS International Conference on Humanoid Robots. Nancy, France, 22nd Nov. 2024. URL: `https://hal.science/hal-04706577` (cit. on p. 27).

[22] C. Trotobas, F. M. Rodrigues Martins Ferreira, J. P. Fernandes Bonfim, M. R. d. F. Moraes, A. M. V. N. V. Petten, H. Resende-Martins, C. Fattal and C. Azevedo Coste. 'A Feasibility Study of a hybrid approach using FES and a Mechanical Orthosis to Restore Hand Movements in Individuals with Tetraplegia'. In: ICNR 2024 - International Conference on NeuroRehabilitation. La Granja, Spain, 5th Nov. 2024. URL: `https://hal.science/hal-04700894`.

Doctoral dissertations and habilitation theses

[23] F. Schlosser-Perrin. 'Simulation of the effects of direct electrical stimulation of the brain using biophysical models of axons'. Université de Montpellier (UM), FRA, 19th Dec. 2024. URL: `https://hal.science/tel-04917305` (cit. on p. 38).

Reports & preprints

[24] S. Otmani, A. Murray, C. Azevedo Coste and F. Bailly. *Maximizing Cycling Efficiency: Innovative Bicycle Drive Mechanisms Tailored to Individual Muscular Capacities - Technical Report*. INRIA - Université de Montpellier, 15th July 2024. URL: `https://hal.science/hal-04647805`.

12.3 Cited publications

[25] C. Azevedo Coste, L. William, L. Fonseca, A. Hiairrassary, D. Andreu, A. Geffrier, J. Teissier, C. Fattal and D. Guiraud. 'Activating effective functional hand movements in individuals with complete tetraplegia through neural stimulation'. In: *Scientific Reports* 12.1 (Dec. 2022), p. 16189. DOI: `10.1038/s41598-022-19906-x`. URL: `https://hal.science/hal-03817189` (cit. on p. 27).

[26] J. Ding, S. A. Binder-Macleod and A. S. Wexler. 'Two-step, predictive, isometric force model tested on data from human and rat muscles'. In: *Journal of applied Physiology* 85.6 (1998), pp. 2176–2189 (cit. on p. 18).

[27] N. Haouchine, P. Juvekar, M. Nercessian, S. Wells, A. Golby and S. Frisken. 'Pose Estimation and Non-Rigid Registration for Augmented Reality During Neurosurgery'. In: *IEEE Transactions on Biomedical Engineering* PP (Sept. 2021), pp. 1–1. DOI: `10.1109/TBME.2021.3113841` (cit. on p. 21).

[28] N. Jiang and D. Farina. 'Myoelectric control of upper limb prosthesis: current status, challenges and recent advances'. In: *Front Neuroeng* 7.4 (2014), pp. 7–9 (cit. on p. 27).

[29] Y. Labbé, J. Carpentier, M. Aubry and J. Sivic. 'Cosypose: Consistent multi-view multi-object 6d pose estimation'. In: *Computer Vision–ECCV 2020: 16th European Conference, Glasgow, UK, August 23–28, 2020, Proceedings, Part XVII 16*. Springer. 2020, pp. 574–591 (cit. on p. 27).

[30] N. A. Lanese, D. H. Myszka, A. L. Bazler and A. P. Murray. 'Six-bar linkage models of a recumbent tricycle mechanism to increase power throughput in FES cycling'. In: *Robotics* 11.1 (2022), p. 26 (cit. on p. 16).

[31] J. Martin and N. Brown. 'Joint-specific power production and fatigue during maximal cycling'. In: *Journal of Biomechanics* 42.4 (2009), pp. 474–479 (cit. on p. 16).

[32] O. Ronneberger, P. Fischer and T. Brox. *U-Net: Convolutional Networks for Biomedical Image Segmentation*. 2015. arXiv: `1505.04597 [cs.CV]`. URL: `https://arxiv.org/abs/1505.04597` (cit. on p. 21).

[33] F. Zhang, V. Bazarevsky, A. Vakunov, A. Tkachenka, G. Sung, C.-L. Chang and M. Grundmann. 'Mediapipe hands: On-device real-time hand tracking'. In: *arXiv preprint arXiv:2006.10214* (2020) (cit. on p. 27).