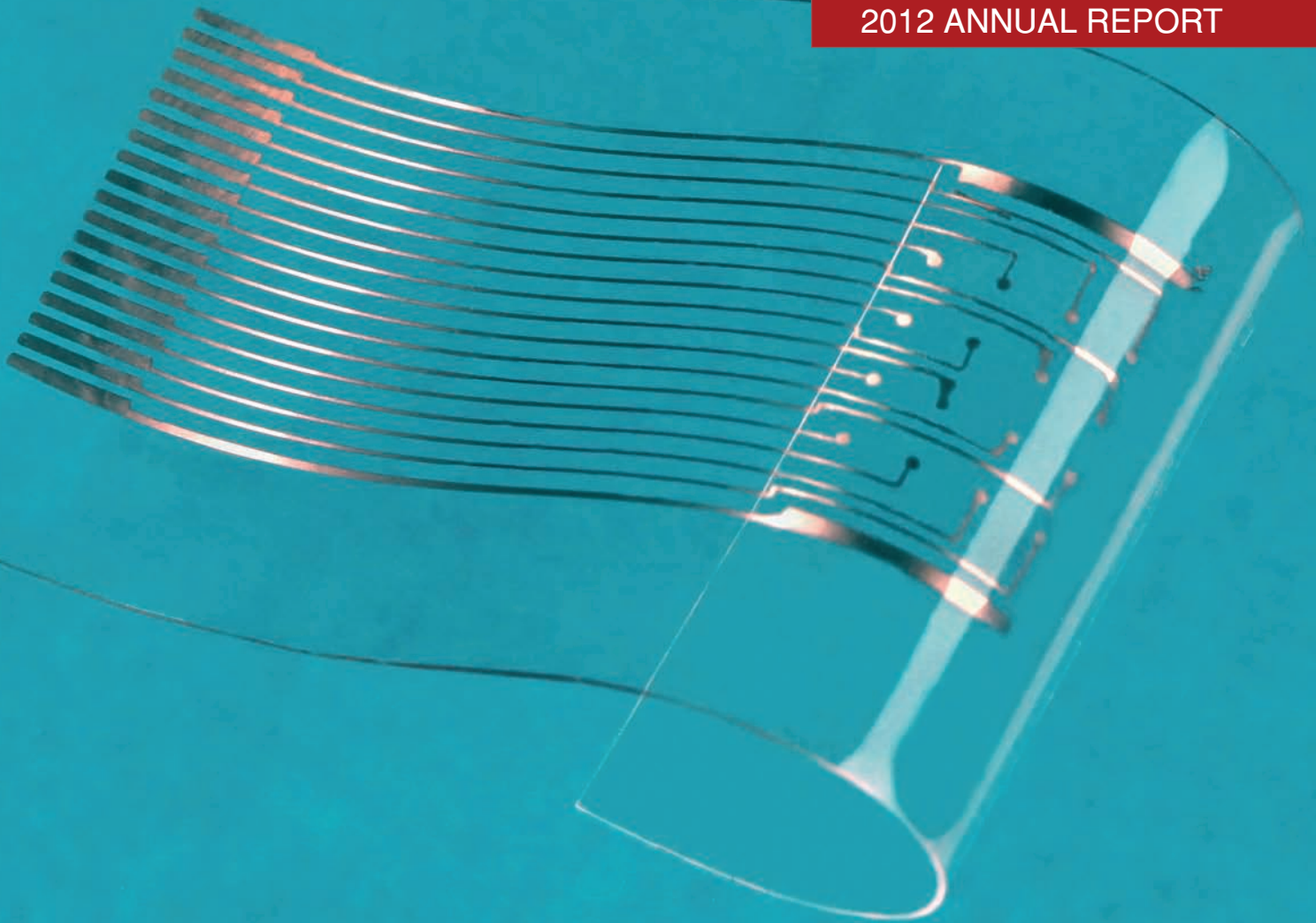




# Center for Neuroprosthetics

2012 ANNUAL REPORT



The EPFL Center for Neuroprosthetics

**Translational  
Neural Engineering  
Laboratory**

**Silvestro Micera**

**Bertarelli Foundation  
Chair in Cognitive  
Neuroprosthetics**

**Olaf Blanke**

**Bertarelli Foundation  
Chair in  
Neuroprosthetic  
Technology**

**Stéphanie P. Lacour**

**Defitech Foundation  
Chair in Non-invasive  
Brain-machine  
Interface**

**José del R. Millán**

**Foundation IRP Chair  
in Spinal Cord  
Repair**

**Grégoire Courtine**





## Welcome to the Center for Neuroprosthetics

The 20th Century witnessed major advances in the investigation and understanding of the brain and its diseases. This culminated in the 1990s with the “decade of the brain”, which also saw the massive arrival of systems and cognitive neuroscience in humans based on the vast availability of non-invasive brain imaging techniques. This acceleration and success in the neurosciences was complemented by a second revolution: breathtaking advances in biotechnology and microelectronics, as well as neural implants that make it possible to target specific regions in the brain, the spinal cord, and the peripheral nervous system.

The Center for Neuroprosthetics enthusiastically embraces these two revolutions and is establishing a truly interdisciplinary area of study for scientific discovery and neurotechnological design, strengthened by its dual affiliation with the School of Engineering and the School of Life Sciences. To meet our ambitious translational goals in neuroprosthetics—that is, the repair and substitution of impaired sensory, motor and cognitive functions—we have now developed strategic partnerships with several medical centers in the Lemanic region as well as with Harvard Medical School.

The well-established treatments of deep brain stimulation for Parkinson's disease and of cochlear implants for hearing loss are just two major success stories in this area. Clearly, much work lies ahead of us while we strive to provide enabling neurotechnological treatments to neurological patients. Stay tuned.

Olaf Blanke  
Director of the Center for Neuroprosthetics  
Ecole Polytechnique Fédérale de Lausanne (Switzerland)

## Mission

The Center for Neuroprosthetics (CNP) capitalizes on its unique access to the advanced technologies and state of the art brain research present on the EPFL campus. Its aim is to develop new technologies that support, repair and replace functions of the nervous system. The development of such technologies or devices, called neuroprostheses, requires a fundamental understanding of the neurobiological mechanisms of the functions that should be replaced or repaired, for example sensory perception, cognitive operations or movement. It also requires technological capabilities to design novel devices, to record and process signals and to translate them into outputs that can commend artificial limbs, bodies and robots, for motor function, or produce signals to activate the brain, in the case of sensory prostheses.

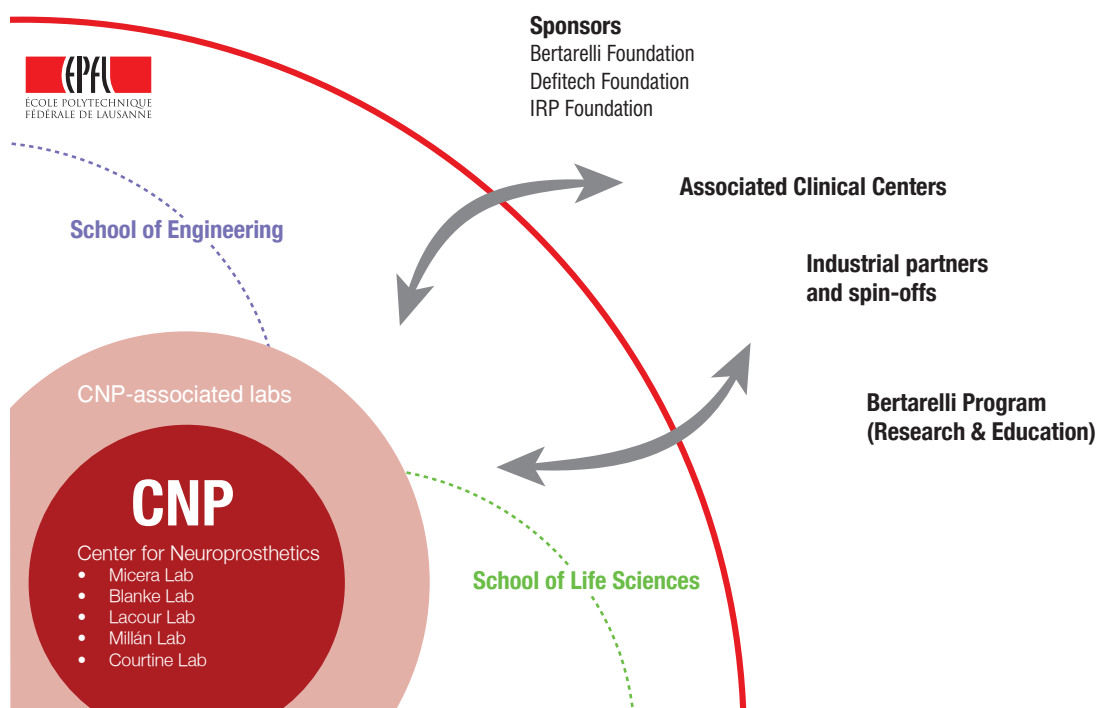
The impact of neuroprosthetics for the treatment of sensory loss and impaired mobility has already been demonstrated. Over 200,000 people with impaired hearing have received cochlear implants and over 80,000 patients suffering from Parkinson's disease and other neurological movement disorders have been treated with deep brain stimulation. With approximately a third of the population in Europe and the US afflicted by brain disorders, major advances in neuroprosthetics are necessary, also including breakthroughs in cognitive neuroprosthetics for treating patients suffering from cognitive deficits such as those caused by Alzheimer's disease and vascular stroke.

Engineering the nervous system to improve sensation, cognition, and mobility, we strive to create major breakthroughs in bioengineering and neuroscience and efficiently translate them to viable clinic applications.

## CNP at EPFL and beyond

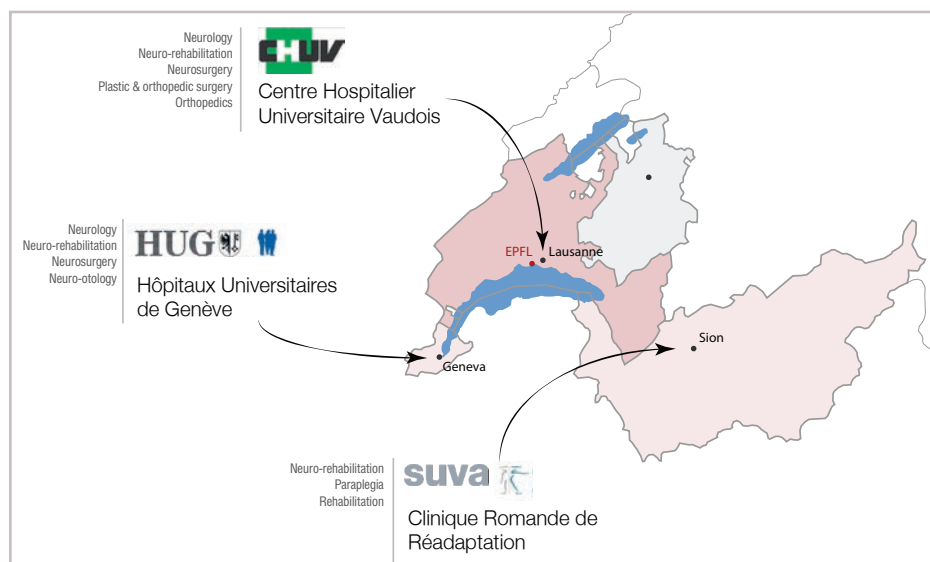
The Center for Neuroprosthetics is part of both the School of Engineering and the School of Life Sciences. It draws upon the EPFL's expertise in biology, neuroscience, brain imaging, and genetics as well as biomedical, electrical, mechanical engineering, and nanotechnology. The Center will also draw upon EPFL's cutting edge research in signal analysis, theoretical and computational neuroscience, the recently launched European Flagship "Human Brain Project" and the Swiss National Center of Competence in Research in "Robotics".

In addition, through support from the Bertarelli foundation, a new research collaboration - dedicated to translational neuroscience and neuroengineering - has been created between Harvard Medical School, EPFL's Institute of Bio-engineering, and the Center for Neuroprosthetics.



## Associated Medical Centers

The Center for Neuroprosthetics is currently developing strategic partnerships with Geneva University Hospital (Hôpitaux Universitaires de Genève, HUG), Lausanne University Hospital (Centre Hospitalier Universitaire Vaudois, CHUV), and a major Swiss Rehabilitation Clinic (Clinique Romande de Réadaptation, CRR in Sion), as well as with the regional biomedical industry.



## Selected Highlights

April 2012

### Inauguration of the Center for Neuroprosthetics

Presentation of the Center's vision and research projects in the presence of EPFL President Patrick Aebischer, sponsor foundations and journalists.

May 2012

### Breakthrough papers in spinal cord repair by Prof. Grégoire Courtine and Prof. Silvestro Micera in Science and Nature Medicine

"Restoring voluntary control of locomotion after paralyzing spinal cord injury". *Science*, 336(6085).

"Versatile robotic interface to evaluate, enable and train locomotion and balance after neuromotor disorders", *Nature Medicine*, 18(7).



Stéphanie Lacour demonstrates flexible electronics. (TEDxHelvetia 2012, credits: Oliver O'Hanlon)

June 2012

### TEDx talks by Prof. Grégoire Courtine and Prof. Olaf Blanke at TEDxCHUV

"Inspiring New Thinking to Restore Function after Spinal Cord Injury" by Prof. Grégoire Courtine.

"Out-of body experiences, consciousness, and cognitive neuroprosthetics" by Prof. Olaf Blanke.



September 2012

### Prof. Silvestro Micera inaugural lesson

"NeuroTechnologies for a Better Quality of Life"

### TEDx talk by Prof. Stéphanie Lacour at TEDxHelvetia

"Stretching Boundaries for Flexible Futures" together with Prof. Jamie Paik.

October 2012

### TEDx talk by Prof. José del R. Millán at TEDxZürich

"Mind-controlled Machines"



José del R. Millán (TEDxZürich 2012)

### Bertarelli Symposium

Organized with the Institute of Bioengineering.

Several research projects funded by the Bertarelli Program in Translational Neuroscience and Neuroengineering between Harvard Medical School and CNP-EPFL were presented.

Invited keynote speakers: Todd Kuiken (Rehabilitation Institute of Chicago), Bernhard Laback (Austrian Academy of Sciences, Vienna) and Christof Stieger (Bern University & Harvard Medical School).

November 2012

### 2012 Cloëtta Foundation Prize for Prof. Olaf Blanke

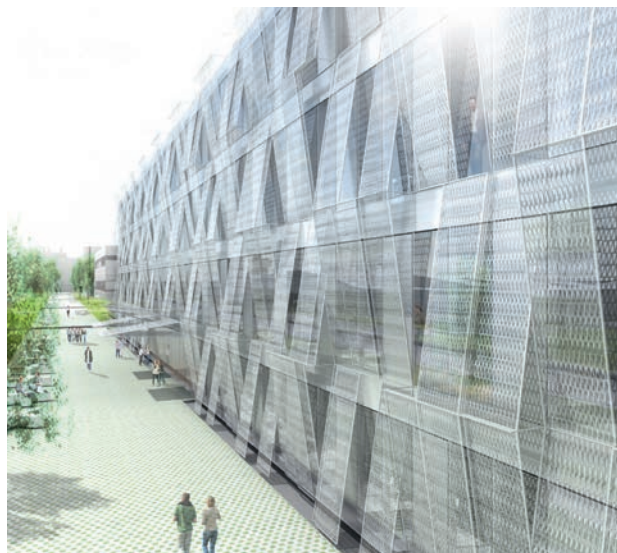
The Cloëtta Foundation Prize was awarded to Prof. Olaf Blanke for his work in neurology and cognitive neuroscience.

December 2012

### EPFL's Center for Neuroprosthetics and the EPFL-Valais/Wallis project

Signature of the agreement by the Council of State of the Canton of Valais and EPFL presidency in Sion. The future health campus in the Sion Hospital area will be home to cutting-edge technology and rehabilitation installations and two new CNP professorships. Research collaborations are envisaged with the HES-SO Valais, Sion Hospital (Hôpital de Sion) and the Clinique Romande de Réadaptation (SUVA).

Due for completion in 2015, the new building of EPFL's School of Engineering will host the five CNP Chairs and their animal and human testing platforms. It will serve as a hub bringing together fundamental research in neuroscience and bioengineering, enabling clinical and technology transfer.

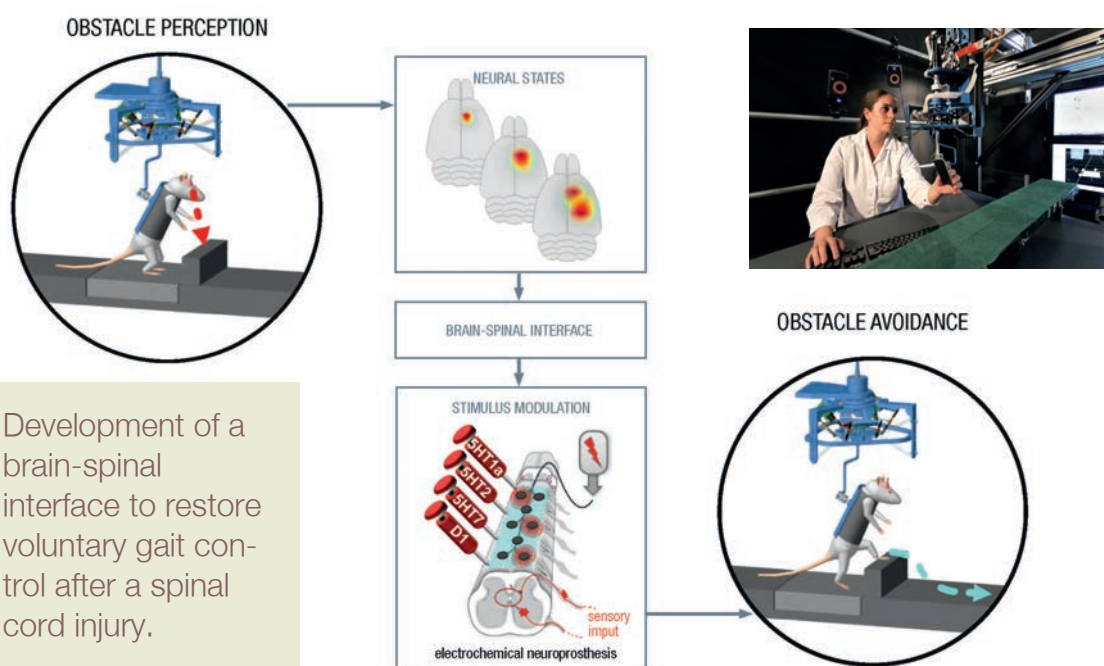




## Walk again

### Restoring sensorimotor functions after spinal cord injury

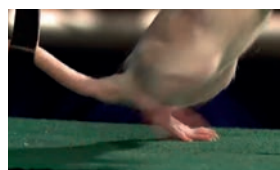
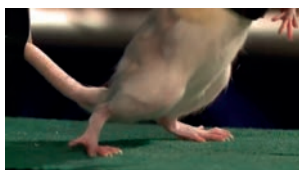
Intentions of a paralyzed rodent with spinal cord injury are decoded from real-time recording of brain activity. Decoded information is directly fed into a brain-spinal interface that computes optimal spinal cord stimulation patterns to execute the desired movement. As a result the animal is capable of locomotion and obstacle avoidance, even though the spinal cord motoneurons are physically separated from the brain.



Development of a brain-spinal interface to restore voluntary gait control after a spinal cord injury.

### Robotic postural neuroprosthesis

Novel robotic postural neuroprosthesis to evaluate, enable, and train locomotion under natural walking conditions. The amount of support can be fine-tuned for each axis according to the animals' capacity.



### Ultra-compliant microelectrode array

This 18 electrodes array is 14mm wide. Such arrays conform to complex, curvilinear biological tissues, such as the brain or the spinal cord, and move along with the tissue. The array is manufactured using standard microfabrication technology with thin gold film and silicone rubber.

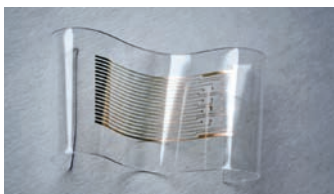
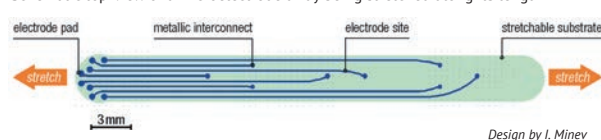


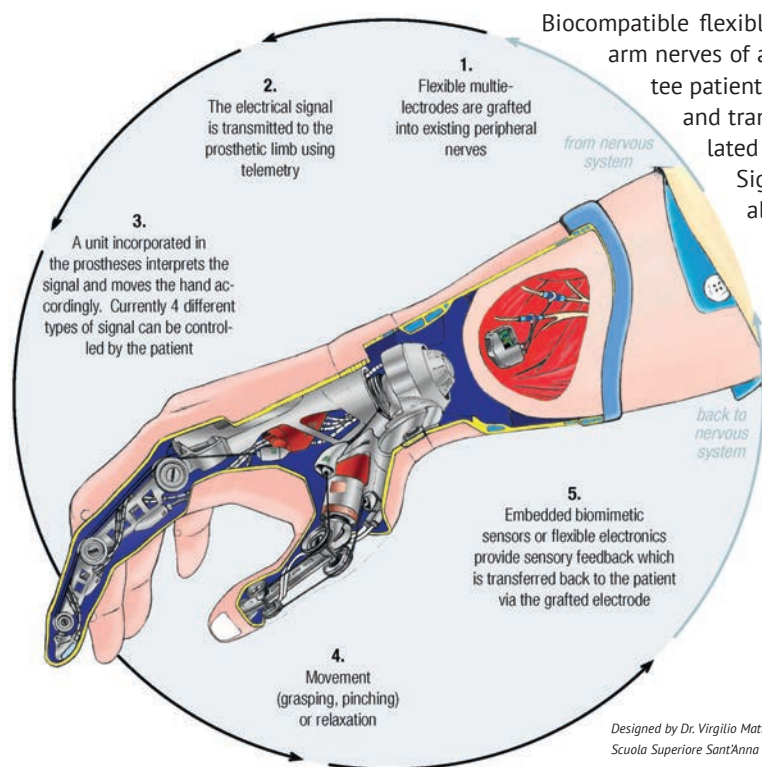
Photo A. Cyganowski

Schematic top-view of a microelectrode array being stretched along its length



# Bionic hand

Restoring sensory and motor functions after arm or hand amputation



Biocompatible flexible electrodes are implanted into different peripheral arm nerves of amputee patients. Movement commands of the amputee patient are decoded from signals in the implanted electrodes and transmitted to the prosthetic hand, where they are translated into movements of the prosthetic hand and fingers. Signals from different sensors in the prosthetic hand can also be transmitted via the implanted electrodes to the peripheral nerve to enable sensory functions such as the sense of touch and of finger position.

Connecting a bionic arm directly to the peripheral nervous system of the arm.

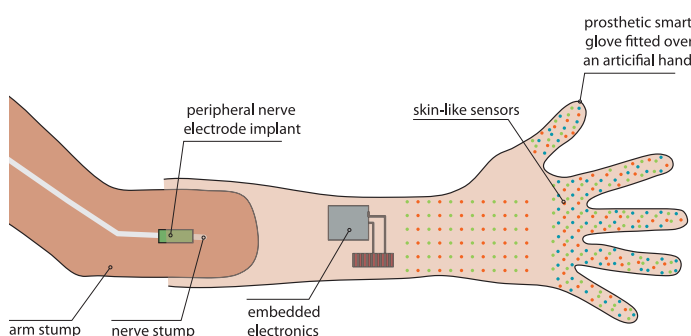
## Representation of real and prosthetic fingers in the brain

The finger representation in primary somatosensory cortex changes massively for the amputated arm and such changes have been shown to lead to phantom limb pain. Future prosthetic devices will be designed that control such brain changes in finger regions avoiding phantom limb pain and optimizing prosthetic hand's feelings and movement.



## An Electronic Skin

The future prosthetic arm will be covered by a sensitive polymer skin. Current challenges are to connect the peripheral nerve fibers to an electronic bio-extensible system and to integrate them into an elastic material capable of responding to biomechanical needs.



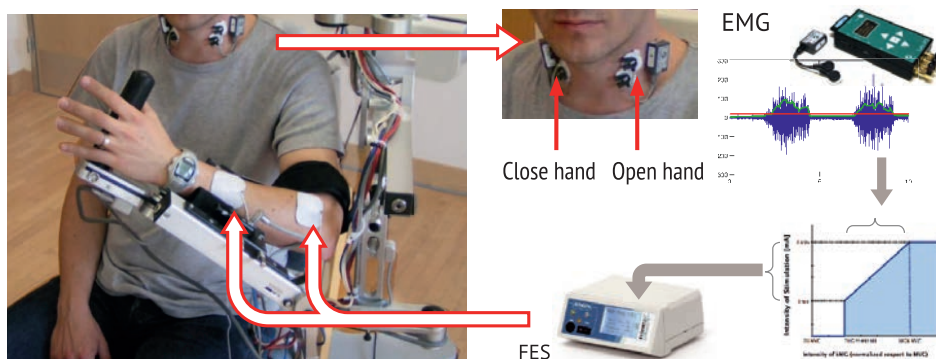
# Rehabilitation of upper limb sensorimotor loss

Providing neuro-technological tools for vascular stroke rehabilitation

Merging insights from robotics and neuroengineering, our devices enable novel neurorehabilitation training for patients suffering from sensorimotor loss of the upper extremity. These tools are complemented by techniques from brain computer interfaces and virtual reality to further enhance rehabilitation outcomes for patients with sensorimotor loss, but also for patients suffering from chronic pain or cognitive deficits.

## Hybrid tools for reaching and grasping rehabilitation

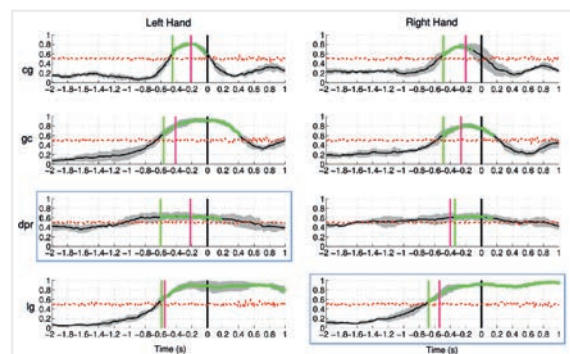
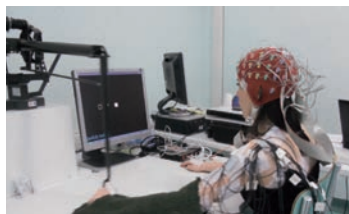
The system consists of a passive upper arm exoskeleton with gravity compensation, a 4-channel functional electrical stimulator (FES) and a wireless surface electromyographic system (EMG). The user controls the opening and closing of his/her own hand by selective activation of neck muscles (left and right sternocleidomastoid).



Stroke rehabilitation via hybrid devices.

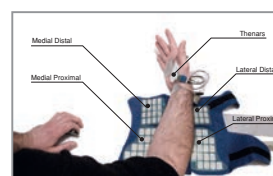
## Movement intention detection

EEG can be used for detecting the intention to make self-paced reaching movements. Our experiments with 12 human volunteers, two of them stroke patients, yield high sensitivity and specificity –i.e. high recognition rates close to the movement onset and low recognition rates during the rest period.



## Precise Neuro-Muscular Electrical Stimulation of hand and fingers

Our electrode arrays facilitate specific flexion and extension of the fingers and also control the wrist.



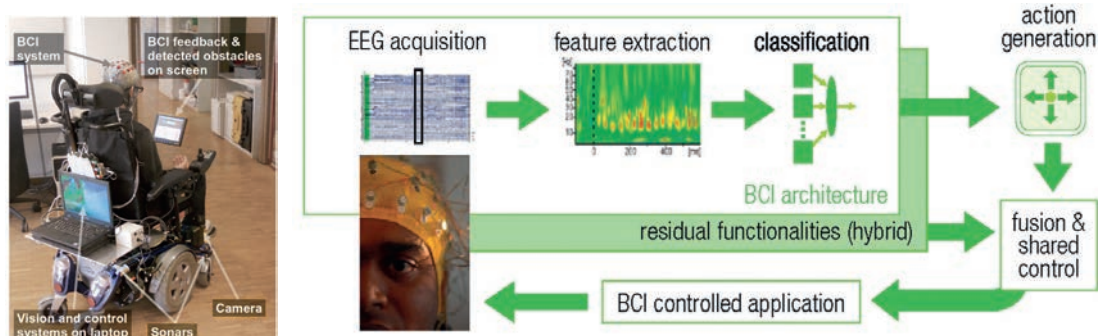


# Human-Computer confluence

## Decoding brain activity for feeling and moving artificial bodies and robots

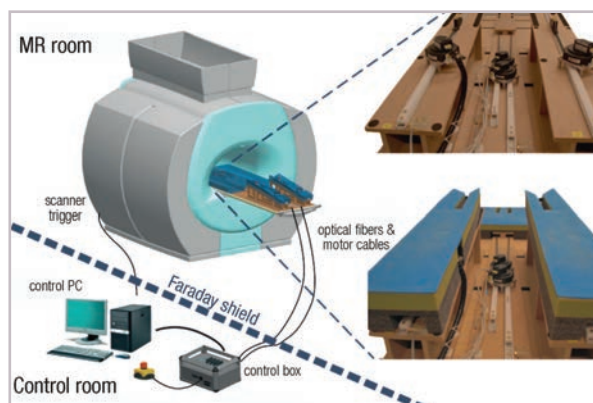
With robust real-time movement control of wearable devices and robots and with pioneering work in brain-machine interface and cognitive neuroscience, novel interaction paradigms are provided for mobility restoration, communication, neuroscience research, and entertainment.

### Non-Invasive Brain-Machine Interaction

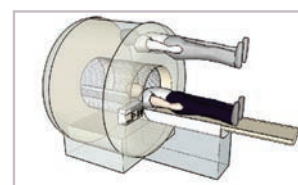


### Neuroscience, robotics and haptics: the brain mechanisms of feeling a virtual and robotic body as your own

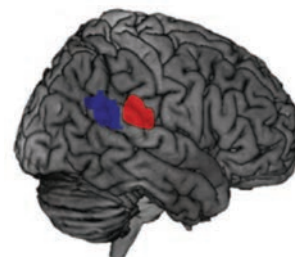
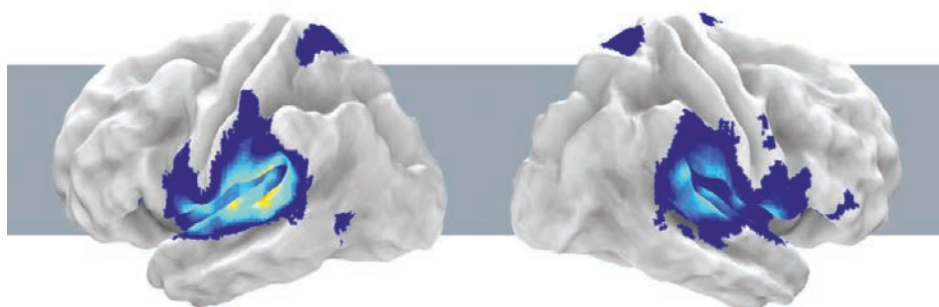
Custom made robotic devices allow us to control visuo-tactile stimulations for the induction of illusory body ownership during fMRI acquisition (including EPFL's ultra-high 7T MR-scanner).



Brain-based neuro-protheses that decode movement intentions and embody robotic and virtual devices.



Functional connectivity analysis reveals that, in addition to temporo-parietal activation, a distributed network is recruited during illusory body ownership and self-location.



Temporo-parietal activity reflects the experience of self-location (red). If the same area is damaged (blue), neurological patients have impairments in self-location.

Translational  
Neural Engineering  
Laboratory

# Micera Lab

<http://tne.epfl.ch>



Silvestro Micera

Silvestro Micera is Director of the Translational Neural Engineering Laboratory at the Center for Neuroprosthetics and the Institute of Bioengineering. He received the Laurea degree in Electrical Engineering from the University of Pisa and the PhD in Biomedical Engineering from the Scuola Superiore Sant'Anna. In 2009 he was the recipient of the "Early Career Achievement Award" of the IEEE Engineering in Medicine and Biology Society. Prof. Micera's research interests include the development of hybrid neuroprosthetic systems (interfacing the nervous system with artificial systems) and of mechatronic and robotic systems for function and assessment restoration in disabled and elderly persons.

## Introduction

The goal of the Translational Neural Engineering (TNE) Laboratory is to develop implantable neural interfaces and robotic systems to restore sensorimotor function in people with different kinds of disabilities (spinal cord injury, stroke, amputation, etc.). In particular, the TNE lab aim is to be a technological bridge between basic science and the clinical environment. Therefore, TNE novel technologies and approaches are designed and developed, also starting from basic scientific knowledge in the field of neuroscience, neurology and geriatrics, with the idea that better understanding means better development of clinical solutions.

## Keywords

Implantable neuroprostheses; rehabilitation robotics; wearable devices; neuro-controlled artificial limbs; reaching and grasping; locomotion; functional electrical stimulation.

## Results Obtained in 2012

In 2012, we have been working very actively to develop and bring to clinical practice several implantable neuroprostheses. In particular, we are currently working with the University Hospital of Geneva (Prof. Guyot) to develop and validate a novel neuroprosthesis to restore vestibular functions in disabled subjects. The TNE is responsible for the integration of the device, and the development of novel approaches to assess the performance of this device and collaborates on the clinical and neurophysiological characterization together with HUG clinical team.

We were also deeply involved in the activities led by Professor Courtine's team to develop a novel neuroprosthesis to restore locomotion using epidural electrical stimulation (EES). This activity produced a publication in Science co-authored by three TNE researchers. On this topic we have been responsible for the development on novel models to better understanding EES, of novel control strategies to improve the performance of EES, and in several experiments to characterize cortical activities using intracortical electrodes during locomotion.

In 2012, we also prepared all the devices and algorithms for the next implant in an amputee of intraneural electrodes, which will happen in Rome in 2013. This new experiment will open, for the first time, the possibility to develop a real-time bidirectional control of hand prostheses using intraneural peripheral electrodes. Finally, we develop a wearable system for functional electrical stimulation to restore grasping in highly disabled subjects. The system is currently in clinical testing in Italy.

## Selected Publications

Carpaneto J, Raos V, Umiltà MA, Fogassi L, Murata A, Gallese V, Micera S (2012). Continuous decoding of grasping tasks for a prospective implantable cortical neuroprosthesis. *J Neuroeng Rehabil*. 9:84.

Monaco V, Galardi G, Coscia M, Martelli D, Micera S (2012). Design and evaluation of NEUROBike: a neurorehabilitative platform for bedridden post-stroke patients. *IEEE Trans Neural Syst Rehabil Eng* 20(6):845-52.

Bassi Luciani L, Genovese V, Monaco V, Odetti L, Cattin E, Micera S (2012). Design and evaluation of a new mechatronic platform for assessment and prevention of fall risks. *J Neuroeng Rehabil*. 9:51.

Van den Brand R, Heutschi J, Barraud Q, DiGiovanna J, Bartholdi K, Huerlimann M, Friedli L, Vollenweider I, Moraud EM, Duis S, Dominici N, Micera S, Musienko P, Courtine G (2012). Restoring voluntary control of locomotion after paralyzing spinal cord injury. *Science* 336(6085):1182-5.

Raspopovic S, Capogrosso M, Badia J, Navarro X, Micera S (2012). Experimental validation of a hybrid computational model for selective stimulation using transverse intrafascicular multichannel electrodes. *IEEE Trans Neural Syst Rehabil Eng* 20(3):395-404.

Panarese A, Colombo R, Sterpi I, Pisano F, Micera S (2012). Tracking motor improvement at the subtask level during robot-aided neurorehabilitation of stroke patients. *Neurorehabil Neural Repair* 26(7):822-33.

Tombini M, Rigosa J, Zappasodi F, Porcaro C, Citi L, Carpaneto J, Rossini PM, Micera S (2012). Combined analysis of cortical (EEG) and nerve stump signals improves robotic hand control. *Neurorehabil Neural Repair* 26(3):275-81.

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## Team Members

### Associate Professor

Silvestro Micera

### Postdoctoral Fellows

Jack DiGiovanna

Stanisa Raspopovic

### PhD students

Marco Capogrosso (visiting)

Martina Coscia (visiting)

Andrea Crema

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### Research assistant

Federica Aprigliano

### Master students

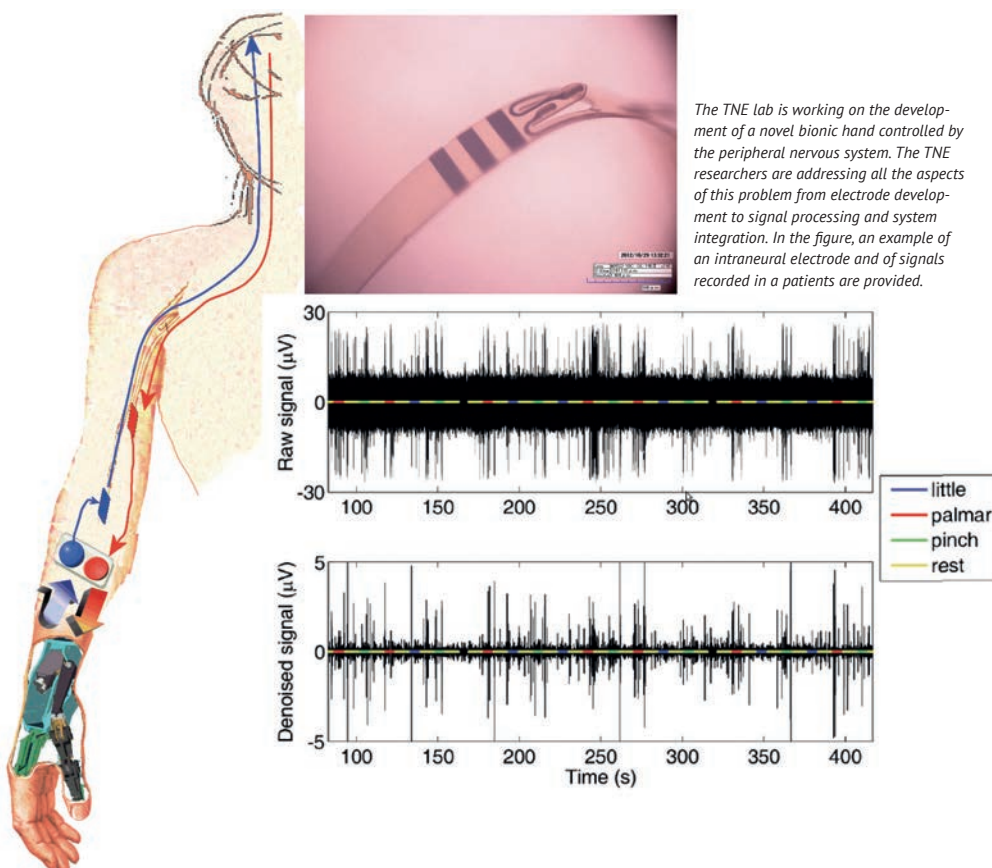
Florian Gothey

Edoardo D'Anna

Matteo Mancuso

### Administrative Assistant

Jennifer Dinkeldein



Bertarelli Foundation  
Chair in Cognitive  
Neuroprosthetics

# Blanke Lab

<http://lnco.epfl.ch>



Olaf Blanke



Olaf Blanke is Director of the Center for Neuroprosthetics at the Ecole Polytechnique Fédérale de Lausanne (EPFL), holds the Bertarelli Foundation Chair in Cognitive Neuroprosthetics, and is Professor of Neurology at the Department of Clinical Neurosciences at Geneva University Hospital. In his research, he applies paradigms from cognitive science, neuroscience, neuroimaging, robotics, and virtual reality in healthy subjects and neurological patients to understand and control neural own body representations, to develop a neurobiological model of self-consciousness, and to apply these findings in the emerging field of cognitive neuroprosthetics and neurorehabilitation.

## Introduction

The Laboratory of Cognitive Neuroscience targets the brain mechanisms of body perception, body awareness and self-consciousness. Projects rely on the investigation of healthy subjects and neurological patients by combining psychophysical and cognitive paradigms, state of the art neuroimaging techniques (fMRI, intracranial and surface EEG), and engineering-based approaches (virtual reality, vestibular stimulation, and robotic devices). For over a decade, stroke, epilepsy and psychiatric patients have been investigated, including invasive brain recordings, brain stimulation and brain imaging.

## Keywords

Multisensory and sensorimotor integration, neuroscience robotics, perception, temporo-parietal cortex, neuroimaging, fMRI, EEG, neuropsychology, neurology, virtual reality, vestibular system.

## Results Obtained in 2012

One of the major developments and results achieved in 2012 was the description of a method for mapping individual finger representations in the somatosensory cortex of the brain and of the cerebellum, using ultra-high field magnetic resonance imaging (Martuzzi et al., 2012; van der Zwaag et al., 2012). This method allowed us to define several distinct representations of each individual finger in the cortex and the cerebellum. Ongoing work extends these findings to the understanding of how these representations are altered in cases of phantom limb pain in amputee patients and patients suffering from paraplegia due to spinal cord injury.

In 2012 we also developed a novel system that integrates the technologies of virtual reality (VR) and brain computer interfaces (BCI) with cognitive neuroscience. Using automatized stimulation we induced ownership for virtual hands at unprecedented levels of control and described the involved electrophysiological brain mechanisms (Evans & Blanke, 2013). Additionally, the study showed that the experimentally-induced extension of ownership to virtual hands recruits highly similar brain mechanisms in fronto-parietal cortex as does motor imagery based BCI. We are currently extending this knowledge to VR- and BCI-based neuroprosthetics translating these insights to patients with limb amputation, limb paralysis following vascular stroke, and the evaluation of patients with invasive brain recordings.



## Selected Publications

Blanke O. Multisensory brain mechanisms of bodily self-consciousness (2012). *Nat Rev Neurosci* 13(8):556-571.

Aspell JE, Palluel E, Blanke O (2012b). Early and late activity in somatosensory cortex reflects changes in bodily self-consciousness: an evoked potential study. *Neuroscience* 216:110-122.

Evans N, Blanke O (2013). Shared electrophysiology mechanisms of body ownership and motor imagery. *Neuroimage* 64:216-228.

Ionta S, Sforza A, Funato M, Blanke O (2013). Anatomically plausible illusory posture affects mental rotation of body parts. *Cogn Affect Behav Neurosci* 13(1):197-209.

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Lopez C, Blanke O, Mast FW (2012). The human vestibular cortex revealed by coordinate-based activation likelihood estimation meta-analysis. *Neuroscience* 212:159-179.

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Van Elk M, Blanke O (2012). Balancing bistable perception during self-motion. *Exp Brain Res* 222(3):219-228.

Ionta S, Heydrich L, Lenggenhager B, Mouthon M, Fornari E, Chapuis D, Gassert R, Blanke O (2011). Multisensory mechanisms in temporo-parietal cortex support self-location and first-person perspective. *Neuron* 70(2):363-74.

Lopez C, Mercier MR, Halje P and Blanke O (2011). Spatiotemporal dynamics of visual vertical judgments: early and late brain mechanisms as revealed by high-density electrical neuroimaging. *Neuroscience* 181:134-49.

Lenggenhager B, Halje P and Blanke O (2011). Alpha band oscillations correlate with illusory self-location induced by virtual reality. *J Neurosci* 33(10):1935-43.

## Team Members

### Professor

Olaf Blanke

### Postdoctoral Fellows

Anna Brooks (visiting)  
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Bruno Herbelin  
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Noriaki Kanayama  
Joan Llobera Mahy  
Roberto Martuzzi  
Estelle Palluel  
Mickael Peer (visiting)  
Mario Prsa  
Roy Salomon  
Andrea Serino  
Michiel Van Elk

### PhD students

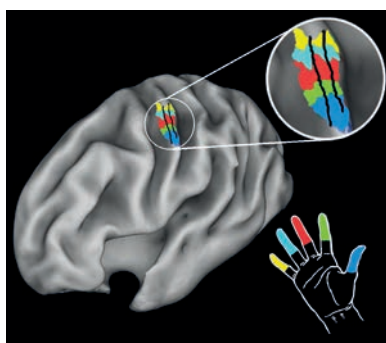
Michel Askelrod  
Steve Berger  
Nathaniel Evans  
Joachim Forget  
Steven Gale  
Danilo Jimenez Rezende  
Mariia Kaliuzhna  
Silvia Marchesotti  
Christian Pfeiffer  
Polona Pozeg  
Giulio Rognini  
Daniele Romano (visiting)  
Ali Sengul

### Master students

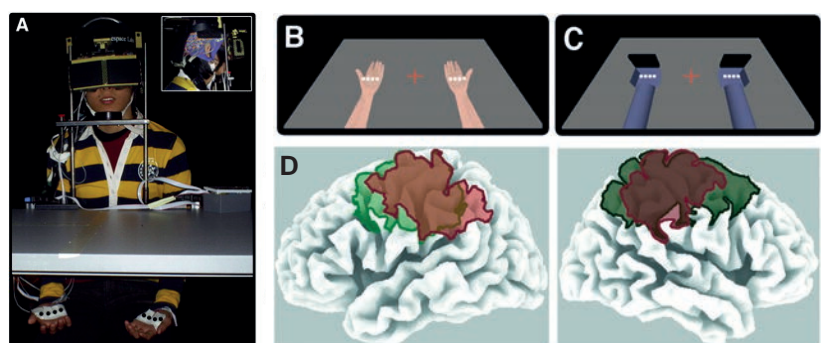
Petr Macku  
Jean-Paul Noel (visiting)  
Ludovica Visciòla  
Maria-Efstratia Tsimpanouli

### Administrative Assistant

Kokorus Gordana



Schematic representation of single finger maps within human primary somatosensory cortex, as obtained using ultra-high field functional magnetic resonance imaging.



A. Experimental setup for inducing illusory hand ownership in an automated, computer-controlled manner using virtual reality while recording 64-channel EEG. B. Participants saw either stereoscopic virtual arms or C, virtual non-body objects. D. Anatomical overlap of fronto-parietal activation during illusion condition (red) and motor imagery (green).

# Lacour Lab

<http://lsbi.epfl.ch>

Bertarelli Foundation  
Chair in  
Neuroprosthetic  
Technology



Stéphanie P. Lacour



Prof. Stéphanie P. Lacour holds the Bertarelli Foundation Chair in Neuroprosthetic Technology at the School of Engineering at the Ecole Polytechnique Fédérale de Lausanne. She received her PhD in Electrical Engineering from INSA de Lyon, France, and completed postdoctoral research at Princeton University (USA) and the University of Cambridge (UK). Her research focuses on the materials, technology and integration of soft bioelectronic interfaces including artificial skin, ultra-compliant neural electrodes for in vitro platforms as well as in vivo implants.

## Introduction

The Laboratory for Soft Bioelectronics Interfaces (LSBI) explores how to shape traditionally rigid electronic circuits into conformable, skin-like formats. Our mission is to engineer and implement novel materials and technologies overcoming the “hard to soft” mechanical mismatch between man-made devices and biological tissues in order to provide improved biocompatibility and enhanced functionality of these hybrid interfaces.

## Keywords

Microelectrode arrays, neural interfaces, stretchability, sensory neurons, neuroprosthesis, tactile sensors, polymers, thin films, biocompatibility, thin film electronics, micro nanofabrication.

## Results Obtained in 2012

Over the last decade, considerable efforts have been spent in developing integrated prosthetic limbs that can restore significant motor functions of the natural limb. One of the remaining challenges to produce prosthetic limbs that would “feel” like the natural limb is to integrate in those mechanical prostheses the sensory feedback embedded in the skin. The LSBI explores novel materials and technological routes to design, manufacture and implement artificial skins, i.e. large-area, compliant surfaces capable to tactile monitoring combined with polymeric neuroprosthetic interfaces.

*Tactile sensory skin:* in 2012, we have optimized the design of a skin-like substrate, which can host microfabricated tactile sensor circuits. The engineered substrates can stretch and relax reversibly like human skin yet provide “safe” mechanical platforms for the most fragile electronic devices. The substrate is made of elastomers and photosensitive plastics. We have also developed the technology to produce ultra-compliant pressure microensors made of elastomeric microcellular polymers and thin film metalization. The sensors have unique conformability and can be tuned to detect the lightest touch but also full weight body load.

*Polymeric neural interfaces:* in vitro, we are testing the hypothesis that the behavior of cells may be altered by modulating the local mechanical microenvironment at the surface of an implant. In vivo, we are developing a range of neural electrodes embedded in soft polymers. We have produced first prototypes of flexible auditory brainstem implants, stretchable spinal cord electrode implants and nerve-like regenerative electrode implants. Acute and chronic evaluation of the neural interfaces is on-going.

## Selected Publications

Lacour SP (2013). Stretchable thin-film electronics. In *Stretchable Electronics*, T. Someya Ed. Chapter 4:81-110.

Granger N, Chew D, Fairhurst P, Fawcett JW, Lacour SP, Craggs M, Mosse CA, Donaldson N, Jeffery ND (2013). Use of an implanted sacral nerve stimulator to restore urine voiding in chronic paraplegic dogs. *Journal of Veterinary Internal Medicine* 27(1):99-105.

Delivopoulos E, Chew D, Minev IR, Fawcett JW, Lacour SP (2012). Concurrent recordings of bladder afferents from multiple nerves using a microfabricated PDMS microchannel electrode array. *Lab on Chip* 12:2540-2551.

Huang YY, Terentjev E, Oppenheim T, Lacour SP, Welland ME (2012). Fabrication and electromechanical characterization of near-field electrospun composite fibers. *Nanotechnology* 23:105305.

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FitzGerald JJ, Lago N., Benmerah S, Serra J, Watling CP, Cameron RE, Tarte E, Lacour SP, McMahon SB and Fawcett JW (2012). A regenerative microchannel neural interface for recording from and stimulating peripheral axons in vivo. *Journal of Neural Engineering* 9:016010.

Minev IR, Chew DJ, Delivopoulos E, Fawcett JW and Lacour SP (2012). High sensitivity recording of afferent nerve activity using ultra-compliant microchannel electrodes: an acute in vivo validation. *Journal of Neural Engineering* 9:026005.

Lacour SP, Graz IM, Bauer S, Wagner S (2011). Elastic components for prosthetic skin. *Conf Proc IEEE Eng Med Biol Soc* 2011 8373-6.

## Team Members

### *Tenure Track Assistant Professor*

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*Ultra-compliant microelectrode array designed to fit and accommodate movement of the spinal cord (courtesy Ivan Minev).*

# Millán Lab

<http://cnbi.epfl.ch>

Defitech Foundation  
Chair in Non-invasive  
Brain-machine  
Interface



José del R. Millán



Prof. José del R. Millán holds the Defitech Chair at the École Polytechnique Fédérale de Lausanne (EPFL) where he explores the use of brain signals for multimodal interaction and, in particular, the development of non-invasive brain-controlled robots and neuroprostheses. In this multidisciplinary research effort, Dr. Millán is bringing together his pioneering work on the two fields of brain-computer interfaces and adaptive intelligent robotics. His research on brain-computer interfaces was nominated finalist of the European Descartes Prize 2001 and he has been named Research Leader 2004 by the journal Scientific American for his work on brain-controlled robots. He is the recipient of the IEEE Nobert Wiener Award 2011 for his seminal and pioneering contributions to non-invasive brain-computer interfaces. The journal Science has reviewed his work as one of the world's key researchers in the field of brain-computer interfaces. Dr. Millán is the coordinator of a number of European projects on brain-computer interfaces and also is a frequent keynote speaker at international meetings. His work on brain-computer interfaces has received wide scientific and media coverage around the world.

## Introduction

The Chair in Non-Invasive Brain-Machine Interface laboratory (CNBI) carries out research on the direct use of human brain signals to control devices and interact with our environment. In this multidisciplinary research, we are bringing together our pioneering work on the two fields of brain-machine interfaces and adaptive intelligent robotics. Our approach to design intelligent neuroprostheses balances the development of prototypes, where robust real-time operation is critical, and the exploration of new interaction principles and their associated brain correlates. A key element at each stage is the design of efficient machine learning algorithms for real-time analysis of brain activity that allow users to convey their intents rapidly, on the order of hundred milliseconds. Our neuroprostheses are explored in cooperation with clinical partners and disabled volunteers for the purpose of motor restoration, communication, entertainment and rehabilitation.

## Keywords

Brain-computer interfaces, Neuroprosthetics, Statistical machine learning Human-robot interaction, Adaptive robotics, Neuroscience, EEG, mental imagery.

## Results Obtained in 2012

A major highlight of 2012 was the final stretch of the TOBI project (Tools for brain-computer interaction) we have been coordinating since 2008. This project, financed by the European Commission, focused on the design of non-invasive brain-machine interfaces that can be combined with existing assistive technologies and rehabilitation practices. Remarkably, an important aspect of the project was to allow potential end-users to test these devices either at the involved research laboratories or at rehabilitation centers. More than 100 users suffering from motor impairments -due to stroke, spinal cord injury or neurodegenerative diseases- tested the designed prototypes (Carlson et al., 2012a, 2012b). Thus providing us an important assessment of the current status of our research field and insights onto the path to follow for further improvements both at the academic and industrial level. The latest results of the project were presented during a scientific workshop we organized in January 2013 in Sion. During this event, end-users publicly demonstrated BCI systems for communication, motor rehabilitation and telepresence.

Moreover, we followed up our work on the development of robust approaches for neuroprosthetic devices. This implies going beyond the standard motor imagery tasks typically employed and focus on other types of signals. In particular, we are interested in brain correlates of cognitive processes that are naturally elicited while humans interact with their environment. Importantly, we have shown the feasibility of decoding some of these processes even if there is no observable behavior, as is the case for decoding intentions of movement (Lew et al., 2012), covert visual attention (Tonin et al., 2012) or decision making processes (Tzovara et al., 2012).



## Selected Publications

Lew E, Chavarriaga R, Silvoni S and Millán JdR (2012). Detection of self-paced reaching movement intention from EEG signals. *Frontiers in Neuroengineering* 5:13.

Tonin L, Leeb R and Millán JdR (2012). Time-Dependent Approach for Single Trial Classification of Covert Visuospatial Attention. *Journal of Neural Engineering* 9:045011.

Carlson TE and Millán JdR (2013). The Robotic Architecture of an Asynchronous Brain-Actuated Wheelchair. *IEEE Robotics and Automation Magazine*.

Tzovara A, Murray M, Bourdaud N, Chavarriaga R, Millán JdR and De Lucia M (2012). The timing of exploratory decision-making revealed by single-trial topographic EEG analyses. *Neuroimage* 4:1959-69.

Courtine G, Micera S, DiGiovanna J and Millán JdR (2013). Brain-machine interface: closer to therapeutic reality? *The Lancet* 381:515-7.

Roggen D, Lukowicz P, Ferscha A, Millán JdR, Tröster G and Chavarriaga R (2012). Opportunistic human activity and context recognition *IEEE Computer*.

Chavarriaga R, Sagha H, Calatroni A, Digumarti S, Tröster G, Millán JdR and Roggen D (2013). The Opportunity challenge: A benchmark database for on-body sensor-based activity recognition. *Pattern Recognition Letters*.

Carlson TE, Tonin L, Leeb R, Rohm M, Rupp R, Al-Khodairy A and Millán JdR (2012). BCI Telepresence: A Six Patient Evaluation. *TOBI Workshop III: Bringing BCIs to End-Users: Facing the Challenge*, Würzburg, Germany, March 20-22.

Carlson TE, Leeb R, Monnard G, Al-Khodairy A and Millán JdR (2012). Driving a BCI Wheelchair: A Patient Case Study. *TOBI Workshop III: Bringing BCIs to End-Users: Facing the Challenge*, Würzburg, Germany, March 20-22.

Khaliliardali Z, Chavarriaga R, Gheorghe LA and Millán JdR (2012). Detection of Anticipatory Brain Potentials during Car Driving. *The 34th Annual International Conference of the Engineering in Medicine and Biology Society*, San Diego, USA, Aug 28-Sep 1.

## Team Members

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### Postdoctoral Fellows

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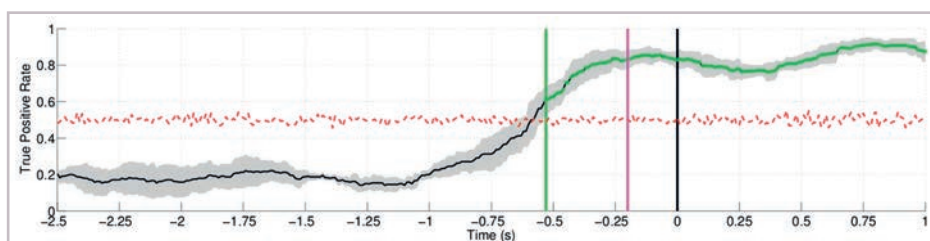
Abdolreza Madi

### Administrative Assistant

Najate Gechoul



A volunteer end-user demonstrates our prototype for BCI-controlled functional electrical stimulation. This prototype enables a stroke patient to voluntarily control the movement of a paralyzed limb. Preliminary results have shown that intensive training using this system has allowed the patients to regain control of their limb.



Decoding movement intentions in a stroke patient (Lew et al., 2012). The plot shows that brain signals provide information about the intention of movement (green vertical line) before any measurable muscular activity and up to 500 ms before the actual action starts (magenta and black lines, respectively).

# Courtine Lab

<http://courtine-lab.epfl.ch>



Grégoire Courtine



Grégoire Courtine was trained in Mathematics and Physics, but received his PhD in Experimental Medicine from the Inserm Plasticity and Repair, France, in 2003. After a Post-doctoral training at Los Angeles (UCLA), he established his own laboratory at the University of Zurich in 2008. In December 2011, he accepted the International paraplegic foundation (IRP) chair in spinal cord repair in the Center for Neuroprosthetics at the EPFL. He received numerous honors such as the UCLA Chancellor's award, the Schellenberg Prize for his advances in spinal cord repair, and a fellowship from the European Research Council (ERC). Several of his works received substantial coverage in the national and international media.

## Introduction

There are over 3,000 persons living with a spinal cord injury (SCI) in Switzerland, and several million worldwide. SCI leads to a range of disabilities that seriously diminish the patient's quality of life. Over the past 15 years, we implemented an unconventional research program with the aim to develop radically new treatment paradigms to restore sensorimotor functions in severely paralyzed people. Our therapeutic interventions are developed in rodents and optimized in non-human primates, but clinical trials are in the implementation phase.

## Keywords

Spinal cord injury, neural repair, neurorehabilitation, neuroprosthetics, brain-machine interface, robotic, neuronal recordings, optogenetic, EMG, kinematic, locomotion, neuromorphology, mice, rats, monkeys, humans.

## Results Obtained in 2012

Over the past 10 years, we have developed, methodically, a series of neuroprosthetic technologies to enable motor control after neuromotor disorders. This includes an electrochemical spinal neuroprosthesis to transform lumbosacral circuits from non-functional to highly functional networks, and a robotic postural neuroprosthesis to establish optimal conditions of balance and support during rehabilitative training. In 2012, we introduced a treatment paradigm that combined all these neuroprosthetic technologies. We showed that rats with a spinal cord injury, leading to complete and permanent paralysis, regained supraspinal control over complex locomotor movements. Anatomical evaluations revealed that training encouraged the brain to elaborate a multiplicity of alternative pathways to regain access to the denervated spinal locomotor circuits. No previous interventions restored voluntary locomotor movements after a paralyzing SCI.

Our objective is to translate these discoveries from rodents to a viable intervention for humans. To achieve this, we have gathered a highly multidisciplinary and synergistic team of advanced basic and clinical investigators at the EPFL and the CHUV. Through this network, we have developed an electrochemical spinal neuroprosthesis uniquely fitted to the human spinal cord, and robotic systems for rehabilitation of subjects with impaired gait. Upon validation by the ethical boards, these new technologies will be tested in spinal cord injured individuals. In parallel, we have established an advanced non-human primate model that will allow us to demonstrate the efficacy and safety of our interventions. Our aim is to prepare the second phase of clinical trials with refined neuroprosthetic technologies. We anticipate that 2013 will be a year full of new, exciting discoveries.

## Selected Publications

Courtine G, Micera S, Digiovanna Millán JdR (2013). Brain-machine interface: closer to therapeutic reality? *Lancet* 381:515-7.

Van den Brand R, Heutschi J, Barraud Q, Digiovanna J, Bartholdi K, Huerlimann M, Friedli L, Vollenweider I, Martin Moraud E, Duis S, Dominici N, Micera S, Musienko PE, Courtine G (2012). Restoring voluntary control of locomotion after paralyzing spinal cord injury. *Science* 336:1182-1185.

Dominici N, Keller U, Vallery H, Friedli L, van den Brand R, Starkey ML, Musienko P, Riener R, Courtine G (2012). Novel robotic interface to evaluate, enable, and train locomotion and balance after neuromotor disorders. *Nature Medicine* 18:1142-7.

Horst M, Heutschi J, van den Brand R, Andersson KE, Gobet R, Sulser T, Courtine G, Eberli D (2013). Multisystem Neuroprosthetic Training Improves Bladder Function After Severe Spinal Cord Injury. *J Urol.* 189:747-53.

Musienko P, Courtine G, Tibbs JE, Kilimnik V, Savochin A, Garfinkel A, Roy RR, Edgerton VR, Gerasimenko Y (2012). Somatosensory control of balance during locomotion in decerebrated cat. *Journal of Neurophysiology* 107:2072-2082.

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Nout YS, Ferguson AR, Strand SC, Moseanko R, Hawbecker S, Zdunowski S, Nielson JL, Roy RR, Zhong H, Rosenzweig ES, Brock JH, Courtine G, Edgerton VR, Tuszynski MH, Beattie MS, Bresnahan JC (2012). Methods for Functional Assessment After C7 Spinal Cord Hemisection in the Rhesus Monkey. *Neuro-rehabilitation and Neural Repair* 26:556-69.

Nout YS, Rosenzweig ES, Brock JH, Strand SC, Moseanko R, Hawbecker S, Zdunowski S, Nielson JL, Roy RR, Courtine G, Ferguson AR, Edgerton VR, Beattie MS, Bresnahan JC, Tuszynski MH (2012). Animal models of neurologic disorders: a nonhuman primate model of spinal cord injury. *Neurotherapeutics* 9:380-392.

Courtine G, van den Brand R, Musienko P (2011). Spinal cord injury: time to move. *Lancet* 377:1896-1898.

Musienko P, van den Brand R, Marzendorfer O, Roy RR, Gerasimenko Y, Edgerton VR, Courtine G (2011). Controlling specific locomotor behaviors through multidimensional monoaminergic modulation of spinal circuitries. *J Neuroscience* 31:9264-9278.

## Team Members

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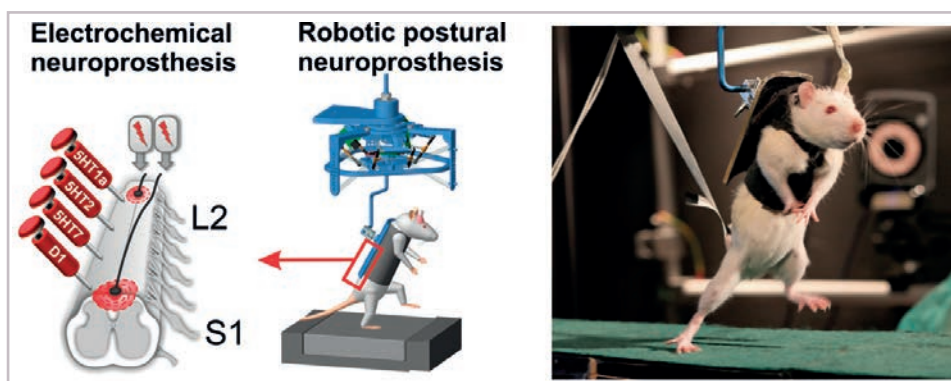
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Julie Kreider  
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Frédéric Michoud  
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Livio Ruzzante  
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A rat received a spinal cord injury leading to permanent paralysis. A robot-assisted training paradigm enabled by an electrochemical spinal neuroprosthesis restored supraspinal control over refined locomotion through the extensive and ubiquitous remodeling of neuronal pathways.

## Distinguished Lecture Series & Seminars

### Distinguished Lecture Series

Dr. Joseph E. O'Doherty  
**Bringing the world of touch to brain-machine interfaces**  
 Keck Center for Integrative Neuroscience, University of California, San Francisco, USA

May 2012

Dr. Adrian Guggisberg  
**Electrical network correlates of behavior and diseases**  
 Cognitive Neuro-Rehabilitation Laboratory, HUG, Geneva, Switzerland

May 2012

### Distinguished Lecture Series

Dr. Juan Aguilar  
**Spinal cord injury immediately changes the state of the brain**  
 Spanish National Paraplegic Hospital, Toledo, Spain

June 2012

Prof. Atam P. Dhawan  
**Emerging Biomedical Technologies of High Potential Impact: Brain Image Analysis and Tissue Characterization**  
 Electrical and Computer Engineering Department, NJIT, USA

July 2012

Dr. Amélie Bédier  
**Micro and nano-engineering for the control of neuronal cell growth and elaboration of a brain prosthesis**  
 LAAS-CNRS, Toulouse, France

September 2012

### Distinguished Lecture Series

Prof. Jose L. Contreras-Vidal  
**Neural Decoding of Movement from Slow Cortical Potentials**  
 Director, Laboratory for Noninvasive Brain-Machine Interface Systems  
 Professor of Electrical & Computer Engineering, University of Houston, USA

September 2012

Prof. Karim Fouad  
**Neuroplasticity following spinal cord injury in rats**  
 Faculty of Rehabilitation Medicine, University of Alberta (CA), USA

September 2012

Dr. Roy Mukamel  
**Neural signatures of voluntary actions and the perception of action consequences**  
 School of Psychological Sciences and Sagol, School of Neuroscience  
 Tel-Aviv, University, Israël

September 2012

Dr. Aaron Schurger  
**Spontaneous cortical activity and self-initiated movement**  
 INSERM-CEA Cognitive Neuroimaging Unit, France

October 2012

### Distinguished Lecture Series

Prof. George Malliaras  
**Organic Electronics at the Interface with Life Sciences**  
 Department of Bioelectronics, Centre Microélectronique de Provence, France

November 2012

### Distinguished Lecture Series

Prof. Tadashi Isa  
**Dissecting the compensatory mechanism after partial spinal cord injury**  
 National Institute for Physiological Sciences, Okazaki, Japan

November 2012

Prof. Dejan B. Popović  
**Functional electrical therapy (FET) for recovery of functions in individuals with disability**  
 Faculty of Electrical Engineering, Belgrade University, Belgrade, Serbia  
 Center for Sensory Motor Interaction, Aalborg University, Aalborg, Denmark

December 2012



# Teaching

Students enrolled in a master program at EPFL have the possibility to obtain an inter-faculty specialization in neuroprosthetics. This “Mineur” in neuroprosthetics covers the essential courses in neurosciences and neuroengineering in the field of neuroprosthetics, including medical applications. The programme is coordinated by Prof. José del R. Millán (School of Engineering, STI) and Prof Olaf Blanke (School of Life Sciences, SV).

Selected courses are ‘Neuroprosthetics’, ‘Fundamentals of Neuroengineering’, ‘Neurosciences I, II, III’, ‘Neuroscience for Engineers’, ‘Flexible bio-electronics’, and courses in biorobotics and computational neurosciences.

[http://cnp.epfl.ch/mineur\\_neuroprothese](http://cnp.epfl.ch/mineur_neuroprothese)



Photo Alain Herzog

## CNP Annual Retreat 2012



Photo Thuy Anh Khoa Nguyen

### 5-6th October 2012, Hotel Prealpina, Chexbres

In October the five CNP research labs (Blanke lab, Courtine lab, Lacour lab, Micera lab and Millán lab) gathered for the first time for their annual retreat in Chexbres. A total of 70 CNP collaborators with 35 PhD Students and 20 post-doctoral researchers and engineers shared their research findings and got to know each other, enjoying the sunny Lavaux vineyard terraces during the fall grape harvest.



The poster session was a tremendous success with 37 posters presentations. There were also five selected oral presentations: “Silicone based neural electrodes” by Dr. Ivan Minev (Lacour lab), “Spinal neuroprosthetic systems to restore locomotion after spinal cord injury” by Nikolaus Wenger (Courtine lab), “The brains behind locomotion” by Dr. Jack Di Giovanna (Micera lab), “The neuroscience of machine-controlled body ownership and agency” by Nathan Evans (Blanke lab), and “EEG-based decoding of cognitive-related signals” by Dr. Ricardo Chavarriaga (Millán lab).

*Front Cover:*

*Compliant microelectrode arrays prepared with elastic thin-film metallization and silicone rubber using photolithography and lift-off. Lacour laboratory  
(Photo Alain Herzog)*

*Layout : Myriam Forgeron*



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