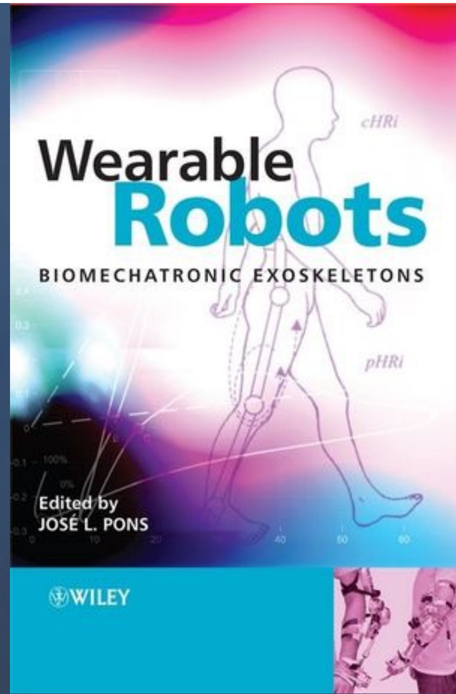
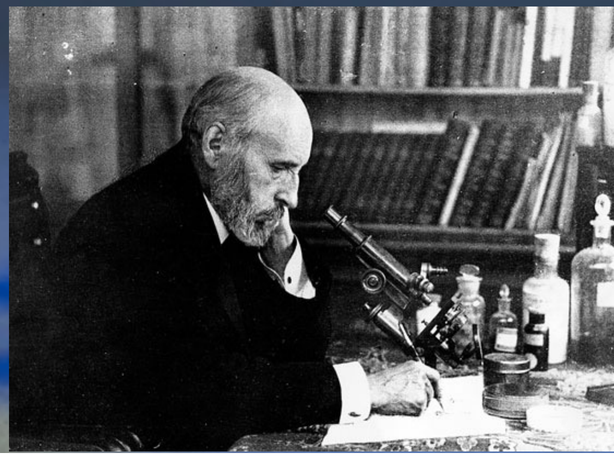
BIOMIMETISMO Y CONTROL EN EXOESQUELETOS PARA NEUROREHABILITATION

JOSÉ L. PONS

CURSO RESISTE 2016





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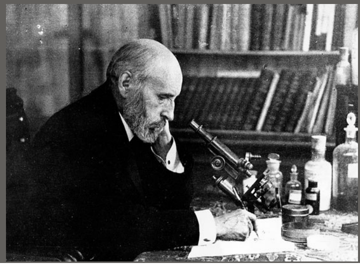
Outlook

Introduction

Motivation, constraints & interactions: hybrid systems

The concept of associative (or causal) rehabilitation

Clinical & Neurophysiological assessment



Introduction :: Motivation

- Neurological conditions leading to severe motor disorders:
  - CVA, 5.5 % of population, 770,000 new strokes annually in US
  - SCI, 800 per million
  - Cerebral Palsy, 2.8 per million
  - Tremor, up to 15% of people 50+

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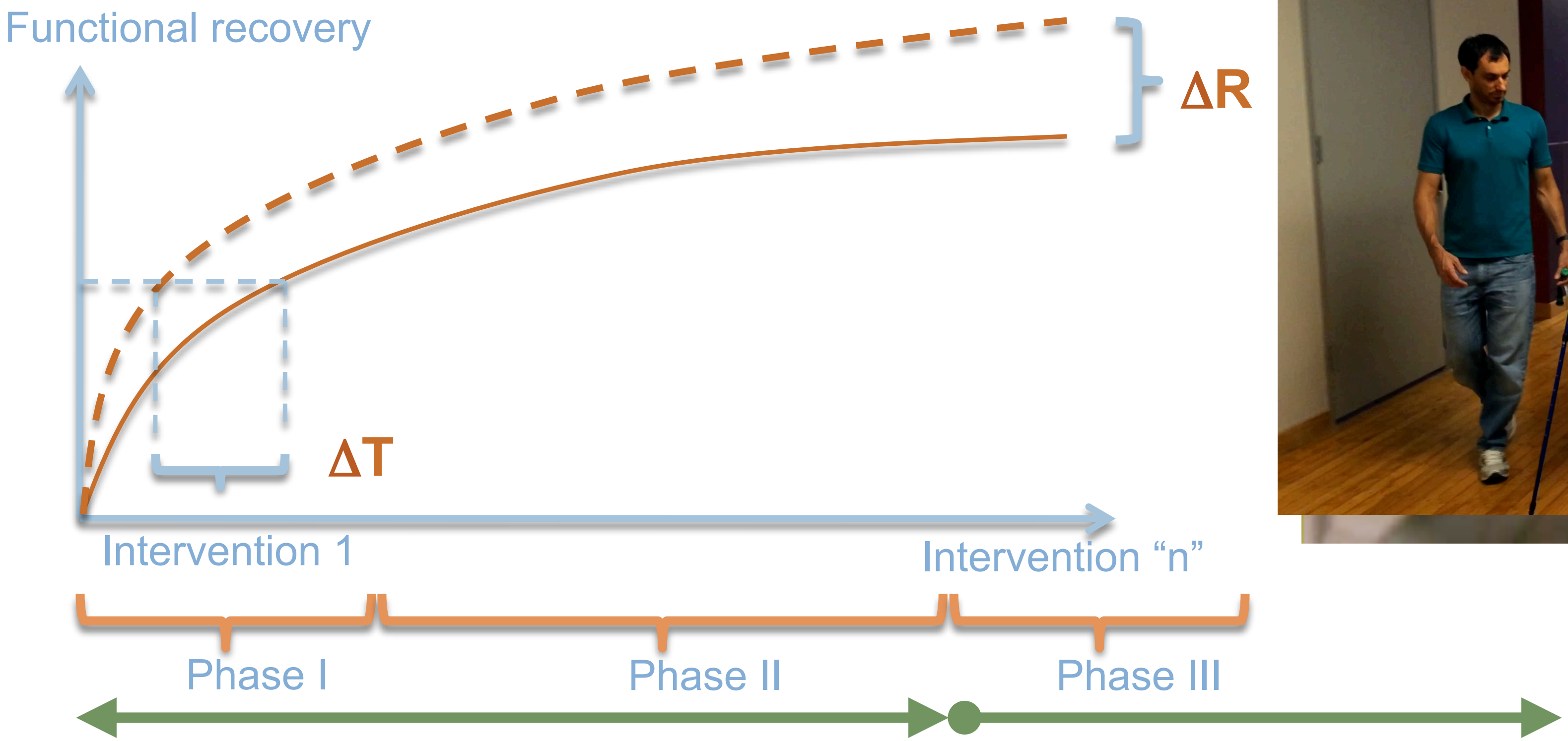
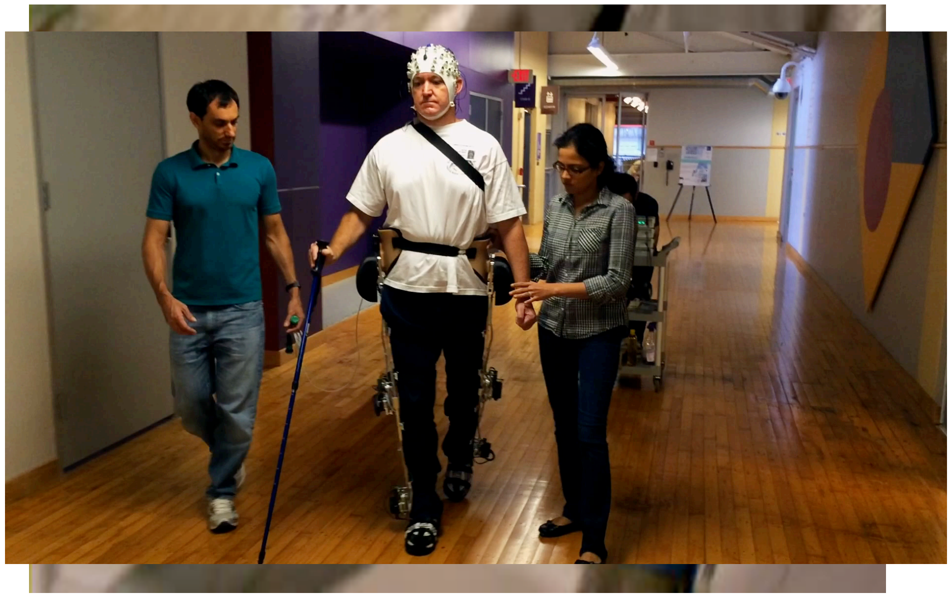
Introduction :: Motivation

- Stroke, SCI, CP…
- Stroke is a global social and health problem.
- Conventional therapy is in most cases insufficient to restore arm's functional capabilities (Langhorne et al. 2011).
- Novel therapies are needed to improve rehabilitation outcomes.

- **High-intensity repetitive task-specific practice might be the most effective principle when trying to promote motor recovery after stroke (Kwakkel et al. 2008)**

Introduction :: Rehabilitation vs. motor substitution

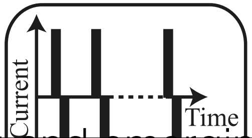




Introduction

- There is a strong evidence that the use of functional electrical stimulation **(FES) improve the reaching and grasping** function after stroke (Thrasher et al. 2009; Popovic et al. 2005).

- The uses of FES presents many advantages, but **there still are some issues** that must be addressed.



- **R** ... till **c**

- W ... of rehabilitation

FES for motor functions rehabilitation	
Advantages	**Disadvantages**
Muscles are used as actuator (preserve and restore muscle mass and function)	High metabolic cost (muscle fatigue)
Stimulate cortical reorganization	musculoskeletal behavior (nonlinear and time varying)

FES and robot can be combined (so-called Hybrid Systems) for rehabilitation to overcome some of these drawbacks.

Exoskeletons ::
Two incompatible mechanical systems

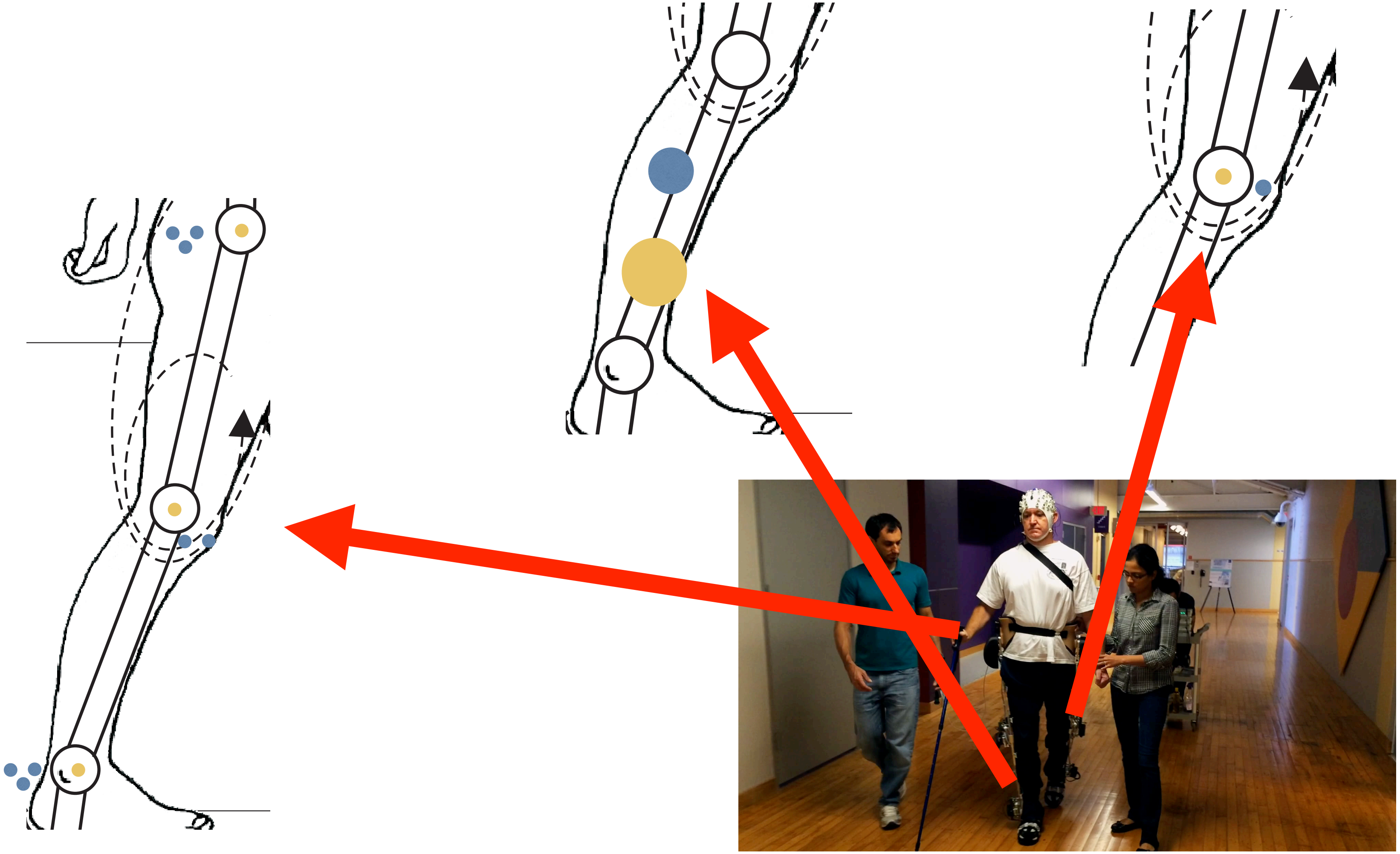
Kinematics

Dynamics

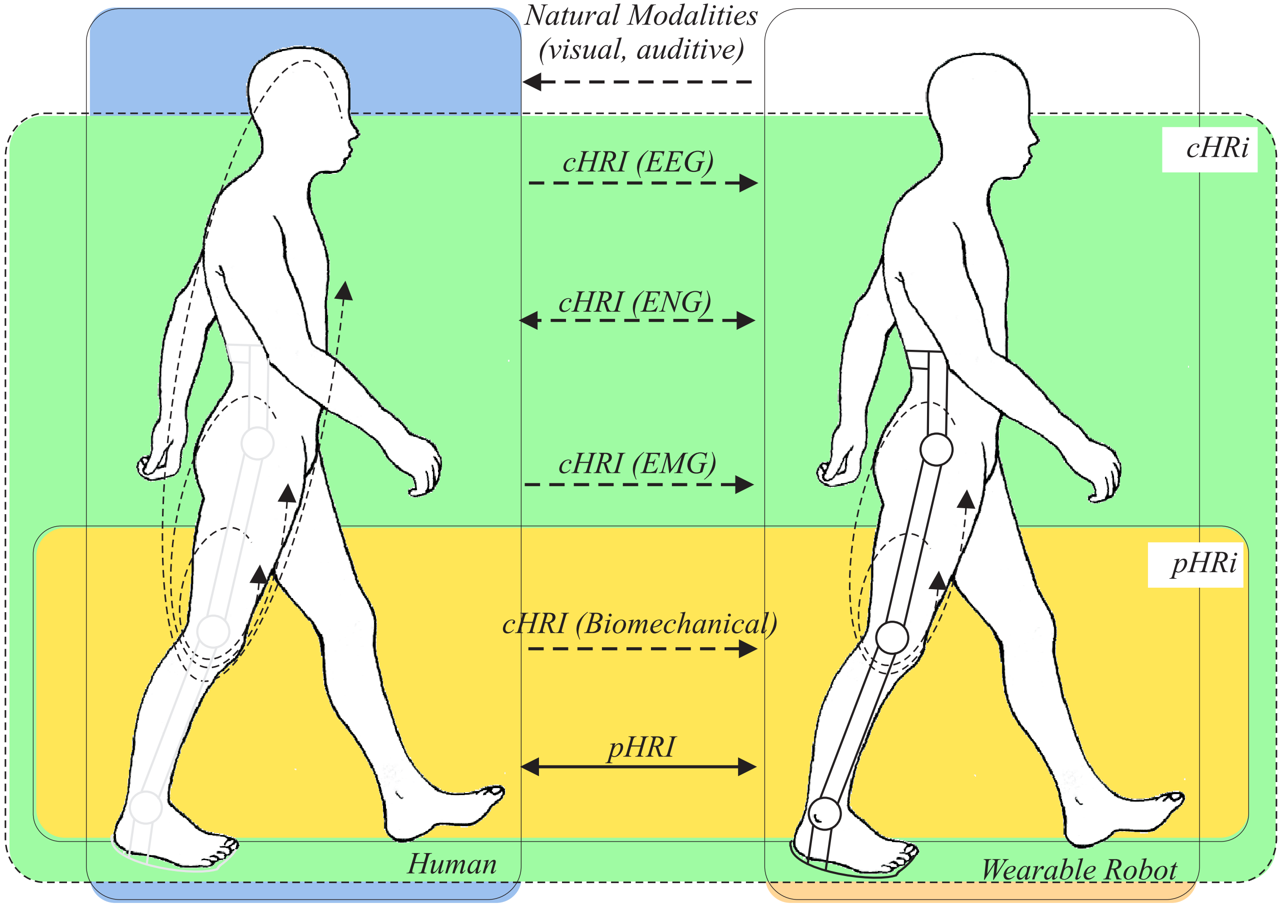
Motor Planning

Motor Coordination

Motor Execution



Introduction ::
Complex sensorimotor interactions



Pons (ed.), John Wiley, 2015

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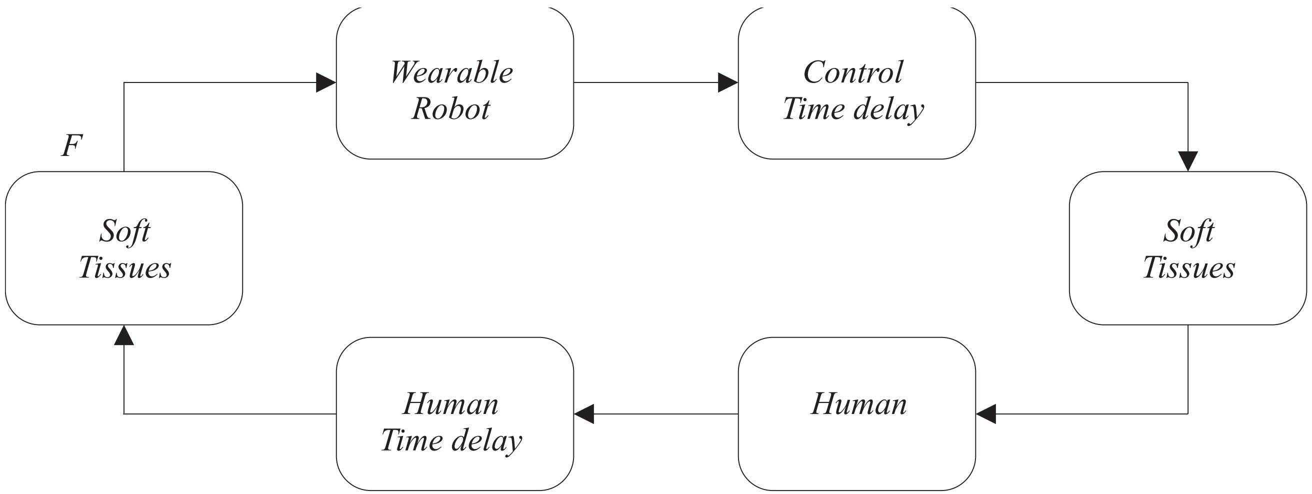
Complex sensorimotor interactions



Pons (ed.), John Wiley, 2015

Kinematics

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Introduction ::
Current SotA assistive WRs

Kinematics

Dynamics

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Introduction ::
WR with healthy volunteers

Kinematics

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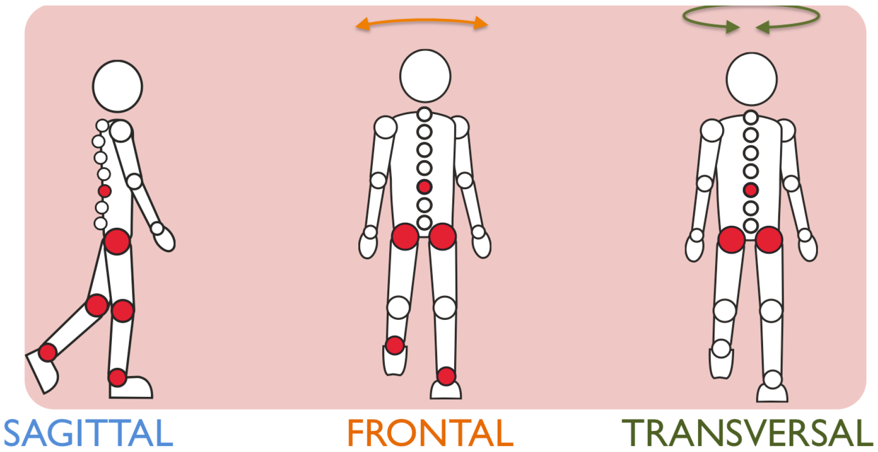

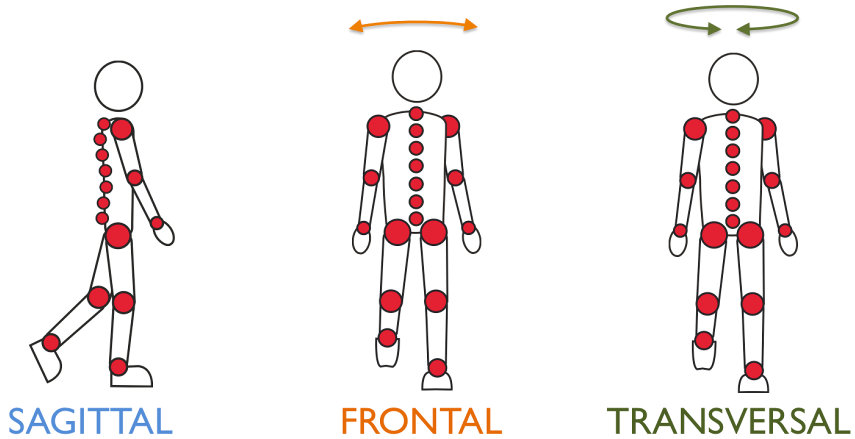

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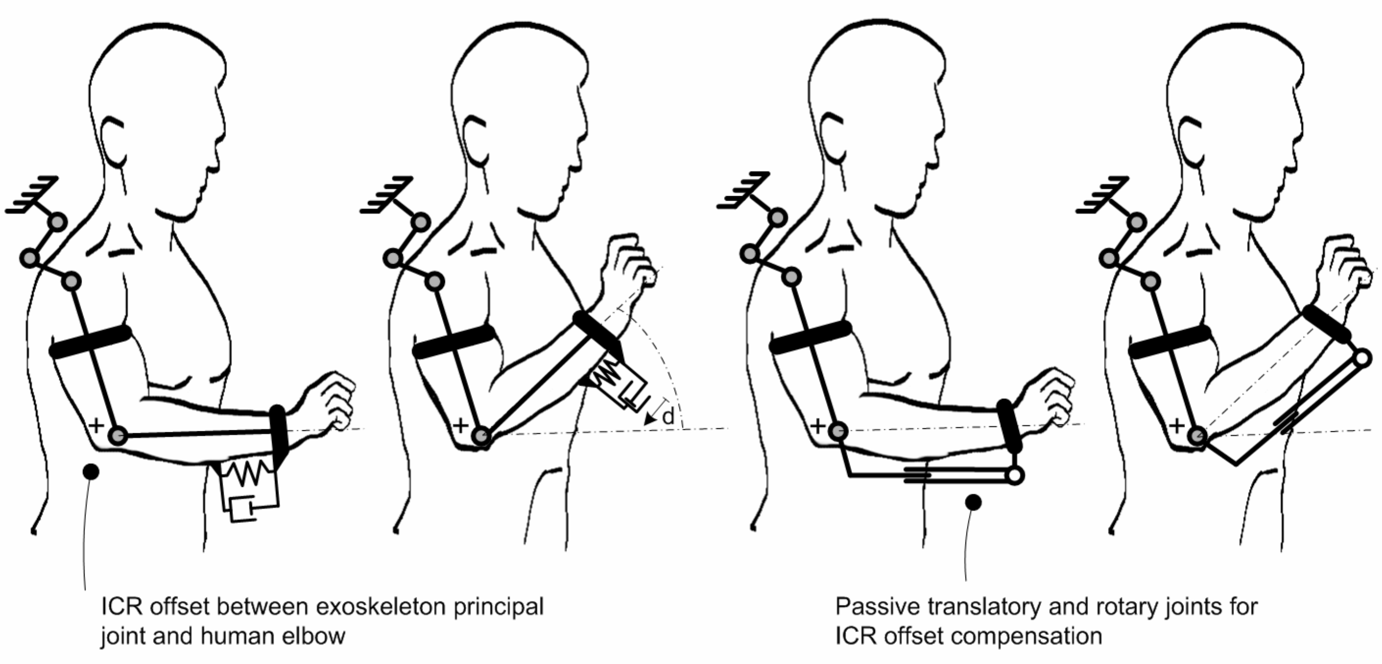

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Pons (ed.), John Wiley, 2015

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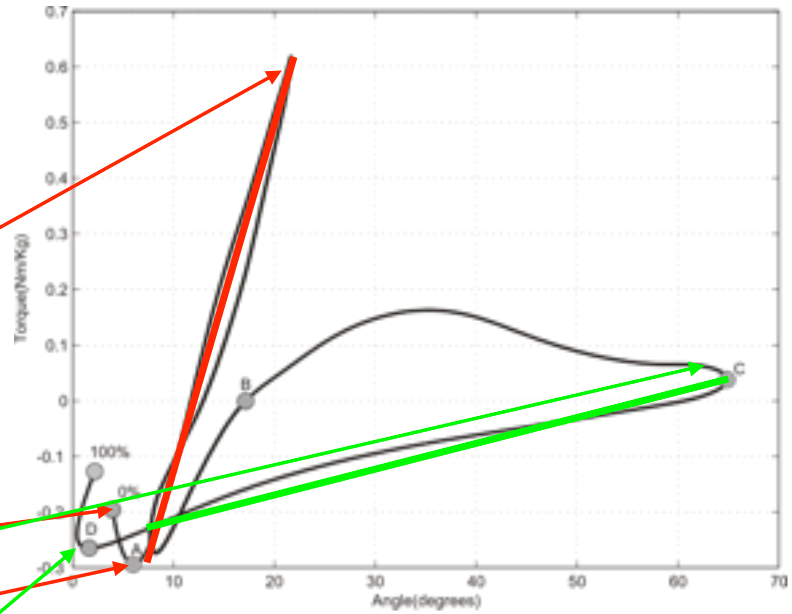

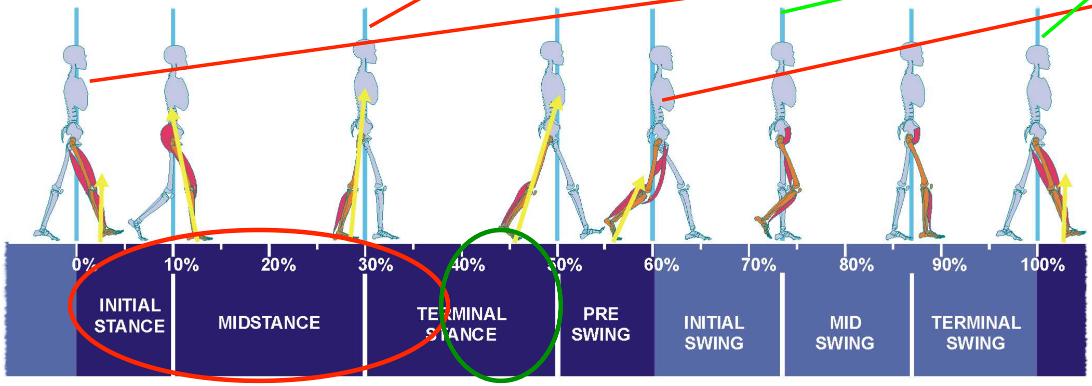

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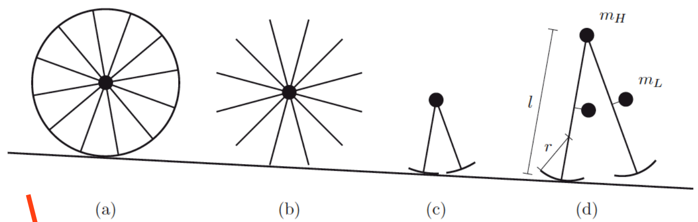
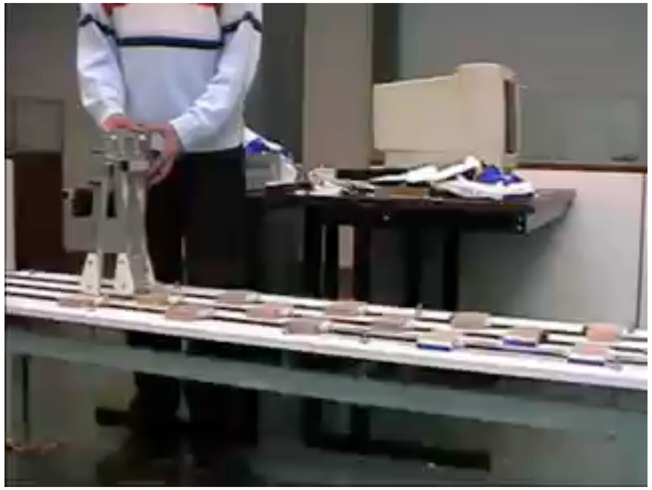
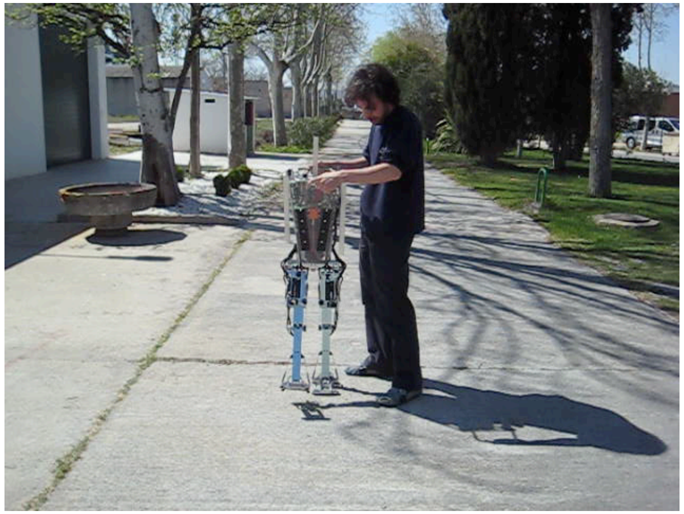
Cullell et al., Mech. Mach. Theory, 2009







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Pons (ed.), John Wiley, 2015

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Take Home Message

1. Two parallel mechanical multibody structures (human anatomic and WR structures) will ingeneral result in incompatible kinematics.
2. Kinematic incompatibility will restrict natural human kinematics and result in (inadmissible) interaction forces.
3. Either biologically inspired joints or redundant joints would reduce kinematic mismatch and improve acceptability.
4. The WR will alter dynamic parameters (added inertia, mass distribution) which will affect the passive dynamics and the efficiency of walking.
5. Current actuator technologies exhibit very dissimilar actuation properties when compared to human muscles (backdrivability, limited torque, reduced compliance…) which limit walking dynamics.

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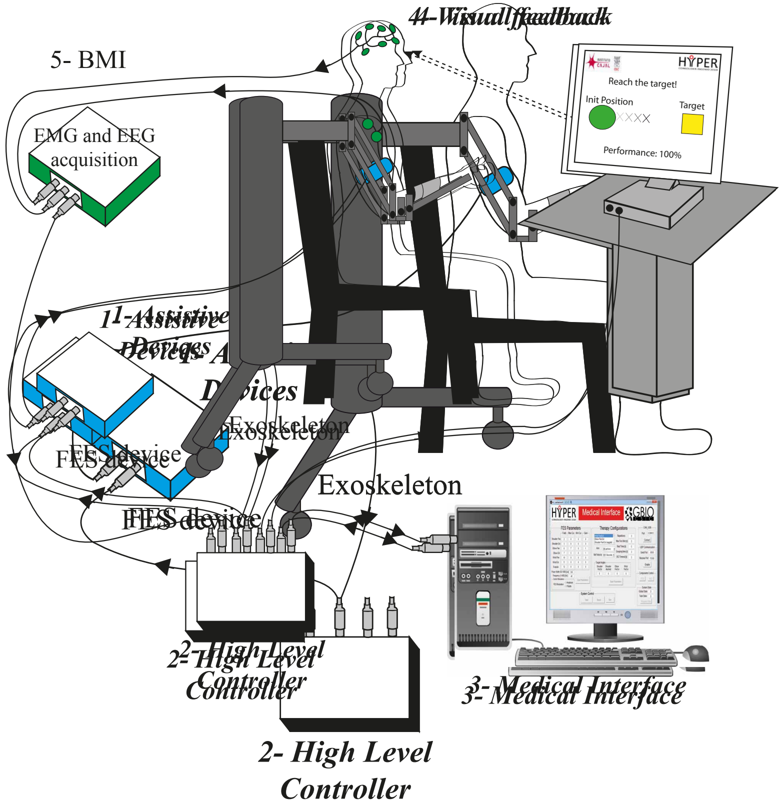
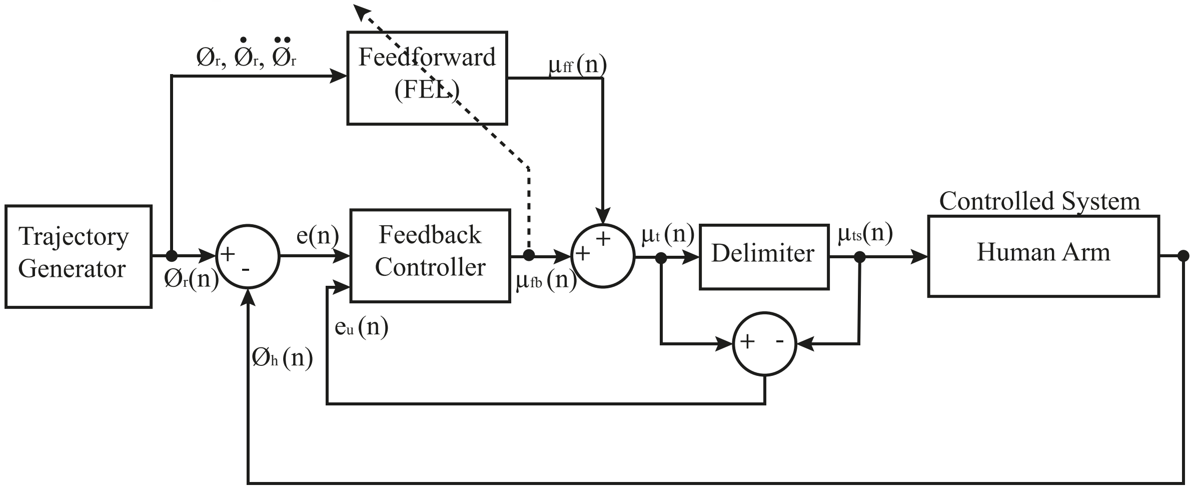
System Integration



- **Assistive Devices (Assistance)**
  - FES: movement assistance
  - Exoskeleton: arm weight compensation
- **High Level Controller (Adaptability)**
  - Real-time architecture for controlling the task execution
- **Configuration Interface & Visual Feedback (Accessibility and Engagement)**
- **EEG-based BMI (Association)**

Concept
FEL controller



The movement of the forearm and upper arm are independent of each other.

Two single-input, single-output (SISO) system.

Kinematics

Dynamics

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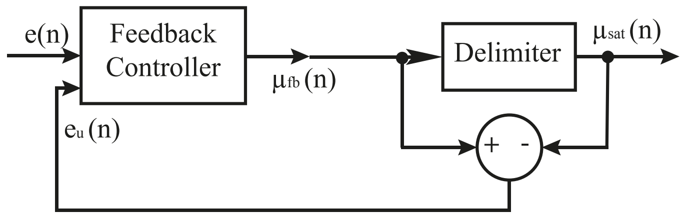
Feedback: Compensates for disturbances.

Feedforward: Learn the inverse dynamic of the musculoskeletal system by receiving as input the desired kinematic profile and using the output of the feedback loop as the correction parameter [Kawato 1989].

Implementation
FEL controller

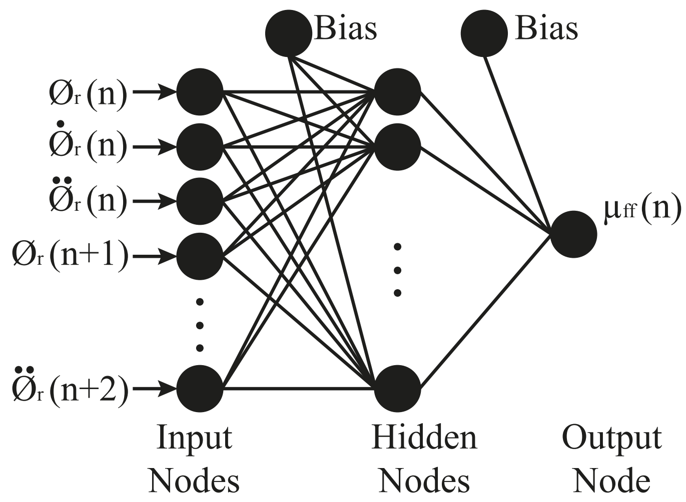
Feedback:

- PID, with anti-wind up.
- Positive output values generated muscle motor unit activations
- Negative output values were ineffective and could lead to windup the integral term, but they were required for the NN to learn.



Feedforward:

- Three-layer neural network (9 input, 9 hidden nodes, and 1 output node)
- The input and hidden layers had an additional bias node (value -1).
- Input was normalized in the range of - 1 to 1 to generate faster learning rates.
- The NN was trained using the gradient descent algorithm after each sample time.
- The NN weights were initialized with small random values close to zero.



Rehabilitation Platform
Example

Stroke Patients without EEG-informed interface

Stroke Patients with EEG-informed interface

Kinematics

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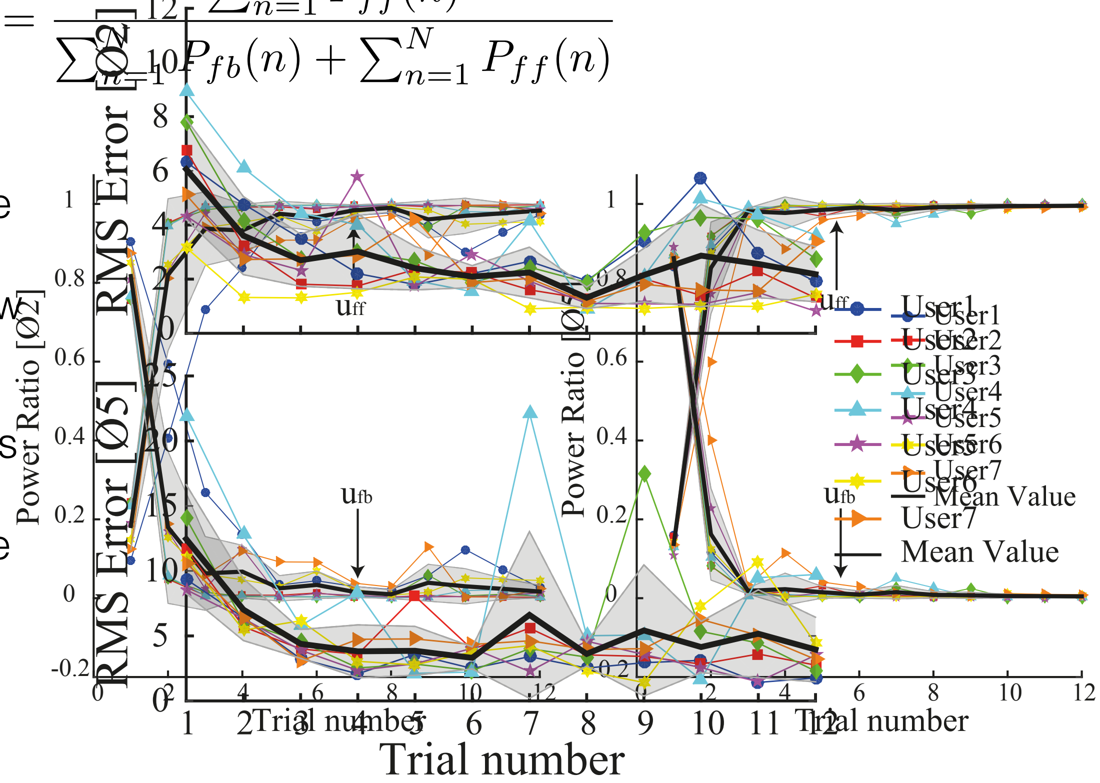
A. Root Mean Square error (RMS)

- Difference between the reference signal and the arm position for the shoulder (Ø2) and elbow (Ø5).
- The tracking accuracy is improved for both joints (shoulder & elbow)since the feedforward learns the inverse dynamic of the system.

B. Power Ratio (PR)

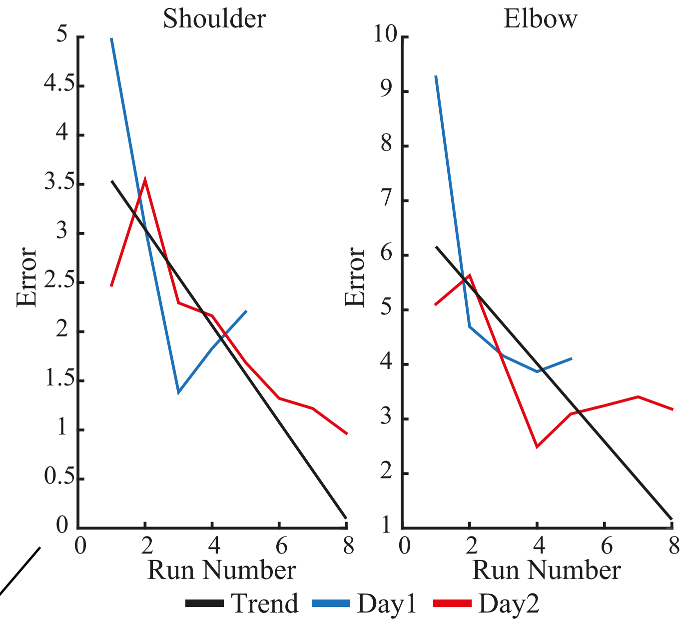
$$PR = \frac{\sum_{n=1}^{N} P_{ff}(n)}{\sum_{n=1}^{N} P_{fb}(n) + \sum_{n=1}^{N} P_{ff}(n)}$$

- Is the relation between the assistance provided by the feedforward (uff) and feedback loops (ufb).
- After some movement repetitions, the inverse dynamic of the system is learned and the movement is driven given by the feedforward loop.



A. Root Mean Square error (RMS)

- Movements were divided in runs (1 run = 8 mov).
- The RMS error for each run was calculated for each joint (shoulder -Ø2- & elbow -Ø5-).
- A best fitting linear regression was calculated (black line) to find the trend of the error.
- In both joint for day 1 (blue) and day 2 (red) there is a decreasing trend (negative slope).



	Shoulder		Elbow	
	Slope Day1	Slope Day2	Slope Day1	Slope Day2
P1	-0,678	-0,304	-1,116	-0,314
Mean	**-0,4914**		**-0,7147**	

Tracking accuracy is improved as the movement is repeated.

Results(III)
Stroke Subject

How this improvement is represented?

1st Trial

20th Trial

The FEL controller is able to learn the inverse dynamic of stroke patients.

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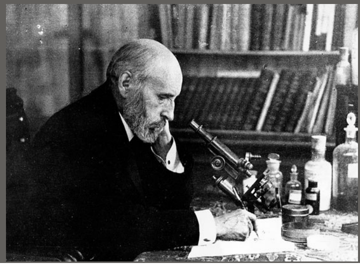

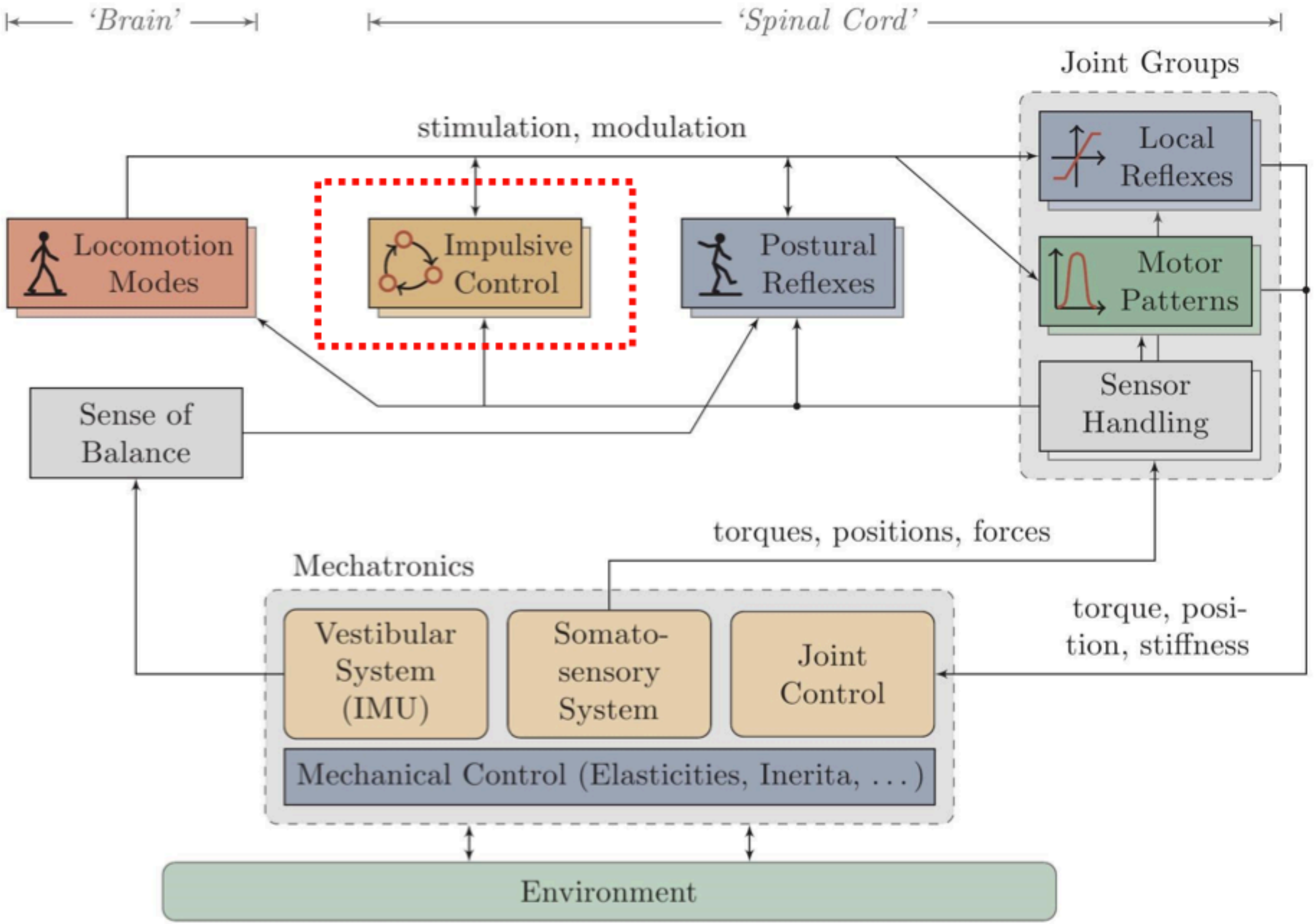

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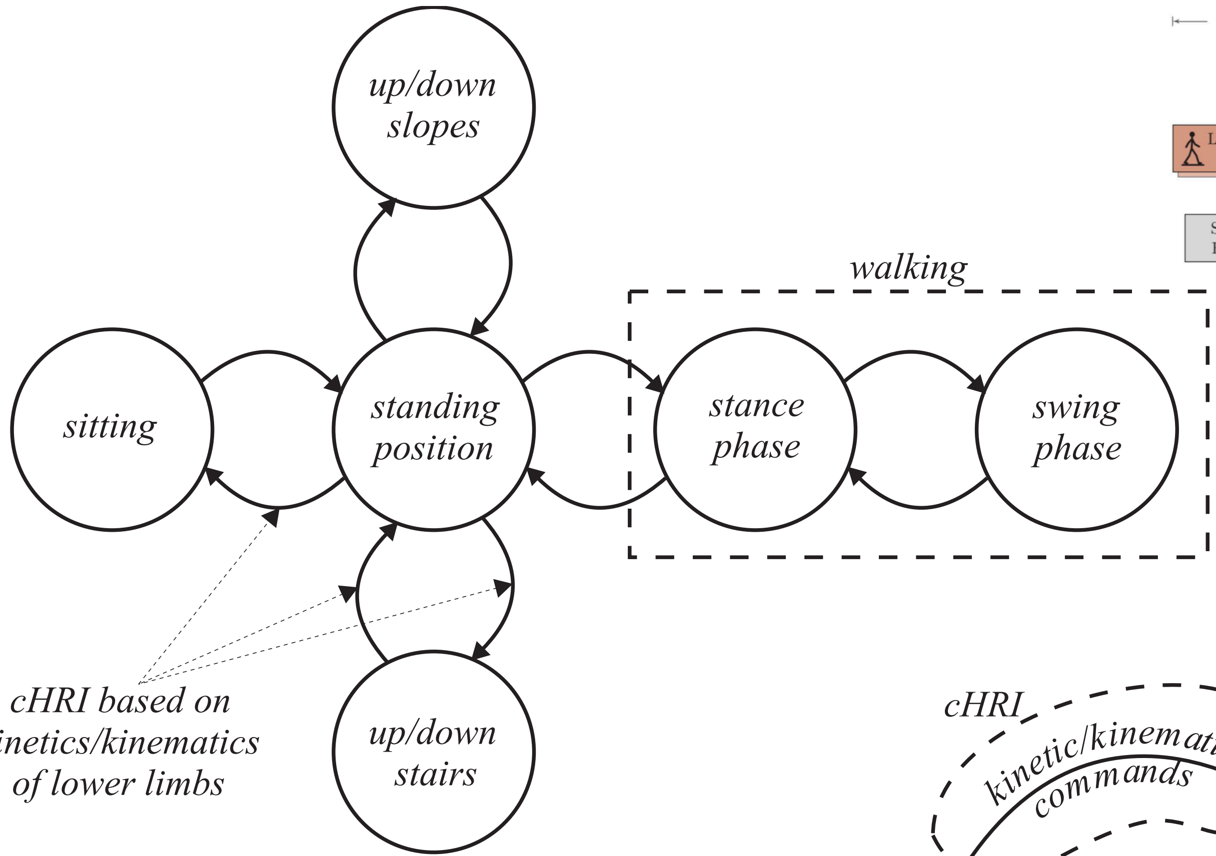

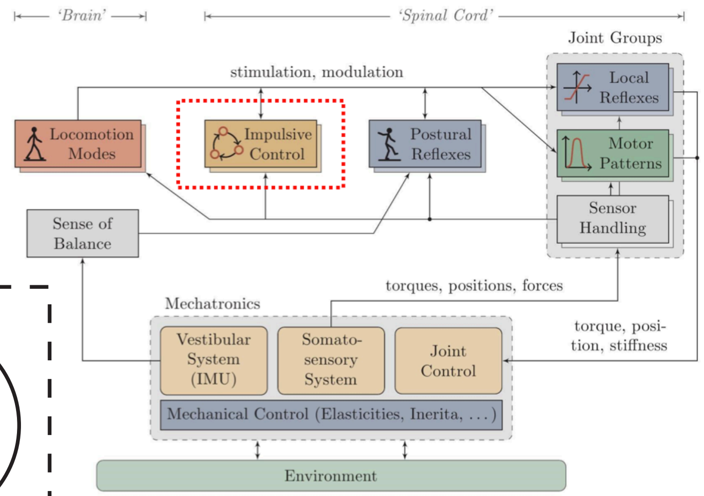

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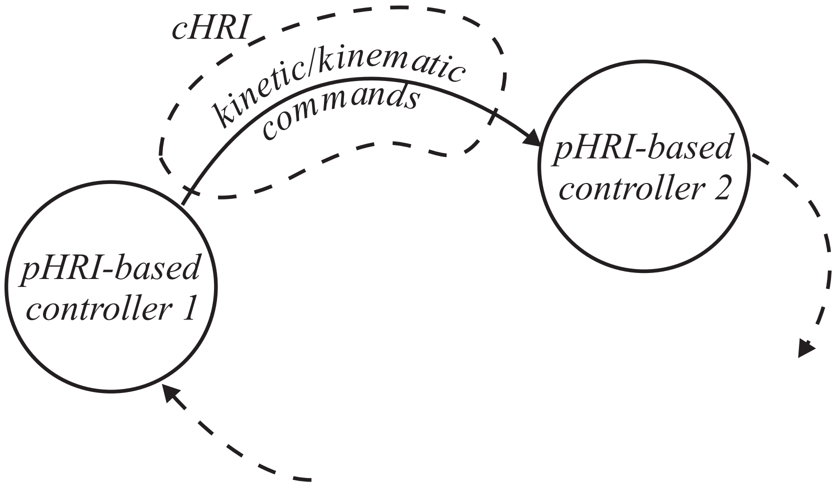

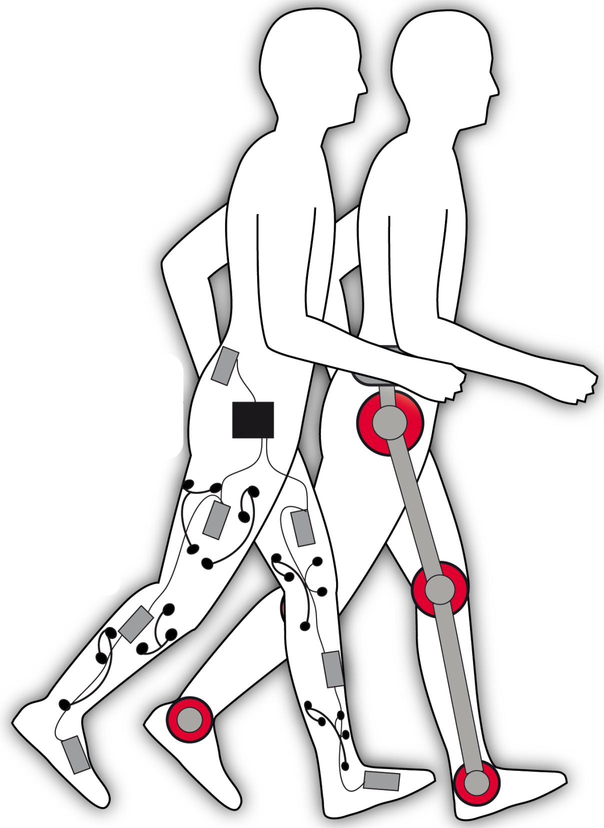

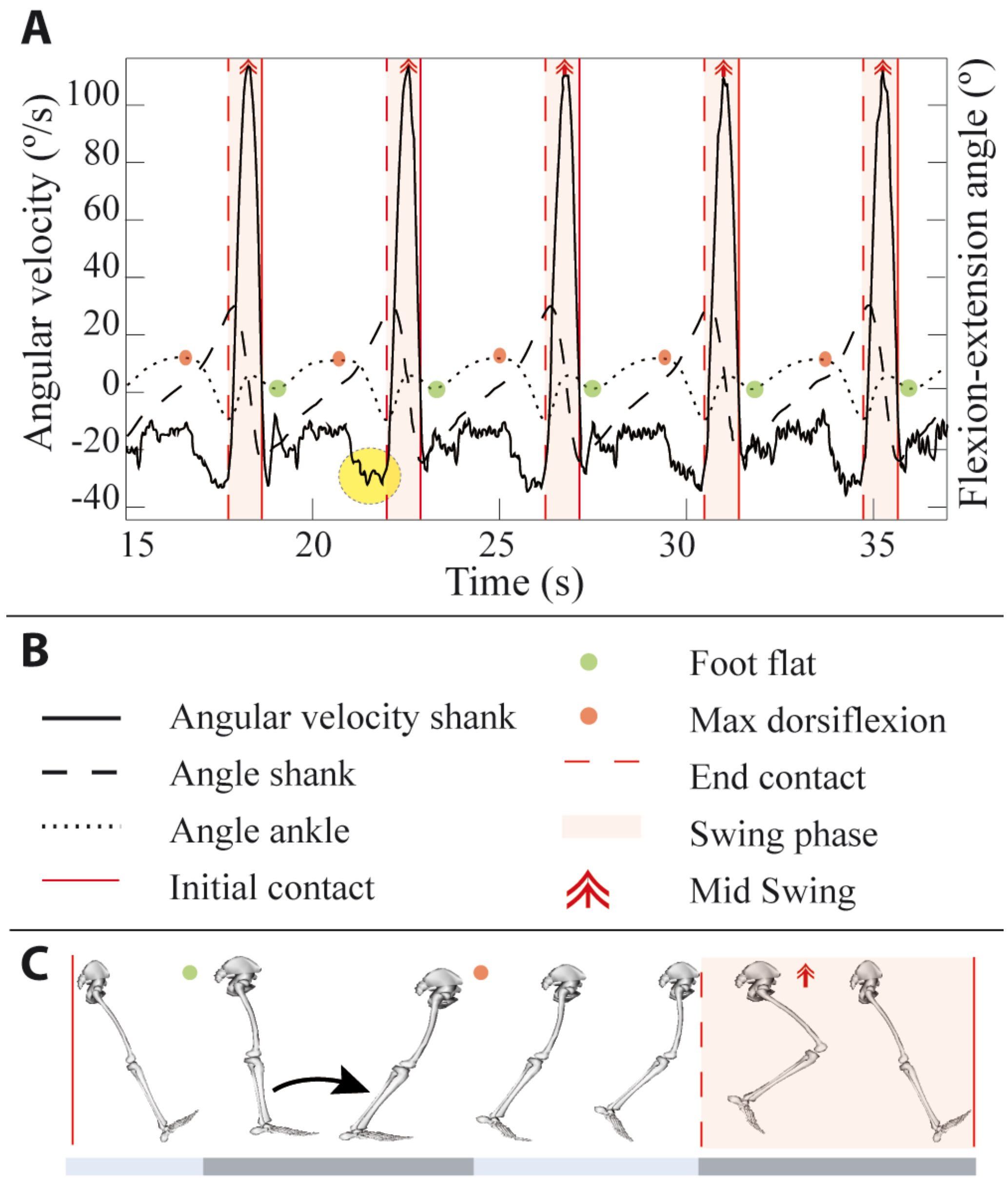

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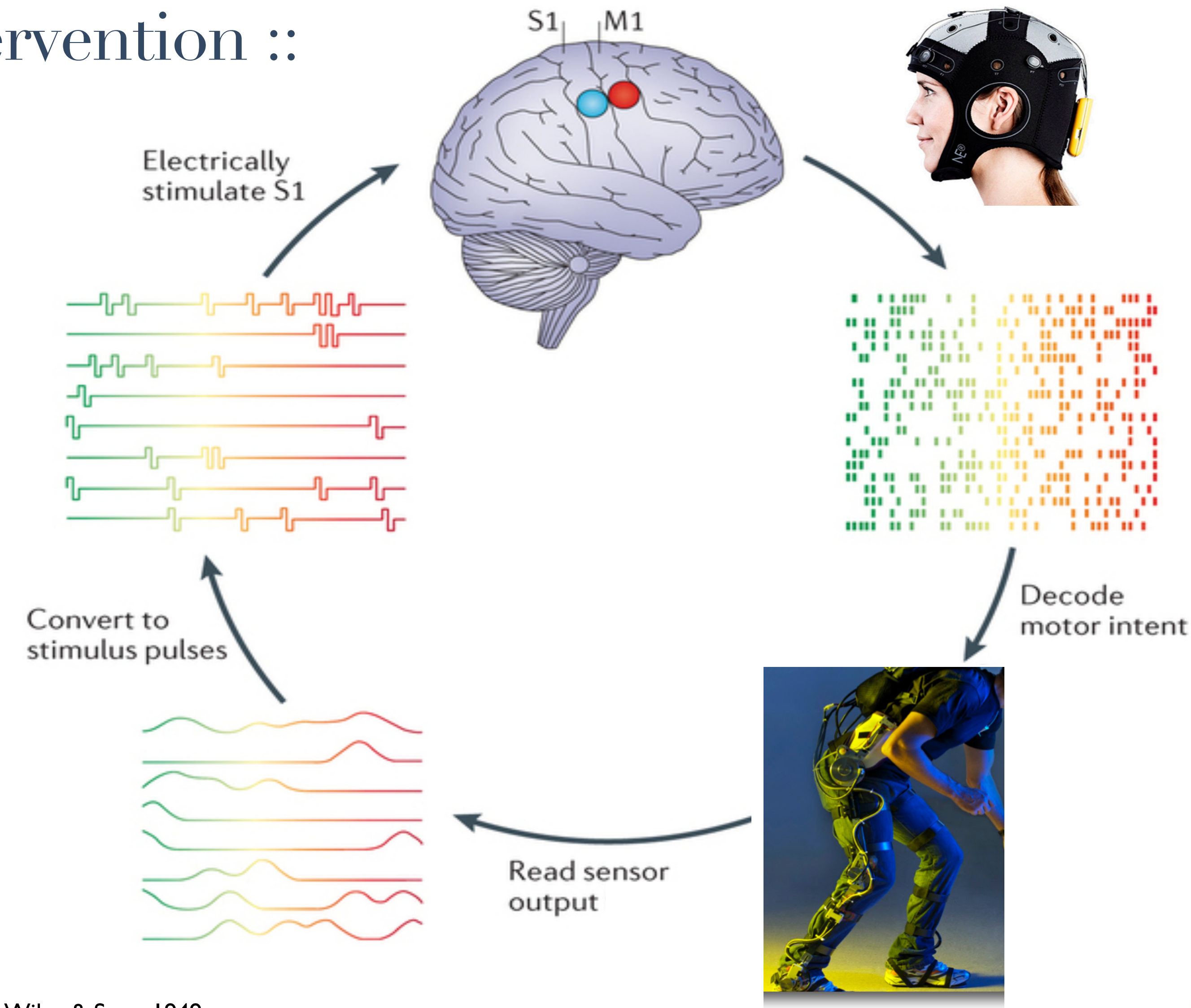
Associative intervention :: The Concept



Kinematics

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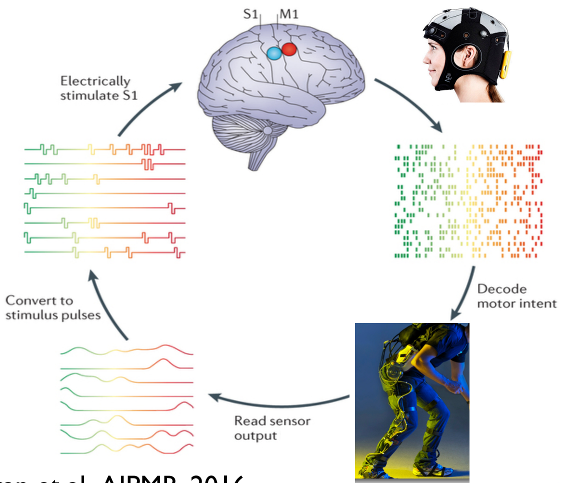
Hebb., **The Organization of Behavior**. Wiley & Sons, 1949

Robotic therapy, through intensive motor therapy, has been shown to induce primary motor cortex neuroplasticity in patients with stroke.

Treatment with dopaminergics, such as Levodopa, enhances neuroplasticity by inducing LTP and LTD in networks responsible of memory formation and learning.

Virtual reality (or enhanced biofeedback) can be coupled with robotic therapy to deliver rewards during training, thus engaging structures which weigh the magnitude of rewards, process abstract rewards, and manage motivation plus reinforcement.



Tran et al., AJPMR, 2016

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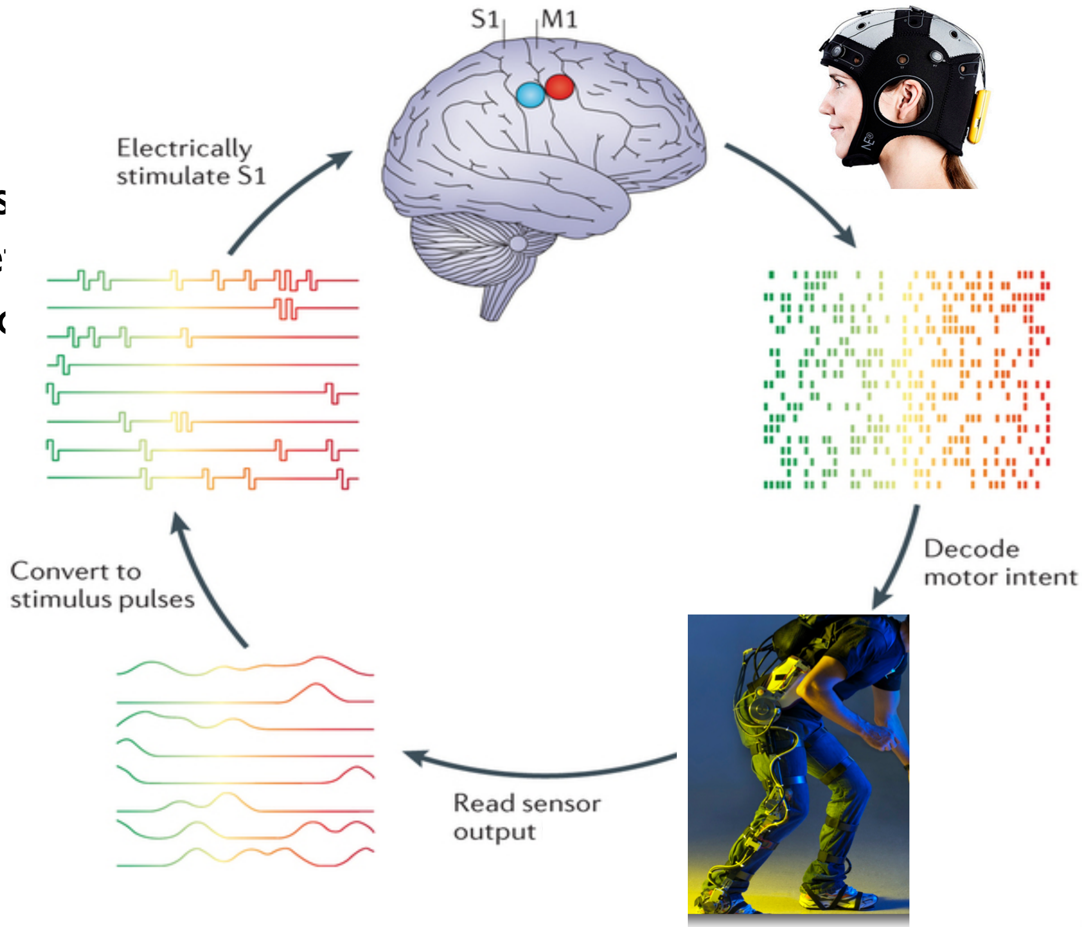

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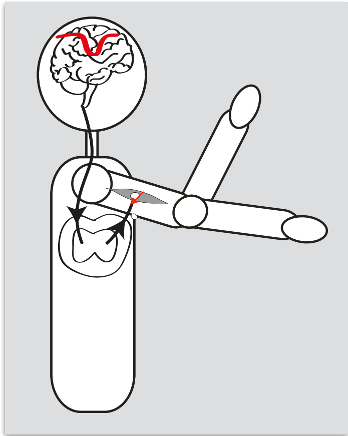
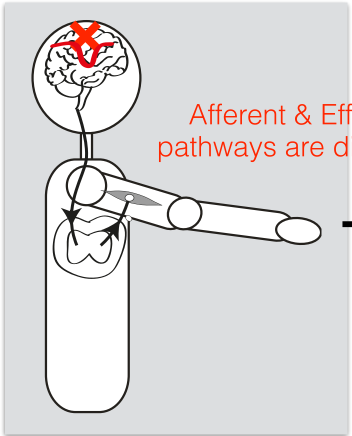
EEG-informed associative assistance
The Concept

Healthy

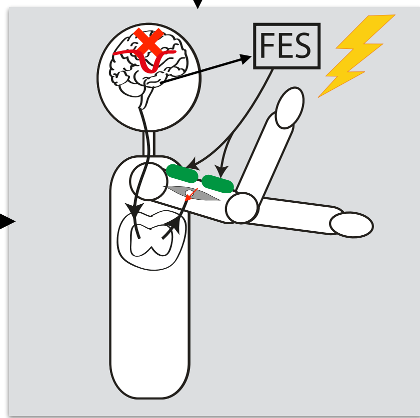


Stroke



Afferent & Efferent pathways are disrupted

"The afferent signal generated artificially induces central nervous system plasticity because it is in causal association with the cortical activity associated with the intention to move"



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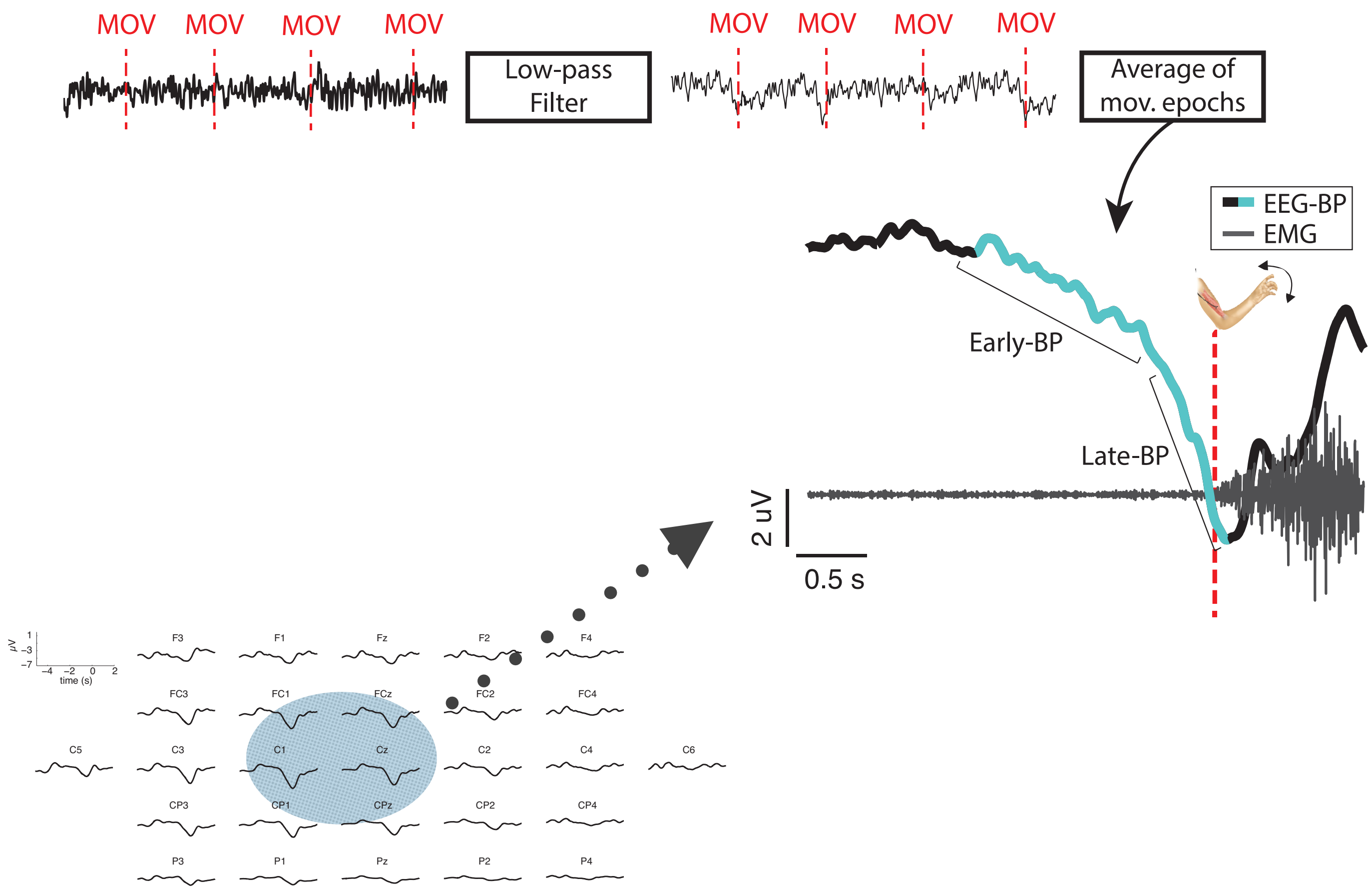
Mrachacz-Kersting et al. 2012

Xu et al. 2014

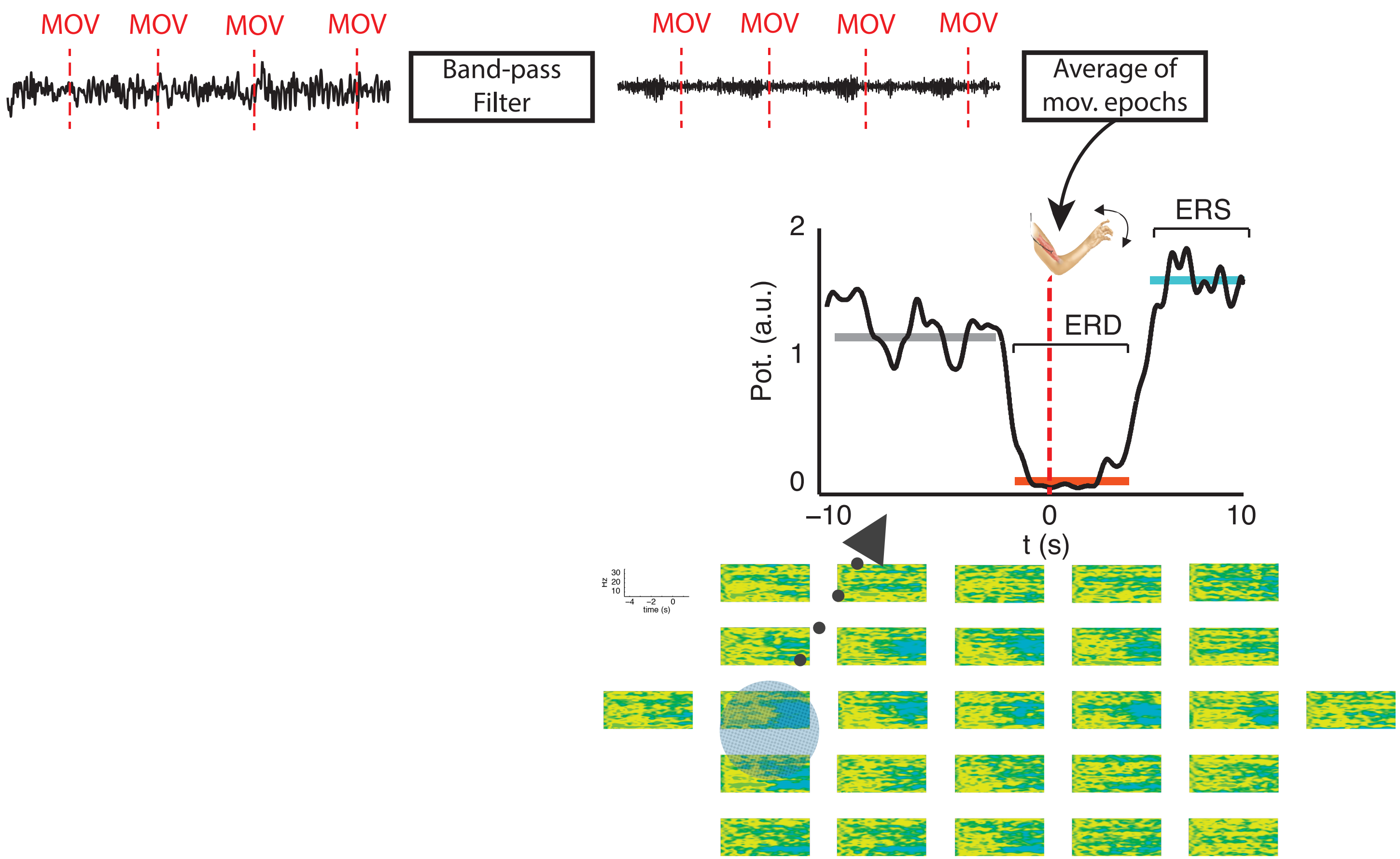
EEG information associated with the movement

A. Slow Cortical Potentials



EEG information associated with the movement

A. Sensorimotor rhythms



Kinematics

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EEG-informed associative assistance
Implementation

Kinematics

Dynamics

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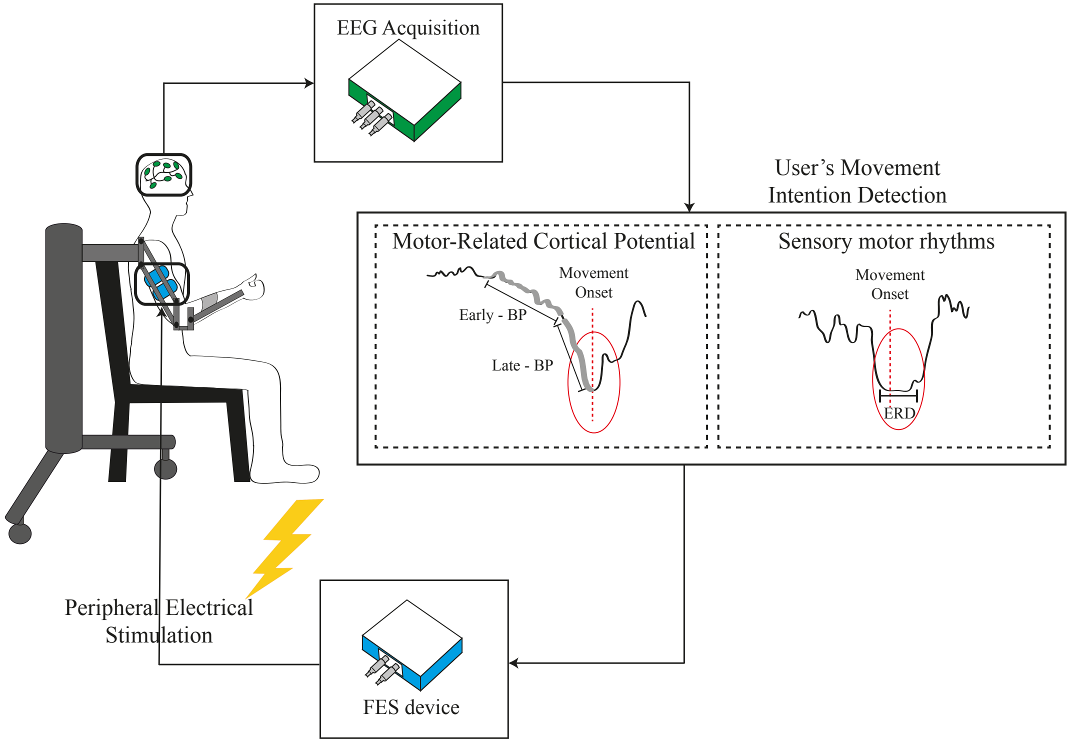
Motor Execution

EEG-informed BMI:

- Timed assistance
- Aimed to elicit associative facilitation



J. Ibáñez et al., "**Detection of the onset of upper-limb movements based on the combined analysis of changes in the sensorimotor rhythms and slow cortical potentials**," J. Neural Eng., vol. 11, no. 5, p. 56009, 2014.

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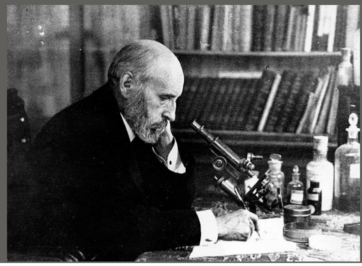
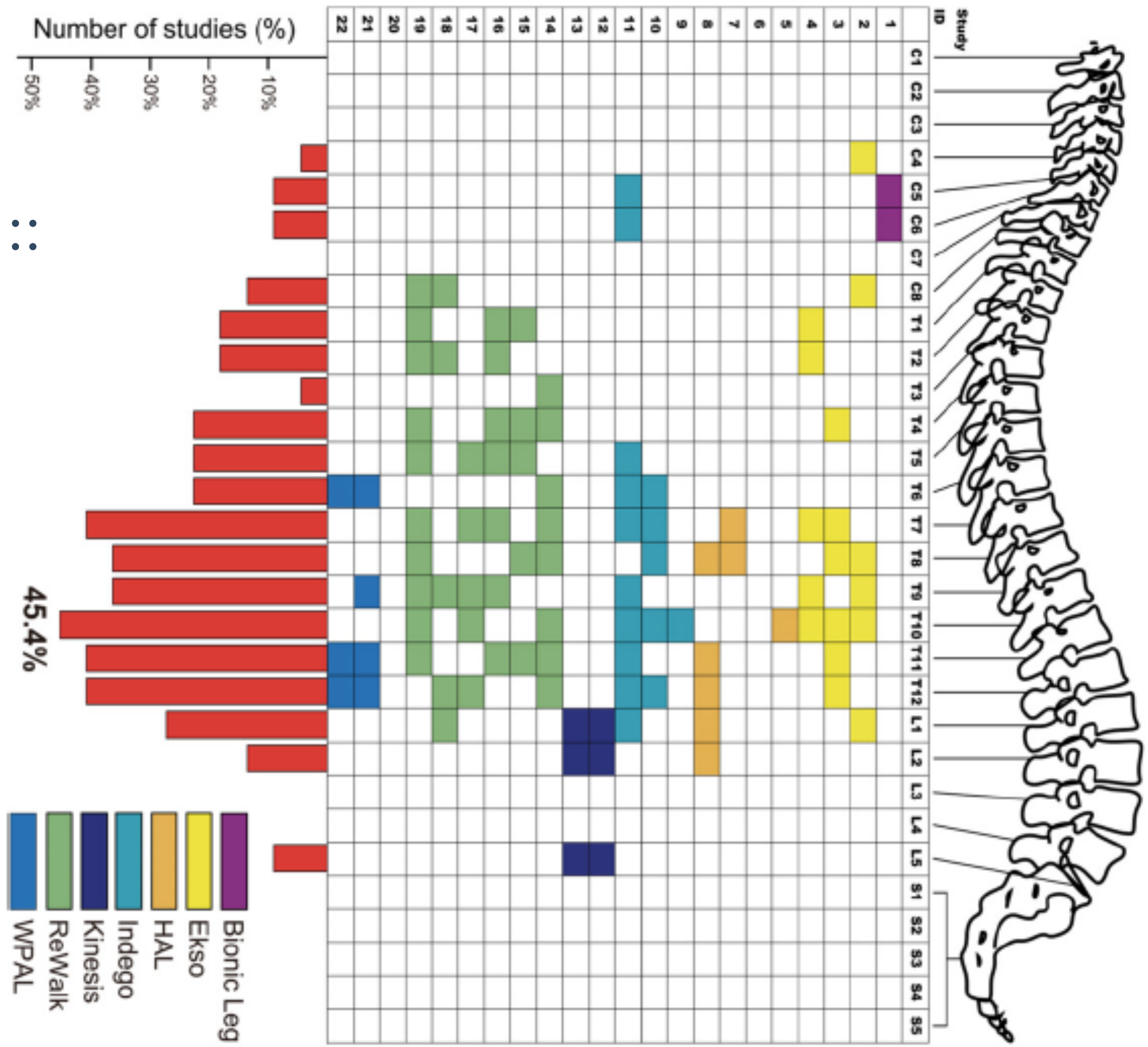


Clinical evidence :: Ongoing trials

	Bionic Leg	Ekso	HAL	Indego	Kinesis	ReWalk	WalkTrainer	WPAL
Exoskeleton								
Degrees of freedom	K	HKA	HKA	HK	KA	HKA	HaHKA	HKA
Weight-bearing devices	W	C	W/C/S	W/C	W/C	C	S	W/B
Sensor measurements	JA, JT, FF	AJA, ACF, FF, Acc/Ori (arm)	EMG, JA, FF, Acc	JA, Acc, Ori	JA, FF, IT, Ori	JA, FF, Ori	IT, JA	JA, JT
Device weight (kg)	3.6	20	15	12	9.2	23	?	13
User height (cm) limit	153–182	158–188	145–185	155–191	<1.85	160–190	?	145–180
User weight (kg) limit	136	100	80	113	90	100	?	80
Gait initiation mode	Foot sensors and knee extension	1. Body tilt 2. Button push	Knee EMG activation	Body tilt	Button push	Body tilt	?	Button push
Unique features	Unilateral	—	—	—	Hybrid (FES)	—	Hybrid (FES), active bodyweight support suspension harness moves with exoskeleton	Frame fits between legs, easy to don within wheerchair
ClinicalTrials.gov registration ID		NCT01701388 NCT02324322 NCT02132702 NCT02065830	—	NCT02202538	—	NCT02322125 NCT01943669 NCT02118194 NCT02104622 NCT01251549 NCT00627107 NCT01454570		—

Contreras et al., **Powered exoskeletons for bipedal locomotion after spinal cord injury**, J. Neural Engineering, 13 (2016) 031001.

Clinical evidence :: Ongoing trials



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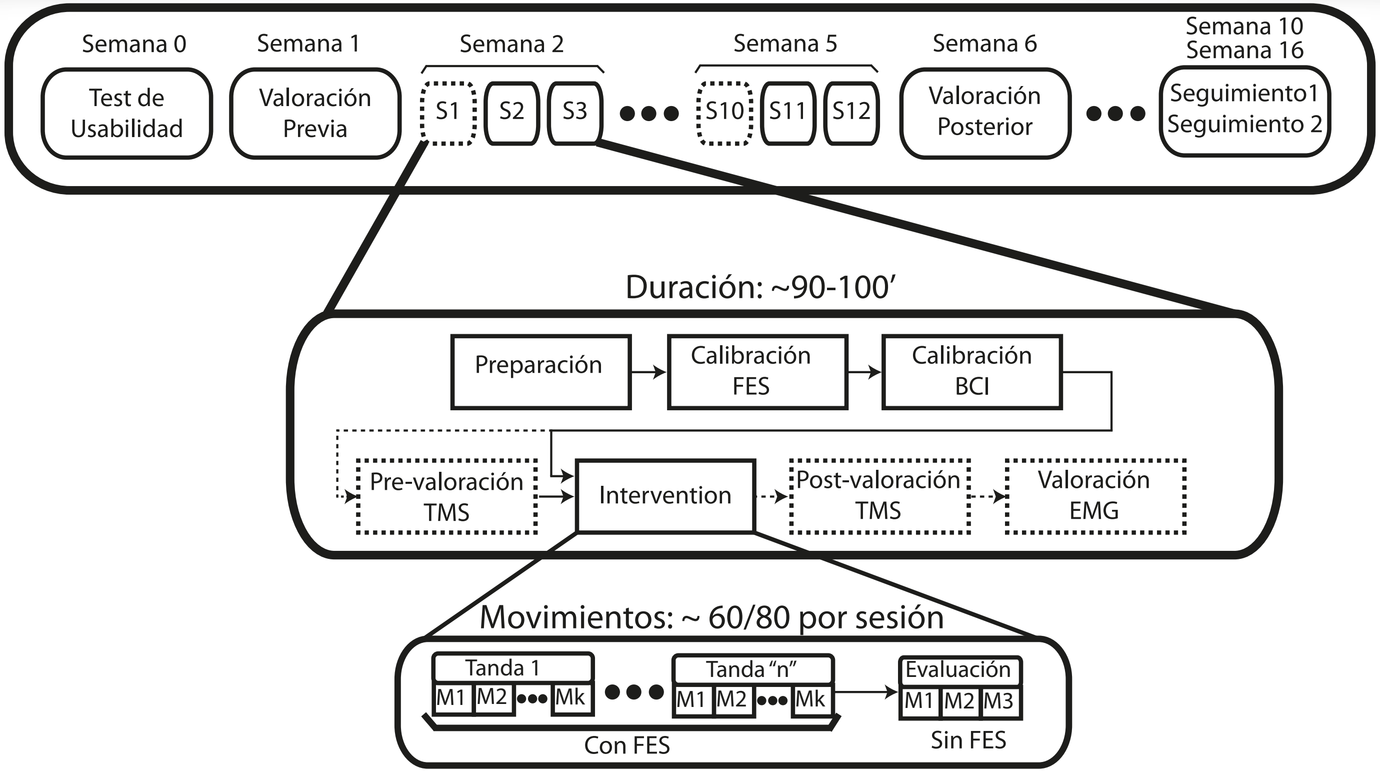
Contreras et al., **Powered exoskeletons for bipedal locomotion after spinal cord injury**, J. Neural Engineering, 13 (2016) 031001.

BCI-based associative assistance
Training and evaluation (Stroke)



Kinematics

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Pre- and post-evaluation to quantify the patients's improvements (clinical scales, neurophysiological, biomechanics and acceptance).

Session: 3 x week; 4 consecutive weeks; Duration ~1

BCI-based associative assistance
Training and evaluation (Stroke)

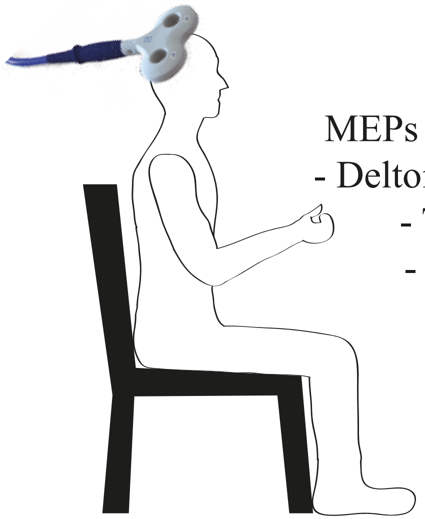
Clinical Scores	Neurophysiological	Kinematics and kinetics	Satisfaction
Box & Block test	MEPs	Assisted and assisted movement	Questionnaire
Modified Ashworth Scale (MAS) spasticity	EEG recording	Task performance	
ARAT	Co-contraction index	Isometric force	
Cognitive index			

- Kinematics
- Dynamics
- **Motor Planning**
- Motor Coordination
- Motor Execution

BCI-based associative assistance
Experimental Protocol

- Pre-assessment (TMS), Post- and Post30- assessment (TMS)

TMS Assessment
5 x 12 single pulse
Intensities: 90, 100, 110, 120, 130



MEPs on muscles:
- Deltoides Anterior
- Triceps
- Biceps

Kinematics

Dynamics

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Motor Execution

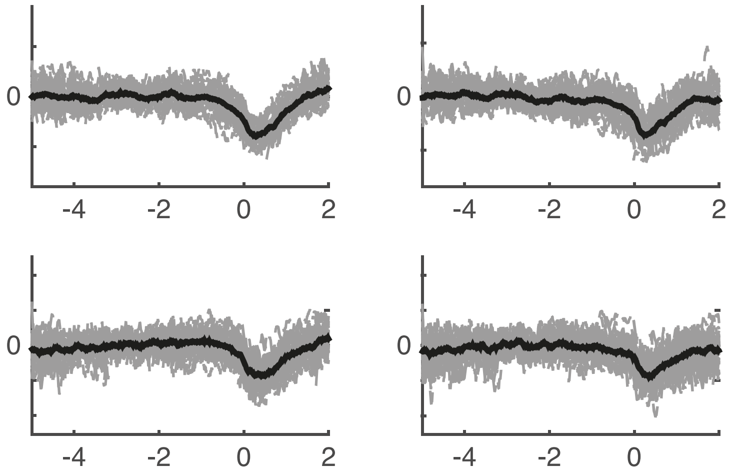
BCI-based associative assistance
Experimental Protocol

Task: Reaching movements
Stimulated Muscles: Anterior deltoid & Triceps
Training phase: 2 x 20 mov. for BCI calibration
Intervention phase: 50 good stimuli

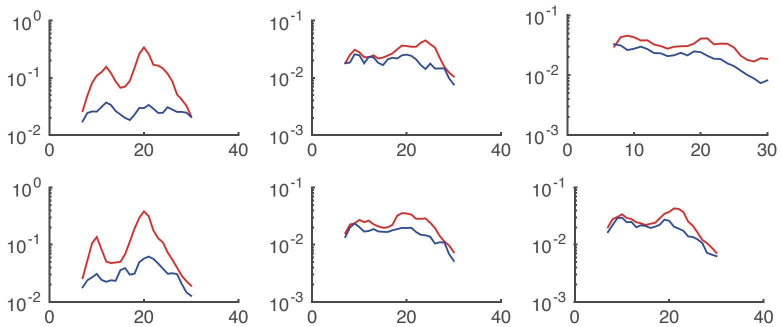
- Intervention

A. Training phase

- User performs 40 movements without stimulation, to train the user's motor intent detector



BP



ERD

Kinematics

Dynamics

Motor Planning

Motor Coordination

Motor Execution

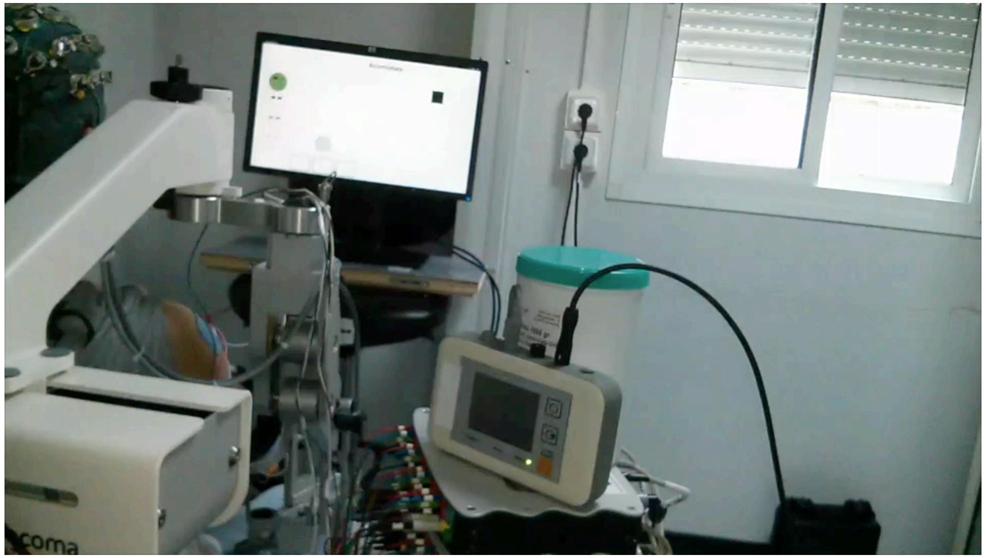
BCI-based associative assistance
Experimental Protocol

Task: Reaching movements
Stimulated Muscles: Anterior deltoid & Triceps
Training phase: 2 x 20 mov. for BCI calibration
Intervention phase: 50 good stimuli

- Intervention

B. Intervention phase

- User performs 50 good movements



Kinematics

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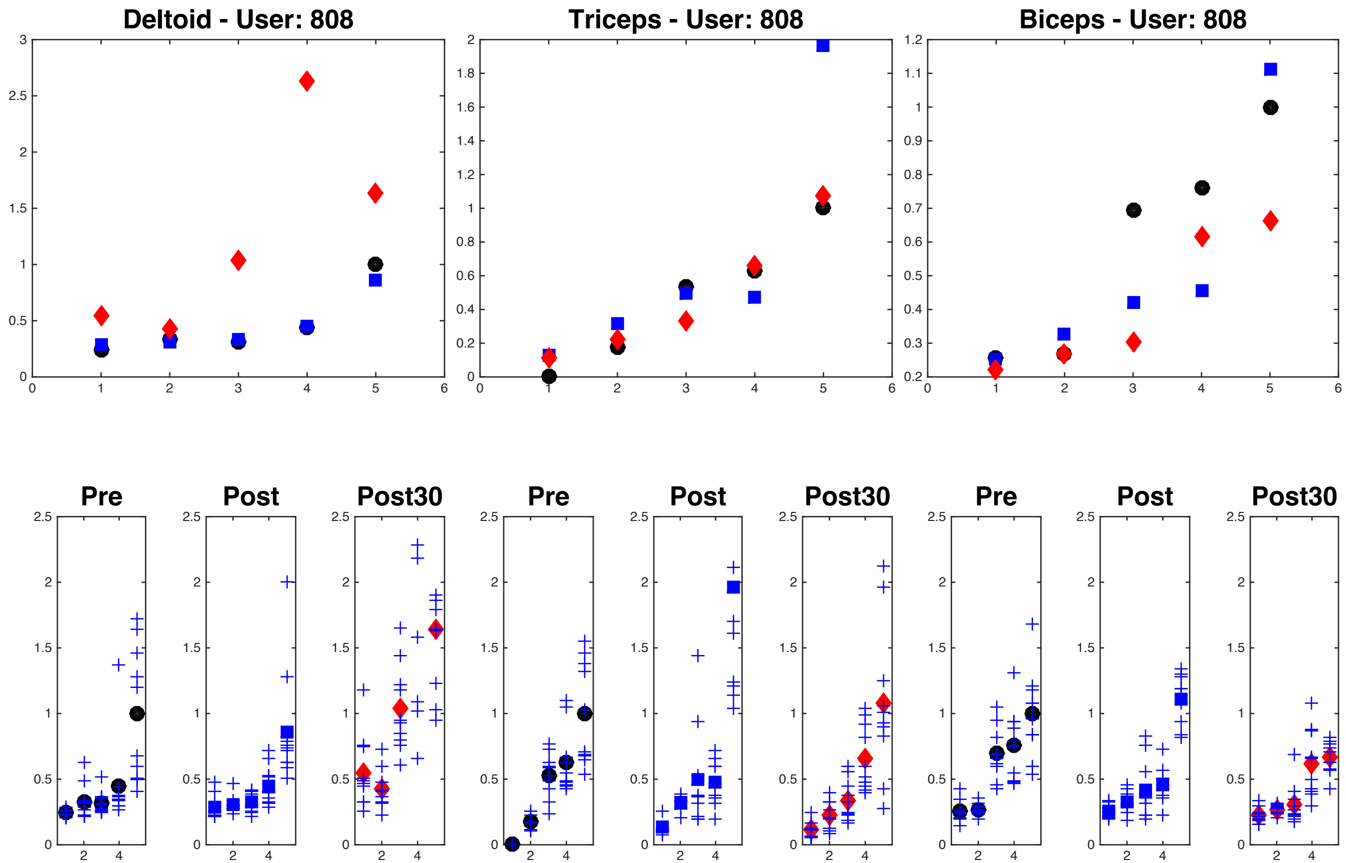
EEG-informed associative assistance
Partial Results (I)

A representative example (I)



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Neurophysiology :: Effects in brain activity

Kinematics

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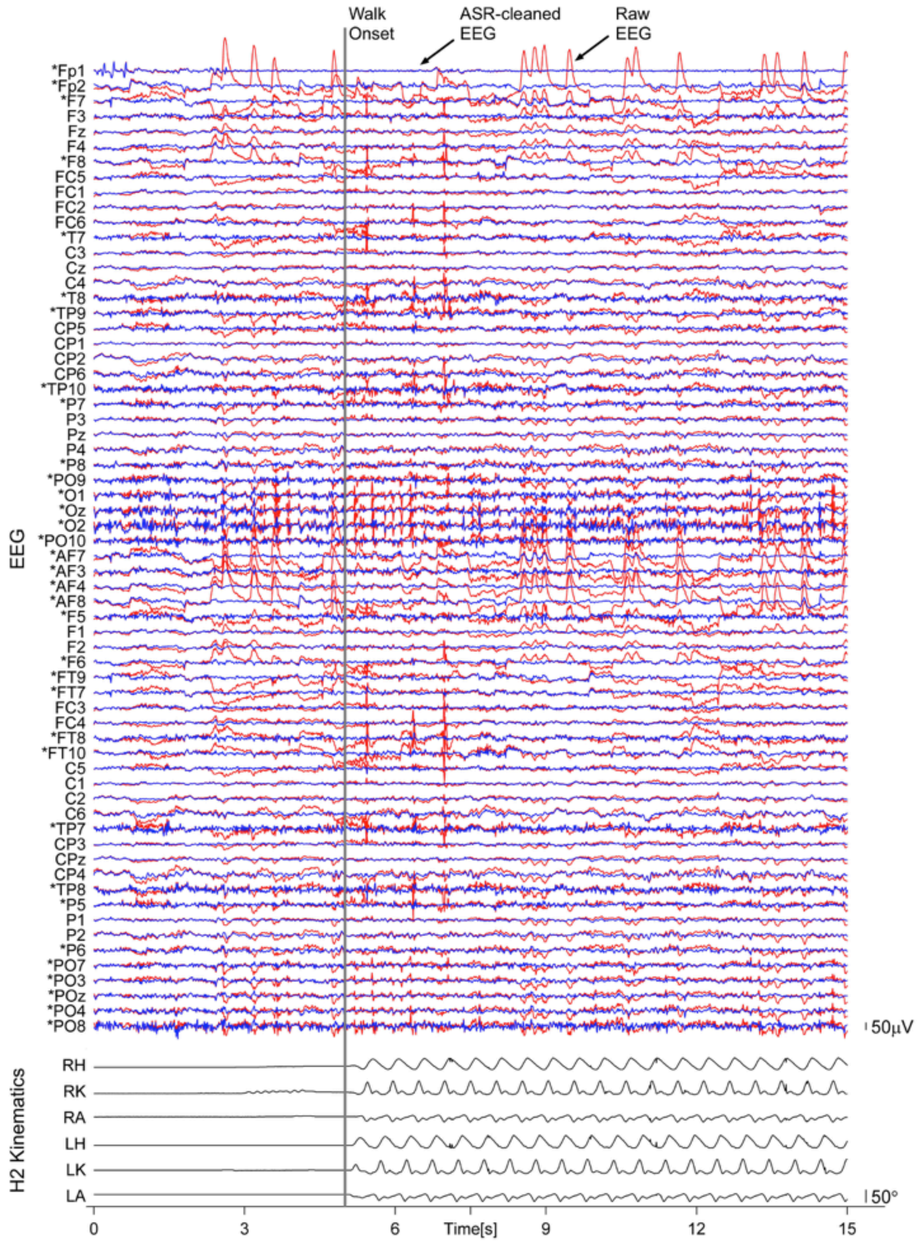
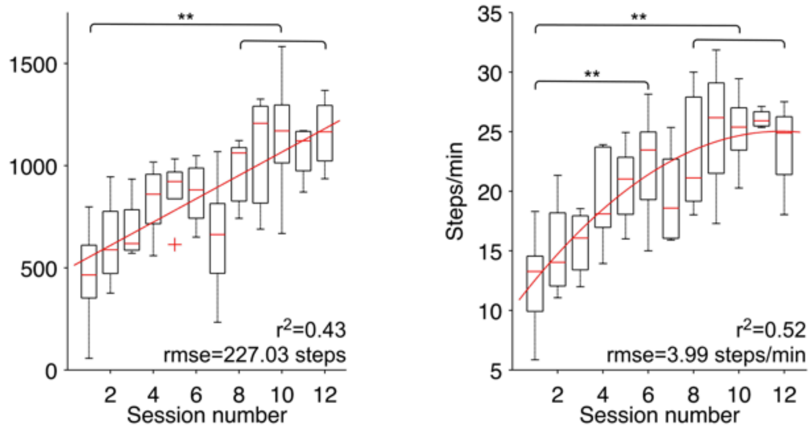
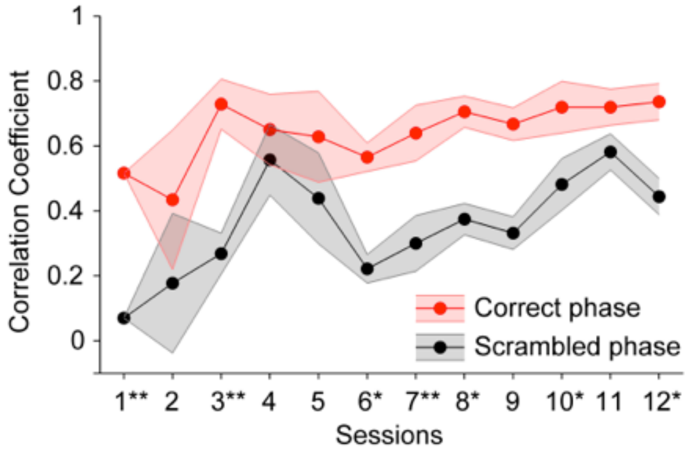
Motor Execution

Bortole et al., J. Neural Engineering and Rehab,, 2015



Neurophysiology :: Effects in EEG vs. function





Contreras-Vidal et al., submitted AJPMR, 2016

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Neurophysiology :: Effects in brain activity

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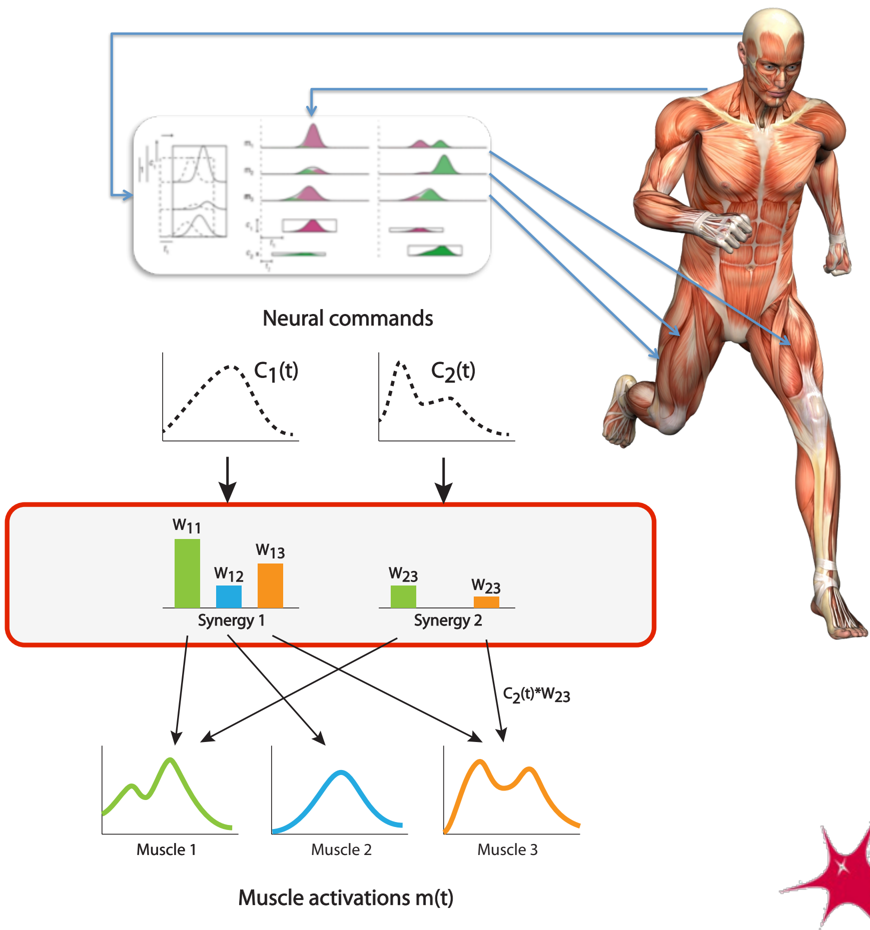
Bortole et al., J. Neural Engineering and Rehab,, 2015

Motor coordination :: Synergy decomposition

- Evidence:
  - Similar synergistic decomposition for similar functions accross subjects [Safavynia2011] [Clark2010]
  - Mucle synergies can be modulated through intense rehabilitation therapy with robots [Salman2010]
  - Pathological synergies can be modulated towards healthy patterns through robotic therapy [Salman2010]
  - Robot training preserves motor modules in healthy volunteers [Moreno2013]



Kinematics

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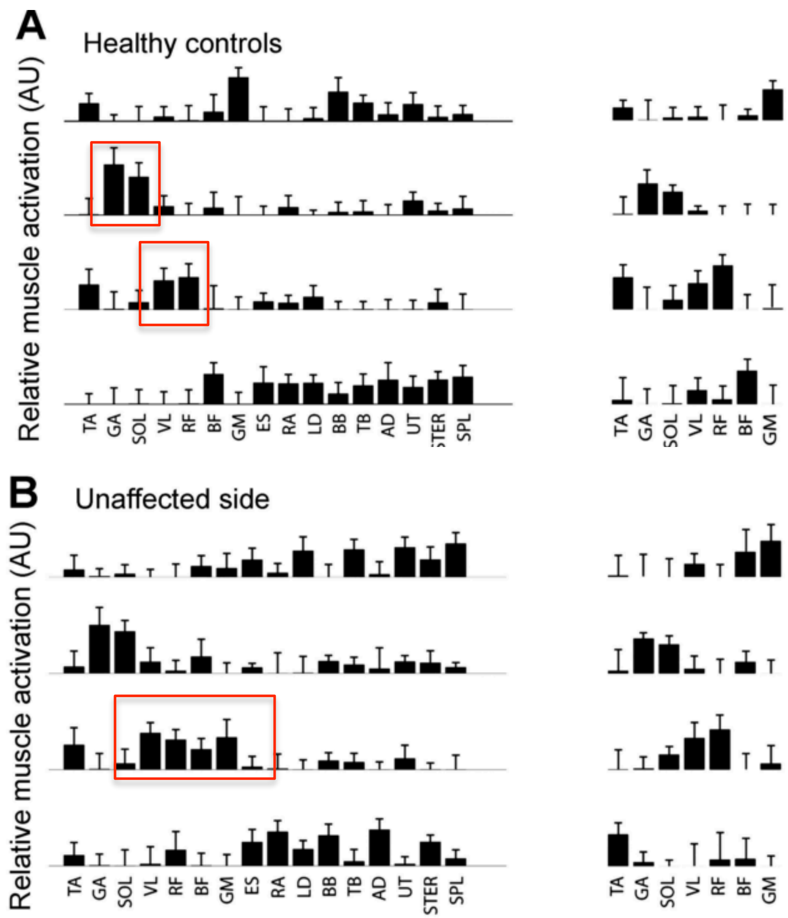
Safavynia and Ting, J. Neuophysiol, 2012
Clark et al., J. Neuophysiol, 2010
Salman et al., Int. Robots and Systems, 2010
Moreno et al., J. Neural Engineering and Rehab., 2013

Motor coordination :: Alterations in Neurological conditions

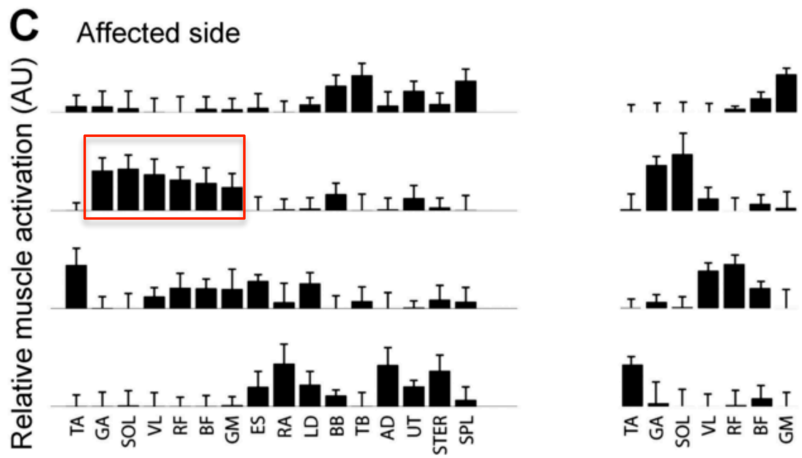


Altered modular control:

- Impulsive motor patterns are maintained after stroke.
- Modular control in stroke patients is kept but changed wrt healthy.
- Both modular control in affected and unaffected sides is altered.

Muscle activation is misdirected

Gizzi et al, J Neurophysiol 2011



Gizzi et al., J. Neuophysiol, 2011

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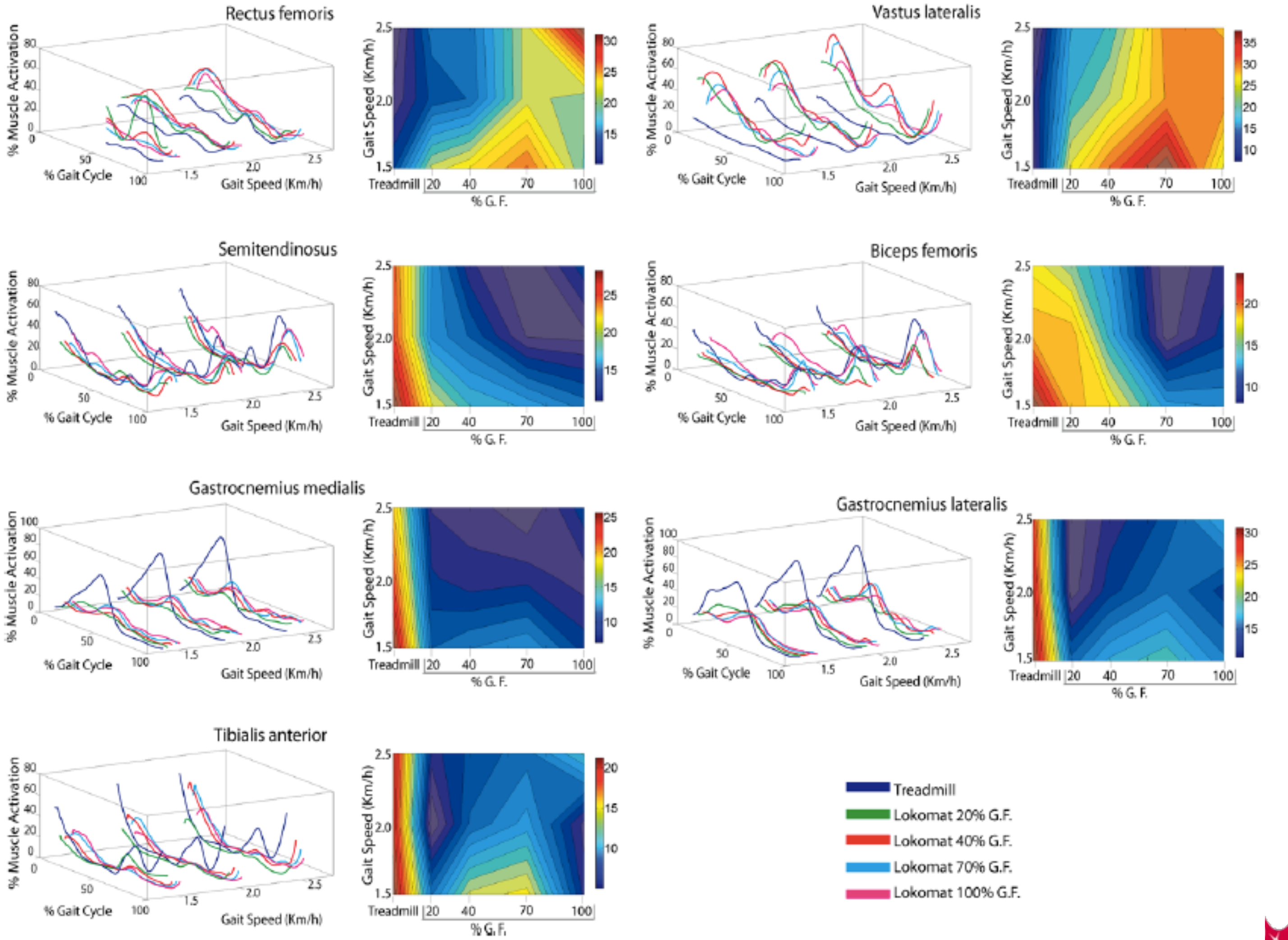
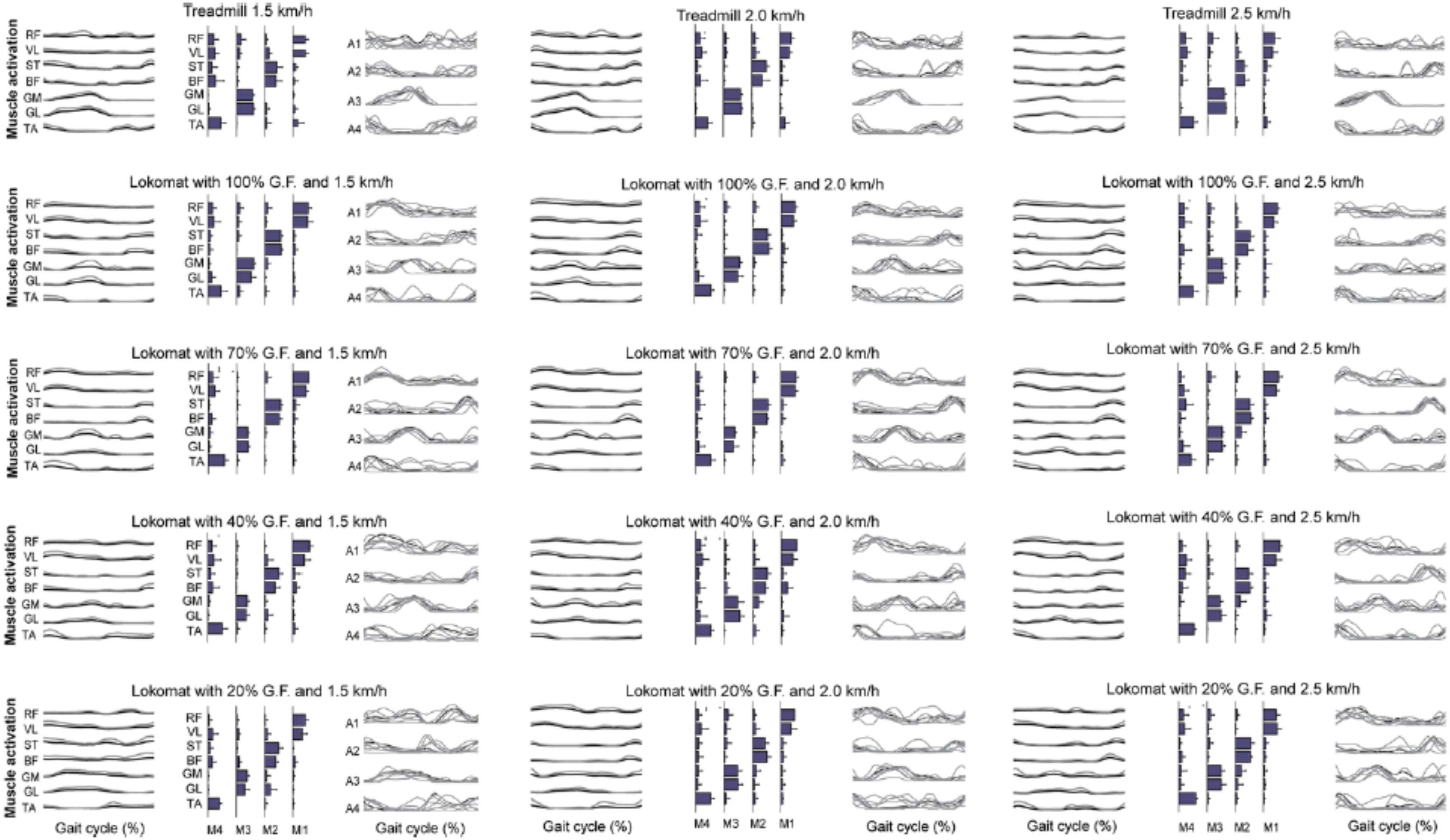
Motor coordination :: Dimensionality



Moreno et al., **Effects of robotic guidance on the coordination of locomotion**, JNER 2013, 10:79

Motor coordination :: Preserved activation

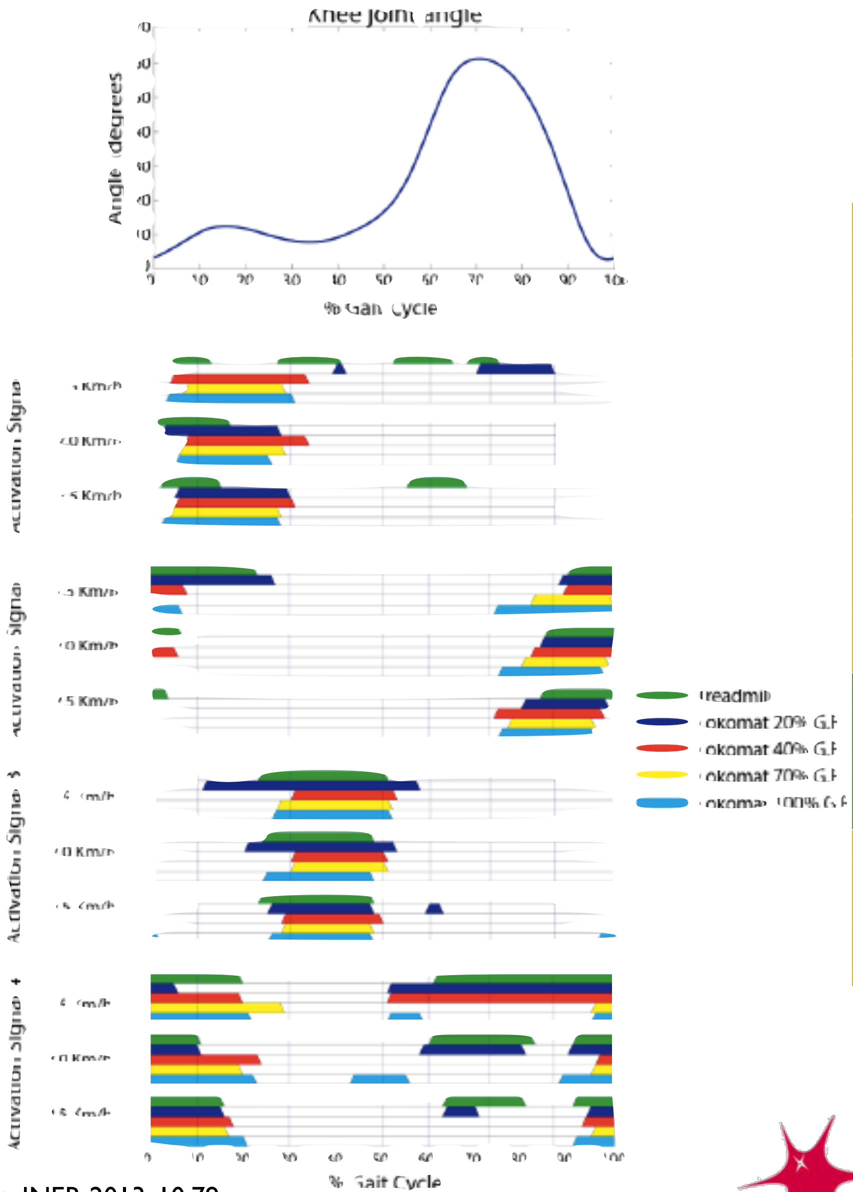


Moreno et al., **Effects of robotic guidance on the coordination of locomotion**, JNER 2013, 10:79

- Kinematics
- Dynamics
- Motor Planning
- **Motor Coordination**
- Motor Execution

Motor coordination :: Preserved activation

- Four motor modules were sufficient to describe the muscular activations across subjects & conditions
- The main modular organization of control in in healthy humans is in general maintained when adding a GF with a robotic trainer.
  - A low-dimensional, burst-like impulsive control, with activation impulses well timed with respect to the gait phases is in general maintained
  - The results indicate that the muscle weightings can be shaped more flexibly than activation primitives by changing the GF.
  - Conditions that are uncomfortable for healthy subjects (20% GF and 1.5 Km/h speed) result in deviations in modules and timing of activations.



Moreno et al., **Effects of robotic guidance on the coordination of locomotion**, JNER 2013, 10:79

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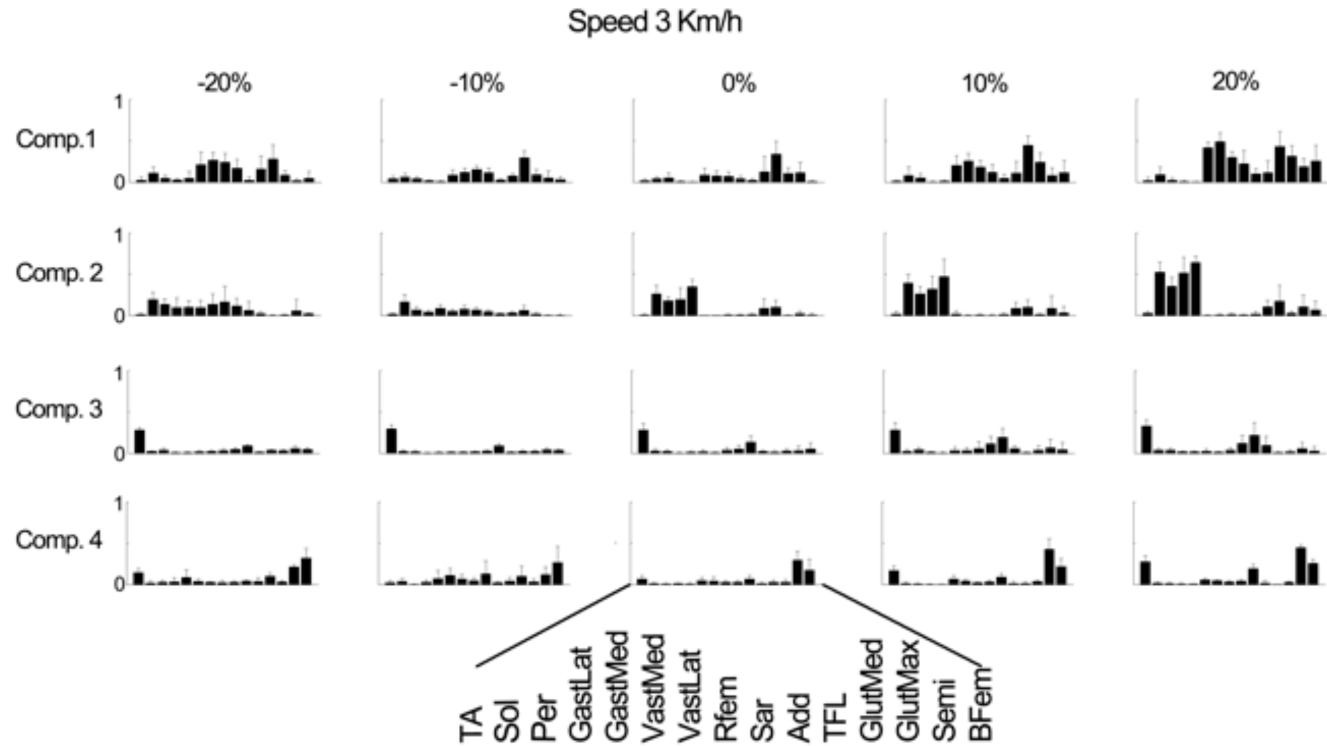

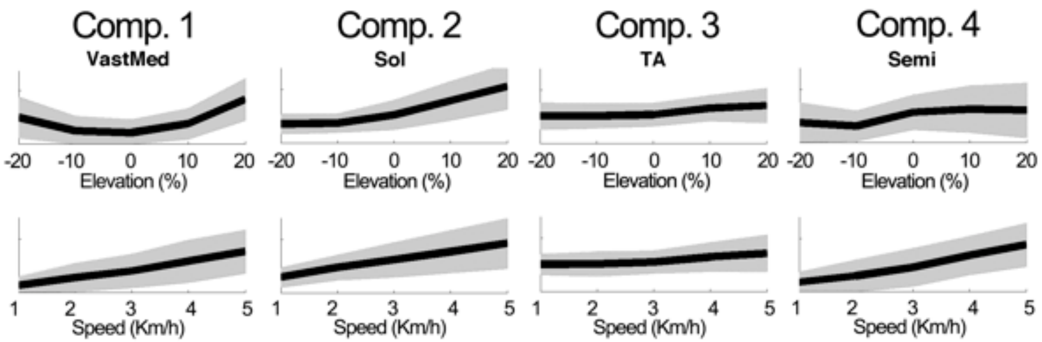

Kinematics

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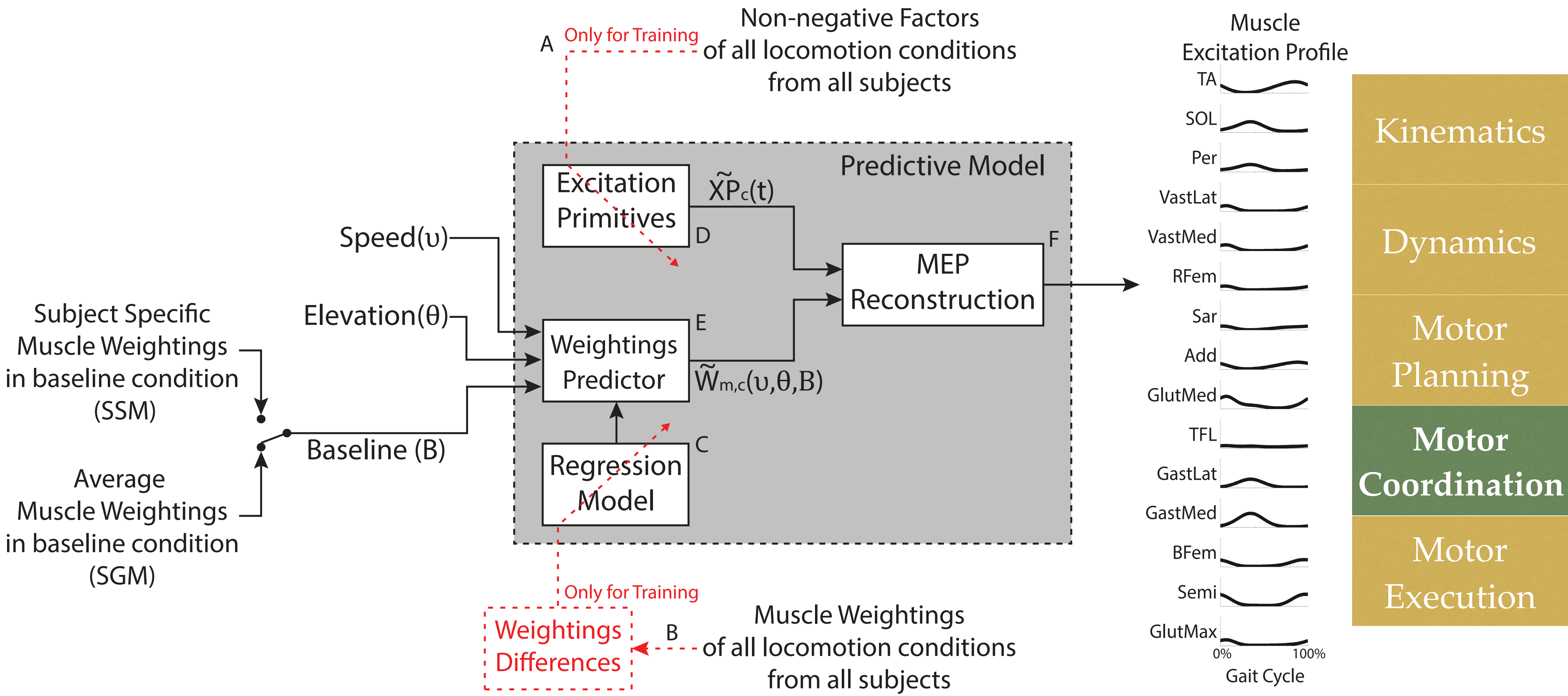
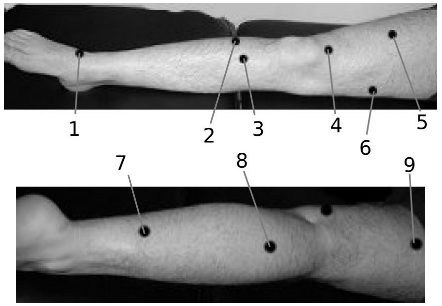
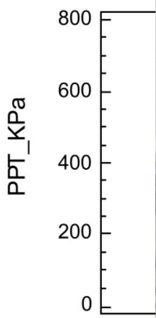
Gonzalez et al., **A predictive model of muscle excitations based on muscle modularity for a large repertoire of human locomotion conditions**, Frontiers in Comp. Neuroscience, 2015

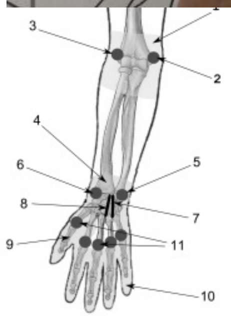


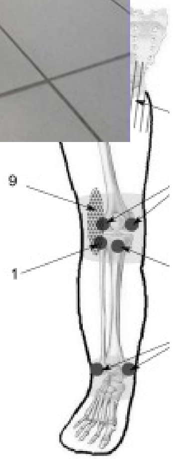
Gonzalez et al., **A predictive model of muscle excitations based on muscle modularity for a large repertoire of human locomotion conditions**, Frontiers in Comp. Neuroscience, 2015

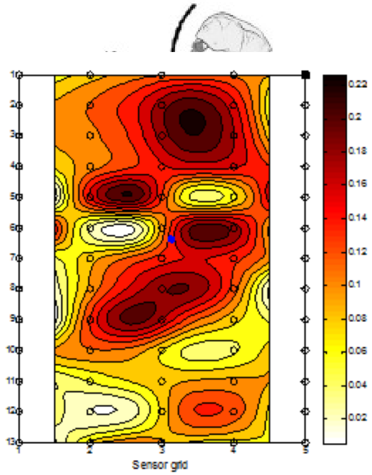
Was :: Improving physical interaction











Kinematics

Dynamics

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Motor Coordination

Motor Execution

Take Home Message

- Both CNS and PNS signals (e.g. EEG and EMG-informed muscle coordination) can be used to command WRs.
- CNS and PNS signals can be used to trigger symbiotic co-control with WRs.
- WRs will in general mediate, through physical interaction, changes in CNS and PNS structures as a result of neural plasticity. This is the basis for WRs in rehabilitation.
- WRs may trigger pathological movement disorders such as spasticity, therefore control strategies should be adapted to the handicapped.
- Neurological conditions may lead either to lack of sensory perception (complete SCI) or exacerbated sensations: attention has to be paid to how mechanical loading of limbs is performed.
- Additional research efforts should be put in place to ascertain how the use of WRs neuromodulates CSN and PNS to improve the efficiency of therapeutic interventions.

Thank you!

jose.pons@csic.es

BETTER

H2R Integrative Approach for the Emergence of Human-like Locomotion

SEVENTH FRAMEWORK PROGRAMME

HYPER
CONSOLIDER-INGENIO 2010

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