Robotics for Lower Limb Rehabilitation

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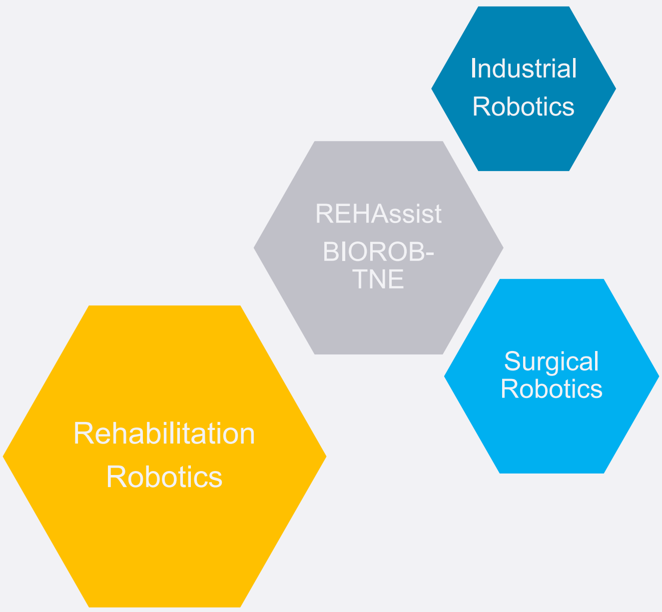
Robotics @ REHAssist



general
introduction

Question 1

Do you speak Robotics ?

- Robotics, definitions and kinematics
- Example of applications
- Control basics

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How do you define a robot?

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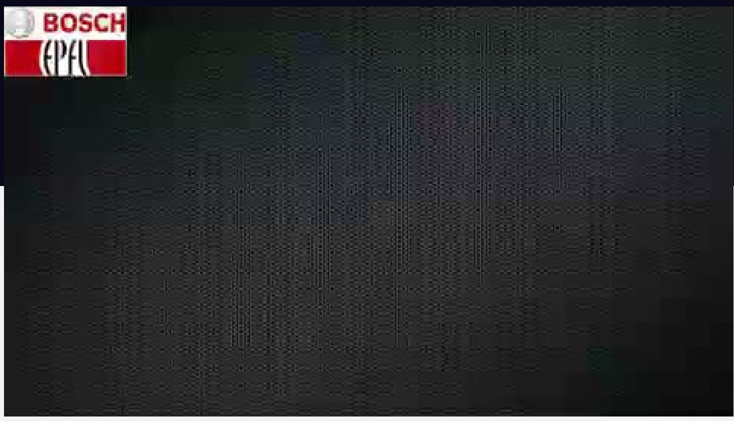
Micro assembly and packaging



Move + Pick object + Move + Place Object

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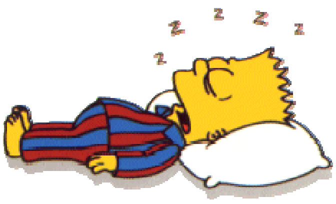
Robot

comes from the Tcheque (**Karel Čapek, 1920**) derivated from ***robota*** (**servage**)

Human Fantasm



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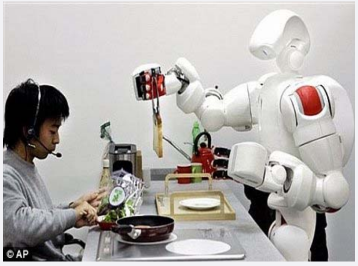
And what else ?



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http://www.chine-informations.com/actualite/robots-chinois-peu-commun_5102.html

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Definitions

We need this machines to be

- **polyarticulated** and **motorised**
- **Intelligents** and **automatised**.

Defintion ISO

Automatically controlled, reprogrammable, multipurpose manipulator programmable in ***three or more axes***.

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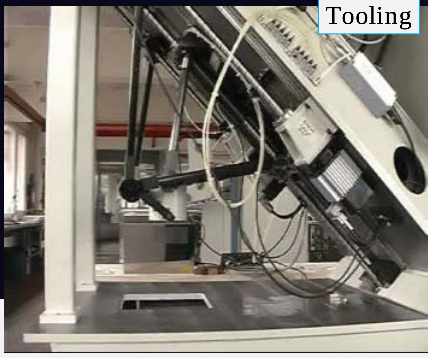
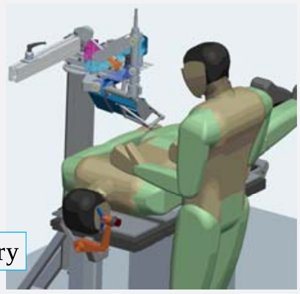
Other examples





Surgery

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Kinematics

Kinematics

Serials

Angulars
>> RRR <<

Cartesians
>> TTT <<

Combined RT
RRT
TRR
RTT
....

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Serial Robots
Angular anthropomorphic structures

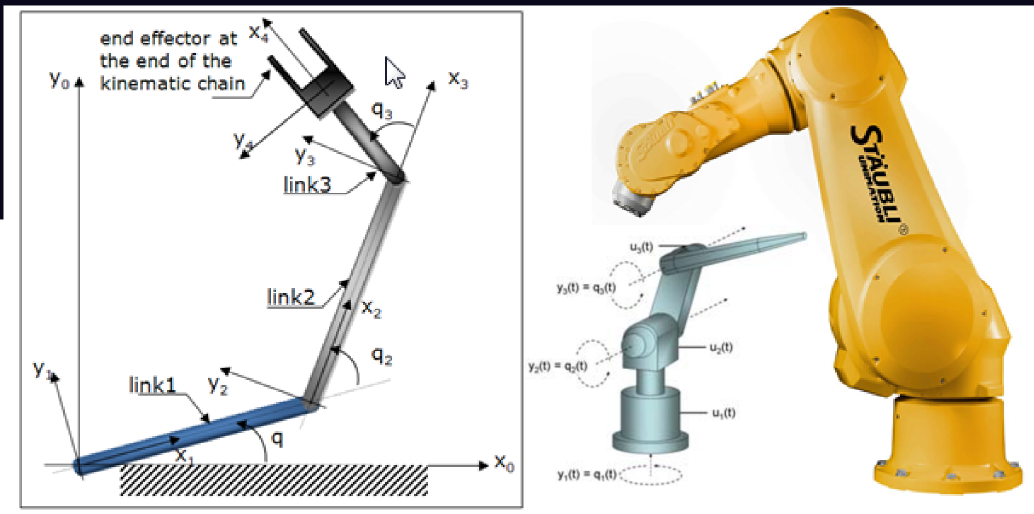
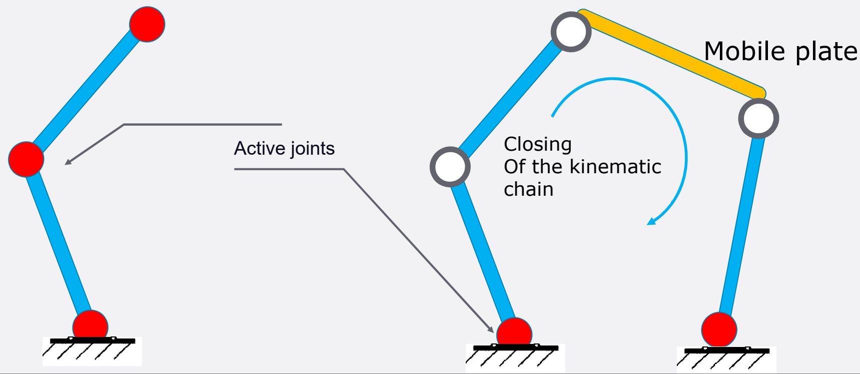


Figure 1, Serial robots. (Left) representation of the principle. (Right) Robot Stäubli TX200

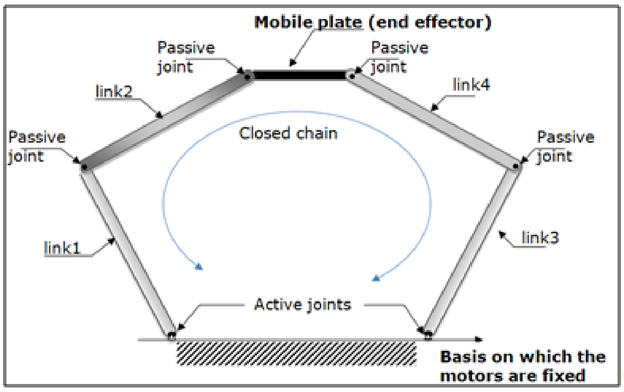
Parallel structures

- ✓ Robots with closed kinematic chains
- ✓ Motors on the basis



Parallel structures

1. All the kinematic **chains** from the basis to the mobile parts are **closed** to the basis.
2. All the **motors are on the basis** and no one is on the structure. The **intermediate joints** in the structure are all **passive**.



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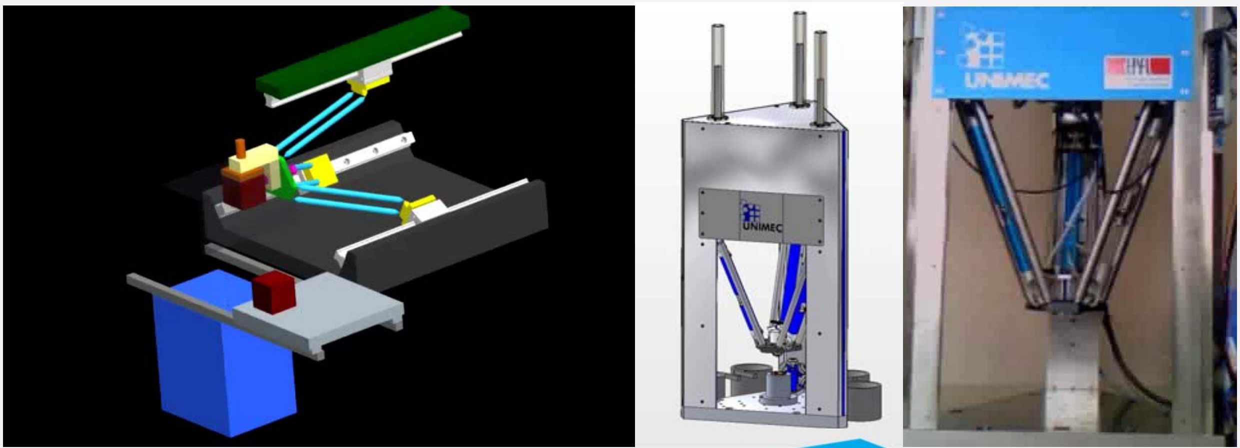
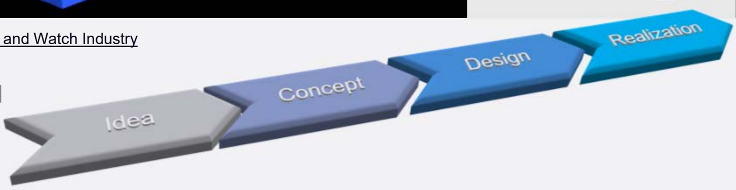
Parallel structures
Examples



Ref. Unirechnology SA and Watch Industry

Ref. Unimec SA and Watch Industry



[Bouri, ISIR 2010]
[Clavel, RSA 2008]

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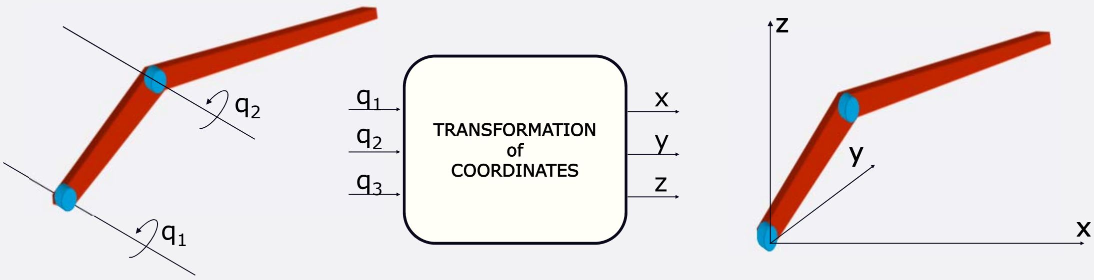
The Coordinate transformation



Joint Referential
Articular R….
Motor R….

Operational Referential
Tool R….
TCP R….
Task R…

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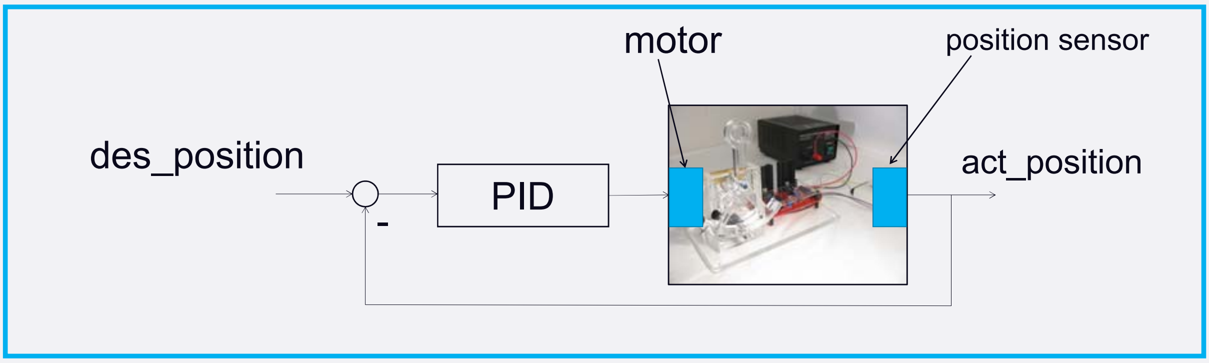
Let us move on with basics of control ….

Position Control



Delta Direct drive for fast pick and place

And what else?

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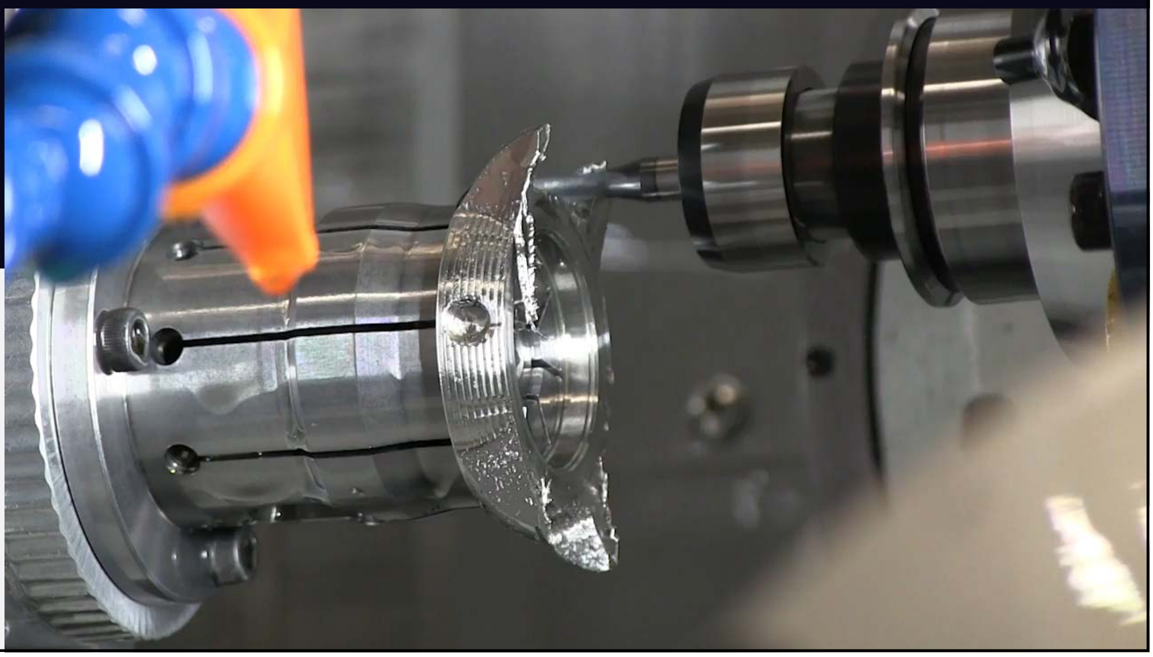
Machining



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Haptic paddle – position control and modelling

1 Device description

Consider the following device (Figure 1). It is a cable driven disc steered by a Brushless Maxon[1] DC motor. It is equipped with two incremental encoders for position measurement. The first one is on the motor shaft and the second one is on the output shaft.

The device parameters are considered as follows:

- M_D and J_D are respectively the Mass and the Inertia of the disc relative to its rotation center.
- r_g is the distance of the center of mass of the disc to its rotation center.
- I_m is the inertia of the motor.
- The gear ratio of the cable based transmission is 15.

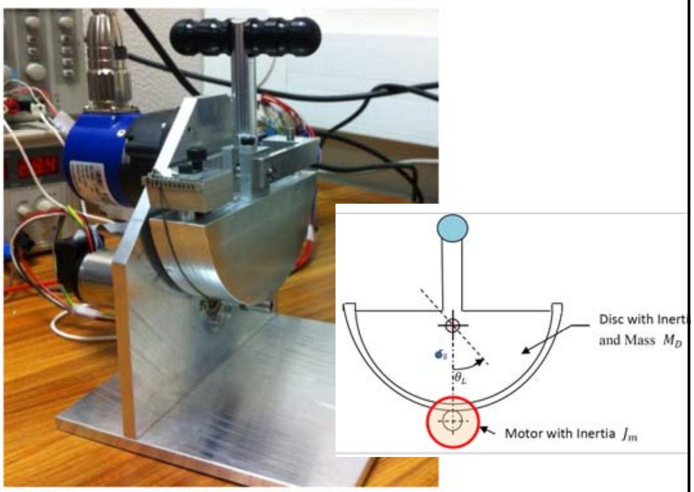

Figure 1-Haptic Device used for position control

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Haptic paddle – position control and modelling

$\sum M = J_{RL}\ddot{\theta}_L = \Gamma_{act} - \Gamma_{dry} - k_{vis}\dot{\theta}_L - \Gamma_g$

$\Gamma_g = M_D . g . r_g . \sin(\theta_L)$

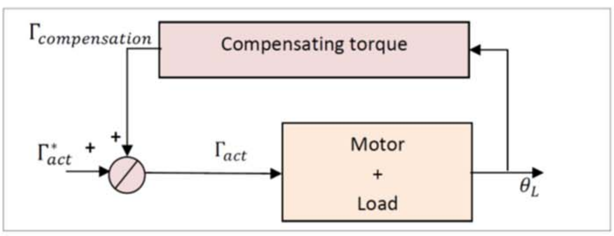
Γ_g is the gravity torque. Γ_{act} is the actuating torque reported at the output side.

$$J_{RL}\ddot{\theta}_L = \Gamma_{act} - \Gamma_{dry} - k_{vis}\dot{\theta}_L - M_D\, g\, r_g \sin(\theta_L)$$

$$J_{RL}\ddot{\theta}_L = \Gamma_{act} - \underbrace{M_D g\, r_g \sin(\theta_L) - \Gamma_{dry} - k_{vis}\dot{\theta}_L}_{\text{Torques (effects) to be compensated}}$$

That means that the compensating torque is given by:

$$\Gamma_{compensation} = M_D g\, r_g \sin(\theta_L) + \Gamma_{dry} + k_{vis}\dot{\theta}_L$$



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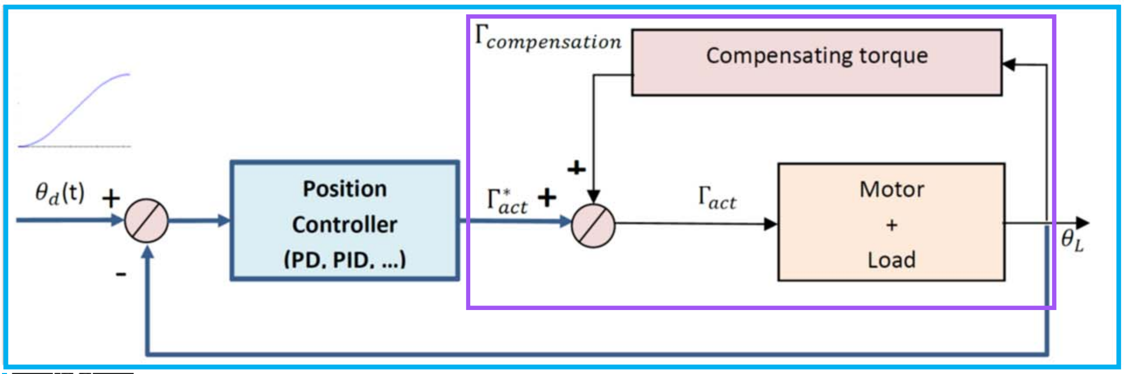
Linearization and exact model compensation

Important

Note that this relation between θ_L and Γ_{act} (eq. 4) is nonlinear. After applying the compensating feedback, the relation between θ_L and Γ^*_{act} becomes linear. This operation is also called exact nonlinear compensation or exact linearisation. Furthermore the obtained system (eq.8) is a double integrator that may be controller by any conventional controller.



Feedforward compensation (a priori control)

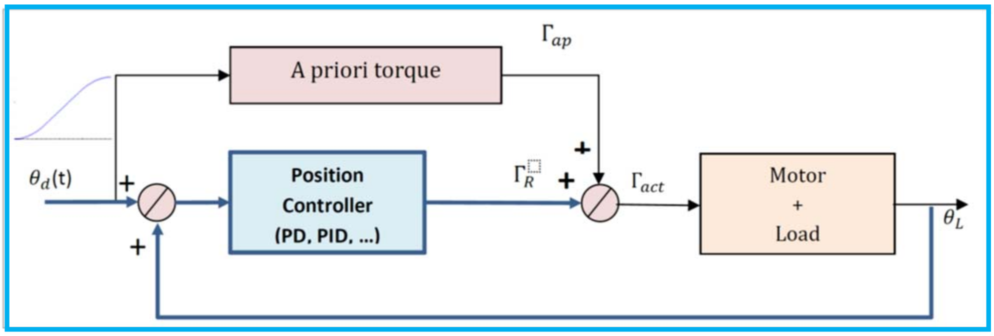
$$\Gamma_{ap} = \Gamma_{motor}(\theta = \theta_d(t), \dot{\theta} = \theta_d(t), \ddot{\theta} = \theta_d(t))$$

$$\Rightarrow \Gamma_{ap} = J_{RL}\ddot{\theta}_d + M_d g\, r_g \sin(\theta_d) + k_{vis}\,\dot{\theta}_d + \Gamma_{dry}$$

- $J_{RL}\ddot{\theta}_d$ → Inertia feed forward "A priori"
- $M_d g\, r_g \sin(\theta_d)$ → Gravity feed forward "A priori"
- $k_{vis}\,\dot{\theta}_d + \Gamma_{dry}$ → Friction feed forward "A priori"

Feedforward compensation (a priori control)

$$\Gamma_{act} = \Gamma_{PID} + J_{RL}\ddot{\theta}_d + M_d g\, r_g \sin(\theta_d) + k_{vis}\,\dot{\theta}_d + \Gamma_{dry}$$



Does not correspond to an exact compensation (!)

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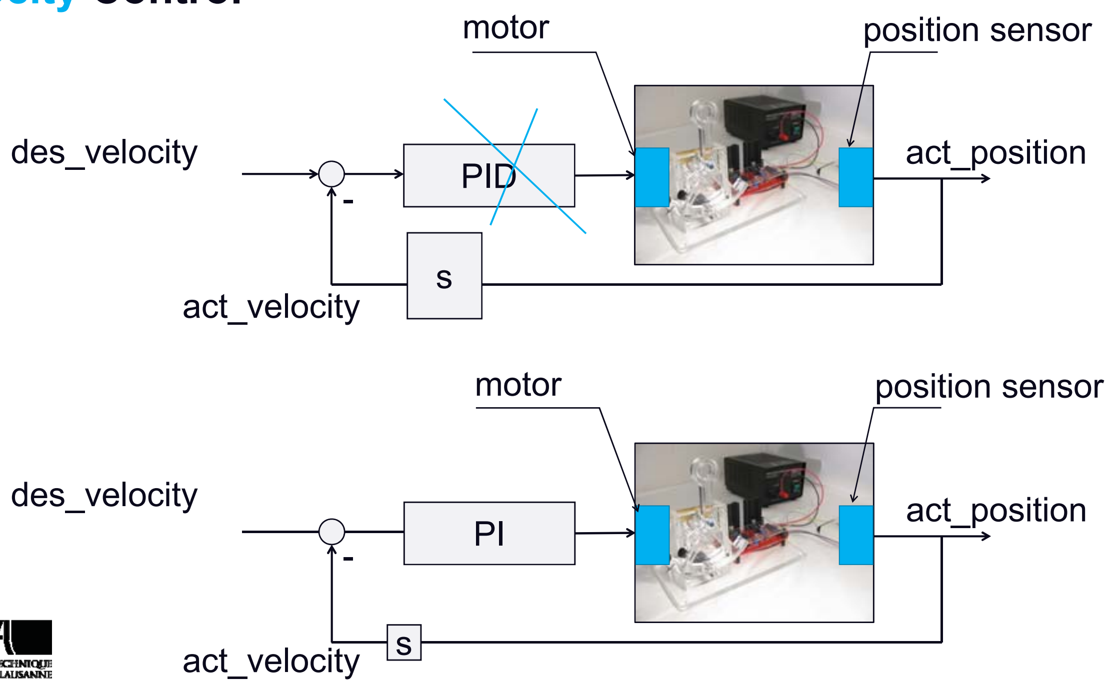
Velocity Control



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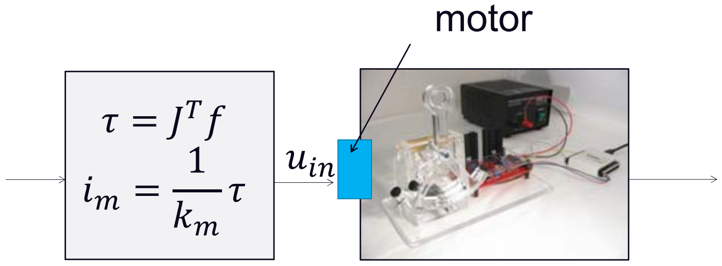
Force Control

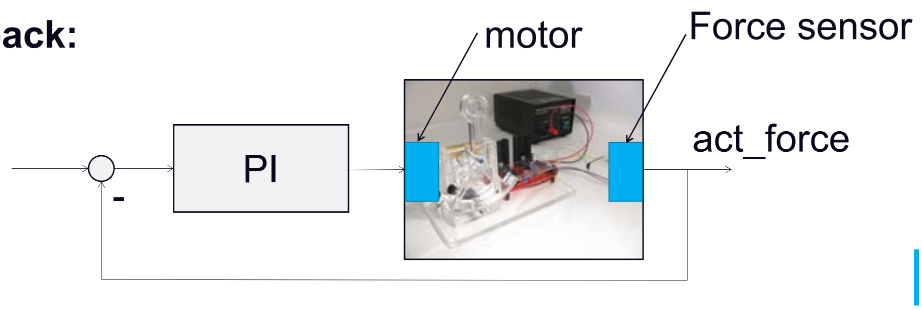
Open-loop:

des_force



Force feedback:

des_force



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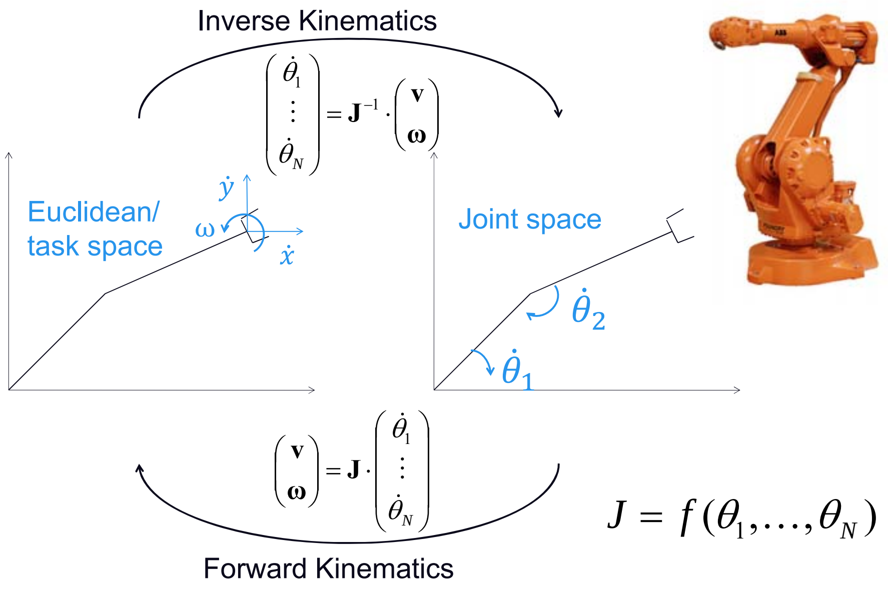
Jacobian



$$J = f(\theta_1, \ldots, \theta_N)$$

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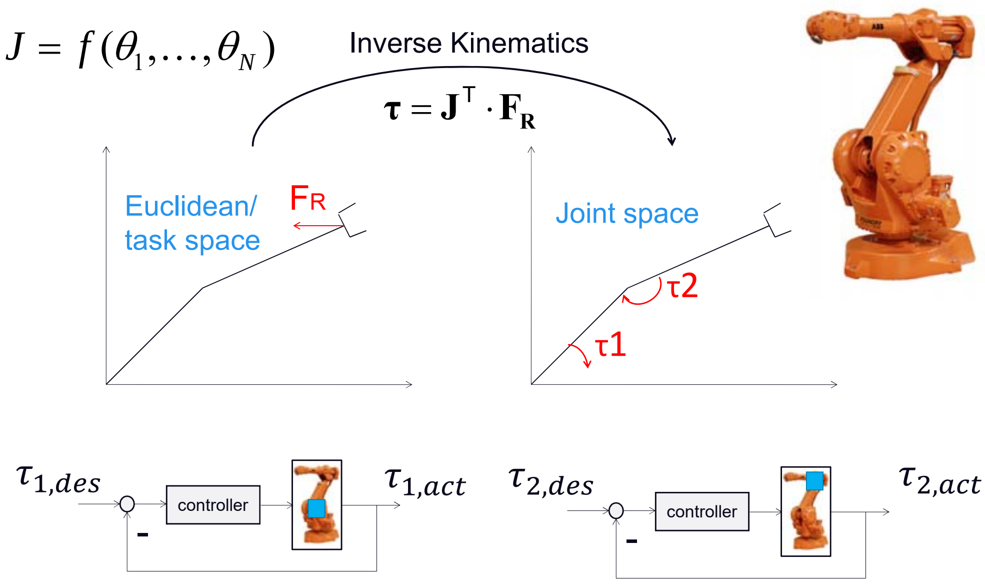
Static Force-Torque Relationship



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Human Robot Interaction

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How Can a Robot Interact with the Environment/ a Human?





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general introduction

Question 2

Do you now speak Robotics ?

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Let us move on….

General
introduction

Mission of this lecture

Why Robotics is a good opportunity to develop the rehabilitation techniques of tomorrow ?

Objective
of this presentation

- ~~Control strategies – Basic concepts~~
- *Lower limb robotic devices*
- *Exoskeleton solutions*
- *Lower limb rehabilitation techniques*

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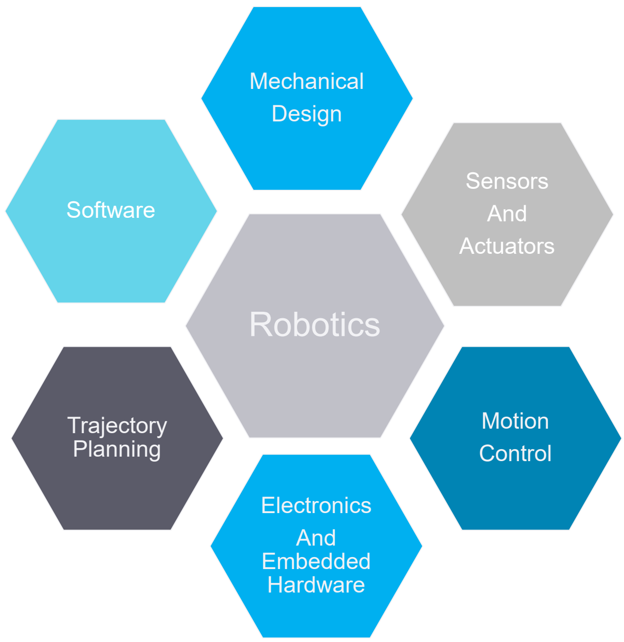

What is Robotics related to?

*Robotics is probably "**THE MULTIDISCIPLINARY** engineering science which implicates all the engineering sciences !"*

In the late ten years….
*Robotics has been closest **to more disciplines***

- *Surgery and rehabilitation*
- *Cognitive neurosciences*
- *Gaming*
- *Building manufacturing*

….

- *Education*

Rehabilitation - Cooking recipe
miam miam

Lower limb Rehabilitation :
Is there any cooking recipe ?

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Rehabilitation of what ? Which objectives?

Motor rehabilitation ?

Sensory rehabilitation ?

Cognitive rehabilitation ?

Others ?

Rehabilitation of whom ?

Spinal Cord Injured (SCI) people ?

People suffering a stroke?

Elderly ?

Others ?

The lecture
Lower limb rehabilitation devices

Why Robotics? — Techniques

From an idea to a device — The 3 MM

The lecture
Lower limb rehabilitation devices

Part 2 — Sitting Position devices

Part 3 — Verticalized devices

Part 4 — Exoskeletons

Motor Rehabilitation: What is and Why?

Rehabilitate a limb is train it in order to recover the mobility? Strengthen muscles, ? Improve sensory functions, coordination,...

- Mobilisation
- Evaluation
- Interaction

Robotics is a solution for rehabilitation because of the presence of elements related to mobilization (through actuators) and evaluation (through sensors)

Mobilisation

- Structures that allow the **transmission of efforts** from one point to another point.
- Actuators producing **mobilization** and providing effort feedback

Evaluation

Thanks to instrumentation (Sensors).

- By closing the loop for control purposes.
- To follow the progress during the rehabilitation phases.
- For safety

Interaction

Strategies of rehabilitation

From an idea to a device
The Lokomat ….

Moving the limb ……

[ref. the Lokomat from the company HOCOM, ZH]

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Rehabilitation techniques
Next door …

The 3 MM approaches

From Motion to Motion

From Motion to Mind

From Mind to Motion ….

From Motion to Motion
The Passive mobilisation

[The device TM2 from Yaskawa]

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From Motion to Mind
Mobilize and interact

- ✓ Rehabilitation by learning
- ✓ Learning by Errors

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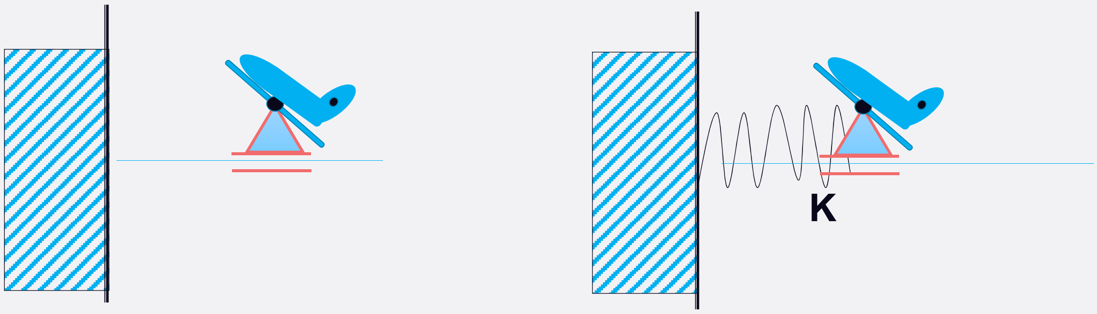
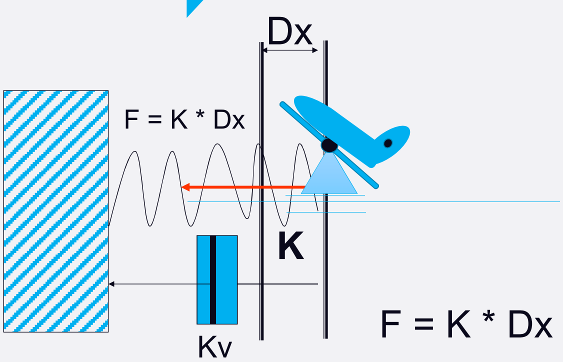
From Motion to Mind
Mobilize and interact

Think it simply ☺



From Motion to Mind
Mobilize and interact

Think it simply ☺ ➡ **Impedance** control

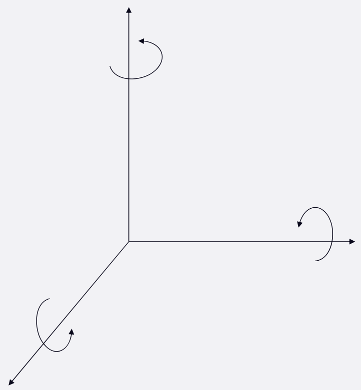


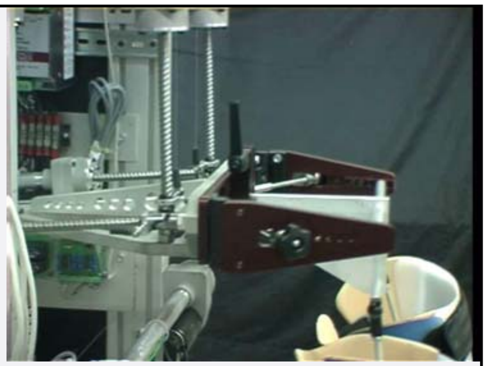
F = K * Dx + Kv * d(Dx)/dt

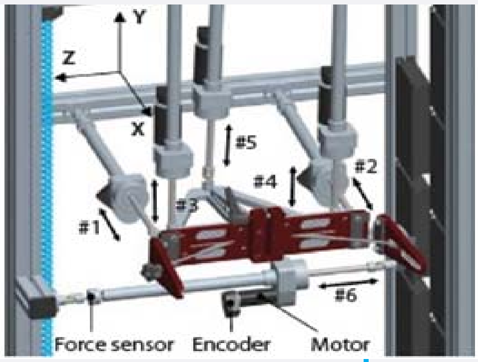
Fmot = Kp * Dx + Kd * d(Dx)/dt

From Motion to Mind
Mobilize and interact

Multi degrees of freedom case
Pelvic Orthosis and selective impedance control







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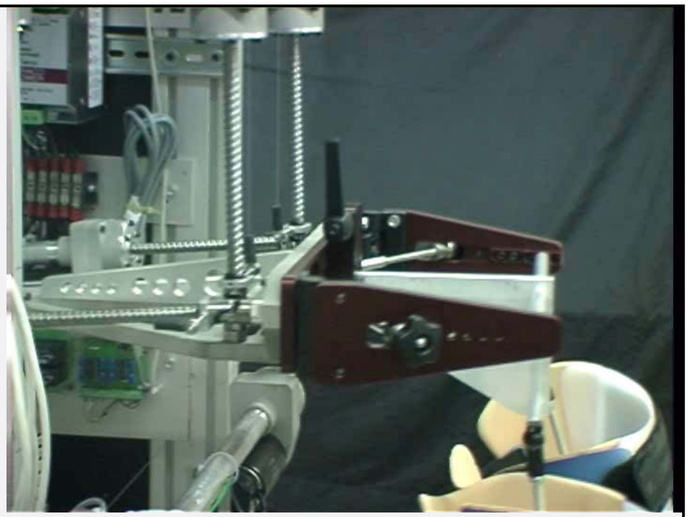

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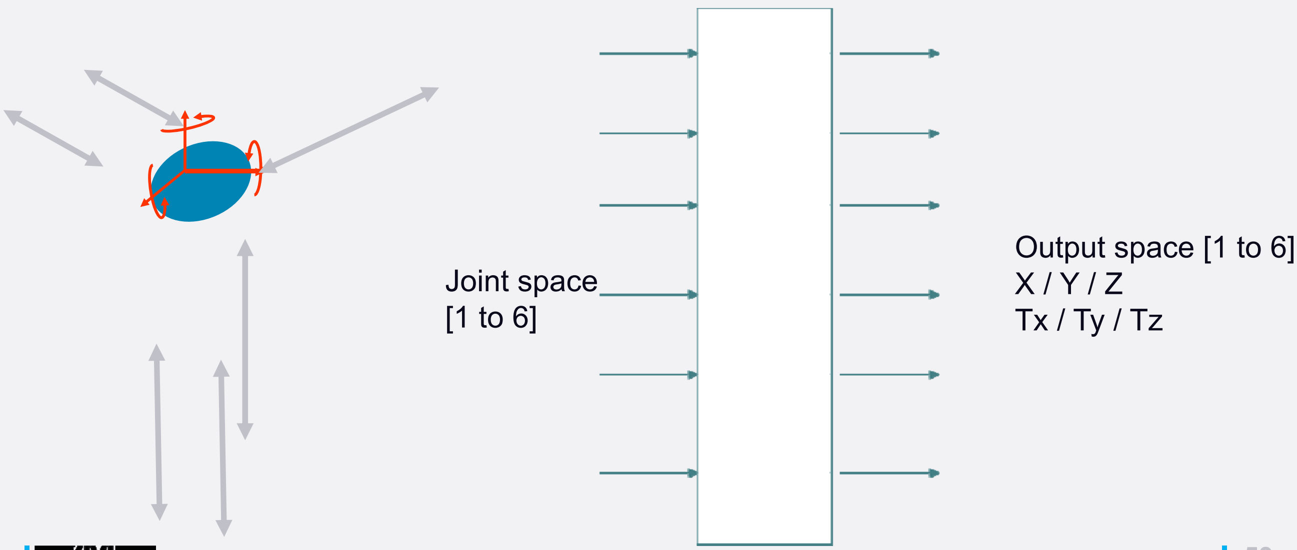
From Motion to Mind
Mobilize and interact

Muti degrees of freedom case
Pelvic Orthosis and selective impedance control



Compliance in joint space implies a coupled compliance in the output spece (X Y Z Tx Ty Tz)

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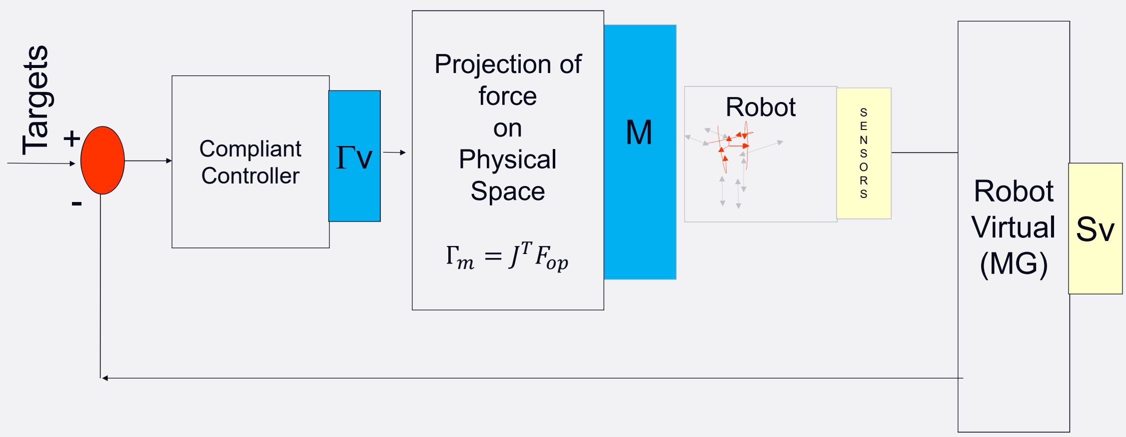
From Motion to Mind
Mobilize and interact

Control loop …. Joint space control



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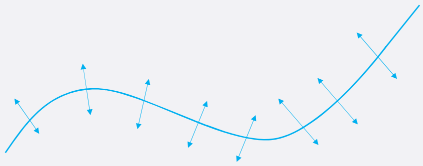
What else?

We may target a desired motion around which there is an attractive field of force

Desired motion



The attractive forces correspond to adjustable impedance values

- **Infinite impedance** corresponds to pure mobilisation
- **Low impedance** implies participation of the subject to follow the trajectory.

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Flexion extension
Interaction through impedance control

- **Infinite impedance** corresponds to **pure mobilisation**
- **Low impedance** implies the **participation** of the subject

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[Olivier, EuroHaptics, 2014]
[Liu, J. Neuro Eng, 2017]
[Liu, Trans. Neur Syst. Rehab, 2018}

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Part 2
Sitting Position Devices

Devices and techniques

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The MotionMaker
From the idea to the device

Mobilize and Electrostimulate, a combined therapy

The interaction between the device and the user is carried out through :
- A given objective of flexion / extension force
- A closed loop muscle electrostiulation

Mobilize and Electrostimulate the muscles

Patent references.
Brodard, R., Clavel, R., Therapeutic and/or training device for a person's lower limbs, U.P.U. A1, Editor. 2004.
Brodard, R., Clavel, R., Dispositif de rééducation et/ou d'entrainement des membres inferieurs d'une personne, E.P.E. B9. 2002.

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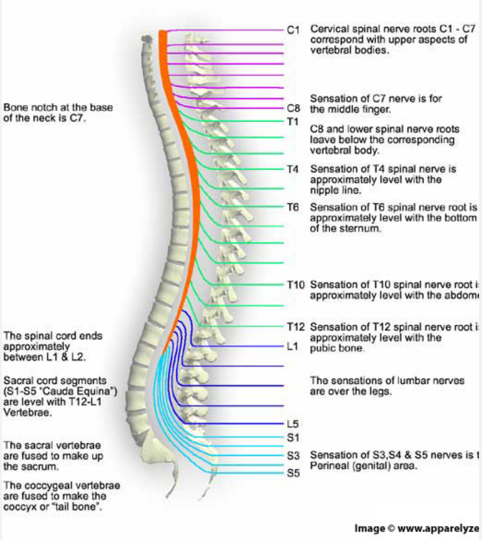
Spinal cord functions and lesions



C1 & C2 :
Immediate death

@ cervical levels C3 to C7 :
Tetraplegia

@ dorsal lumbar level T1 to L1 :
paraplegia + possible incontinence

Lowest than L2 :
Neuralgias (nerve root damages)

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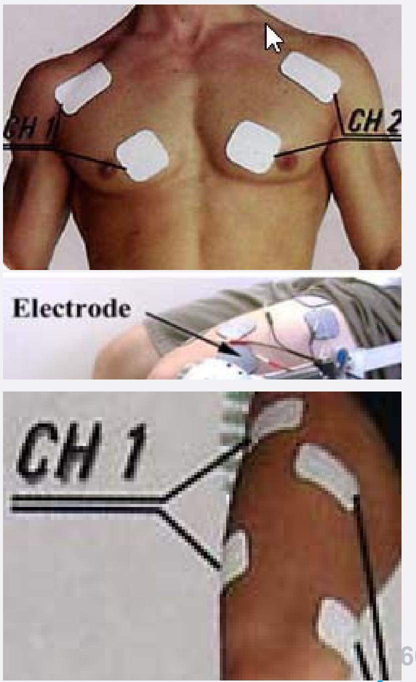
The electrodes

There is **one pair of electrodes** to electrostimulate one muscle.

The **electrostimulator produces a difference of potential** through the muscle which contracts



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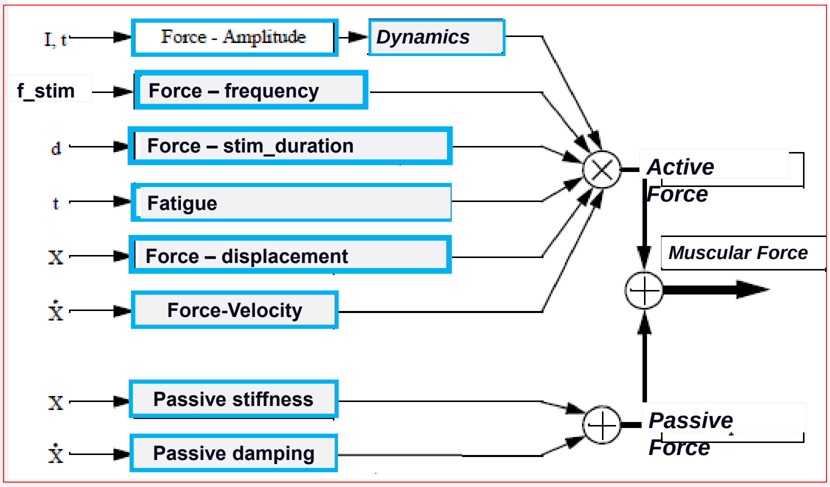
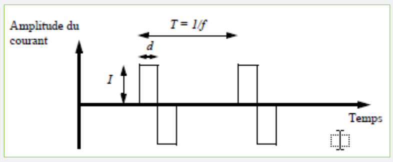
Electro-induced muscular activity

[Hill & Hammerstein model]





Muscular frorce is a superposition force between a voluntary force and the electro induced force

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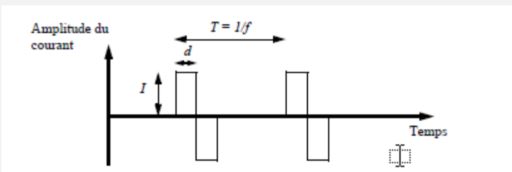
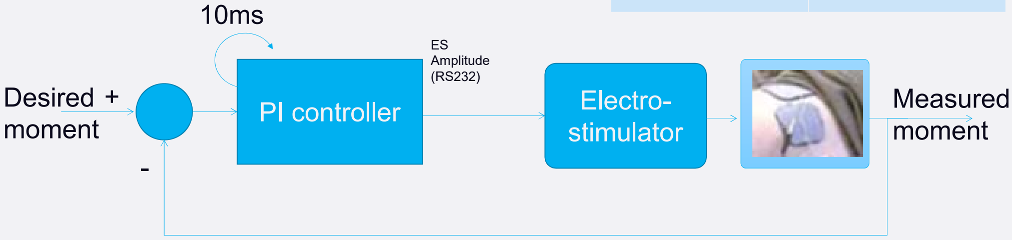
Closed loop Muscle Electrostimulation



Signal Information	Value
Frequency (f)	50 Hz
Amplitude (I) Control signal	0-150mA
Pulse width (d)	250 us



- **What is important ?**
- **What are the parameters of this controller?**

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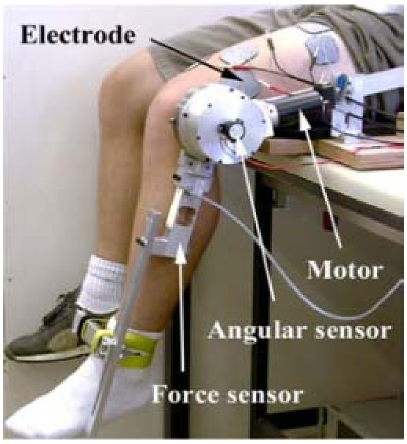
Proof of concept
Knee Orthosis

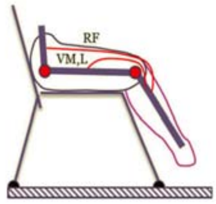


Concept:
- Mobilisation

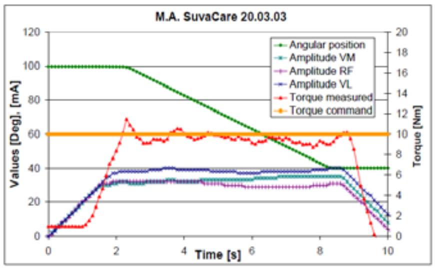
+
- Force control through electrostimulation

Knee Orthosis Setup

Demonstrator
2001



Muscle recruitment for knee extension



- 8 subjects participated –
- 6 finished the CT-
- 2 Stopped : they completely retrieved their voluntary forces.
- 1 did not respond to ES

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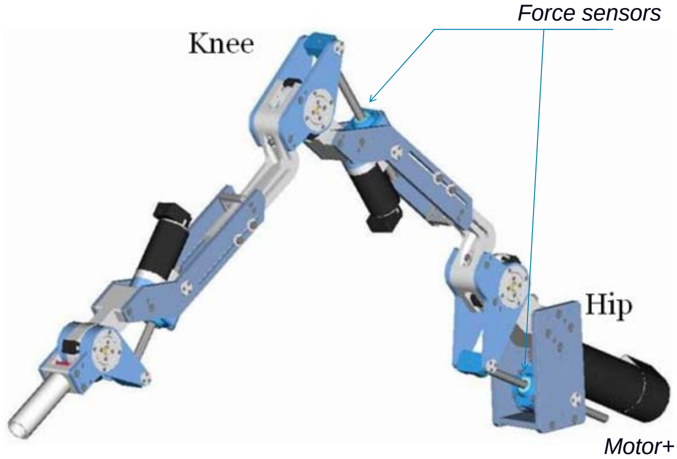
[Schmidt, IFES, 2004]
[Bouri, Springer, 2014]

Second step

Extension to a 2 Legs orthosis (Right and Left Limb)



[Metraillet, EMBS, 2006]
[Bouri, Springer, 2014]

The approach

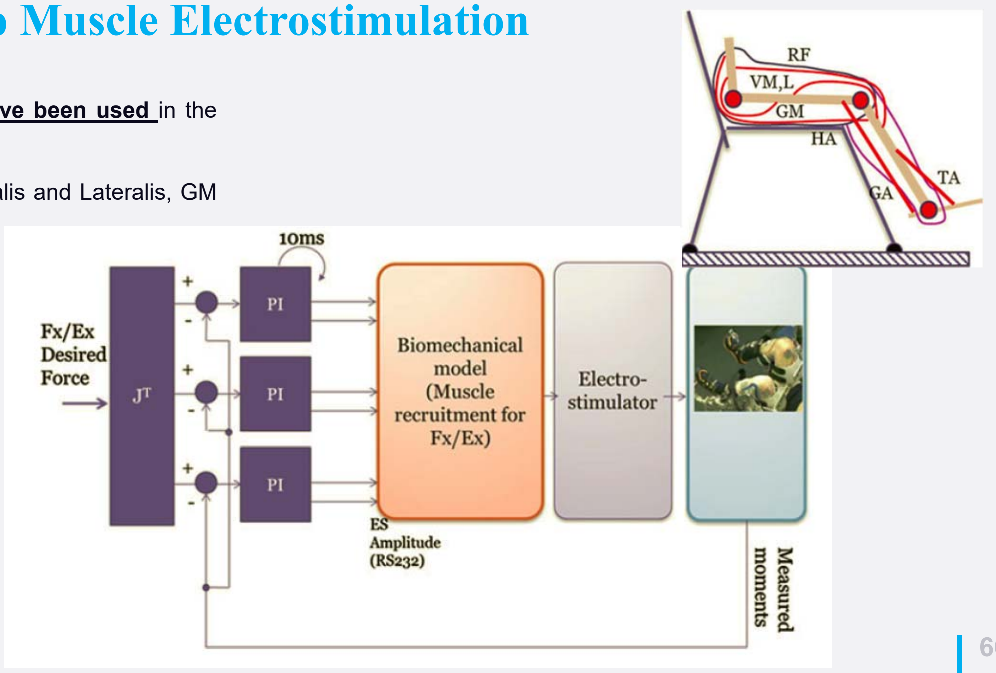
1. Mobilize the paralyzed (partially or completely) lower limbs – with a defined movement of flexion /extension.
2. Electrostimulate the muscles accordingly to the chosen movement (ie, the muscle recruitment must be carried out accordingly to the chosen movement).
3. Impose **an objective to the subject (desired force)** and close the electrostimulation control loop through the measured exerted force at the foot.

This is called **the challenge** !

Closed loop Muscle Electrostimulation

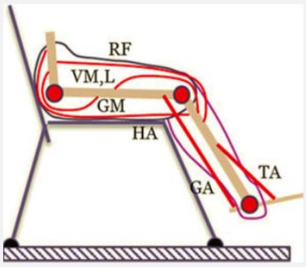
Total of **7 muscles have been used** in the loop:

- RF Rectus Femoris,
- VM, L Vastus Medialis and Lateralis, GM Gluteus maximus.
- HA Hamstring,
- GA Gastrocnemius,
- TA Tibialis Anterior



The Electrostimulation Control loop

The muscle
recruitment



Joint	Flexion movement	Extension movement
Hip	Rectus Femoris (RF)	Gluteus Maximus (GM)
Knee	Hamstring (HA)	Vastus Medialis and Lateralis (VM + L)
Ankle	Tibialis Anterior (TA)	Gastrocnemius (GA)

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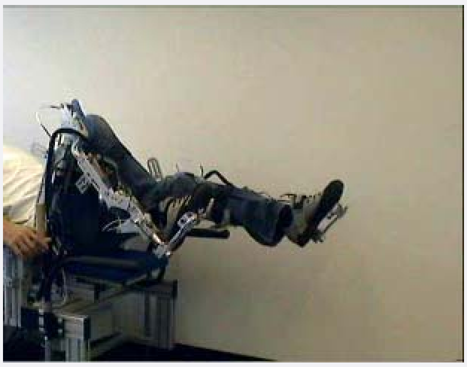
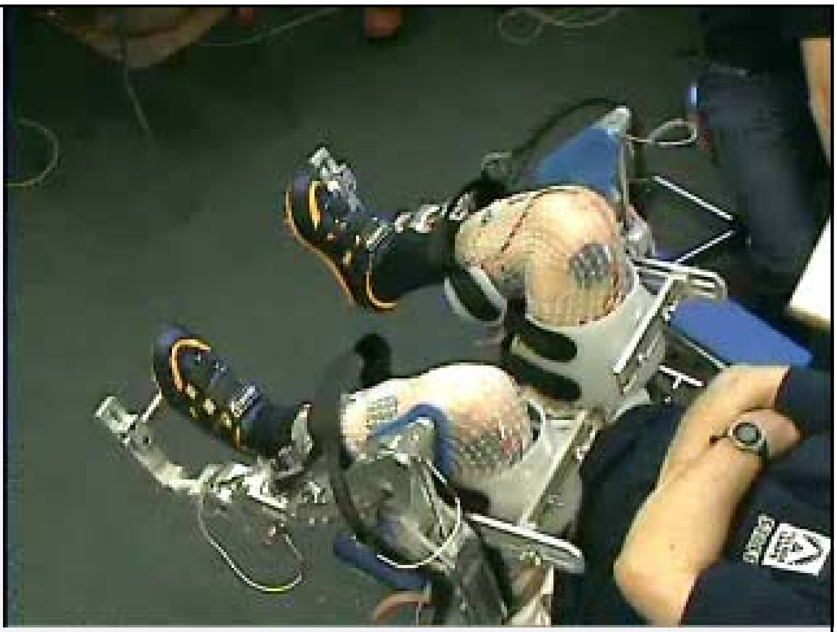
MotionMaker
The movie





SCI subject

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MotionMaker
The product

[ref, Swortec SA, CH]

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MotionMaker
The transfer table

The transfer phase should be taken with a special care!

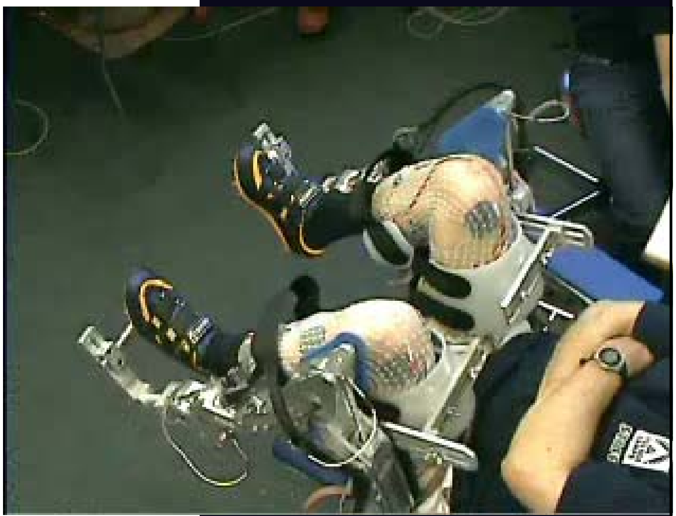
Transfer table

EPFL prototype
Used for the first CT

- 4 Subjects with incomplete lesions
- 1 subject with complete lesion (ASIA-A).

- During 8 weeks with 2/3 sessions of 60 mins per week.

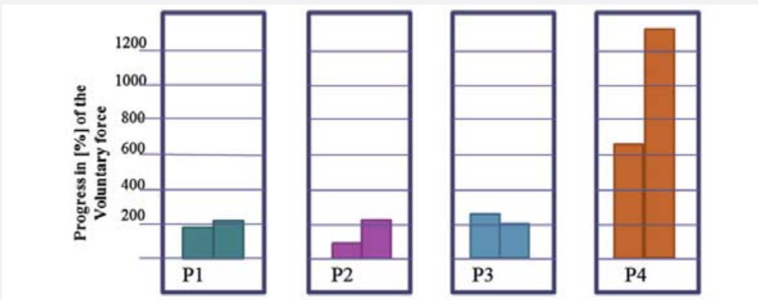
MotionMaker
The clinical trial



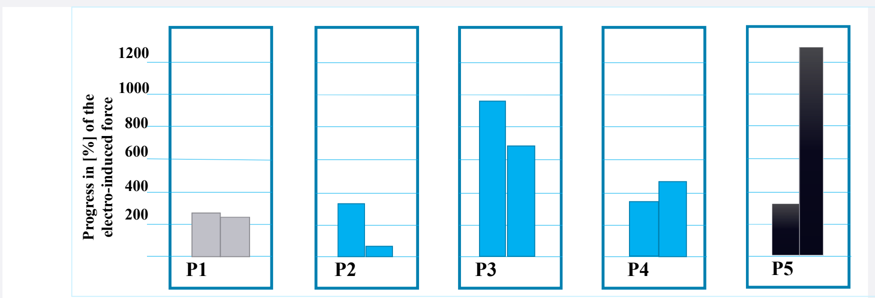
CT
Results

[Right bar : Right leg]

Progress of the voluntary force



Progress of the electro-induced force



[Metraillet, EMBS, 2006]
[Bouri, Springer, 2014]

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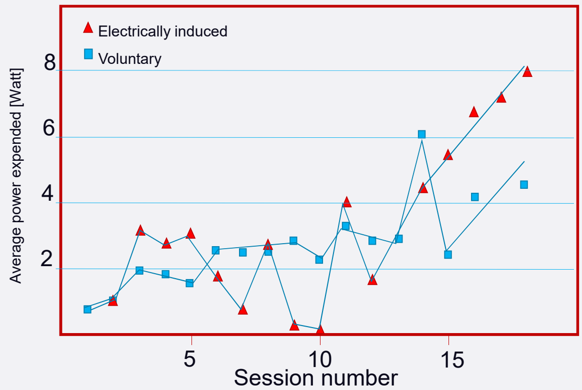
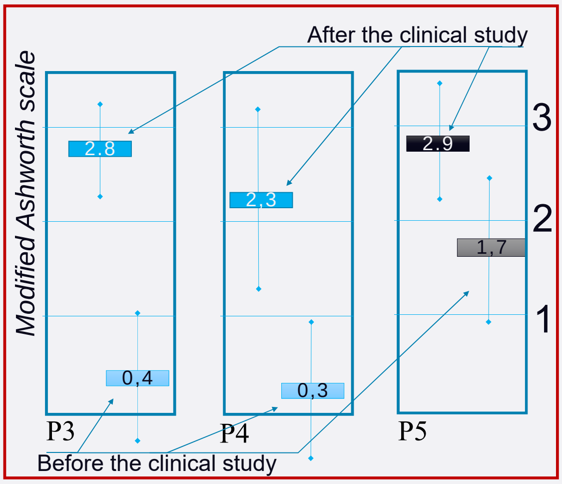
CT
Results

Progress of the Voluntary and electrically induced expended power for one subject



Progress of the mean and standard deviation of spasticity



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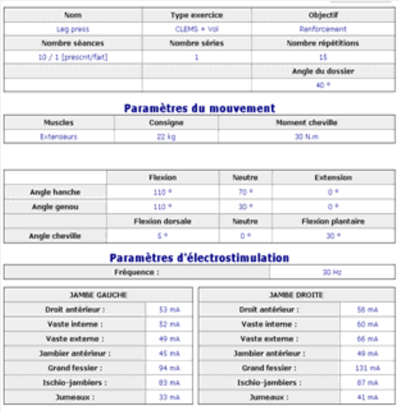
Clinical Results 2008-2012 at the “Centre Romand de Rééducation” – 25 subjects

CT- Follow up @the Rehabilitation Center of Sion
Results

Around **40 subjects has used the MMaker during 2008-2012**
We will present the results of around 25 subjects

Clinical Procedure
- Evaluation of the subjects – Voluntary versus Electroinduced
- Exercise session programmed
- Reporting



Nom	Type exercice	Objectif
Leg press	CLEMS + Vol	Renforcement
Nombre séances	Nombre séries	Nombre répétitions
10 / 1 [prescrit/fait]	1	15
		Angle du dossier
		40 °

Paramètres du mouvement

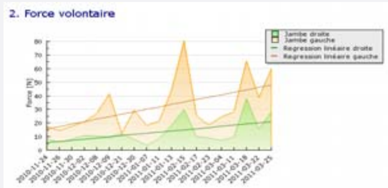
Muscles	Consigne	Moment cheville
Extenseurs	22 kg	30 N.m

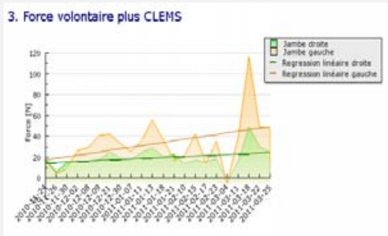
	Flexion	Neutre	Extension
Angle hanche	110 °	70 °	0 °
Angle genou	110 °	30 °	0 °
	Flexion dorsale	Neutre	Flexion plantaire
Angle cheville	5 °	0 °	30 °

Paramètres d'électrostimulation

Fréquence :	30 Hz

JAMBE GAUCHE		JAMBE DROITE	
Droit antérieur :	53 mA	Droit antérieur :	56 mA
Vaste interne :	52 mA	Vaste interne :	60 mA
Vaste externe :	49 mA	Vaste externe :	66 mA
Jambier antérieur :	45 mA	Jambier antérieur :	49 mA
Grand fessier :	94 mA	Grand fessier :	131 mA
Ischio-jambiers :	83 mA	Ischio-jambiers :	87 mA
Jumeaux :	33 mA	Jumeaux :	41 mA





EPFL ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

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CT- Follow up @the Rehabilitation Center of Sion
Results

Id Subject	MM use (hours)	Improvement left Leg Extension [%]	Improvement Right Leg Extension [%]	Averaged Progress [%]	Appreciation
15	104	2380	675	1527.5	Very Strong
14	12	1460		1460	Very Strong
11	6	1233	790	1011.5	Very Strong
12	24	1545	258	901.5	Very Strong
24	60	680	800	740	Very Strong
5	48	327	863	595	Very Strong
26	36	927	198	562.5	Very Strong
8	72	550	130	340	Strong
27	6	77	575	326	Strong
1	44	183	243	213	Strong
37	34	191	176	183.5	Strong
2	8	137	168	152.5	Strong
10	90	107	168	137.5	Strong
46	30	97	57	77	Average
35	28	84	47	65.5	Average
31	20	-31	112	40.5	Weak
53	14	20	45	32.5	Weak
16	20	18	39	28.5	Weak
23	18	40	15	27.5	Weak
42	26	21	23	22	Weak
41	32	18	7	12.5	Weak
6	18	-1	14	6.5	Weak
32	48	29	-29	0	NAI
3	6	-13.3	12	-0.65	NAI
13	16	-21	-39	-30	NAI
19	22	-73	-67	-70	NAI

[NAI]
Non Appreciated Improvement

EPFL ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

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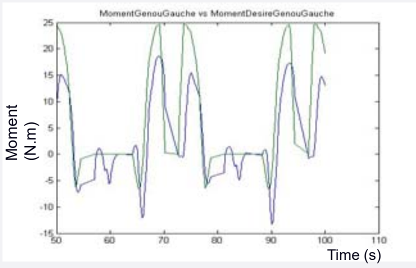
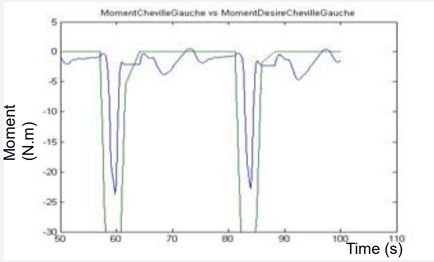
CT- Follow up @the Rehabilitation Center of Sion
Results

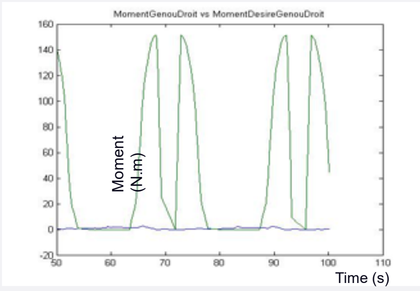
Desired vs. Measured moments

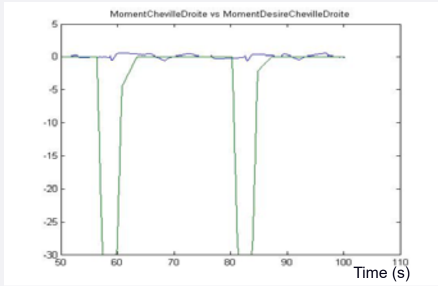
Well electrostimulated muscle





Innervation problem and non-responding muscle





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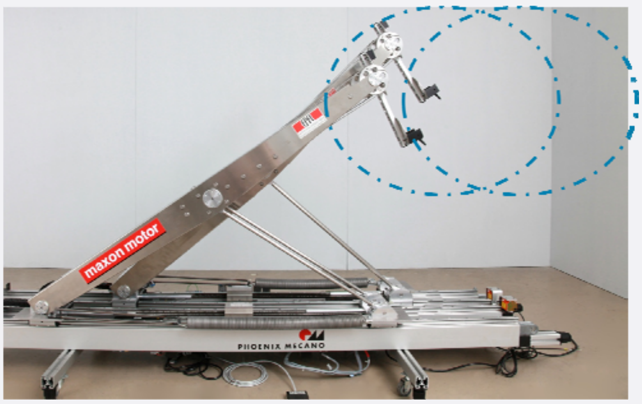
Why using a parallel kinematics
The Lambda



No need of anthropomorphic adjustment

Parallel kinematics

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[Bouri, Robio, 2009]
[Bouri, Springer, 2014]

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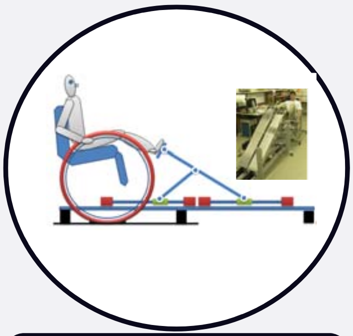
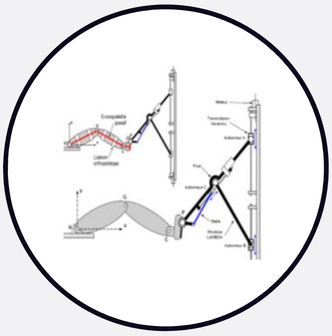
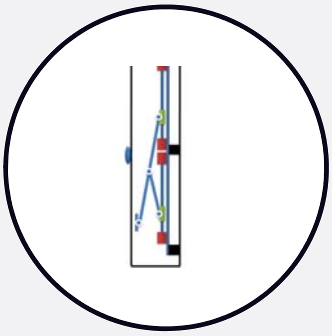
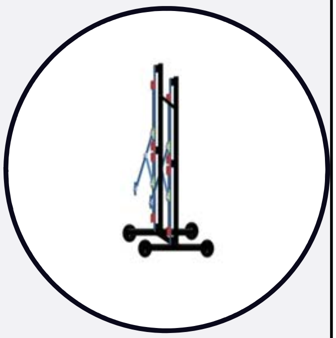
Why using a parallel kinematics
The Lambda

More versatile, different dispositions, adaptable to wheelchairs)

May be verticalized,...

Cabinet use

May be used with Rollers

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The Lambda Health System
A coming soon product

The approach **combines mobilization and immersive** VR

{ref LHS SA, CH]

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Part 3
Verticalized Rehabilitation Devices

Verticallized Systems
The Lokomat from HOKOMA, ZH, CH

- Actuated Hip and Knee for each leg.
- Following Ankle joint
- Use of a treadmill
- BodyWeight support
- …
- First prototype that has been sold (more 200 pieces around the world) was totally passive
- An impedance control is also implemented

The lokomat….
And what else

G-eo from Reha Technologies (CH)
(www.reha-technology.com)

Reo Ambulator from Motorika.com (US)
(www.motorika.com)

The lokomat….
And what else

walkBot from WalkBot (KR)
(www.motorika.co.kr)

Lopes from Uni Twente (NdI)
(https://www.utwente.nl/en/et/bw/research/projects/lopes/)

The Kineassist
from KineaDesign, IL, USA

- Overground Walking
- BodyWeight support
- Pelvis orthosis.
- Fall down safety.

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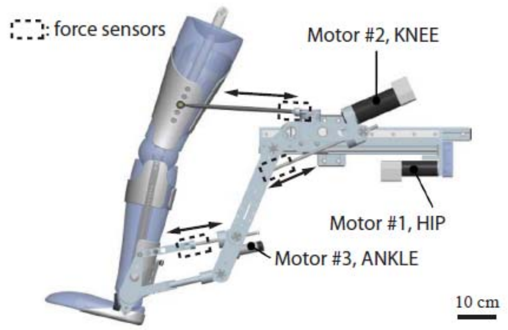
The WalkTrainer™ developed by EPFL with the Swiss foundation of paraplegics and the company Swortec SA, VS, CH

www.swortec.ch

Leg Orthosis and leg interface



(a) Schematic view of the leg orthosis.

(b) Realization of the leg orthosis.

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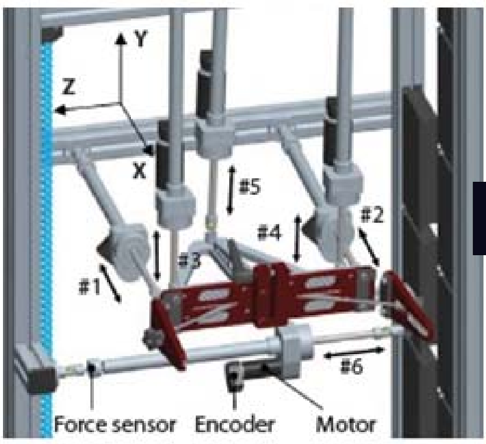
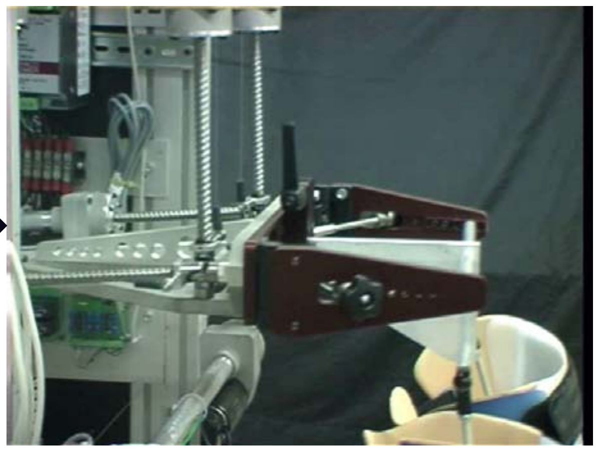
The “Pelvic Orthosis” mobilize the 6 degrees of freedom of the pelvis.
The 6DOFs pelvic motion is coordinated with the leg movements





3 x 2 x 1 Kinematics

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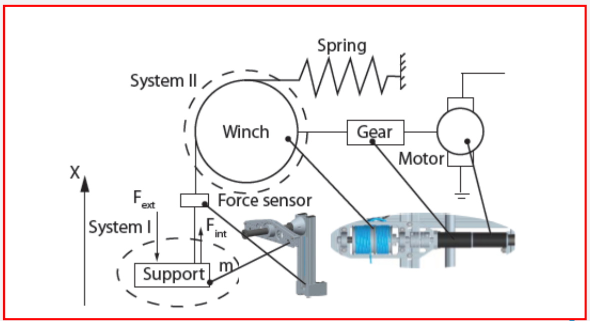
WalkTrainer
The bodyweight support

Force control loop is carried out during walking.



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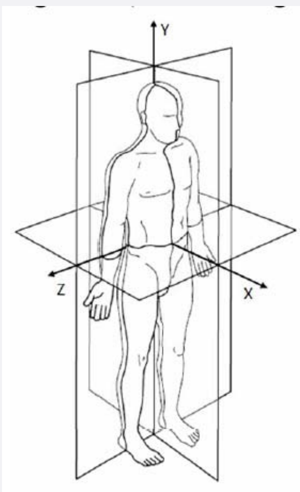
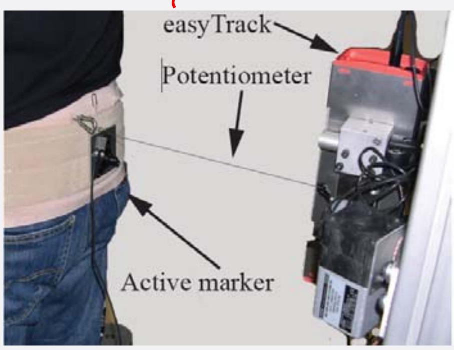
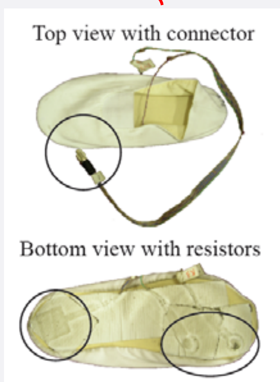
WalkTrainer
Pelvic Motion Measurement







Fourier decomposition model

$$d(t) = a_0 + \sum_{i=1}^{4} (a_i \cos(i\omega t) + b_i \sin(i\omega t))$$

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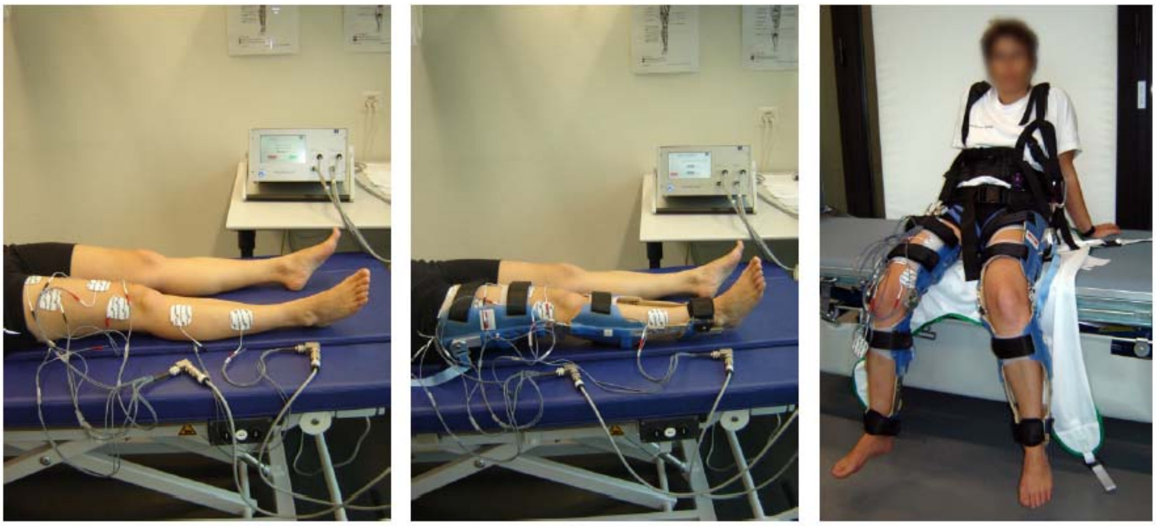
WalkTrainer
Clinical trials - Preparation



(a) Electrode placement. (b) Exoskeleton placement. (c) Harness fixation.

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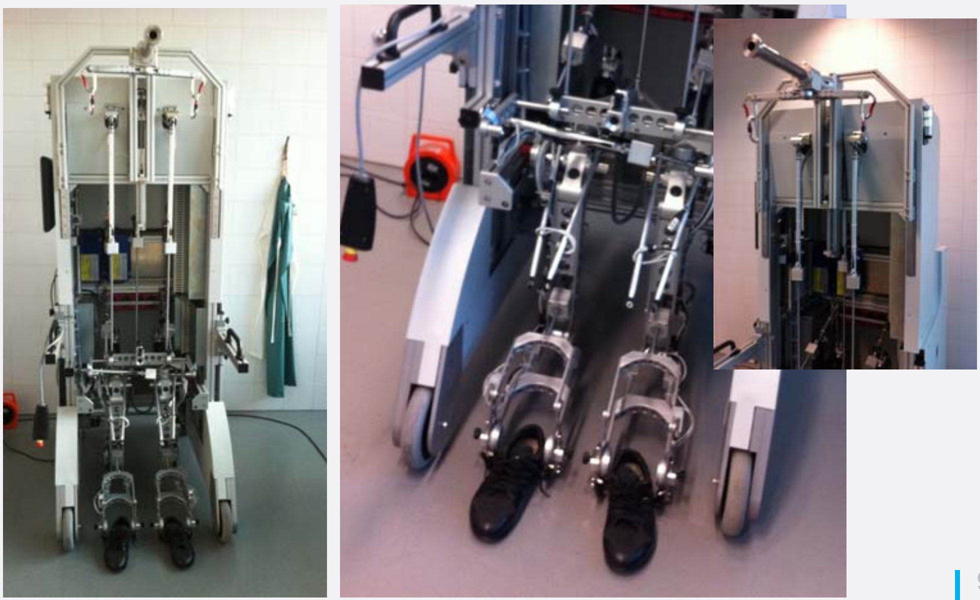
The WalkTrainer : The Movie

WalkTrainer
The product



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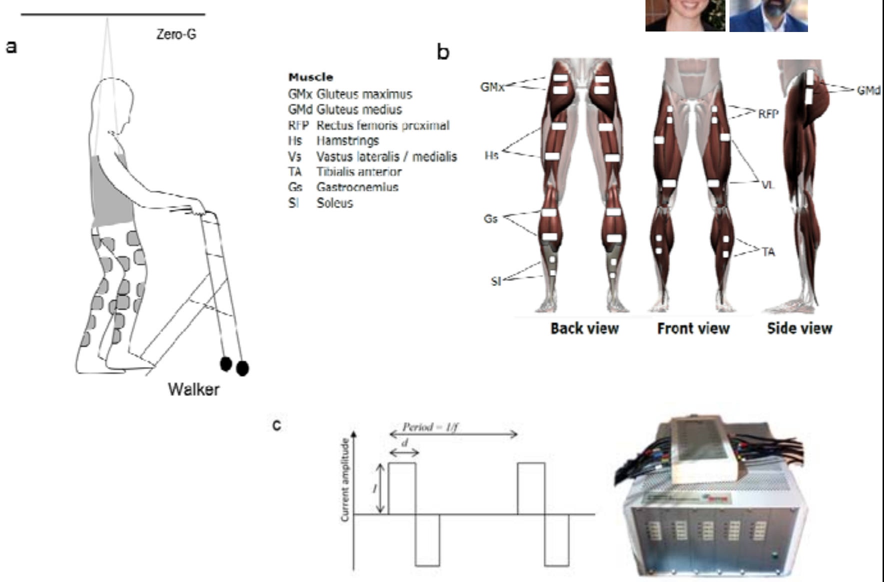
FES driven Walking

Closed-Loop Functional Electrical Stimulation for Gait Training for Patients with Paraplegia



[Bouri et al, ROBIO 2018]

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Triple Flex

CLOSED LOOP FUNCTIONAL ELECTRICAL STIMULATION FOR GAIT TRAINING FOR PARAPLEGIC PATIENTS

Mohamed Bouri, Aurélie Selfslagh, Debora Campos, Seidi Yonamine, Ana Donati, Solaiman Shokur

WALK AGAIN

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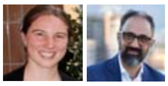
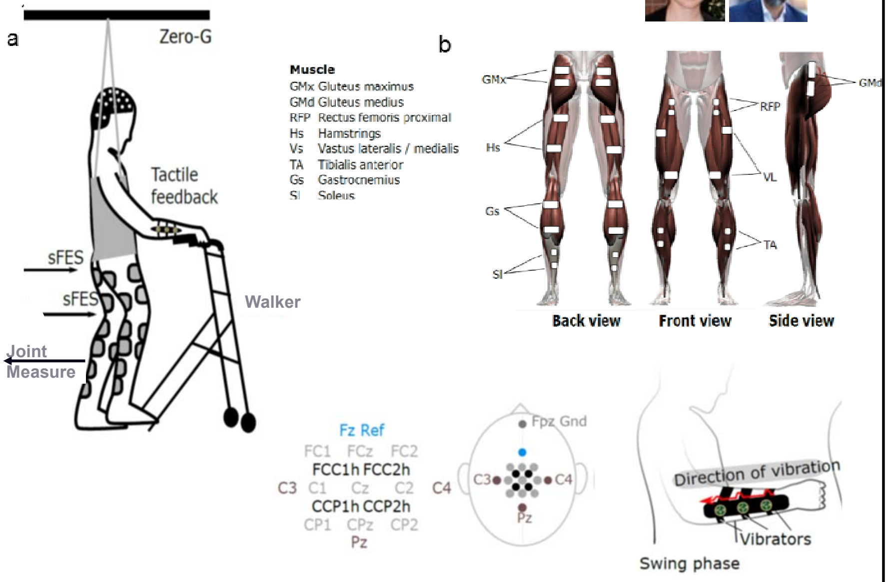
BCI + FES driven Walking

Closed-Loop Functional Electrical Stimulation for Gait Training for Patients with Paraplegia…

More with brain control and Sensory substitution





[Selfslagh et al, in revision SciRep 2019]

Part 4
Exoskeletons

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The dream

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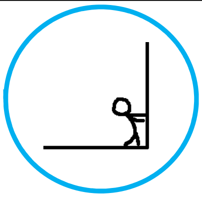
Exoskeletons
Definition

The "Chinese Brain Teaser"



An external covering or integument, especially when hard, as the shells of crustaceans (opposed to endoskeleton). [Ref, Dictionnary.com]

- EXO + SKELETON
- External + Rigidly (attached)
- **rigidly interfaced to the limb** through **dedicated components** to transmit **motion** or **torques.**

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Classified by IFR as personal service robot **or a service robot for personal use**
IFR, 2012

Biomechanical considerations

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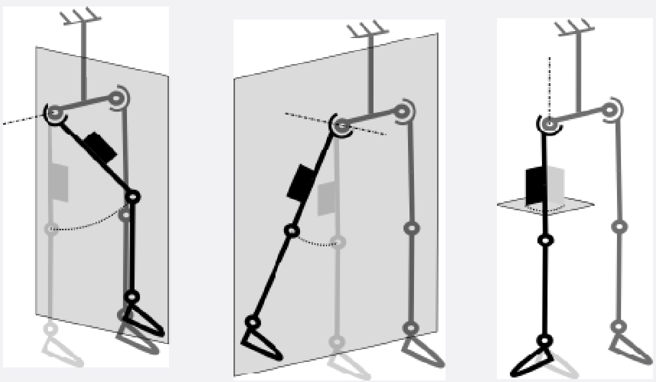
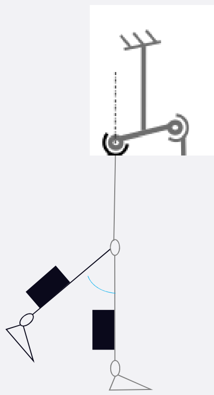
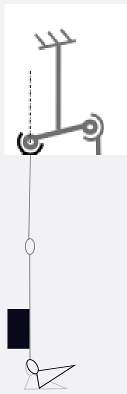
- Hip is a spherical joint



- Knee is a pivot

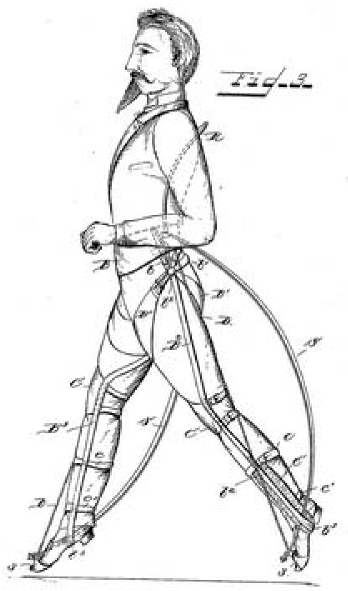


- Ankle



Exoskeltons
The origins

Since when ?



Yagn's "apparatus for facilitating walking"
(Nicholas Yagn/USPTO)

1889

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Exoskeltons
The origins

The first Built

General Electric's **1966** Hardiman.
the first device built.

Did not work because of control problems

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Opening the door !

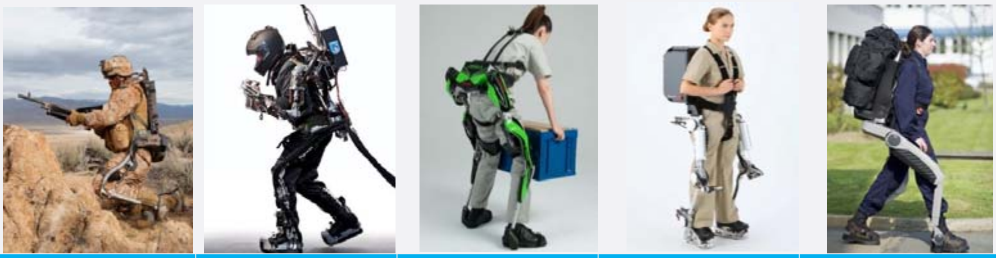
Walk Assistance
The HAL device from Cyberdyne

Motivations:

- Walk as others
- Re-feel the vertical posture
- Parity with others
- Therapeutical motivations

Dave Mac Colman,
C6, Rex user

Force amplification



HULC	Sarcos/ Raytheon	Kawasaki Power Assist Suit	Panasonic Power Loader Light	HERCULE
24 kg	68 kg	?	38 kg	25 kg

WalkAgain for Paraplegics

Ekso	ReWalk	REX	Indego	ExoAtlet	EMY
U.S.A	Israël	NZ	U.S.A	RUSSIA	FRANCE
23 kg	18 kg	39 kg	12 kg	25 kg	-

Many others!

- The Phoenix (SUITX) / USA
- The santosDumont / Brazil
- Lopes /Netherlands
- EMY II / France
- IHMC Robotics
- ROCKY / MEX
- BRAINWALKER / Russia
- VARILEG /SWITZERLAND
- NASA X1,
- ……

Motivations

- Walk as others
- Re-feel the vertical posture
- Parity with others
- Therapeutical motivations

Dream !

Dave Mac Colman, C6,
Rex user

Having Children that had never seen me walk meant so much to me.

Alvaro's mother.
Marsi Bionics user.

I dream so many times of watching him walking but he does not walk, Crying

Didier, the husband of Silke Pan
TWIICE User.

The best gift you offered to me is seeing my wife walking.

Daniel
IHMC Exoskeleton User

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There is NO Comment on his happiness wearing an exoskeleton

Daily living activities
targeted

Overground Walking

Transitions Sit-Stand

Upstairs - Downstairs

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

page 0108

Medical device or a Robotic Suit?

Cyberdyne CEO Yoshiyuki Sankai speaks at a news conference at the health ministry on Wednesday, with the robot suit on display. | KAZUAKI NAGATA

BUSINESS / TECH

Japan recognizes Cyberdyne's robotic suit as medical device

The HAL device from Cyberdyne

For medical use

HAL® for Medical Use - Lower Limb Model [European Model] is only handled in Germany. Contact the following with regard to inquiries about the training with HAL®.

The HAL

For medical use

What is it at the end?

The Lokomat….
And what else

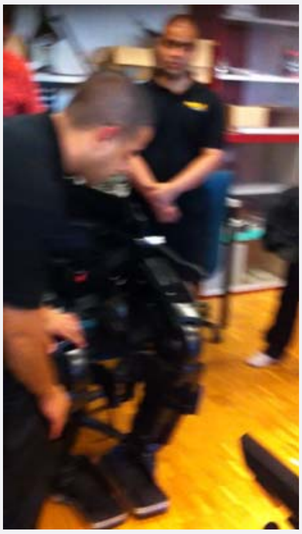
Pure mobilization with stability management

The REX device from Rex Bionics

Walk – pure mobilization

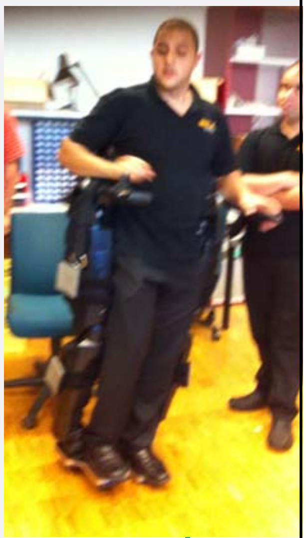
The Rex device from Rex Bionics

1-Transfert



2-Walking

3-Stability



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Pure mobilization device

The EKSO from Ekso Bionics

Walking with the EKSO

Rehabilitation or Not Rehabilitation?

The EKSO

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Most known commercial exoskeletons

Rex
Rex Bionics

ReWalk
Argo Med Tech

Ekso
Ekso Bionics

Hal
Cyberdyne

SuitX
www.suitX.com

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Exoskeletons for Activities for daily living

The challenges related to **wearability**, **autonomy** and **safety**.

Assistance rather than mobilization

Adapt to the subject capabilities

Adapt to the needs of the required task

TWIICE
A lightweight exoskeleton for paraplegics

www.TWIICE.ch

September 2017

Related PhD thesis

- Tristan Vouga, Romain Baud and Jemina Fasola

SONCEBOZ

fischer CONNECTORS

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The idea is not new

First discussions

Define objectives with respect to new challenges

Develop an exoskeleton for teenagers or young adult paraplegic, light weight and adjustable.

Can we do it in **less than 10 months**
September 2014 to August 2015

The mechanical design has to be kept simple
Embedded Electronics
Motion control
Gait generation
Clinical and human aspects

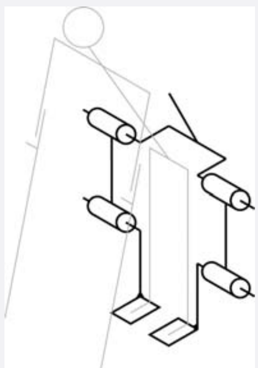
The development must go on….

Consolidate your team for having multidisciplinary skills.

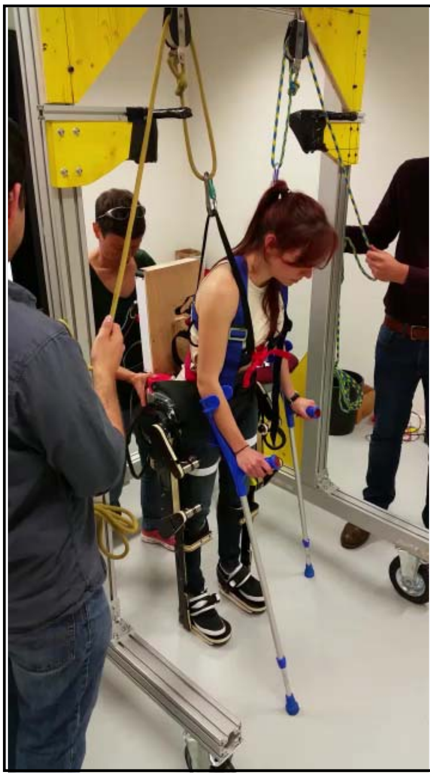
Overview

- Lower-limbs exoskeleton for disabled teenagers.
- 2 degrees of freedom per leg: hip and knee.
- Balance with crutches.
- Fully wearable.
- Targeted patients
    - 10 to 14 years old
    - 135cm to 150cm
    - Up to 50 kg
    - Able to use crutches

CYBATHLON



August, 2015



June 2016

TWIICE™ A light exoskeleton for people with paraplegia

- Lightweight structure <14kg
- Brushless motors with belt transmission and harmonic drive.
- Adjustable segments length.

After 18 months, 3 PhD students and 1 Enigneer

*Patent pending

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TWIICE-1 for teenagers and small sized adults

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To promote exoskeletons for activities of daily living for paraplegics

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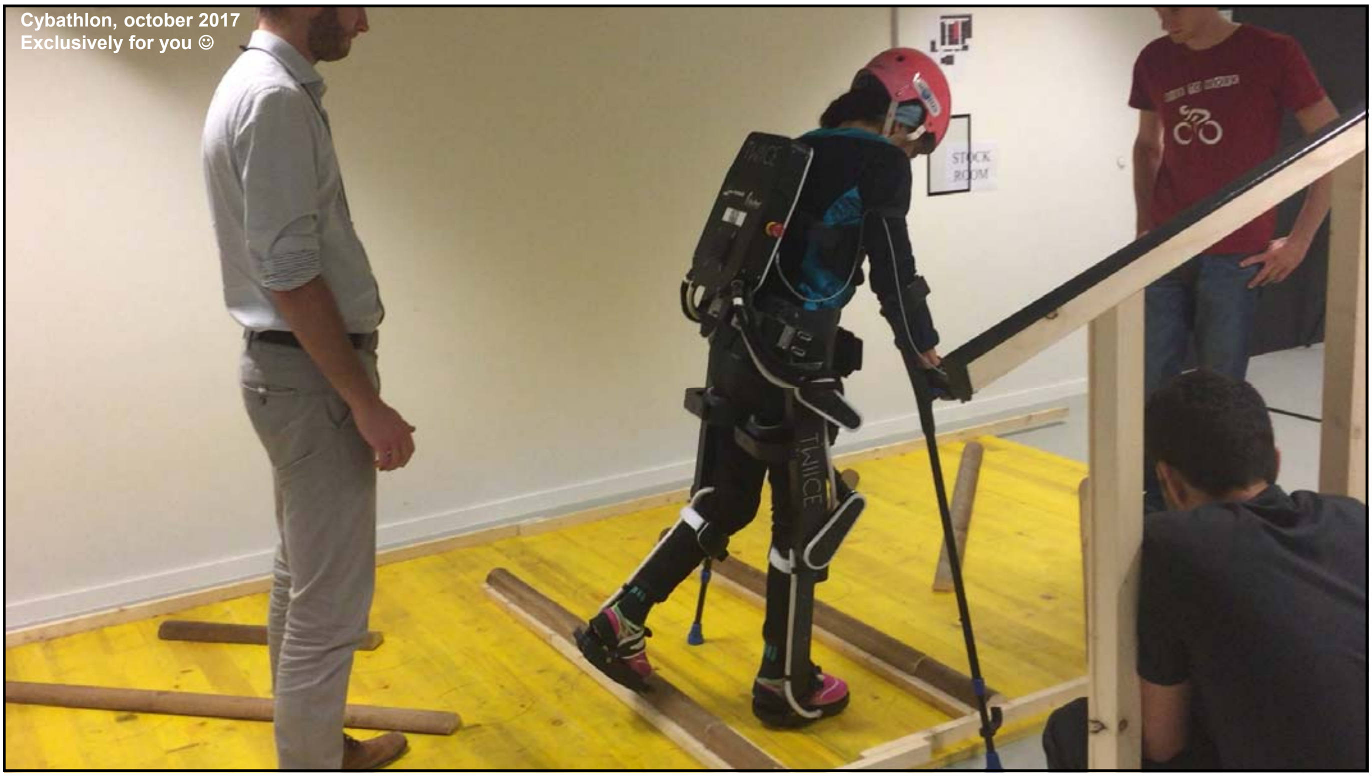
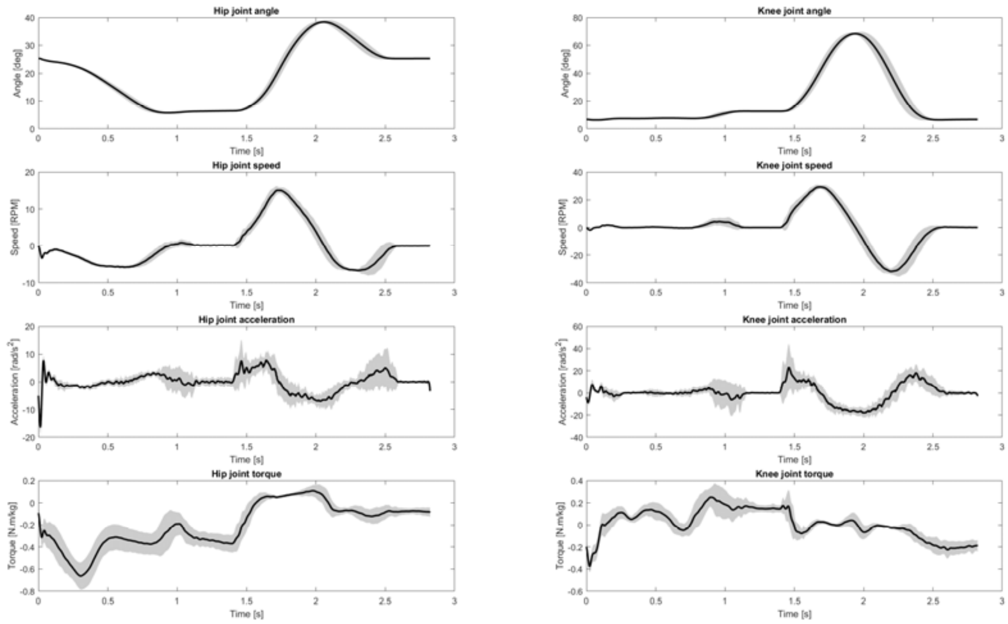
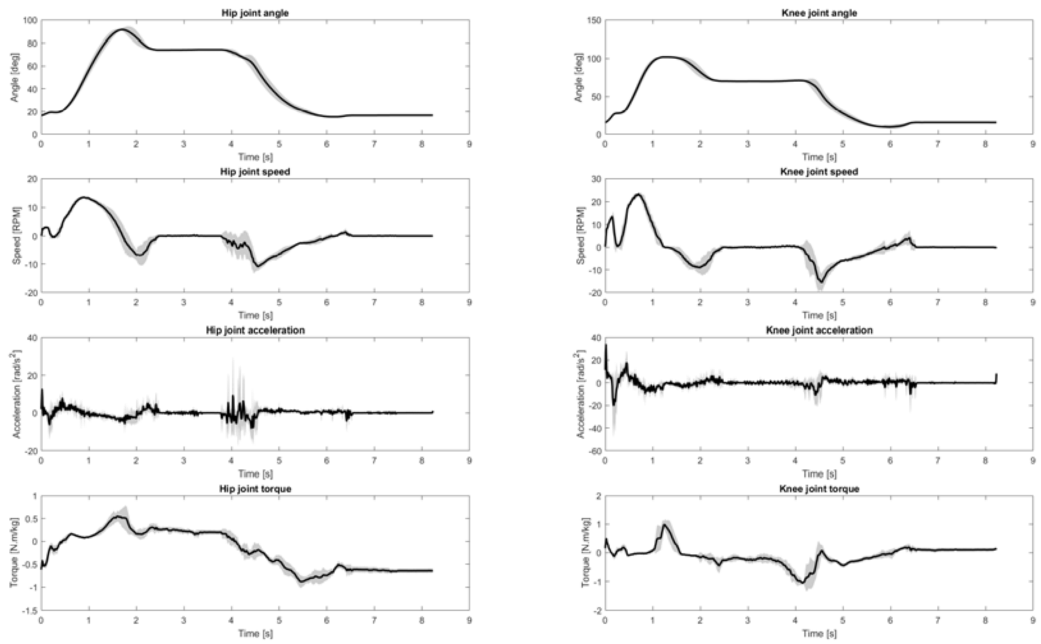
TWIICE


Cybathlon, october 2017
Exclusively for you ☺
STOCK ROOM
TWIICE

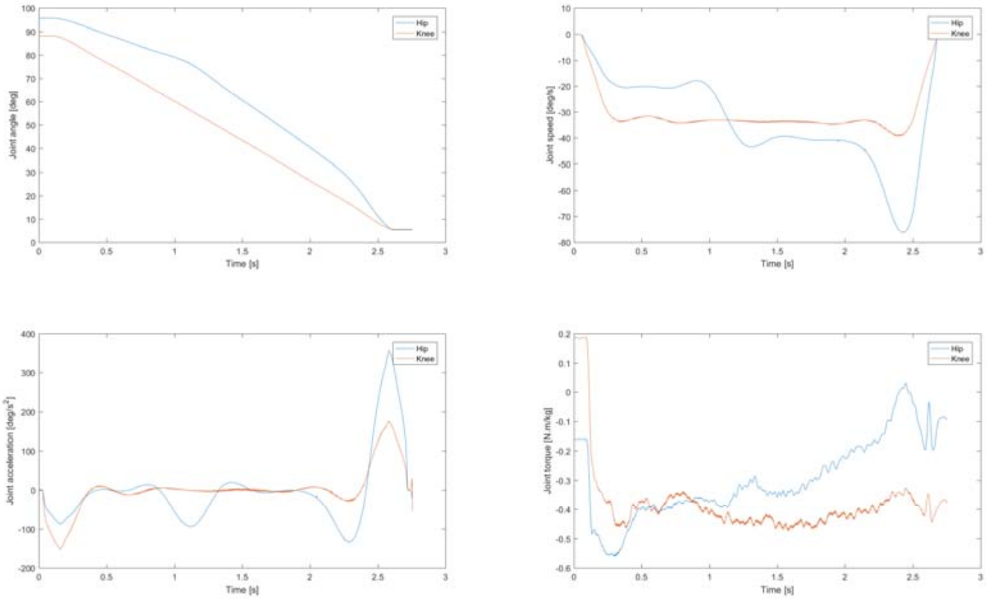
Walk @ 1km/ h

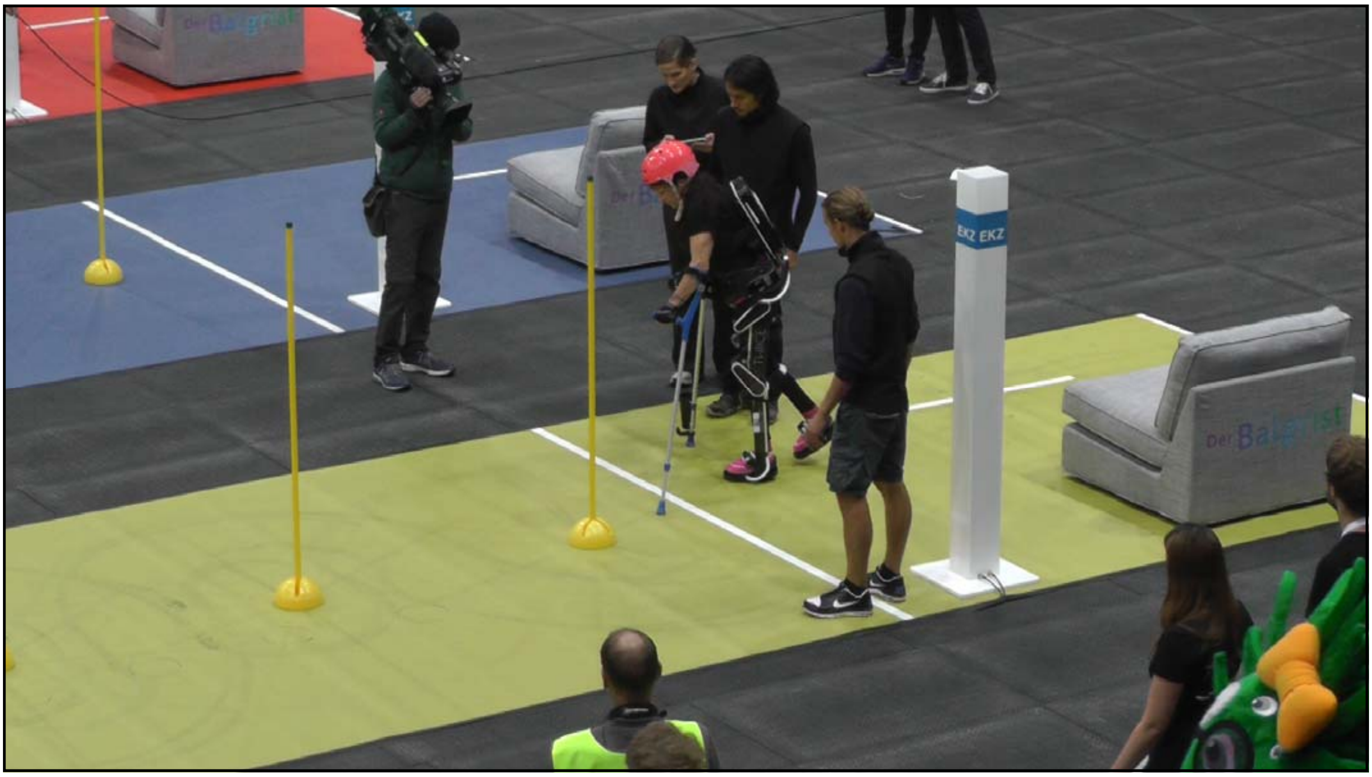


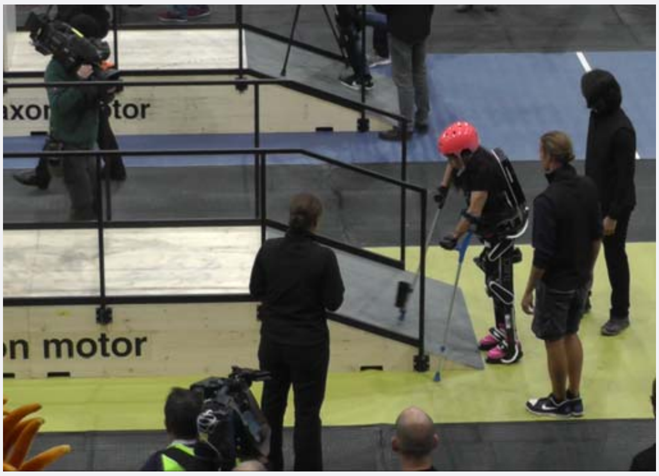
Stairs

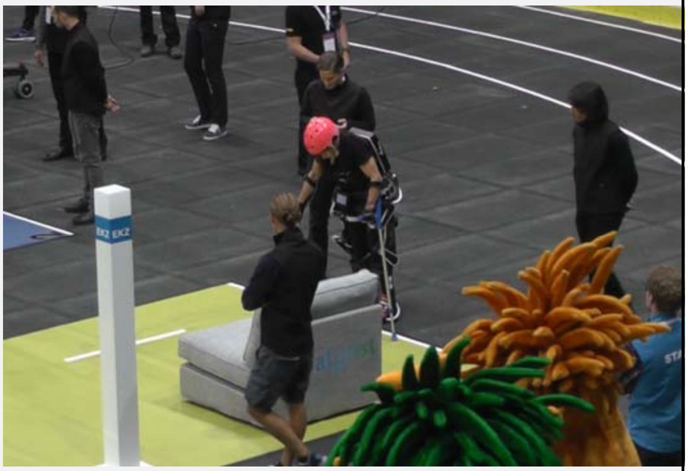


Sit to Stand


Joint angle [deg]
Joint speed [deg/s]
Joint acceleration [deg/s²]
Joint torque [N.m/kg]
Time [s]
Hip
Knee


EKZ EKZ
Der Balgrist


n motor

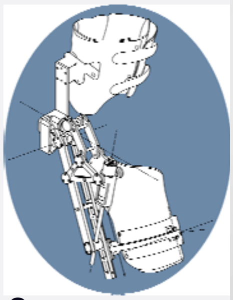


Daily Assistance - Not Mobilization

HiBSO
Hip Ball Screw Orthosis
PhD thesis of **Jeremy Olivier, Romain Baud**

HIP orthosis specifications

- Totally 3 DOF Orthosis
- Actuated in the sagittal plan
- Free in the other DOF

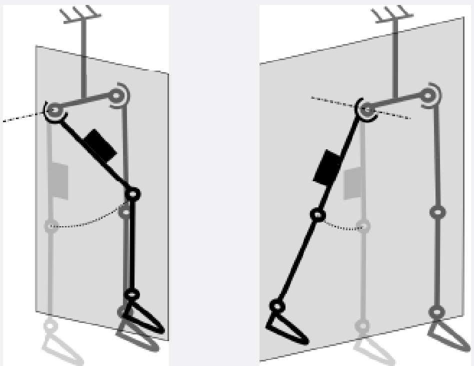


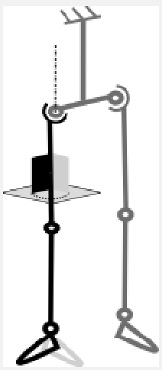
Screw transmission

robotics
Swiss National Centre of Competence in Research

HiBSO, Hip Ball Screw Orthosis
PhD thesis of **Jeremy Olivier**

- Hip is a spherical joint





Flexion/Extension: –10 to 120 → **Actuated**

adduction/abduction: –30 to 40 → **Passive**

internal/external rotation: –35 to 35 → **Passive**

RMS torque during level walking: ~ **0.3 Nm/kg**

Maximum angular velocity: ~ **140 deg/s**

Peak torque during sit-to-stand transitions: ~ **1Nm/kg** (when the hip flexion angle is around 70 deg)

EPFL
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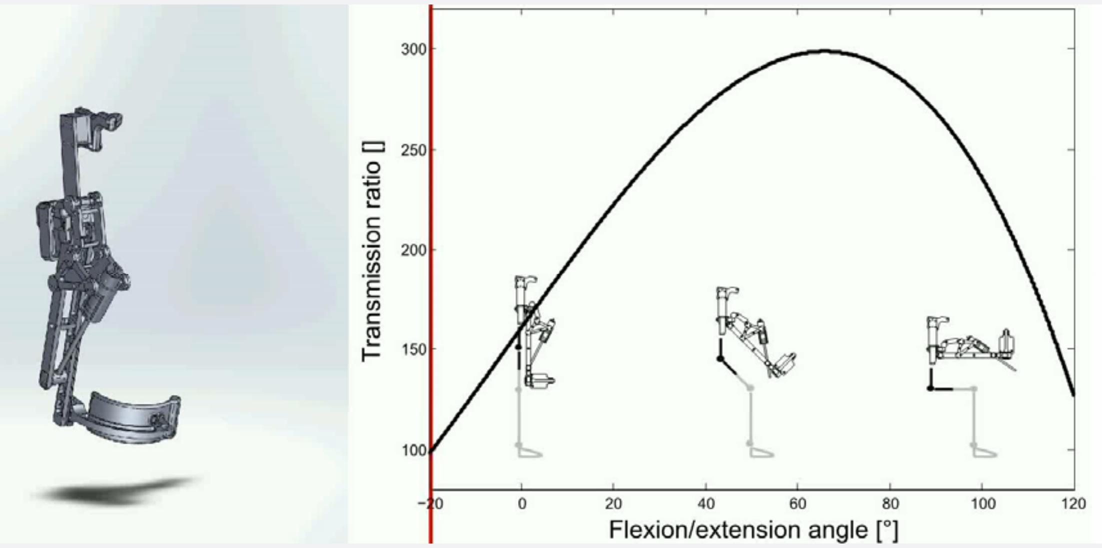
Amplification mechanism



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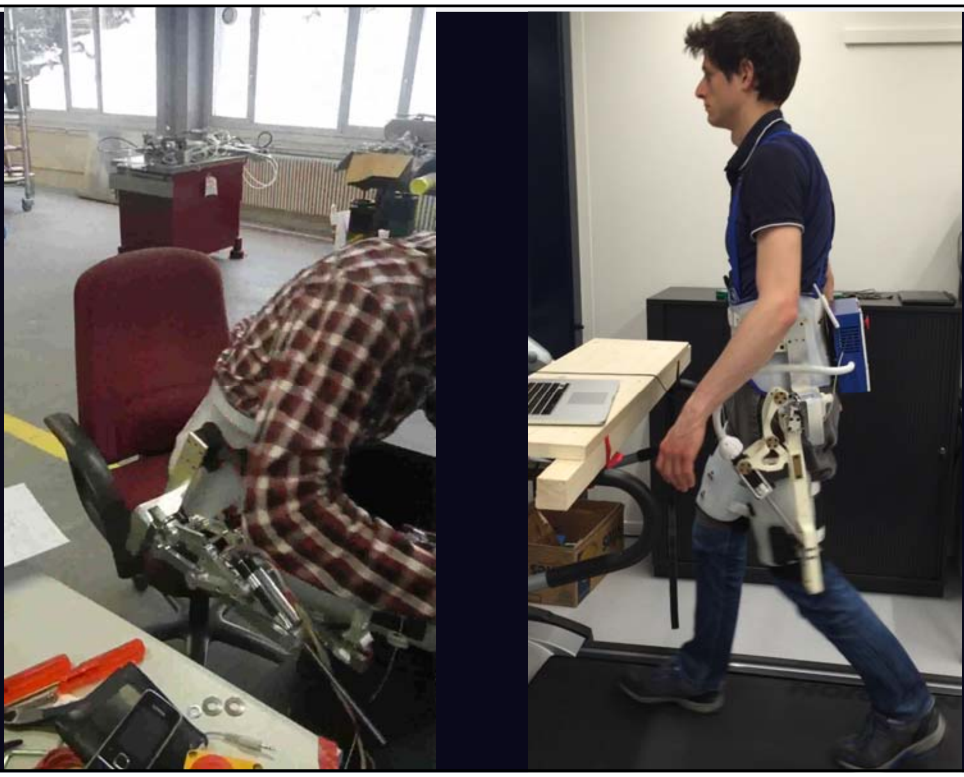

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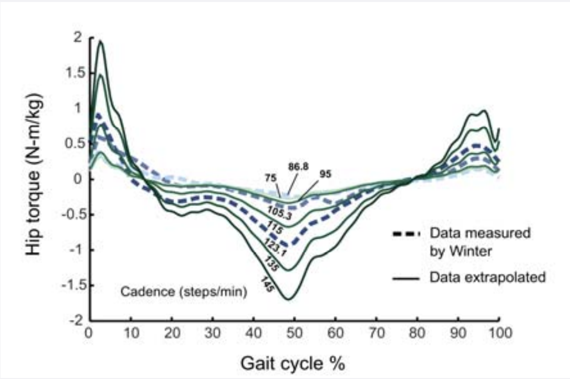
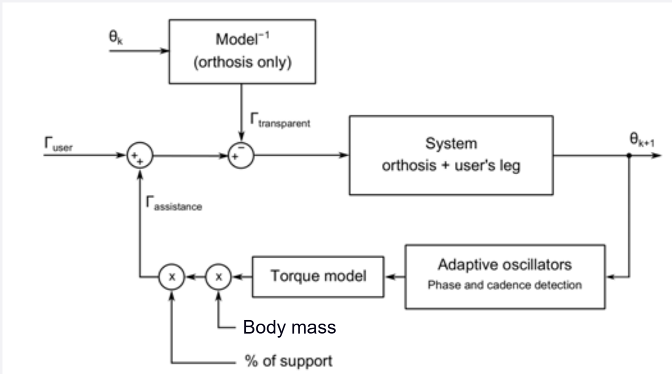
Flexible adaptive oscillators

$$\Gamma_{assistance}(stride, cadence) =$$
$$(A + B \cdot cadence + C \cdot cadence^{2}) \cdot \left(a_0 + \sum_{i=1}^{23} a_i \cdot \cos(i \cdot \omega \cdot stride) + b_i \cdot \sin(i \cdot \omega \cdot stride) \right)$$





HiBSO – Hip Ball Screw Orthosis

Test on the influence of a hip flexion/extension assistance of 10%

Method

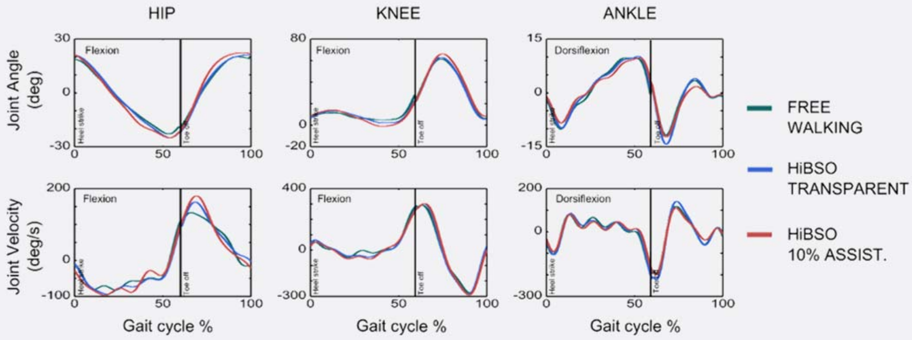
- **Measurement**
  - **Kinematics tracking**
  - **Heart rate**
- **Trials of 10 minutes**
  1. **Without orthosis**
  2. **With the orthosis actively compensated (transparent)**
  3. **With the orthosis assisting 10%**
  4. **Without orthosis**

Results

Kinematics

Noticeable effects on all the joints (not only at the hip)

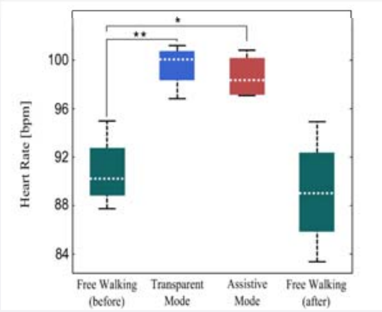
Greater influence during the swing phase



Heart rate

Important increase in heart rate with the orthosis

No significant decrease with 10% assistance compared to transparent mode



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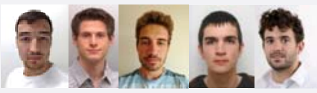
AUTONOMYO Exoskeleton

An Active Impedance Controller to Assist Gait in People with Neuromuscular Diseases



MS Swiss Multiple Sclerosis Society

ASRIMM

fsrmm

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Autonomyo
An exoskeleton for subjects with Myopathy

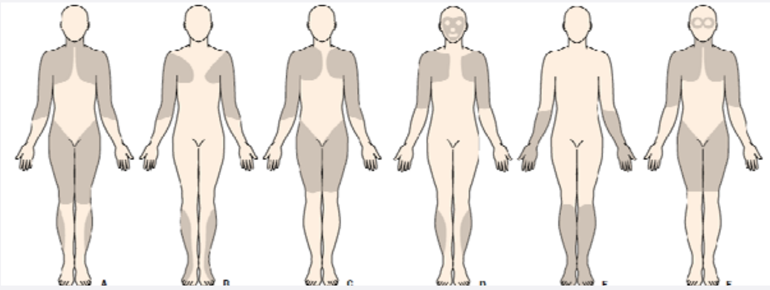

Figure *Predominant affected area (shaded) regarding different types of dystrophy: A) Duchenne-type and Becker-type, B) Emery-Dreifuss, C) limb-girdle, D) facioscapulohumeral, E) distal and F) oculopharyngeal. Reproduced from A. E. H. Emery, "The muscular dystrophies," BMJ, vol. 317, no. 7164, pp. 991–995, Oct. 1998* ***[7]***.

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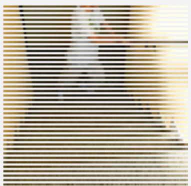
LOWER LIMB ASSISTANCE FOR WALKING DISORDERS

About 7% of the population is not (or with major difficulties) able to walk 1/4 of a mile (400m) [1]

STROKE
Incidence of **1.1 million** people **per year** in Europe

MULTIPLE SCLEROSIS
Prevalence ~1/1000
500'000 persons in the EU

ELDERLY PEOPLE
About 7% of the population over 55 years old need assistance to walk
6.6 million in the EU



NEUROMUSCULAR DISEASES
Prevalence ~1/5000
100'000 persons in the EU

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1) D. Blackwell, J. Lucas, and T. Clarke, "Summary health statistics for U.S. adults: National Health Interview Survey, 2012," National Center for Health Statistics, 2014.

Evaluation of the Ekso (from Ekso Bionics) with 3 subjects with myopathy @ Villa Beretta (Lecco, Italy)

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Test Ekso with subjects with myopathy

P1 – Myopaty mitochondriale, Woman, 68 yo

50 m

~ 50 m

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Test Ekso with subjects with myopathy

P2 – Dys. Myotonic Steinert, Man, 52 yo

3 m

~ 70 m (with

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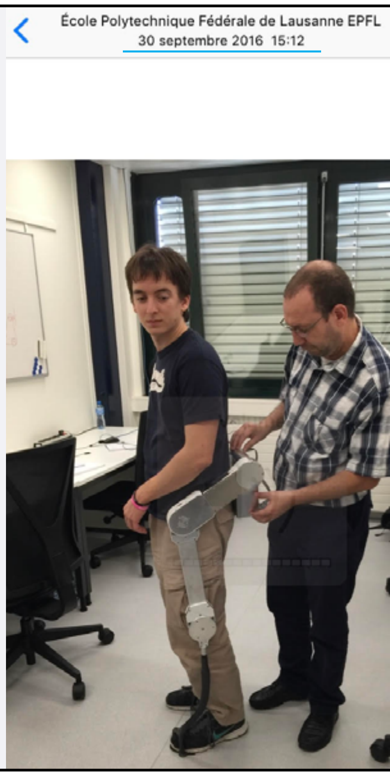
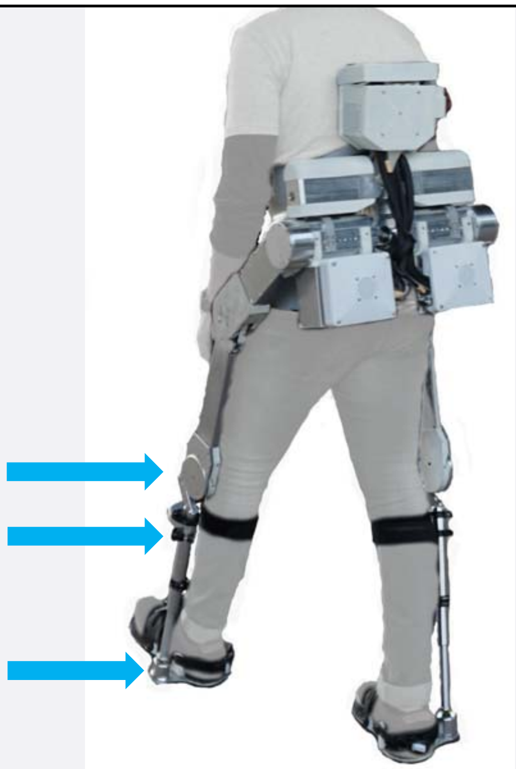
Autonomyo
First tests, October 2017



Autonomyo
Design iterated



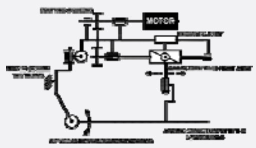
Autonomyo
3 DOFs / leg

Total weight: 25 kg

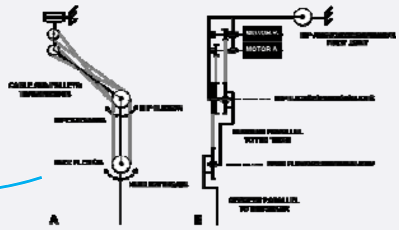
Electronics
Batteries 770 Wh
6x Motors + gearbox

Adjustable thigh and shank length

Ankle-Foot
Flexible ball joint 3 DOFs
Flexible shoe sole



Hip adduction – nominal 80 Nm
Gear + ballscrew i=1:1500



Hip, knee flexion – nominal 40 Nm, max 60 Nm
Gear + cable-pulley i=1:200

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WALKING ASSISTANCE - CHALLENGES

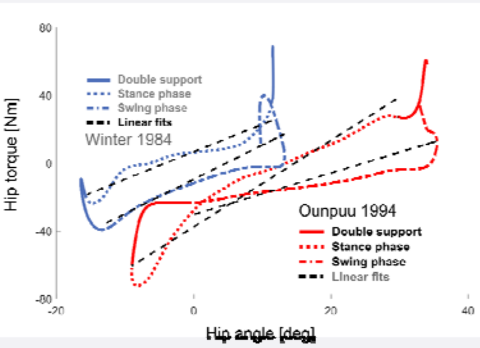
Move according to the user intention

- **Adjust assistance at each joint**
- **Synchronize action of the exoskeleton with the user**
  - **Start and terminate walking upon intention**
  - **Allow the user to control velocity**
    - **Only the joints are accessible for measures**

ACTIVE VARIABLE IMPEDANCE

Variable impedance is a key in locomotion

- **Absorb shocks and perturbations**
- **Energetically very efficient**



Example of hip torque vs angle curve during level walking

Combining human-impedance with exoskeleton-impedance

→ Linear addition of contributions in stiffness

→ Average of equilibrium position

$$\tau_{joint} = k_m \cdot (\alpha - \alpha_0)$$

$$\tau_{joint}' = k_m' \cdot (\alpha - \alpha_{0m}') + k_{exo} \cdot (\alpha - \alpha_{0exo})$$

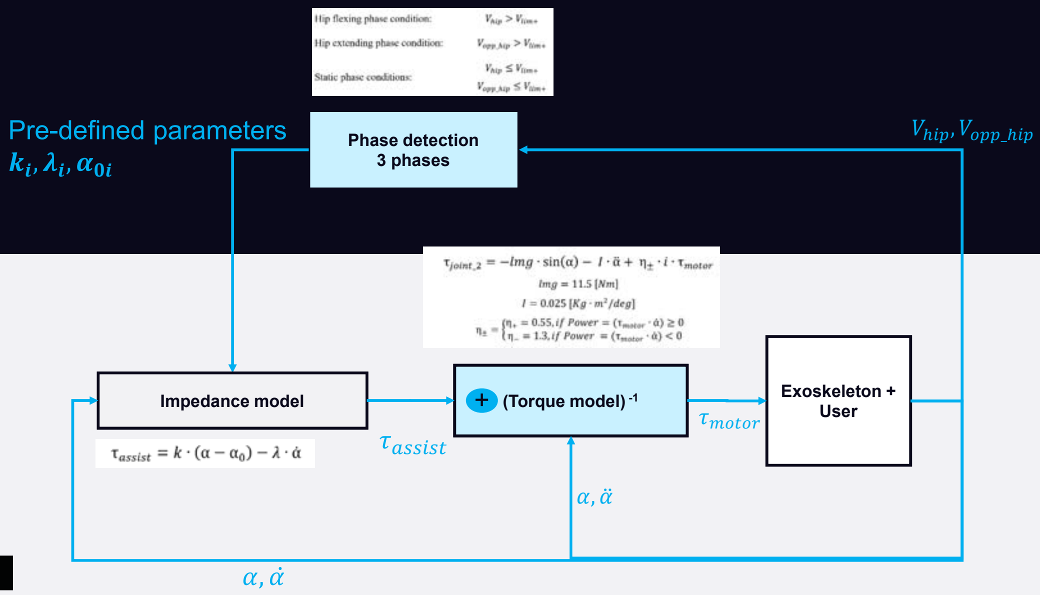
$$k_{assisted} = k_m' + k_{exo}$$

$$\alpha_{0assisted} = \frac{k_m' \cdot \alpha_{0m}' + k_{exo} \cdot \alpha_{0exo}}{k_m' + k_{exo}}$$

Active impedance allow to adapt and tune the level of assistance

Ortlieb, Biorob, 2018

Assistance stragy
Concept



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TRIGGERING TORQUES AND DELAY

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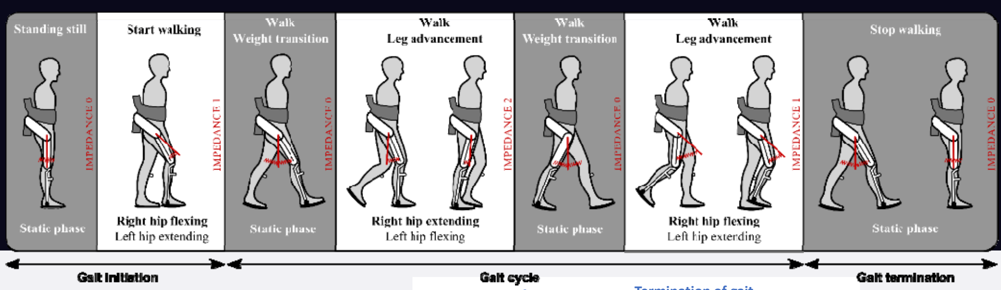
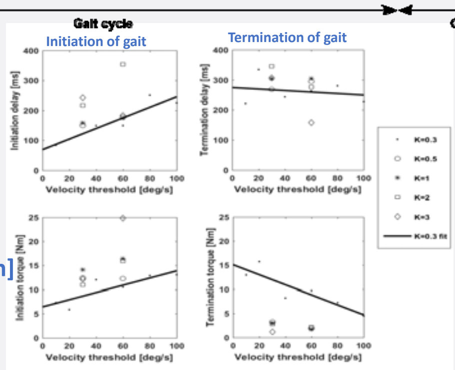


Delay [ms]

Torque [Nm]



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PILOT

Limb girdle muscular dystrophy

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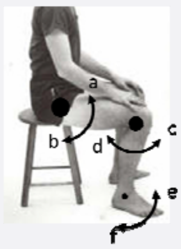
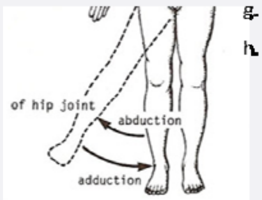
MRC muscle test from 0 to 5

0 no force applied
1 feel contraction – no motion
2 motion without gravity
5 normal strength





	right	left
a. Hip flexion	1	0.5
b. Hip extension	1	1.5
c. Knee flexion	0.5	0.5
d. Knee extension	2	1.5
e. Dorsiflexion	2.5	2.5
f. Plantar flexion	2.5	2.5
	right	left
g. Abduction	1.5	1
h. Adduction	1.5	1.5

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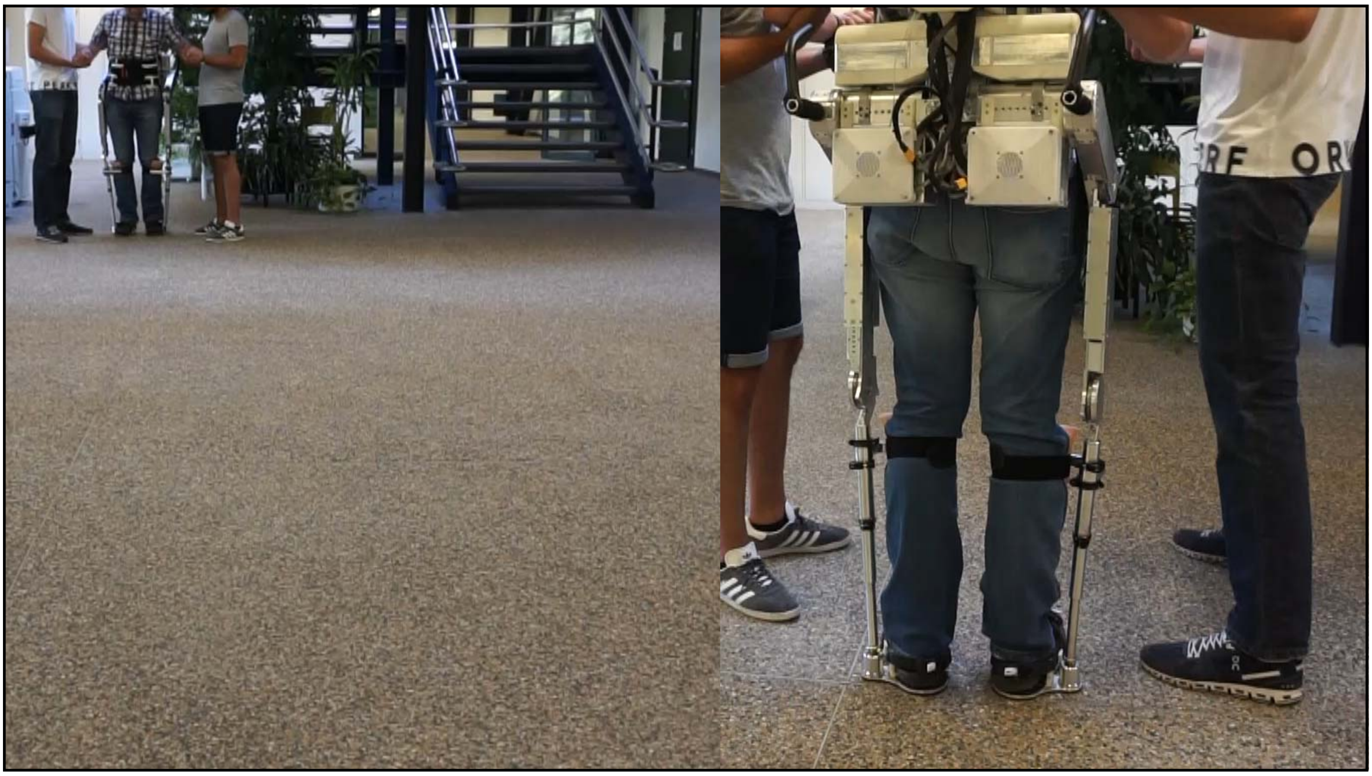

Variable impedance control

Finally

- **Potential of active impedance in Assistance strategies**
- **Impedance allows to adjust the level of assistance and let the user control the gait pattern and walking velocity**
- **Motion detection is sensitive to muscle weakness.**

  Could be improved by ground force sensors.
- **Requirement of torque / force sensors…. Even with good models**

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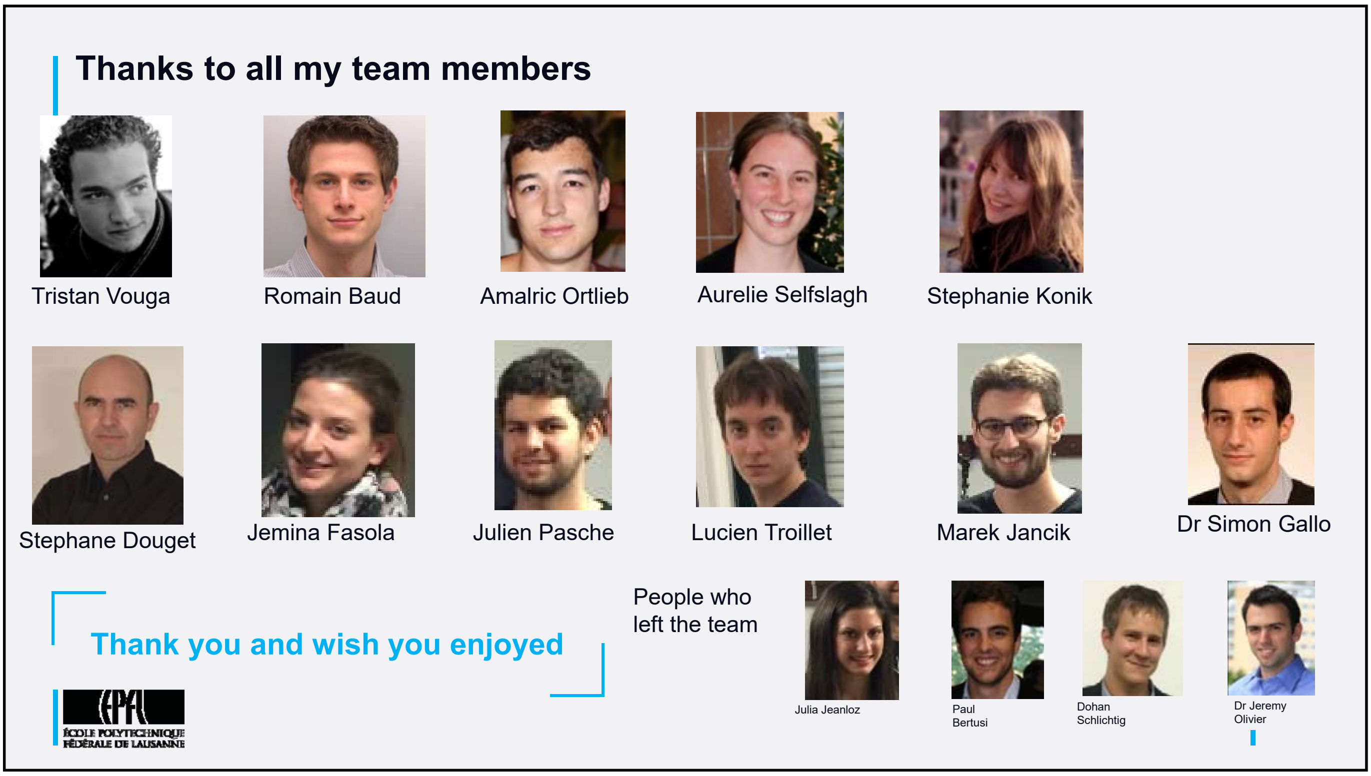
Thanks to all my team members
Tristan Vouga
Romain Baud
Amalric Ortlieb
Aurelie Selfslagh
Stephanie Konik
Stephane Douget
Jemina Fasola
Julien Pasche
Lucien Troillet
Marek Jancik
Dr Simon Gallo
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People who left the team
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Paul Bertusi
Dohan Schlichtig
Dr Jeremy Olivier
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