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European Commission
TEMPUS

TEMPUS project - HUTON

Assisting humans with special needs:
Curriculum for HUman-TOol interaction Network

Friday October 17th

13:30 – 17:00

Workshop: **Project centered education: HUTON**

VENUE: Scuola Politecnica, Villa Cambiaso

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CYBERLEGs

Design of applied research study: Mechatronic example

Physical (p-) and cognitive (c-) human-machine interface of CYBERLEGs Wearable robotic modules for transfemoral amputees

M. Munih, R. Kamnik, D. Lefeber, R. Ronsse, N. Vitiello

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Goals

- «Powered» lower-limb exoskeletal machines and prostheses
  - Main design challenges and possible solutions
- Design the physical (p-) and cognitive (c-) HRI of two wearable robots (FP7-EU CYBERLEGs project)
  - a light-weighted wearable hip orthosis
  - a powered transfemoral prosthesis

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Outline

- Introduction to *wearable robotics*
  - *What*, *why,* and *design challenges*
- The CYBERLEGs project: motivations and vision
- Active Pelvis Orthosis (APO)
  - α-prototype (year 1)
  - β-prototype (year 2)
  - Future developments
- Active transfemoral prosthesis and whole-body awareness control
- Mitigation of the risk of fall
- Conclusions

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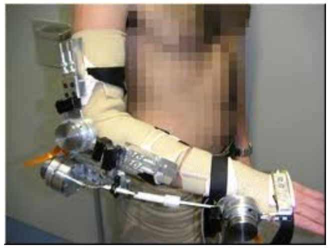
What and why

- A wearable robot is a **system composed of actuators, sensors, mechanism/s, and a human-robot interface**
- Movement assistance, augmentation, rehabilitation, and/or substitution, …
- Application fields
  - Elderly persons
  - Chronic motor disabilities
  - Post-stroke and/or post-trauma rehabilitation
  - Tremor suppression
  - Prosthetics
  - Human augmentation

Lokomat

Rewalk

Sarcos



Wotas

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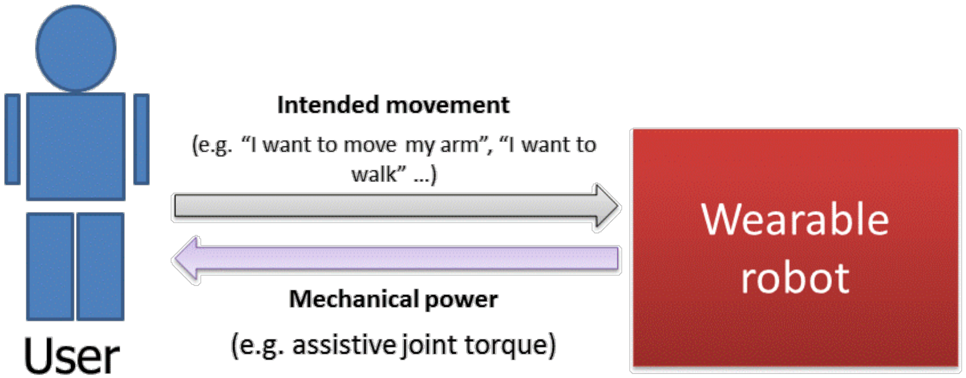
Main design goals

- Wearable robots interact with humans both physically (mechanically) and cognitively
- Main requirements
  - Mechanical (or physical) human-machine interface (**p-HRI**)
    - Comfortable
    - Safe
  - Cognitive human-robot interface (**c-HRI**)
    - Intuitive
    - Redundancy



- Other factors enhancing system acceptability
  - attractive design (a wearable exoskeleton is not a vacuum cleaner!)
  - minimum size and encumbrance
  - no noise
  - affordable price

JL Pons, EMB Magazine, 2010
JL Pons, 2008

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CYBERLEGs project

CYBERnetic LowEr-Limb CoGnitive Ortho-prosthesis

Scuola Superiore Sant'Anna – SSSA
Project Coordinator: Dr. Nicola Vitiello

Universite catholique de Louvain – UCL
Prof. Renaud Ronsse

Vrije Universiteit Brussel – VUB
Prof. Dirk Lefeber & Prof. Romain Meeusen

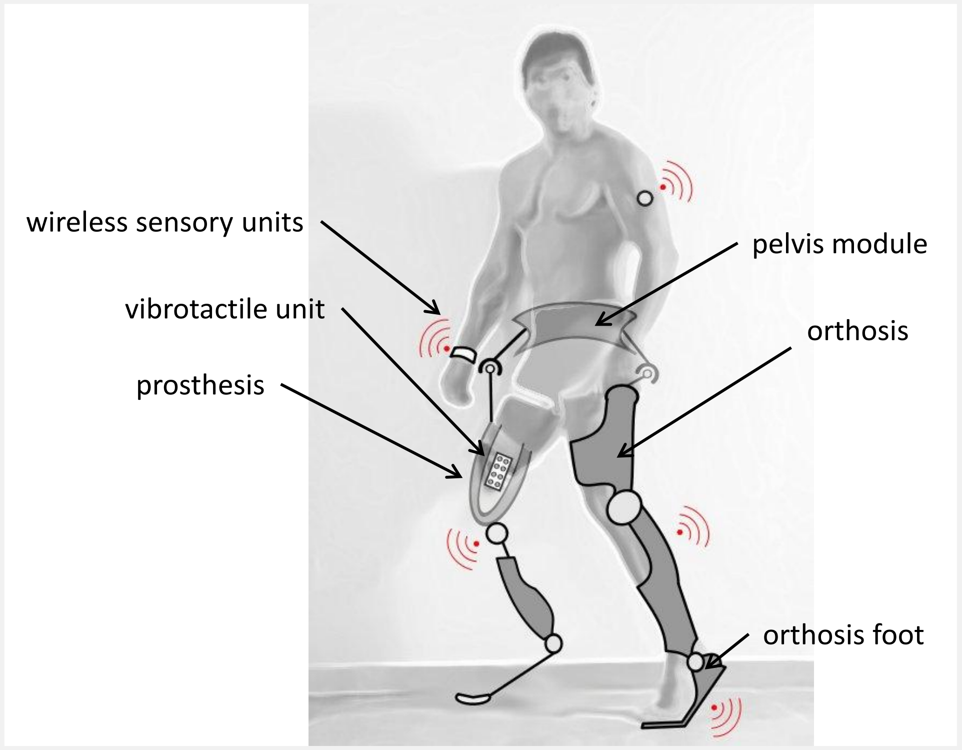
Univerza V Ljubljani – UL
Prof. Marko Munih

Fondazione Don Carlo Gnocchi - FDG
Dr. Raffaele Molino Lova

www.cyberlegs.eu

Duration: 3 years
Start date: February 1, 2012
Budget: 3,45 M€
EU Contribution: 2,54 M€
Project Coordinator: Nicola Vitiello
Leading institution: The BioRobotics Institute, Scuola Superiore Sant'Anna

CYBERLEGs is an artificial cognitive **ortho-prosthesis** for dysvascular trans-femoral amputees lower-limb functional replacement and assistance in daily living activities



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Motivations

- Lower-limb loss is a disabling condition which affects health and well-being of persons worldwide
- Incidence of all-cause lower-limb amputations
  - Lowest: 0.4 over 10,000 in Japan
  - Highest: 10 over 10,000 in Native American communities (e.g. Navajo Region, US)
- Vascular diseases are the main cause of lower-limb amputation (about 80% in US): dysvascular amputation
- Ageing is a risk factor

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Motivations

- Lower-limb amputation can be at several levels
  - foot-level
  - calf-level
  - thigh-level (namely “transfemoreal”)
- Transfemoral amputation are estimated to be around 20%
  - 60,000 per year in US & Europe
  - 3,800 per year only in Italy (80% are dysvascular)

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Motivations

Why transfemoral amputation is a big challenge for the amputee daily life?

- More energy, less speed
  - 40% of the speed, 2.5 times more energy
- Steps, Stairs and other ups & downs
  - Inclines and stairs become challenging
  - Step-by-step, and no more step-over-step
- More "mental energy", less gait stability
  - "conscious effort of thinking about walking with the prosthesis"
  - "stumbling"
  - "semi-controlled fall"
  - "uncontrolled fall"

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Motivation

- Energetic, cognitive and stability challenge **are not fully overcome by any passive or active prosthesis**
- Most (around 80%) of dysvascular amputees do not use any prosthesis
  - Cardio-vascular apparatus not able to afford the effort
  - Amputees prefer other more intuitive, more stable devices, e.g. wheelchair
  - Active or semi-active prostheses require a long time to re-learn how to walk
  - Active prostheses have a low energetic autonomy

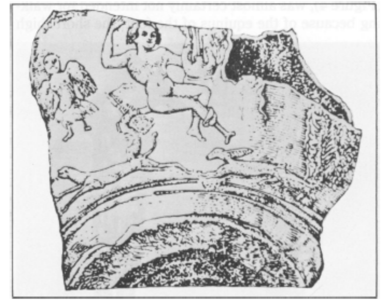

Figure 2. Fragment of vase showing amputee with pylon. (Reprinted from Atlas of Limb Prosthetics, C.V. Mosby, 1980).

[…] Herodotus, in his History, written in 484 b.C., tells of a Persian soldier, Hegesistratus, captured by the enemy, imprisoned in the stocks, and encased by his foot. He escaped by cutting off part of his foot, and replaced it later with a wooden prosthesis. […]

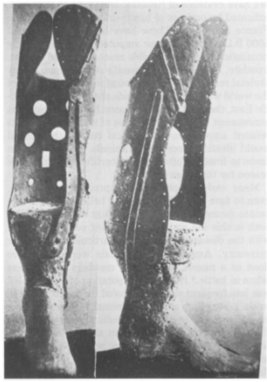

Figure 5. Seventeenth century lower limb prosthesis, probably made for a congenital deformity. (Reprinted from Historic Artificial Limbs, Paul B. Hoeber, Inc., 1930).

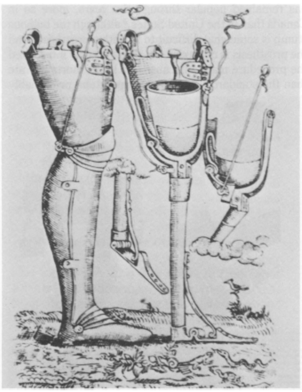

Figure 13. Paré's above knee prosthesis with articulated joints (Reprinted from Limb Prosthetics—1972, Robert E. Krieger Publishing Co., 1972).

iWalk (Herr, MIT)

Össur Power Knee

Sellegren K.R., Iowa Orthop J. 1982; 2: 13–27

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Vision

- *Metabolic* efficiency
  - Active orthosis and prosthesis
- *Cognitive* efficiency
  - *Non-invasive, and intuitive HRI*
- *System energy* efficiency
  - Use of passive compliances

Patent pending

N. Vitiello, et al., “Technological aid for transfemoral amputees”, PCT/IB2013/055065, 2013.

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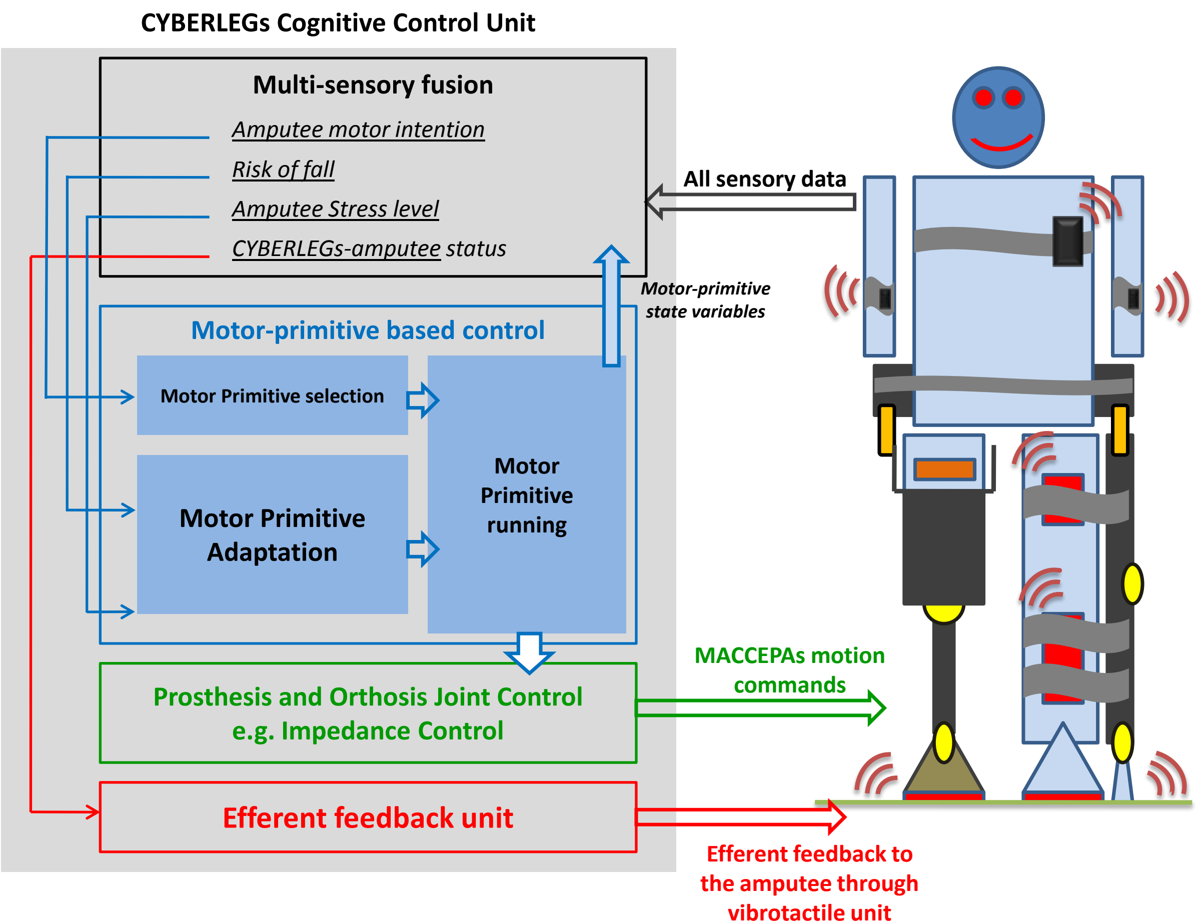
When the story started …



- SSA:
  - Active Pelvis Orthosis (APO)
  - Knee-ankle-foot orthosis (KAFO)
  - Feedback unit
  - Mitigation fall risk
  - Integration
- UCL:
  - Assistive strategies
- VUB:
  - Powered prosthesis
- UL:
  - Wearable Sensory Apparatus (WSA)
  - c-HRI based on movement observation
- FDG:
  - Clinical validation

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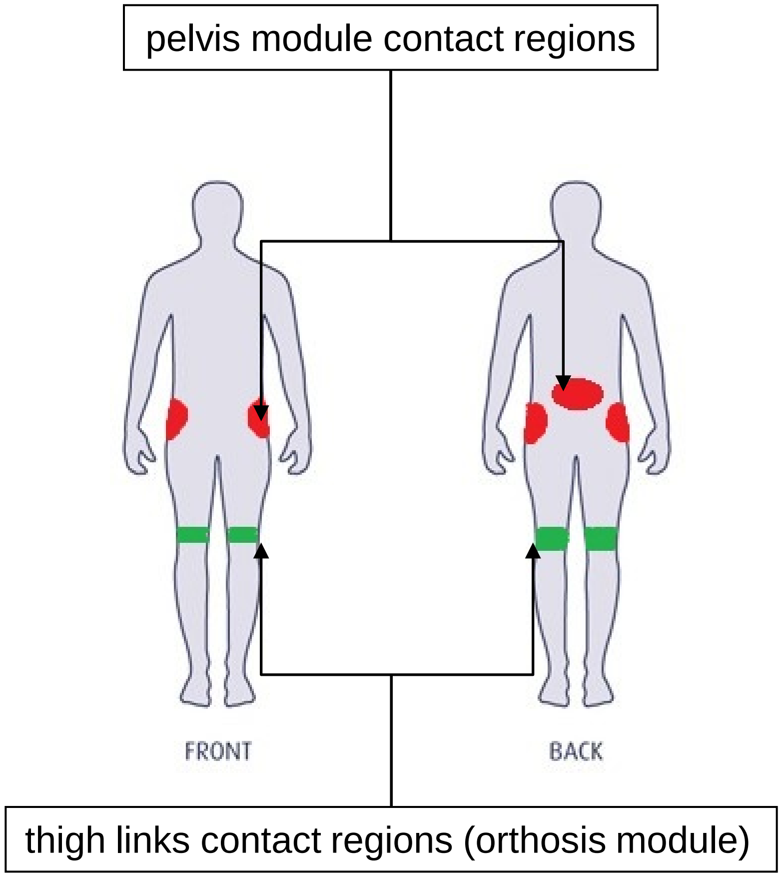
α-APO design requirements (I)

- Lab prototype
- p-HRI:
  - Light-weighted → moving parts with low-size and low inertia
  - Exchangeable links → both right-/left-leg amputees
  - Matching intra- and inter-subject variability
  - Comfortable user-device interfaces
  - Highly *transparent* to user movement
    - Parasitic stiffness lower than 10 N·m/rad in the frequency spectrum of human movement



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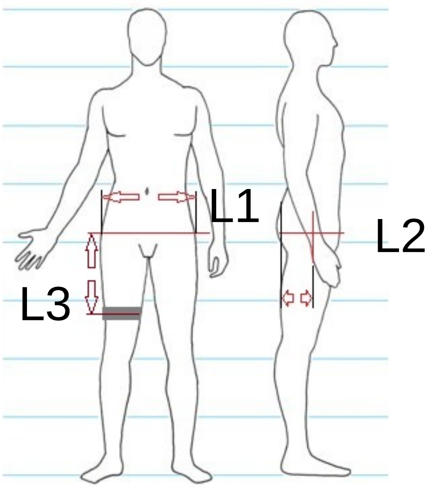
α-APO design requirements (II)

- p-HRI:
  - Rigid linkages, capable of transferring mechanical power to the user
  - 2 degrees of freedom (DOF) for each leg:
    - (1 active) hip flexion-extension
    - (1 passive) hip adduction-abduction
    - no hip intra-extra rotation
- c-HRI:
  - non-invasive
  - intuitive interaction



- Maximum weight: **<5 kg** (w/o batteries/control unit)
- Maximum assistance: **50%** normal-cadence torque
  - Peak hip flexion-extension torque: **35 Nm**
- Link inertia: **<10%** of human thigh inertia
- Target user weight: **80-85kg**
- Inter-subject variability:
  - Pelvis width (**L1**): 350 440 mm
  - Hip joint – backside support (**L2**): 120 175 mm
  - Thigh link length (**L3**): 310 370 mm

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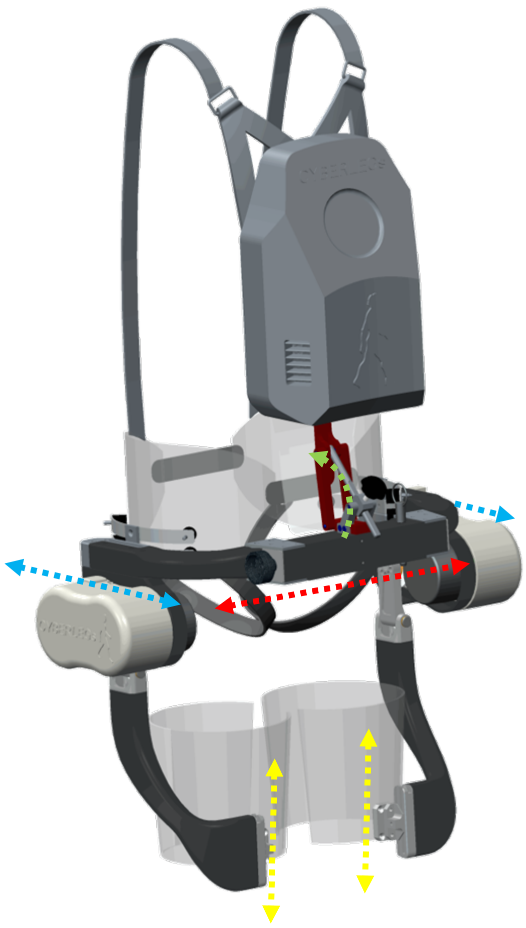
α-APO overview

- Carbon-fibre-based frame
- Total weight: ~5 kg
- Cuffs tailored on the human body
- Adjustable elements
  - Backside support position
  - Trunk cuffs distance in the frontal plane
  - Thigh cuffs vertical position and inclination
  - Belt and straps length
  - Position of actuator axis in the antero-posterior direction
- Changeable link to interface the prosthesis socket
- Easy-to-change links



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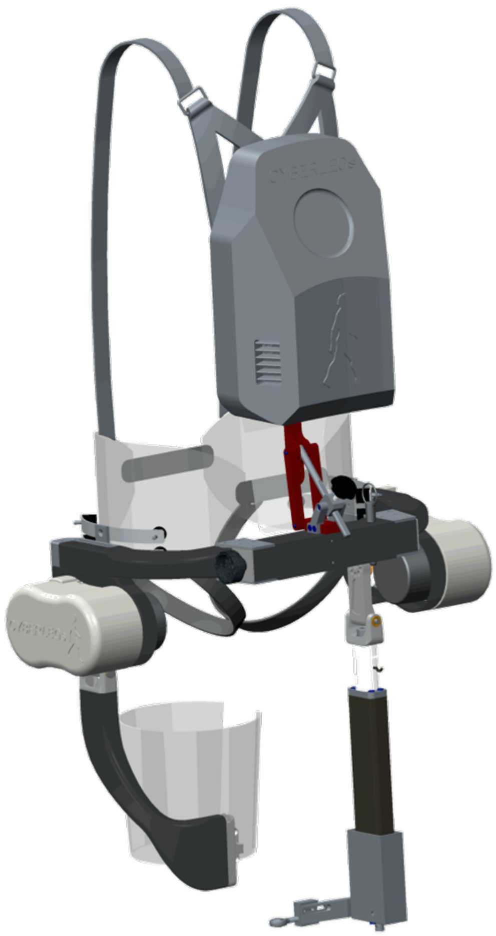

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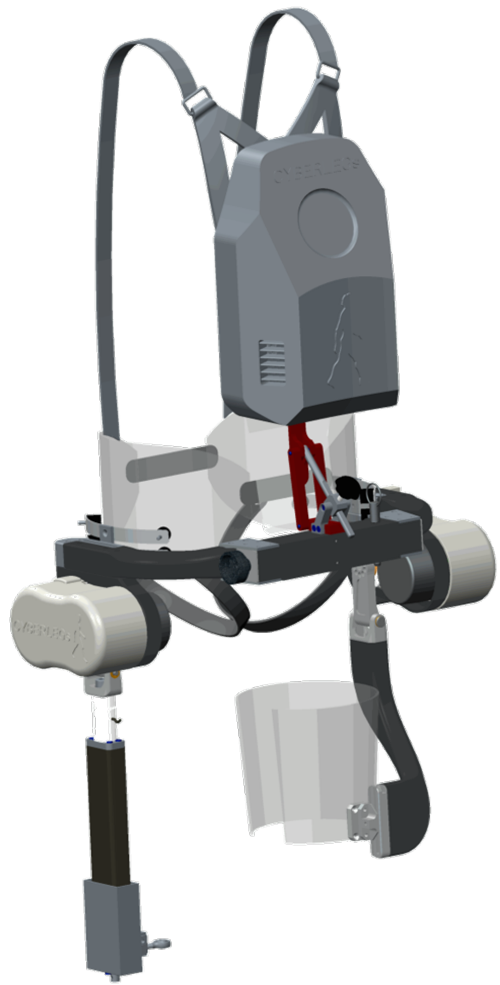

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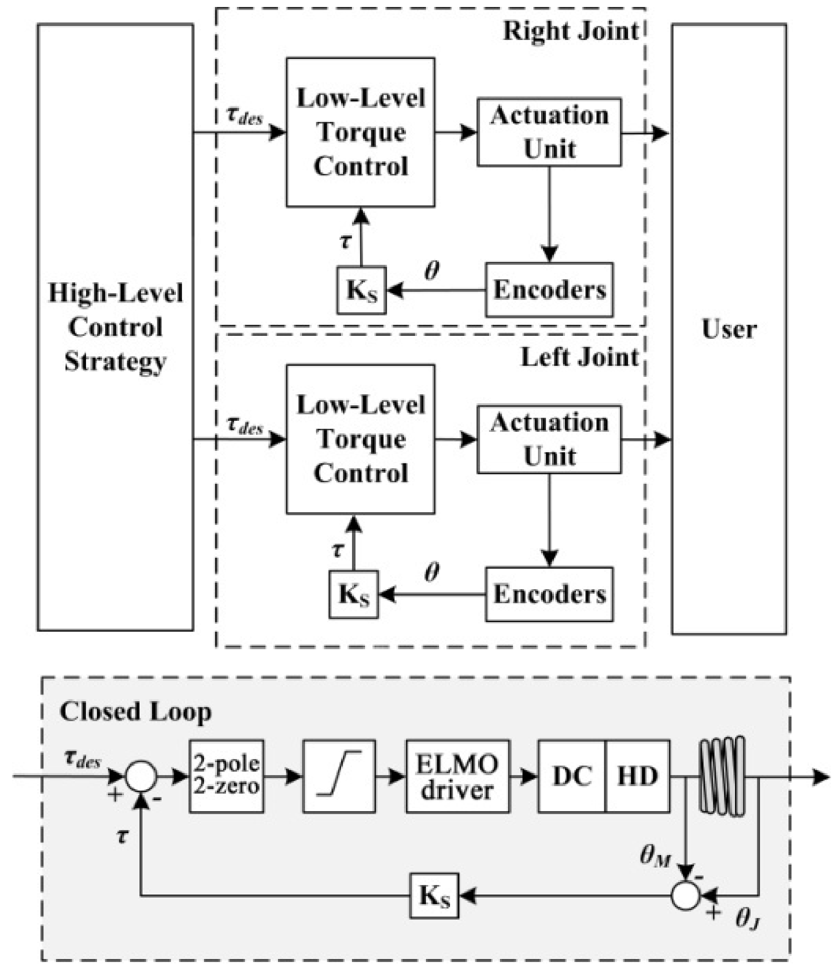
α-APO: control system (I)

- Low-level torque control
  - Torque error converted in motor torque instead of motor velocity
- High-level layer (**c-HRI**)
  - Flexible assistance through adaptive oscillators (AO)
- Safety loop
  - Actuation switched off when:
    - Measured torque ≥ 30 N·m
    - Joint speed ≥ 400 /s
    - Emergency button



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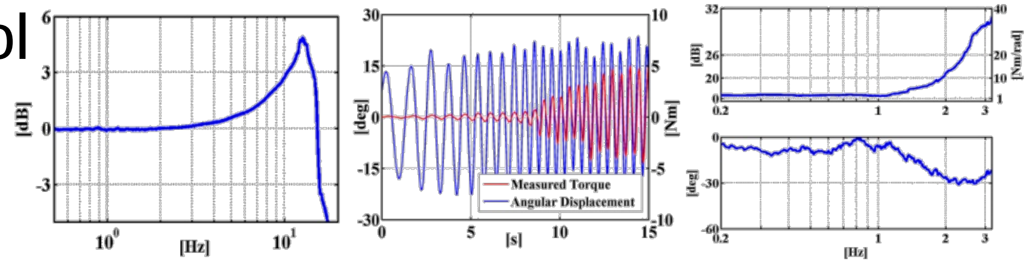
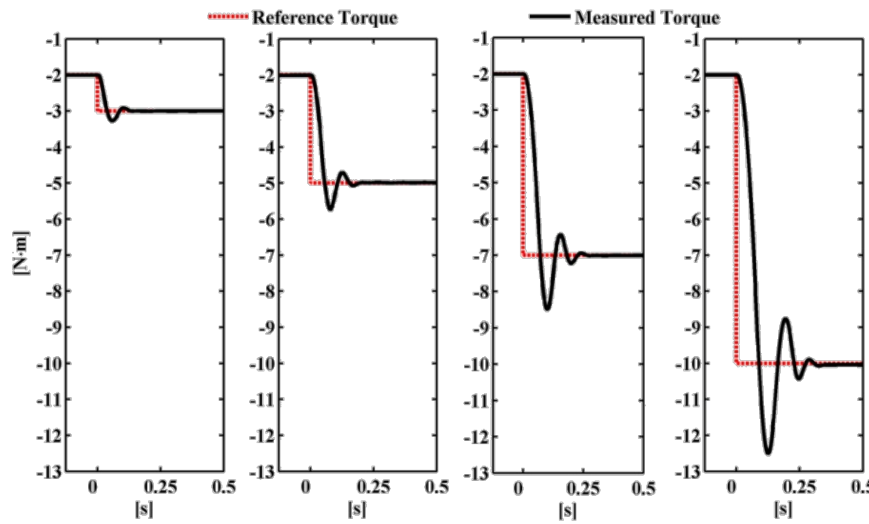
α-APO: control system (II)

- Characterization of the closed-loop torque control
  - Step response
  - Chirp response
  - Output impedance
- Closed-loop bandwidth: 15.5 Hz
- Output impedance: 1-35 N·m/rad, in the range 0.2-3.2 Hz
  - Parasitic torque: <0.5 N·m at normal cadence → high transparency





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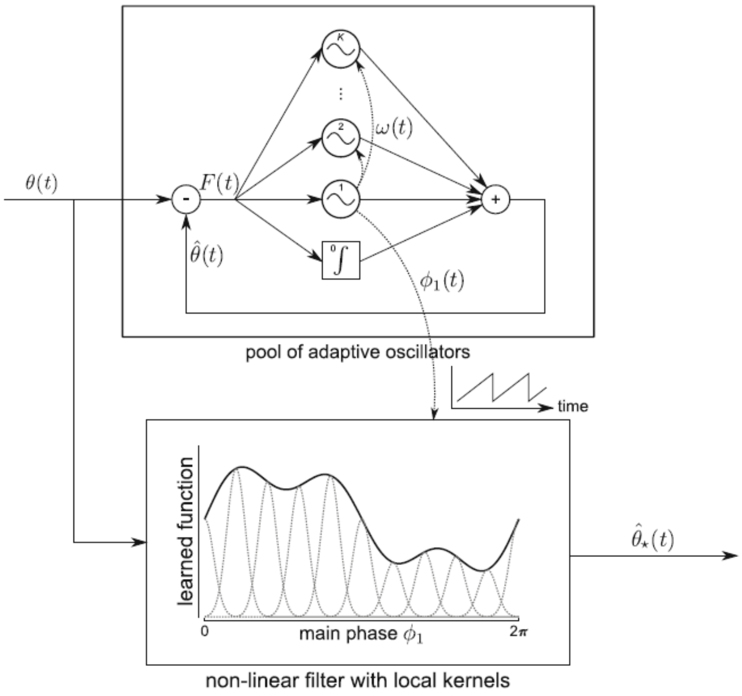
c-HRI: AO-based assistive strategy

- AFO-based adaptive stiffness control
- Hopf oscillator as AOs and a set of 60 Gaussian functions as kernel of the non-linear filter
- This architecture learns **frequency** (and then the phase) and **envelop** of a quasi-periodic teaching signal, and provides a reliable prediction of the joint angle vs. gait phase within the gait cycle

$$\begin{aligned}\dot{x}(t) &= \gamma\left(\mu^2 - (x(t)^2 + y(t)^2)\right) x(t) + \omega(t)y(t) + \nu F(t)\\ \dot{y}(t) &= \gamma\left(\mu^2 - (x(t)^2 + y(t)^2)\right) y(t) - \omega(t)x(t)\\ \dot{\omega}(t) &= \nu F(t)\frac{y(t)}{\sqrt{x(t)^2 + y(t)^2}}\end{aligned}$$



Ronsse et al., MBEC, 2011

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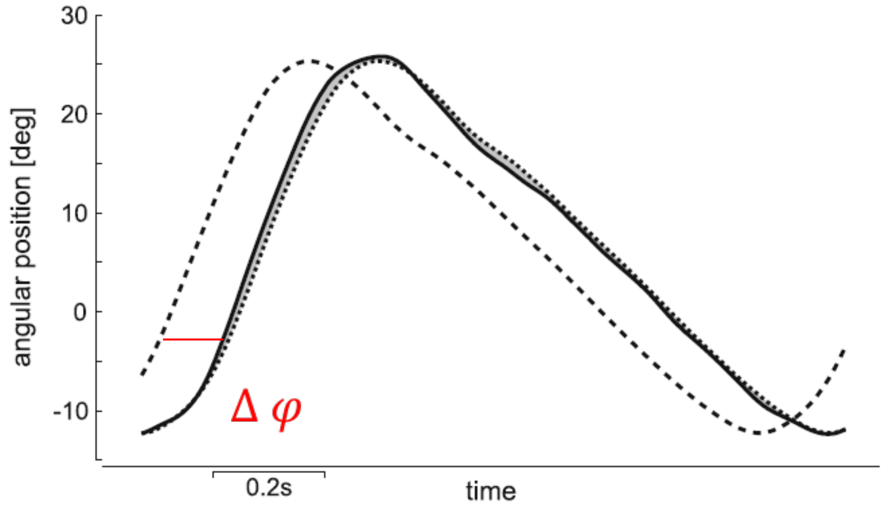
- -> Estimate of both the hip joint angle $\widehat{\theta}_J(\varphi)$ and its future value at a phase $\varphi + \Delta\,\varphi$, namely $\widehat{\theta}_J(\varphi + \Delta\,\varphi)$, being $\Delta\,\varphi$ a phase lead tuneable by the experimenter
- The assistive torque is then computed by setting the $\tau_{des} = K_v \cdot [\widehat{\theta}_J(\varphi + \Delta\,\varphi) - \widehat{\theta}_J(\varphi)]$, being K_v a tuneable virtual stiffness



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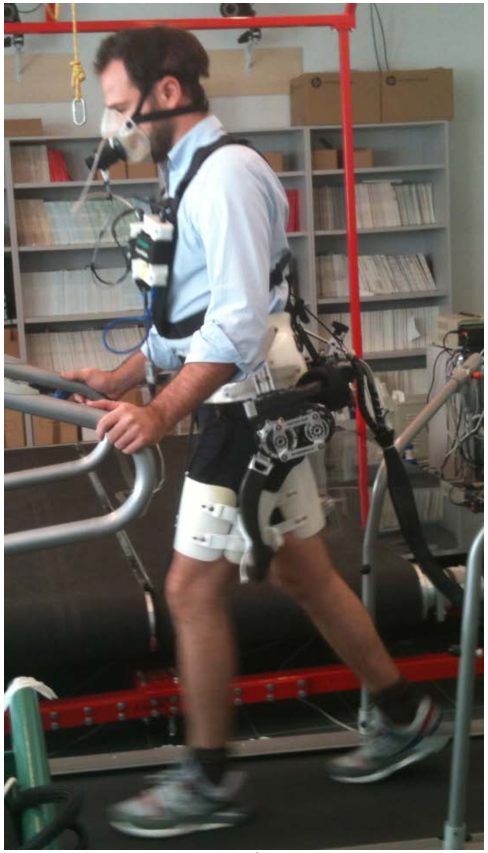
Physical effort estimate: methodology

- Assessment of physical effort through the measure of Oxygen Uptake (OXYCON Mobile ®, Jaeger, Germany)



- Three healthy subjects
- Comparison of different conditions:
  - no exoskeleton
  - exoskeleton under null-torque control
  - exoskeleton under assistive mode
- Treadmill speed: **2.4 km/h**
- Treadmill inclination: **3%**

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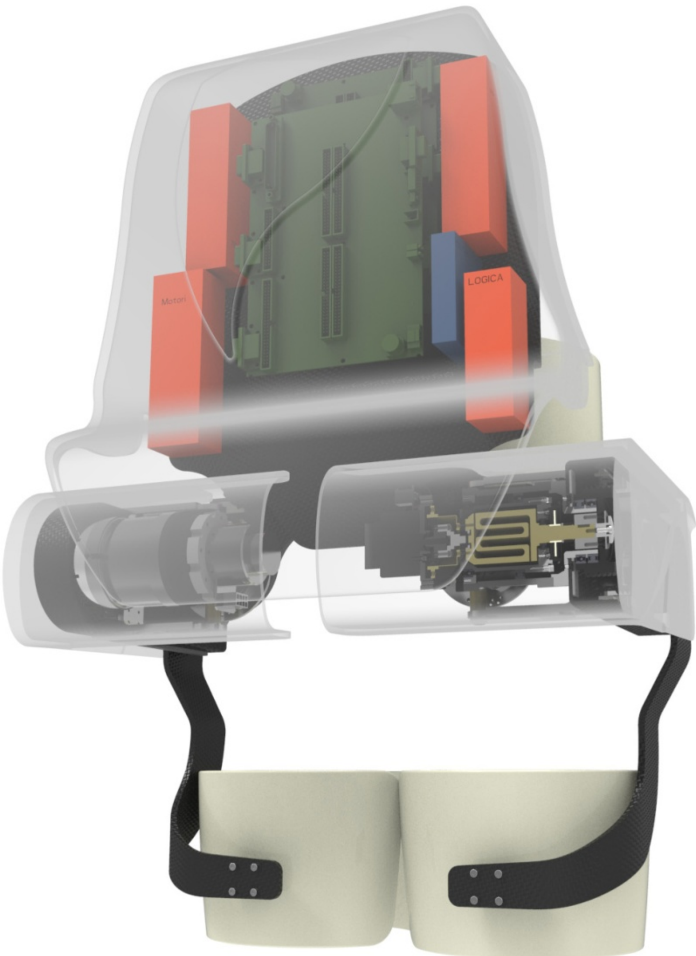
β-APO: advancements with respect to α-APO

- Placement of actuation units on the back-side
  - More physiological arm swinging
- Passive DOFs
  - Free adduction-abduction
  - Free intra-extra rotation
- Fully wearable and portable system
  - Embedded electronics
  - Battery operated



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β-APO: actuation unit (SEA)

Component specifications		
DC Motor Maxon EC 45 flat brushless 70W	Rated torque	128 mN·m
	Max torque	1150 mN·m
	Nominal power	70 W
	Nominal voltage	24 V
Harmonic Drive CPL-14A-100-2A	Gear ratio	100:1
	Max continuos torque	13 N·m
	Repeated peak torque	32 N·m
	Peak torque	45 N·m
Absolute rotary encoder Netzer DS 37 – 17 bit	Resolution	17 bit
	Max reading speed	3500 rpm
	System accuracy	< 0.025°
Performance at SEA output	Max continous torque	**13 N·m**
	Peak torque	**36 N·m**
	Max speed	90 rpm
	Joint stiffness	100 N·m/rad

Physical data		
Encumbrance	Lenght	160 mm
	Diameter	70 mm
Weight		**~1 kg**

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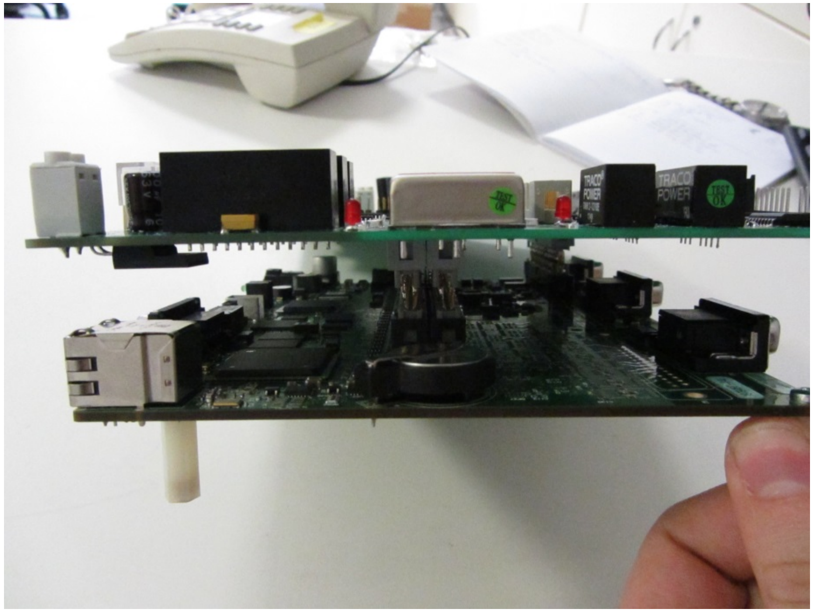
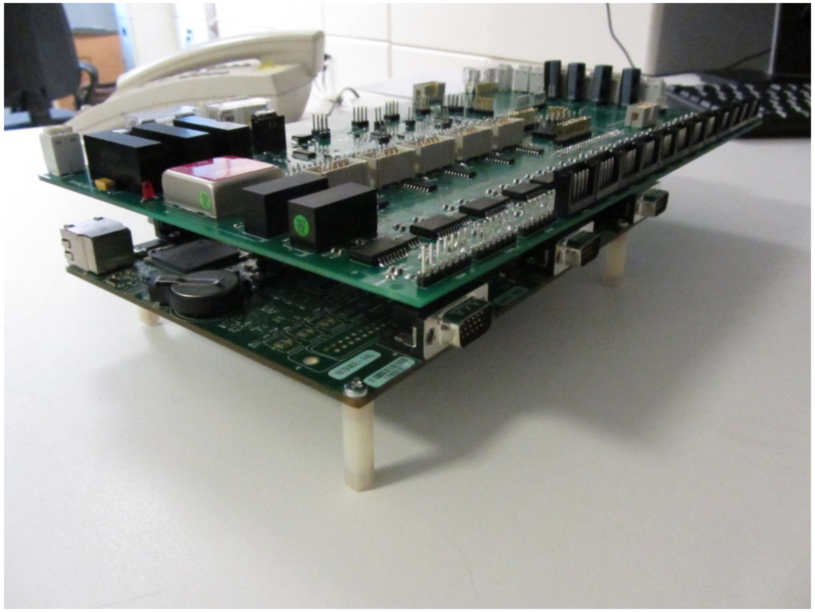
β-APO: custom electronics





- Board-to-board connection
- Power consumption: 900 mA, 12.5 V

- Connection/control to/of the other CYBERLEGs modules (prosthesis and knee-ankle-foot orthosis)

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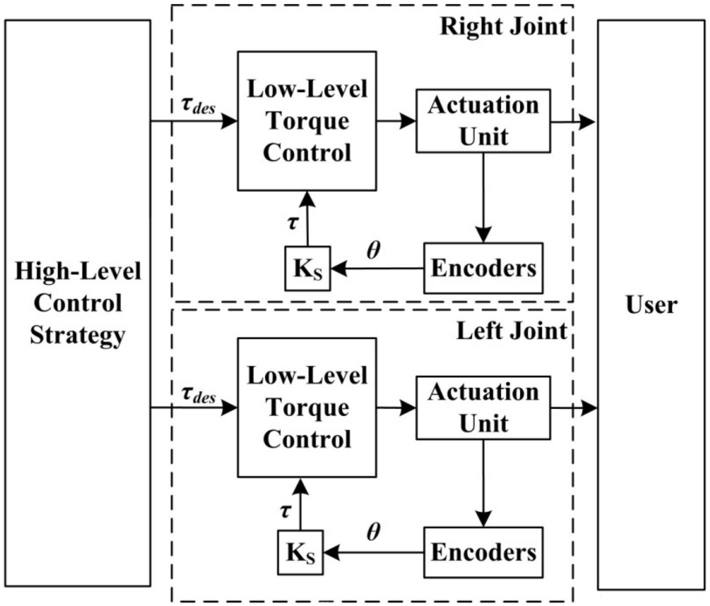
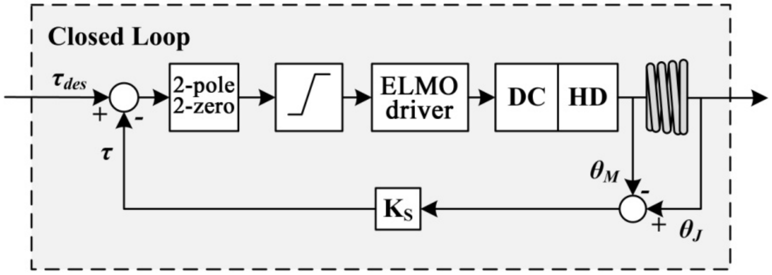
β-APO: control system

- Low-level torque control
  - Improved performance
- High-level control strategy
- Control Unit
  - Real-time controller (sbRIO-9632, National Instruments)
  - High-level layer 100 Hz
  - Low-level layer 1 kHz
- Safety Loop
  - Actuation switched off when:
    - Measured torque ≥ 30 N·m
    - Joint speed ≥ 400 /s
    - Emergency button





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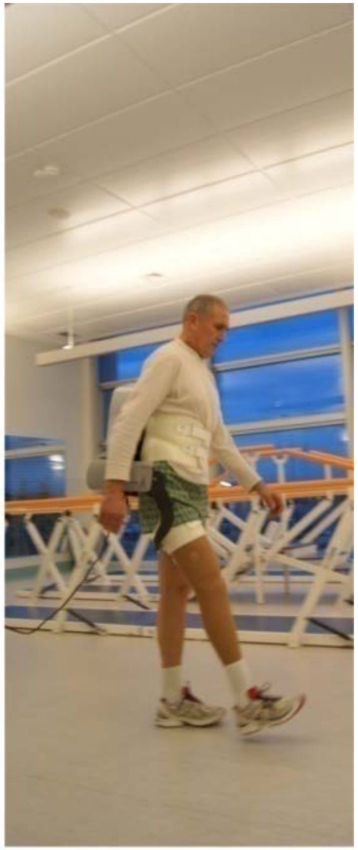
β-APO: prototype (I)

- Low-output joint impedance in zero-torque mode
  - 0.63 N·m/rad (0.5 Hz)
  - 5.29 N·m/rad (3.0 Hz)
- Total weight: ~**8.5 kg**
- Comfortable and safe usability
  - Test with amputee subject
    - Transparent mode
    - Assistive mode



Bellini at FDG, Firenze, Apr 2014

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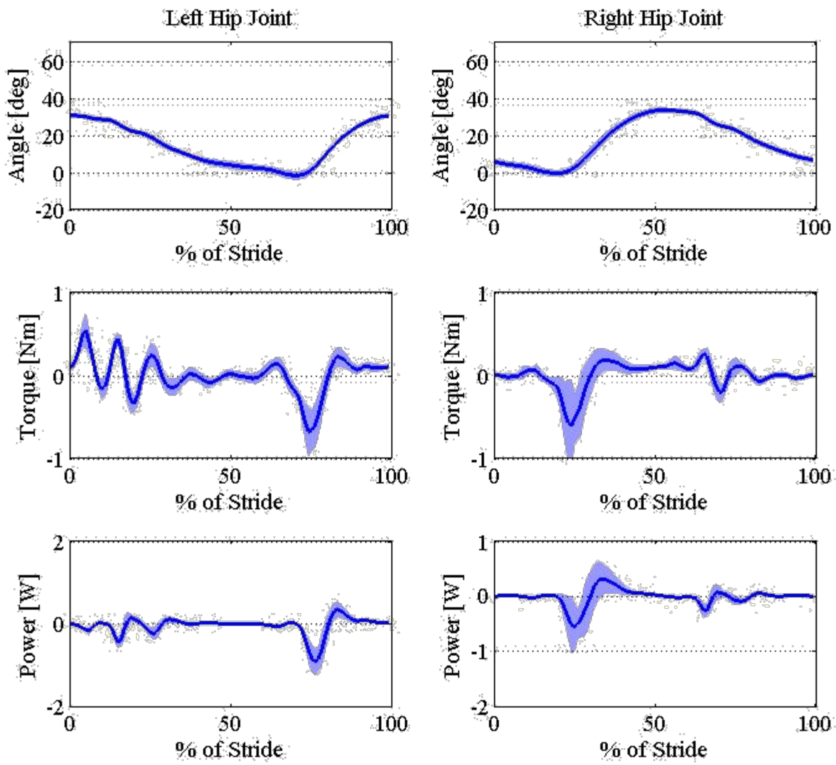
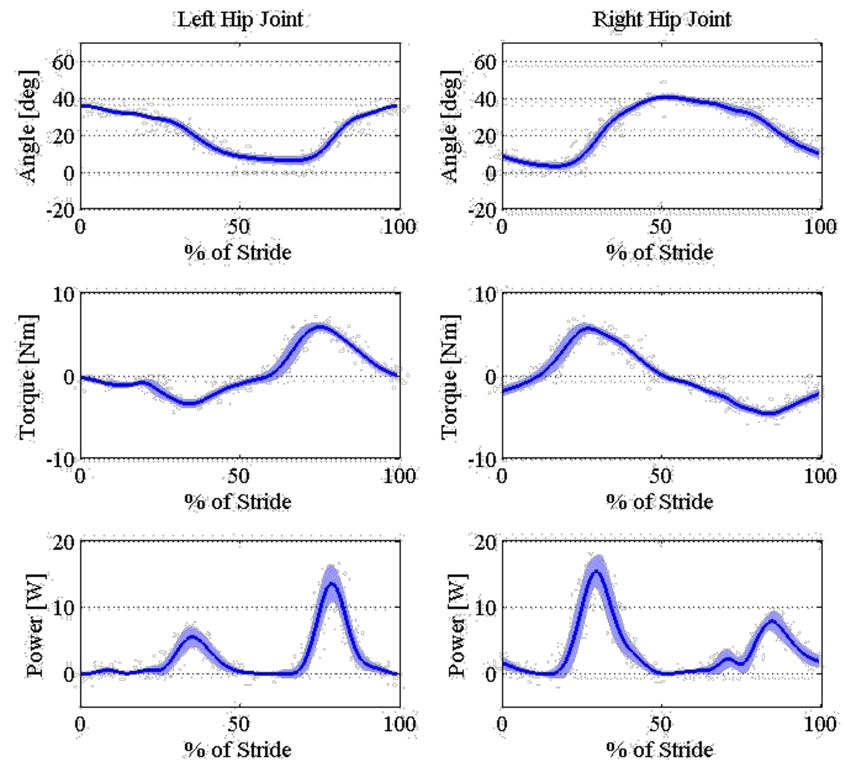
β-APO: prototype (II)

Transparent mode (TM)



Assistive mode (AM)



- Data collected with a transfemoral amputee
- Transparent mode vs. moderate assistance
- High transparency of the system
- Treadmill speed: 2.4÷3.3 km/h
- Feedback from amputee: […] smooth assistance, significant reduction of the perceived effort […]

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- Introduction to *wearable robotics*
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Non-invasive control of an active transfemoral prosthesis

- Powered 2-DOF transfemoral prosthesis
- c-HRI: whole-body awareness control
  - Use of a wearable sensory system to:
    - monitor human movement
    - identify the locomotion-related task and transitions (e.g., ground-level walking, gait initiation/termination, sit/stand, stair ascending/descending)
  - No subject-specific calibration
  - No electrodes placement
  - Quick training, highly intuitive
  - Subjects instructed to “walk as naturally as possible”

α-prototype

β-prototype

Prosthesis Team leader: prof. Dirk Lefeber (VUB)
Human-robot interface team leders: prof. Marko Munih, prof. Roman Kamnik (UL)

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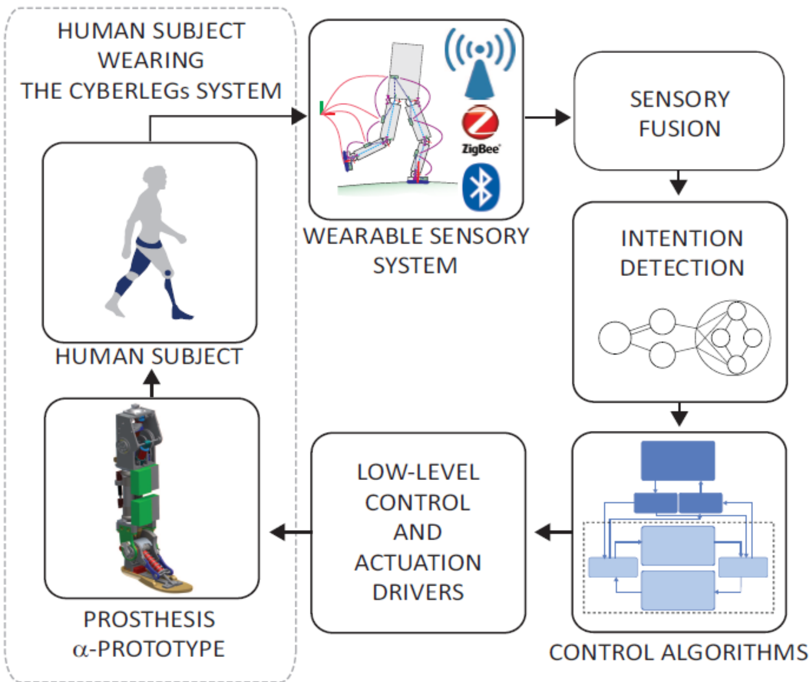
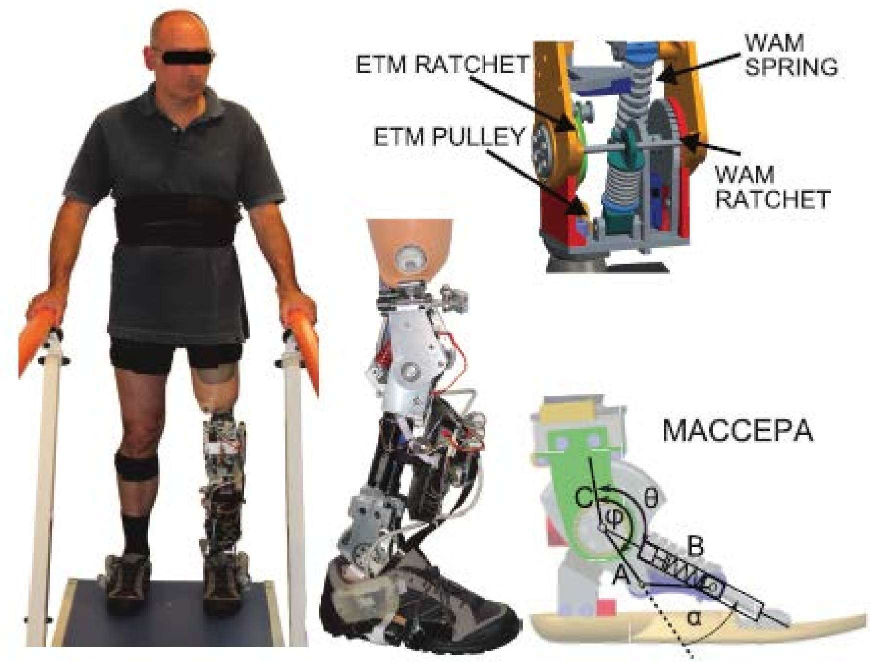
Non-invasive control of an active transfemoral prosthesis

Experiment with the α-prototype





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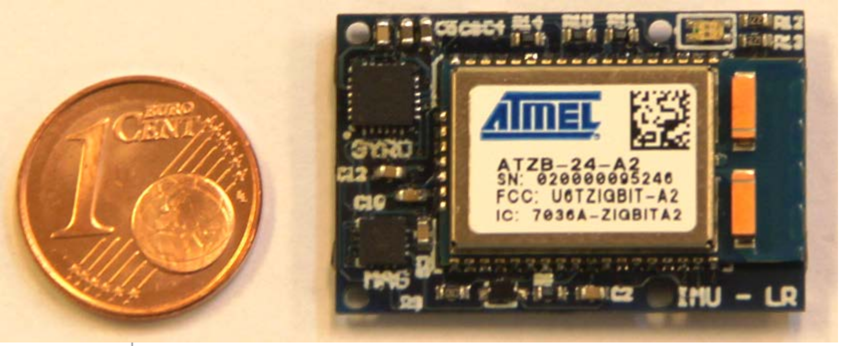
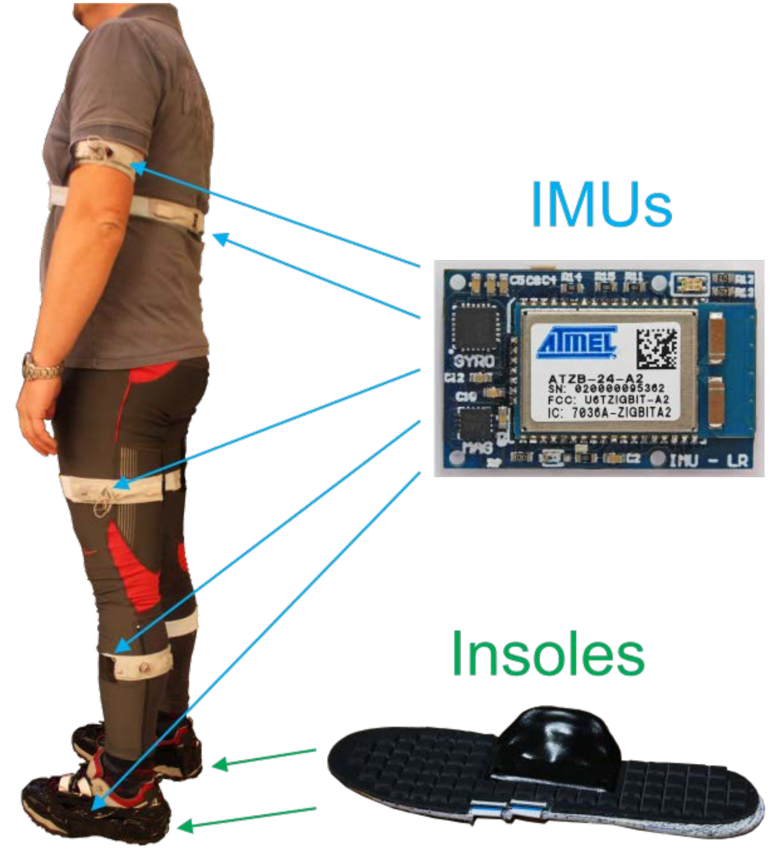
Wearable sensors

Inertial sensors

- **Sensor & transmitter** both on the same board
- **Gyroscope**
- **Magnetometer**
- Atmel ZigBit module with onboard microprocessor ATmega1281
- **Accelerometer**





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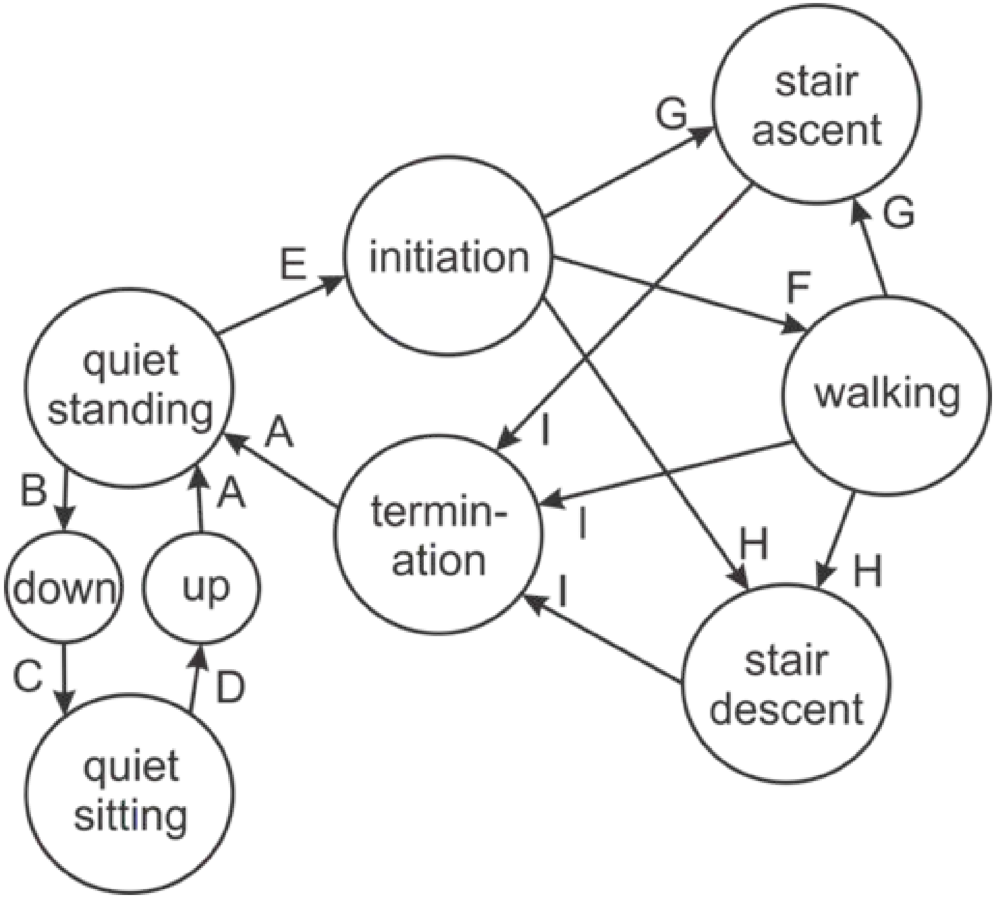
Healthy - Maneuver identification algorithm

State diagram with maneuver transitions labeled with letters (May 2014)



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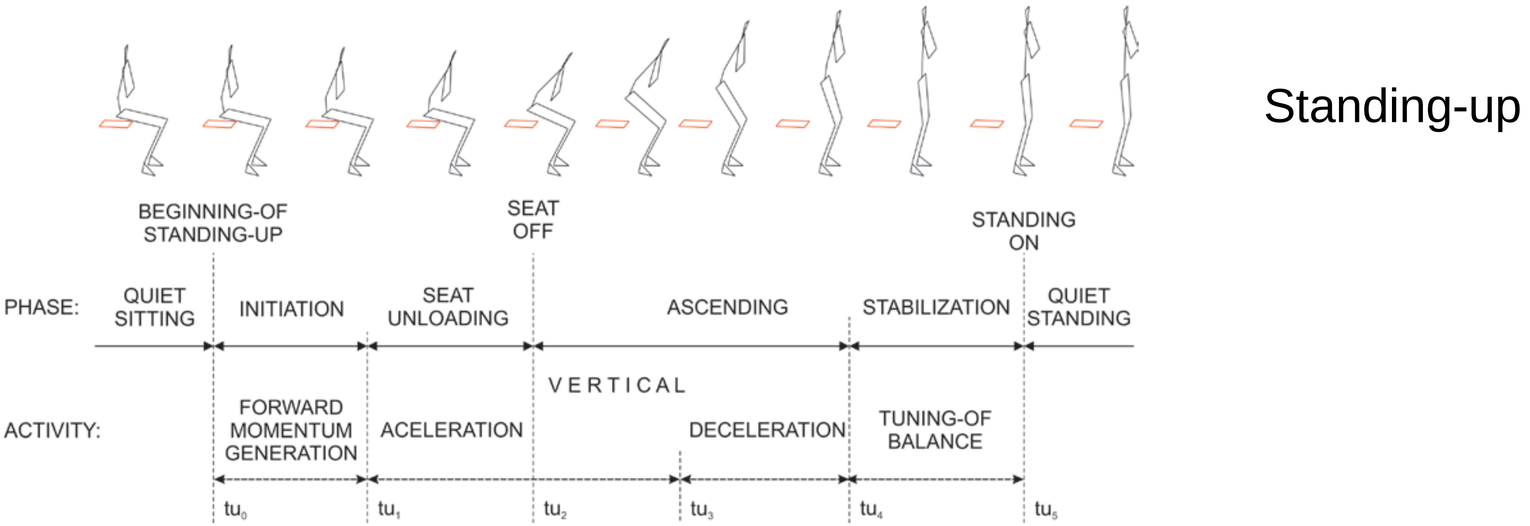
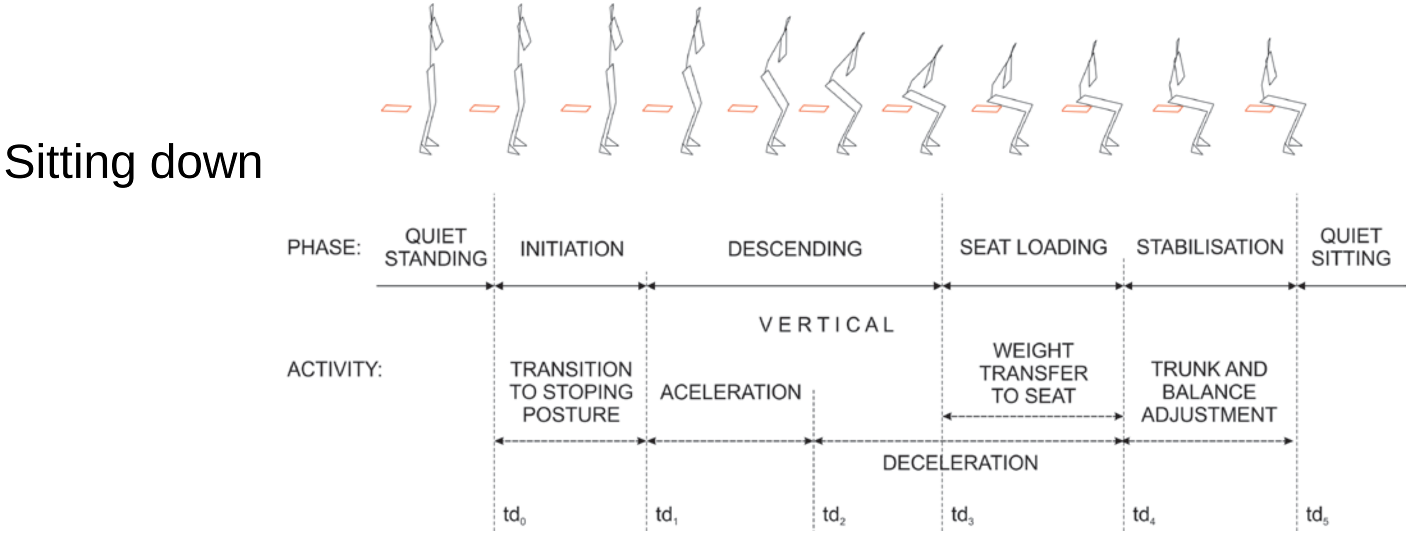
Multi-sensory fusion algorithms

Phase detection in standing-up/sitting down





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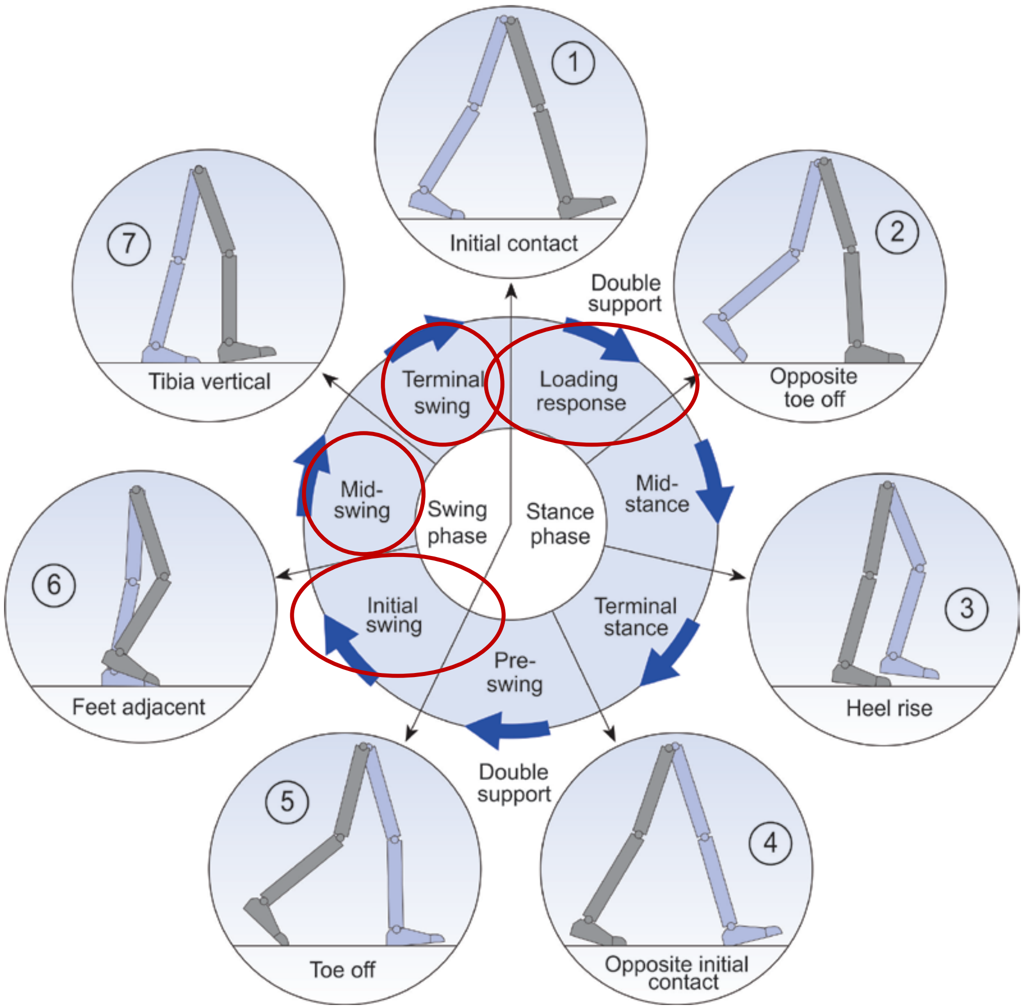
Multi-sensory fusion algorithms

Phase detection in walking



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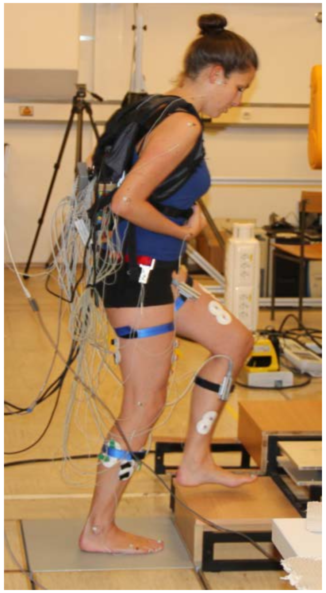
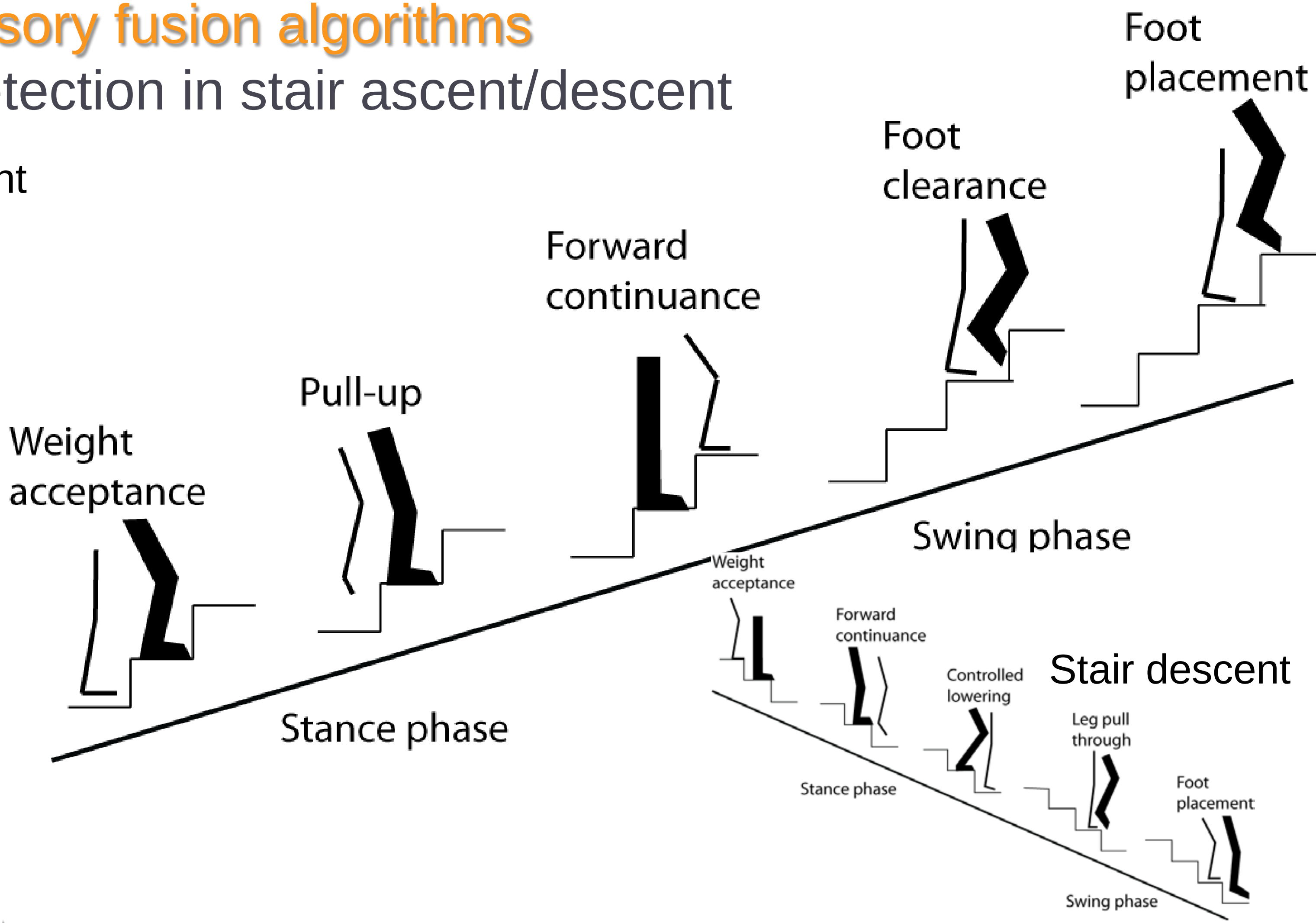
Multi-sensory fusion algorithms

Phase detection in stair ascent/descent





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Plausible transitions detected by maneuver recognition algorithm

Label	Flag	Transition	Rule
A	5	Quiet standing	$abs(\omega_{ZthighR}) < 0.1$ & $abs(\omega_{ZthighL}) < 0.1$ & $abs(\omega_{ZshankR}) < 0.1$ & $abs(\omega_{ZshankL}) < 0.1$ & $abs(\omega_{ZfootR}) < 0.1$ & $abs(\omega_{ZfootL}) < 0.1$
B	40	Sitting-down	$\omega_{ZthighR} > 0.5$ & $\omega_{ZthighL} < -0.5$ & $abs(\omega_{ZshankR}) < 1.5$ & $abs(\omega_{ZshankR}) < 1.5$ & $abs(\omega_{ZfootR}) < 0.5$ & $abs(\omega_{ZfootL}) < 0.5$ & Lflat=1 & Rflat=1
C	45	Quiet sitting	$abs(\omega_{ZthighR}) < 0.15$ & $abs(\omega_{ZthighL}) < 0.15$ & $abs(\omega_{ZshankR}) < 0.15$ & $abs(\omega_{ZshankL}) < 0.15$ & $abs(\omega_{ZfootR}) < 0.15$ & $abs(\omega_{ZfootL}) < 0.15$
D	50	Standing-up	$\omega_{ZthighR} < -0.5$ & $\omega_{ZthighL} > 0.5$ & $abs(\omega_{ZshankR}) < 1$ & $abs(\omega_{ZshankL}) < 1$ & $abs(\omega_{ZfootR}) < 0.5$ & $abs(\omega_{ZfootL}) < 0.5$
E	6	Initiation	$\omega_{ZfootR} < -0.5$ OR $\omega_{ZfootL} > 0.5$
F	10	Walking	($\omega_{ZfootL} > 0.7$ & $\omega_{ZshankL} > 0.5$) OR ($\omega_{ZfootR} < -0.7$ && $\omega_{ZshankR} < -0.5$)
G	20	Stair Ascent	(amput =0 & Lflat=1 & Rflat=0 & (($\varphi_{kneeR} > SA_{knee}$ && $\varphi_{hipR} > SA_{hip}$) OR (($\varphi_{kneeR} + \varphi_{hipR}) > (SA_{hip} + SA_{knee})$))) OR (amput=1 & Rflat=1 & Lflat=0 &($\varphi_{hipL} > 40$ & $\varphi_{kneeL} > 60$) OR (($\varphi_{kneeL} + \varphi_{hipL}) > (SA_{hip} + SA_{knee})$)))
H	30	Stair Descent	(amput=0 & Lflat=0 & Rflat=1 & $\varphi_{kneeR} > SD_{knee}$ & $\varphi_{kneeL} < SD_{ang}$ & $\varphi_{hipL} < SD_{ang}$ & $\varphi_{hipR} < SD_{ang}$) OR (amput =1 & Rflat=0 & Lflat=1& $\varphi_{kneeL} > SD_{knee}$ & $\varphi_{hipL} < SD_{ang}$ & $\varphi_{hipR} < SD_{ang}$ & $\varphi_{kneeR} < SD_{ang}$)
I	4	Termination	$abs(\omega_{ZthighR}) < 0.1$ & $abs(\omega_{ZthighL}) < 0.1$ & $abs(\omega_{ZshankR}) < 0.1$ & $abs(\omega_{ZshankL}) < 0.1$ & $abs(\omega_{ZfootR}) < 0.1$ & $abs(\omega_{ZfootL}) < 0.1$

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Tunable thresholds for input signals

Tunable thresholds	Explanation	Typical value
SA_{knee}	Threshold for knee angle determining stair ascent maneuver	60
SA_{hip}	Threshold for hip angle determining stair ascent maneuver	40
SD_{knee}	Threshold for knee angle determining stair descent maneuver	40
SD_{ang}	Threshold for leg angles determining stair descent maneuver	20
thrL, thrR	Threshold for ground reaction force (grfL, grfR) determining stance phases	300

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Rules for phases during walking maneuver

Flag	Transition	Rule
11	Left stance (L)	$\omega_{ZfootR} > 1$ & $\omega_{ZfootL} < 0.4$ & grfL > thrL & grfR < thrR
12	Left-Right double stance (LR)	$\omega_{ZfootL} > 0.2$ & $\omega_{ZfootR} < -0.5$
13	Right stance (R)	$\omega_{ZfootR} > -0.2$ & $\omega_{ZfootL} < 1$ & grfR > thrR & grfL < thrL
14	Right-left double stance	$\omega_{ZfootL} > 0.2$ & $\omega_{ZfootR} < -0.5$

Rules for phases during stair ascent

Flag	Transition	Rule
21	Right lifting (RL)	grfL > thrL & grfR < thrR & $\omega_{ZfootR} < -0.5$ & $\omega_{ZfootL} < 0.1$
22	Right placement (RP)	grfL >100 & $\omega_{ZfootR} > 1.5$ & $\omega_{ZfootL} < 0.1$
23	Left lifting (LL)	grfR > thrR & grfL < thrL & $\omega_{ZfootL} > 0.5$ & $\omega_{ZfootR} < 0.1$
24	Left placement (LP)	grfR > 100 & $\omega_{ZfootL} < -1.5$ & $\omega_{ZfootR} < 0.1$

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CYBERLEGs

Phase detection algorithm

Rules for phases during stair descent

Flag	Transition	Rule
31	Controlled Lowering (CL)	(amput=0 & grfR > thrR & $\phi_{kneeR} > 20$) OR (amput=1 & grfL > thrL & $\phi_{kneeL} > 20$)
32	Foot Placement (FP)	(amput=0 & grfL > thrL & $\omega_{ZfootL} < 0.2$) OR (amput=1 & grfR > thrR & $\omega_{ZfootR} > -0.2$)
33	Weight Distribution (WD)	(amput =1 & abs(ω_{ZfootL}) < 0.1 & $\omega_{ZshankL} > -0.2$ & $\omega_{ZthighL} > -0.2$) OR (amput=0 & abs(ω_{ZfootR}) < 0.1 & $\omega_{ZshankR} < 0.2$ & abs($\omega_{ZthighRL}$) < 0.2)

Rules for sit-to-stand and stand-to-sit maneuver

Flag	Transition	Rule
5	Quiet standing	$\omega_{ZthighR} > -0.2$ & $\omega_{ZthighL} < 0.2$
40	Sitting-down	$\omega_{ZthighR} > 0.5$ & $\omega_{ZthighL} < -0.5$ & abs($\omega_{ZshankR}$) < 1.5 & abs($\omega_{ZshankL}$) < 1.5 & abs(ω_{ZfootR}) < 0.5 & abs(ω_{ZfootL}) < 0.5 & Lflat=1 & Rflat=1
45	Quiet sitting	abs($\omega_{ZthighR}$) < 0.15 & abs($\omega_{ZthighL}$) < 0.15 & abs(($\omega_{ZshankR}$) < 0.15 & abs(($\omega_{ZshankL}$) < 0.15 & abs(ω_{ZfootR}) < 0.15 & abs(ω_{ZfootL}) < 0.15
50	Standing-up	$\omega_{ZthighR} < -0.5$ & $\omega_{ZthighL} > 0.5$ & abs($\omega_{ZshankR}$) < 1 & abs($\omega_{ZshankL}$) < 1 & abs(ω_{ZfootR}) < 0.5 & abs(ω_{ZfootL}) < 0.5

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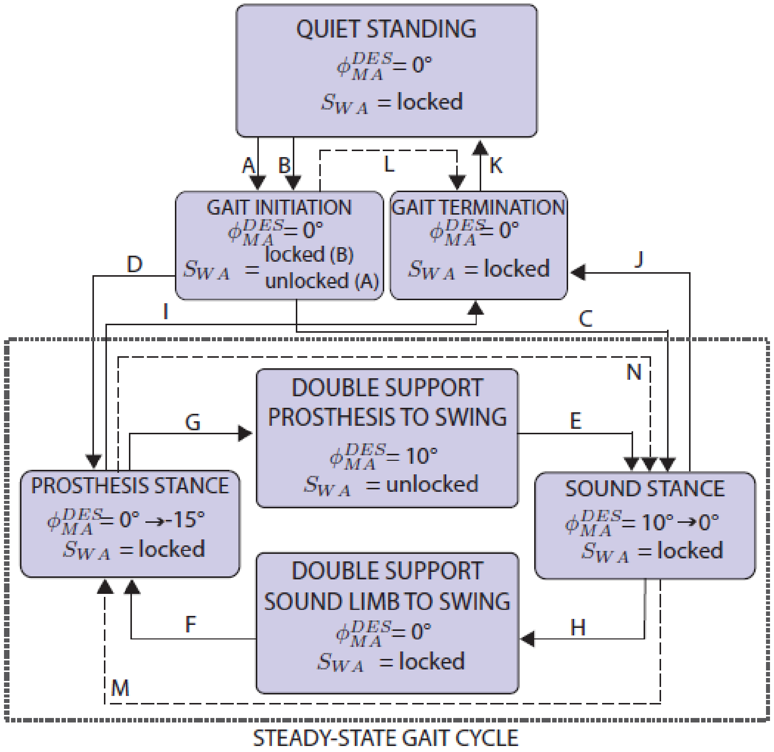
Non-invasive control of an active transfemoral prosthesis

Experiment with the α-prototype



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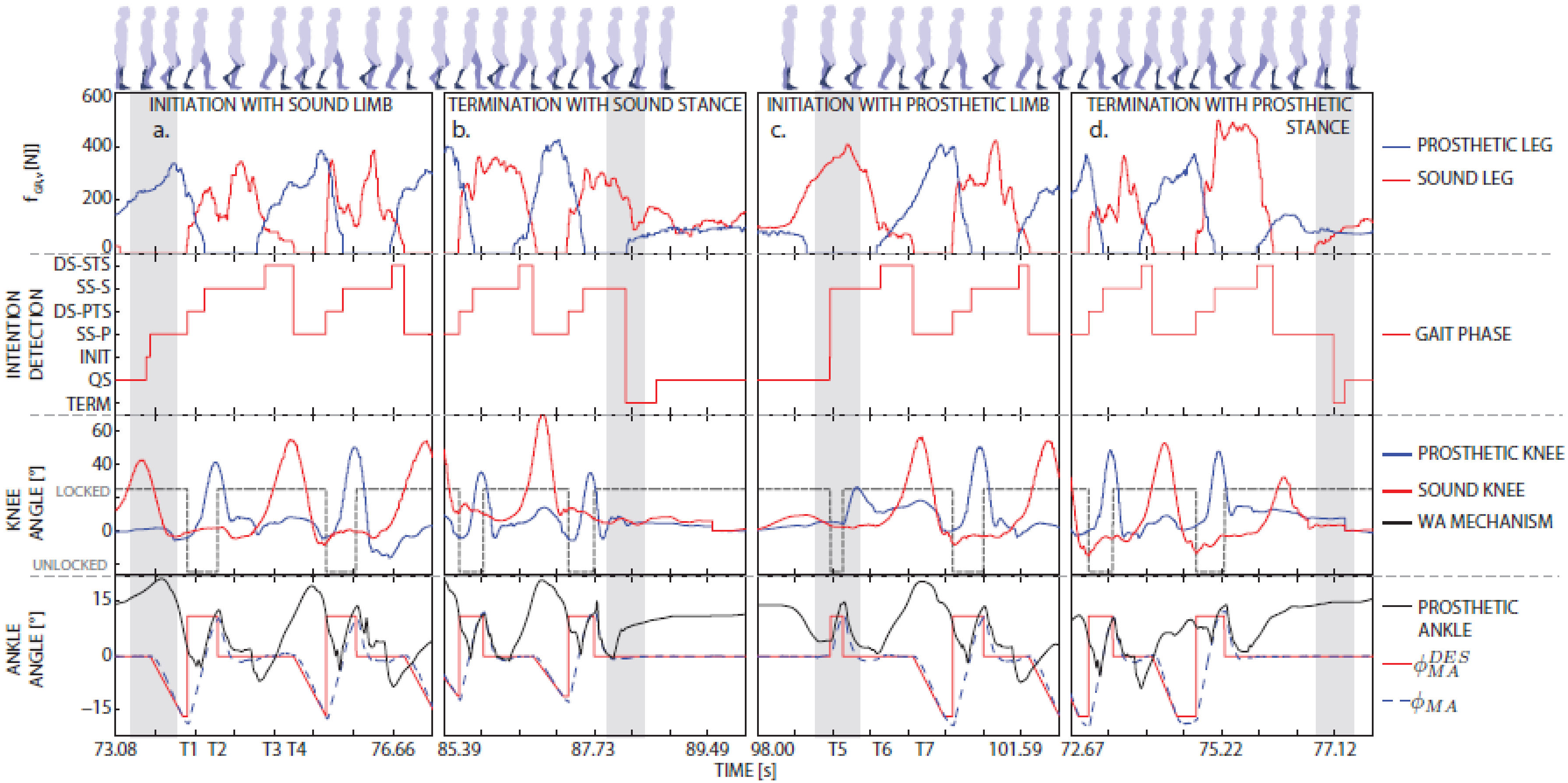

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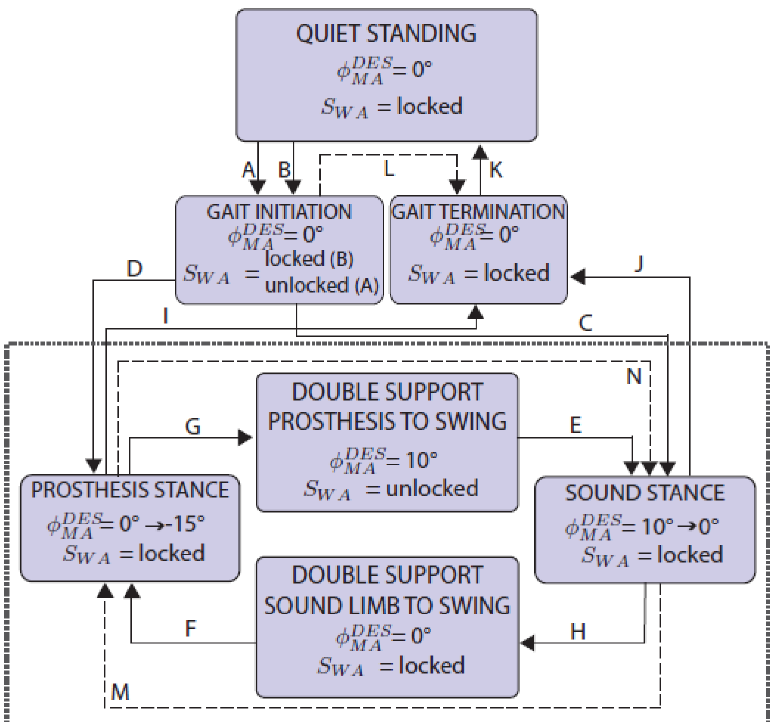

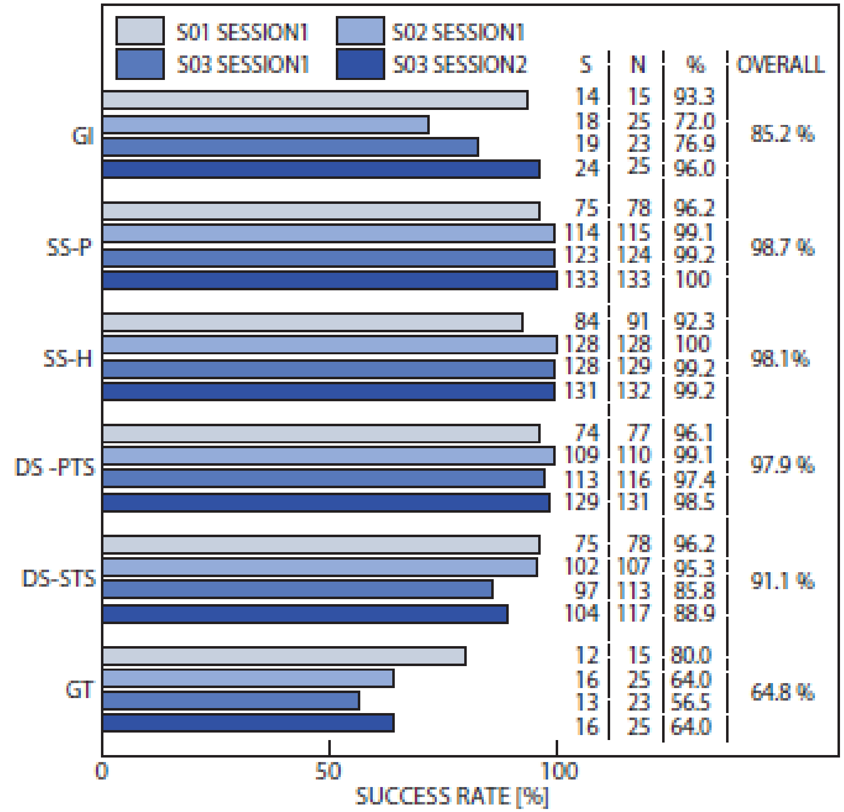

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Conclusions (future perspectives)

- Wearable robotics is a catching and interesting research domain
- Bioengineers can really **be the playmakers**

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industry:

Thank you for attention.

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