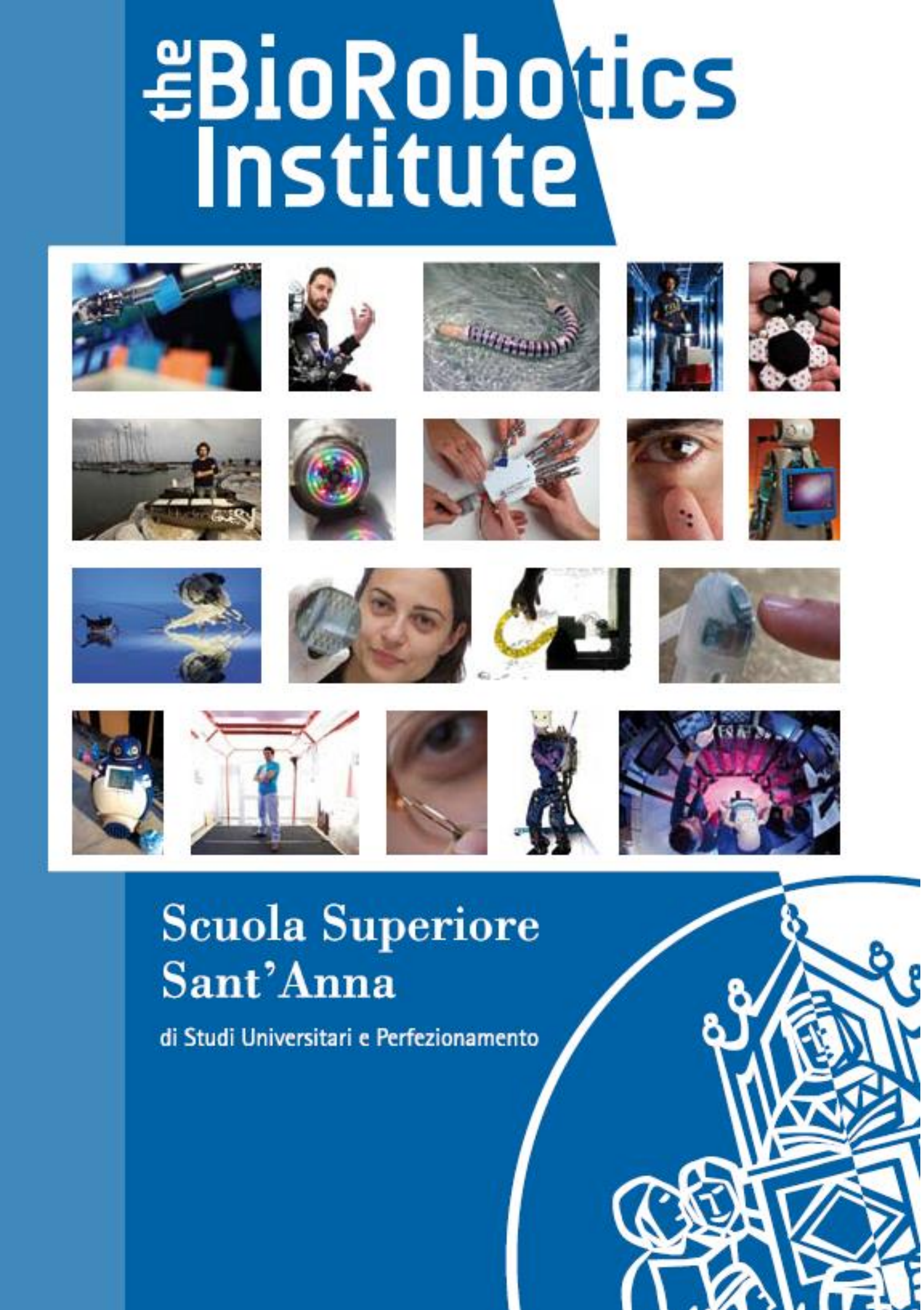


ShanghAI Lectures, Pisa, Italy

Wearable robots for sustainable ageing

Nicola Vitiello
Assistant Professor
Wearable Robotics Laboratory, Head
Email: n.vitiello@sssup.it

The BioRobotics Institute

@ Polo Sant'Anna Valdera

Viale R. Piaggio 34
56025 **Pontedera (Pisa)**
Tel. +39 050 883000

www.biorboticsinstitute.eu

Contents

- Introduction
  - Human-exoskeleton symbiosis
  - Ergonomics in wearable robotics
- Upper limb: NEUROExos
  - NEUROExos elbow module (1 DOF)
  - NEUROExos shoulder-elbow system (4 DOF)
- Lower limb: CYBERLEGs project
- Conclusions

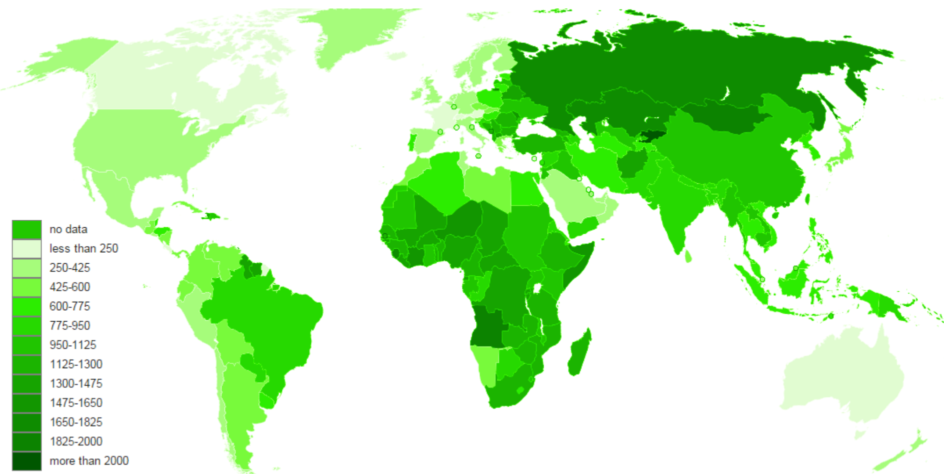
Disclaimer:

Dr. Nicola Vitiello is currently the main shareholder of IUVO s.r.l., a start-up company with interests in the commercial exploitation of the APO and its actuation technology.

Contents

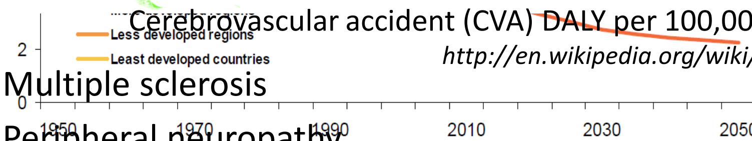
Challenge of world population aging

- The proportion of those that requir **support for active aging**, or care in their old age **is increasing**, while th proportion of those that are asked provide this support is declining. **Ar ageing society leads to concrete problems**, threatening the sustainability of welfare and economic system
- In 40 years, 35% of European population will be older than 60
- Yearly, 500.000 people experience a stroke in US, 1.1 M in EU



Cerebrovascular accident (CVA) DALY per 100,000 inh.

http://en.wikipedia.org/wiki/Stroke



Number of working-age person (15-65 y) per older person (>65 y)

UN Ageing Report 2013: http://www.un.org/en/development/desa/population/publications/pdf/ageing/WorldPopulationAgeing2013.pdf

- Multiple sclerosis
- Peripheral neuropathy
- Parkinson's disease
- Stroke
- **Permanent neurological damage**
- **Long-term assistance and rehabilitation**

- **Rehabilitation covers a leading role in facing these issues**
- **Due to the growing numbers, it is essential to propose novel solutions for an enhanced and augmented productivity of the rehabilitation treatments**

Peripheral artery diseases lead to lower-limb amputations

Diabetes affects more than 285 million people **globally and that number is expected to grow by more than 50 percent in the next 20 years to 438 million people.**

- The most impairing comorbidity factor are dysvascular diseases that leads to **gait disorders** or even **amputation**.
- Difficulty and pain in walking brings to an inactive lifestyle that generates a **vicious circle** with the disease progression.

Global SHERPA: http://www.globalsherpa.org/nutrition-market-obesity-malnutrition
WIKIPEDIA: http://en.wikipedia.org/wiki/Stroke

- Lower-limb loss is a disabling condition
- Incidence of all-cause lower-limb amputations
  - 0.4 over 10,000 in Japan
  - 10 over 10,000 in Native American communities (e.g. Navajo Region, US)
- Vascular diseases are the main cause of lower-limb amputation: ~80% in US
  - ~60.000: new transfemoral amputees per year in US & EU28
- Ageing is a risk factor

Transfemoral amputation is challenging

- More energy, less speed: 40% of the speed, 2.5 times more energy
- Steps, Stairs and other ups & downs
- More “mental energy”, less gait stability

Human-exoskeleton symbiosis



Is "physical" human-exoskeleton symbiosis doable?

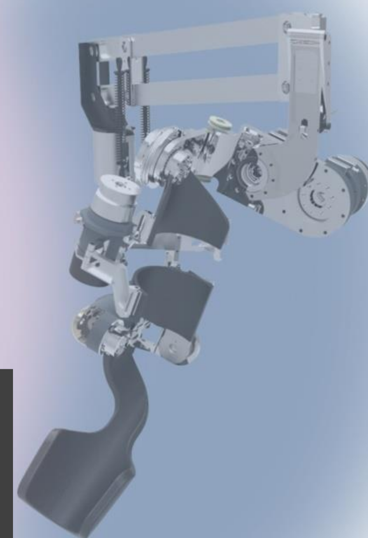
In 1960s, in *Man-Computer symbiosis* , J.C.R. Licklider formulated a vision of *human-computer symbiosis* in which computers and humans would **become fluidly interdependent and share goals.**

In 2010s, in many tasks, human and computer share goals and are interdependent.

Human-exoskeleton symbiosis

Compliant system +
Brain plasticity +
Natural damping +
Intelligent and adaptable +

Intra- and inter-user variability -
Spastic reactions -
Acceptability -

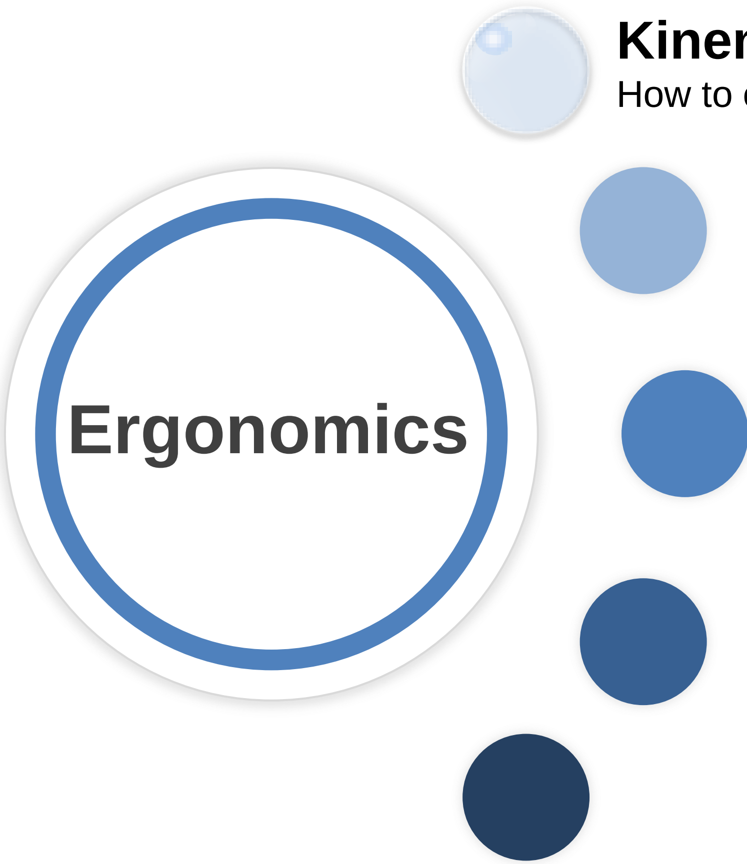


+ Robust and fast
+ Repeatable and precise
+ High power
+ Easy to set/control

- “Stupid” behavior
- Not flexible
- Heavy/cumbersome

- Tightly fit **BUT** comfortable
- Lightweight **BUT** structurally reliable
- Strong **BUT** transparent

Five pillars for an ergonomic design

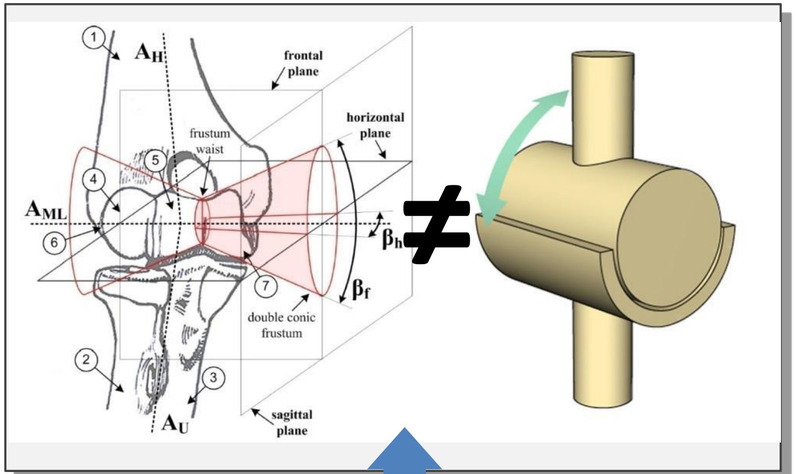


Kinematic design

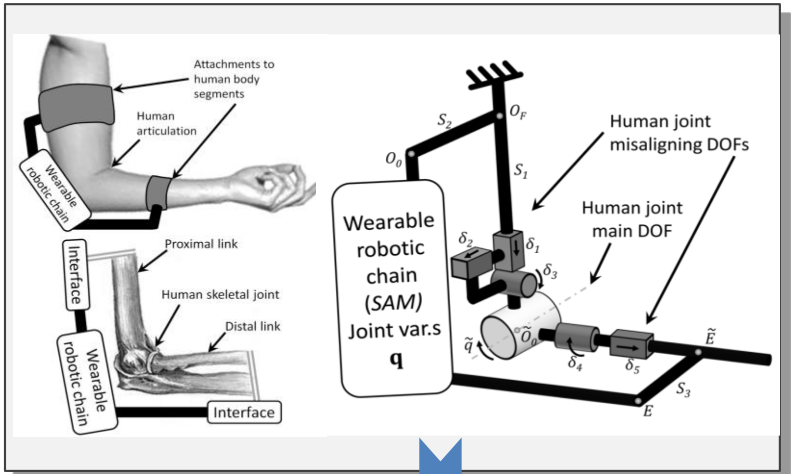
How to couple human and robotic chains

Ergonomics – Kinematic Design

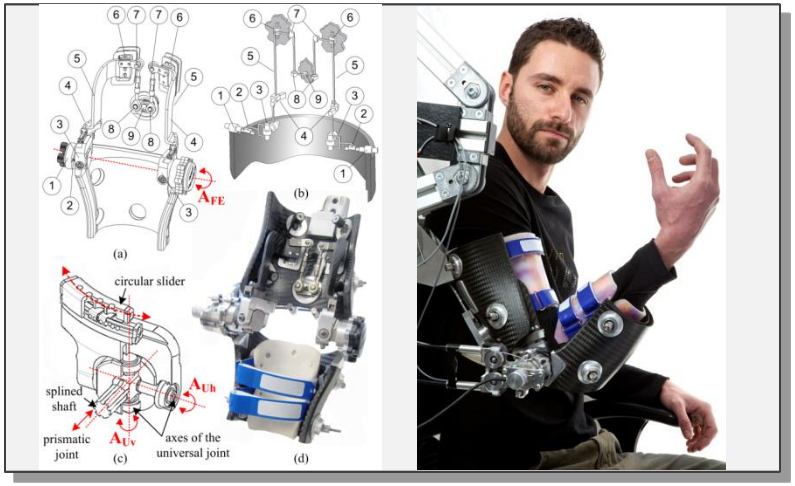
Study of human articulations



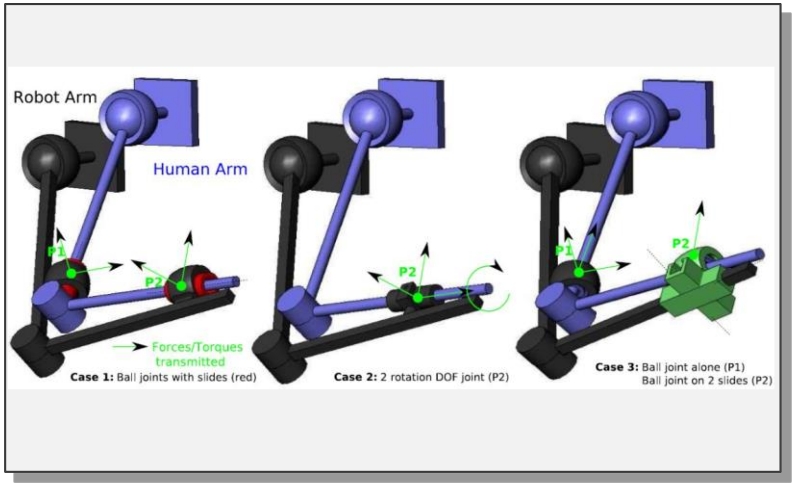
HR kinematic chains modeling



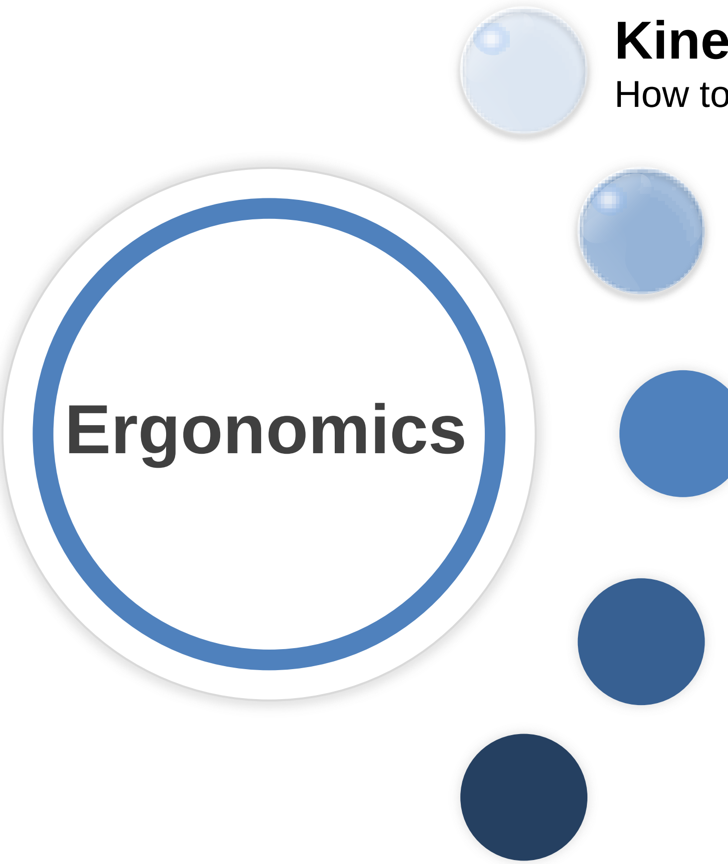
Implementation and validation



Interface kinematic design



Five pillars for an ergonomic design

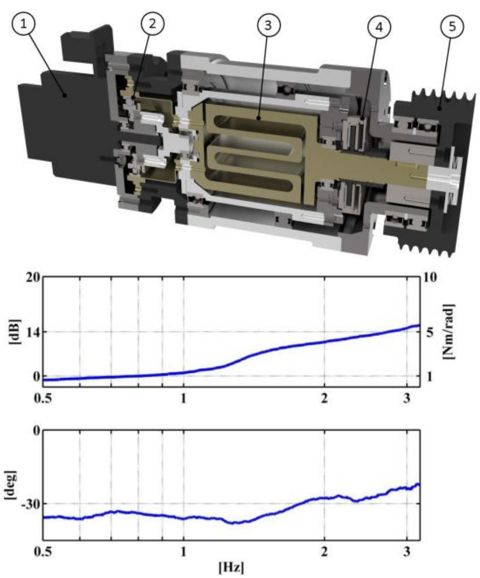


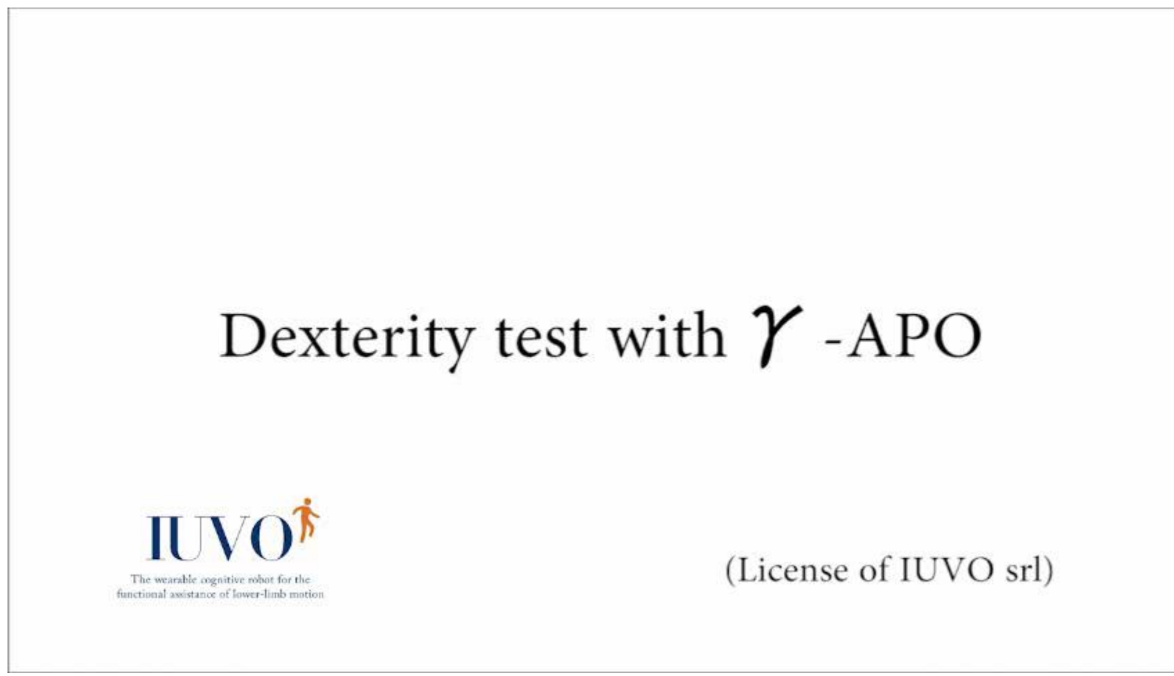
Kinematic design
How to couple human and robotic chains

Output impedance
How to make the robot “transparent” to user residual movement abilities

Ergonomics – Output Impedance

- A “cooperative” wearable robot must be perceived as an extension of wearer’s body → it has to be TRANSPARENT
- Compliance must be physically endowed in the system
- Embedding mechanical compliant element is one of the biggest issues





Five pillars for an ergonomic design

Ergonomics

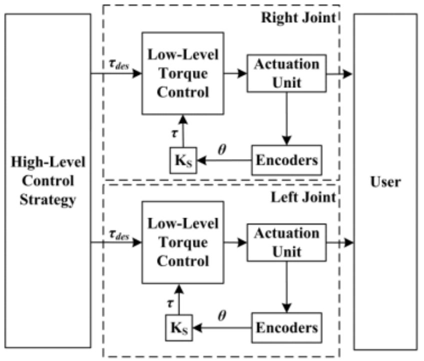
Kinematic design
How to couple human and robotic chains

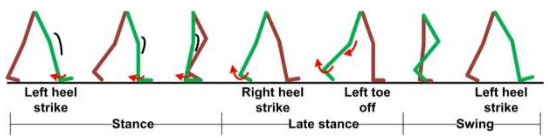
Output impedance
How to make the robot “transparent” to user residual movement abilities

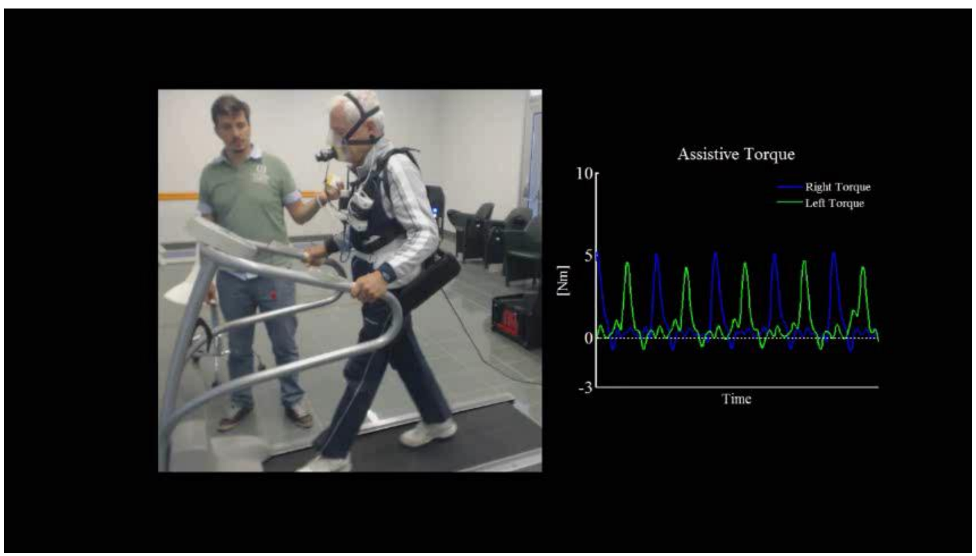
Intuitiveness
How to make the robot understanding your intentions

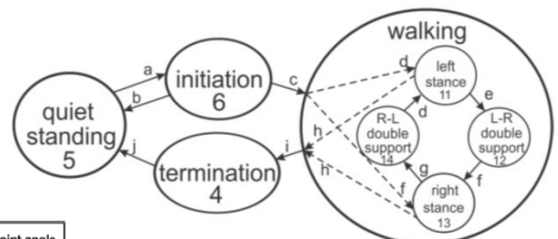
Ergonomics – Intuitiveness

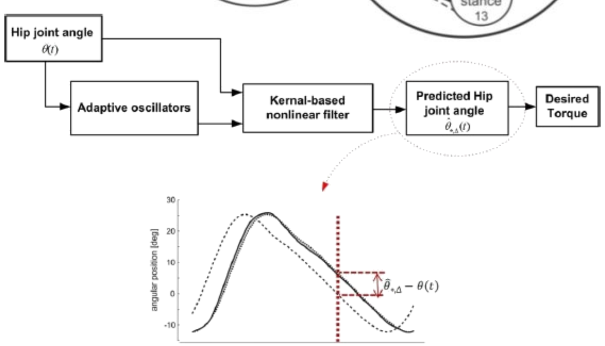
- Control of interaction torque, through SEA elastic element reading (safety & reliable)
- Intention detection, through Adaptive Frequency Oscillators
- Assist as needed strategy based on biomechanical dataset and finite-state machine
- Natural-like assistance profile











Five pillars for an ergonomic design

Ergonomics

Kinematic design
How to couple human and robotic chains

Output impedance
How to make the robot “transparent” to user residual movement abilities

Intuitiveness
How to make the robot understanding your intentions

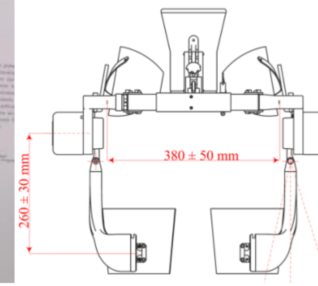
Mass distribution
How to reduce and allocate weight

Ergonomics – Mass distribution

Design guideline: **adding masses far away negatively affects the metabolic consumption**

- Trial-and-error design
- Lightweight materials
- Integrated power/control electronics, minimized wiring
- Actuation units located away from the moving parts
- Even mass distribution around the natural COM










Five pillars for an ergonomic design

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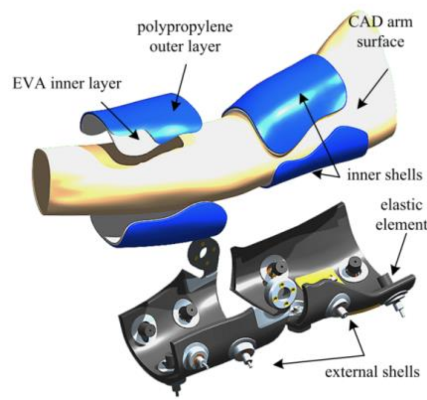
How to make the robot understanding your intentions

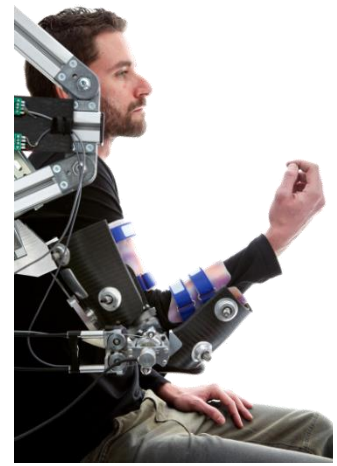
Mass distribution
How to reduce and allocate weight

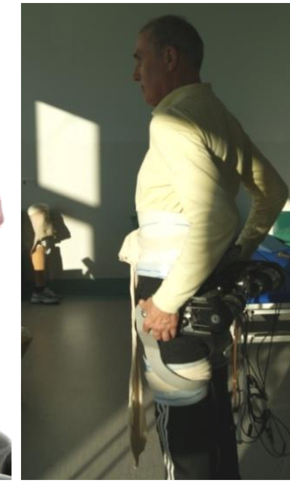
Tailoring
How to customize the robot to user needs

Ergonomics – Tailoring

- Inter-subject variability
  - Adjustable and replaceable modules for anthropometric tuning
  - Tailored customized orthotics
- Control algorithm parameterization on actual arrangement
- Cosmetic, appearance







Contents

NEUROExos – Early treatment of elbow spasticity

- Clinical definition of spasticity: velocity-dependent resistance to stretch, where a lack of inhibition results in hypertonia and hyperflexia

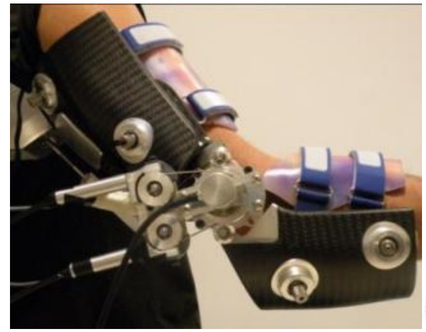
- Nonpharmacological treatment of spasticity:
  - use of splinting devices (Marshall, 2007)
  - use of plaster casts (Moseley, 2008)
  - repetitive, slow and passive exercises for muscle elongation executed by the therapist

- Studies suggest that rehabilitation in the early stages (1-4 week after the event) following a neurological disease can promote recovery and improve outcomes (Langhorne et al., 2011; Prange et al., 2006)

- **The scope of this work was the development of a wearable robot for the early treatment of elbow spasticity following CNS lesions (e.g. following stroke, diplegia, multiple sclerosis)**

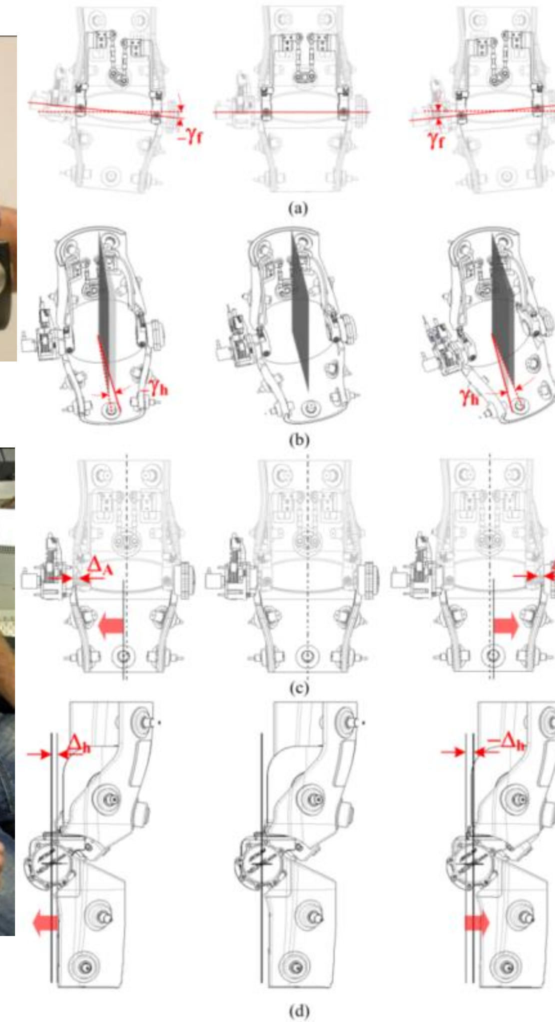
NEUROExos – Lab prototype

- Passive 4-DOFs mechanism for joint axes self-alignment
  - Human elbow as a LOOSE hinge joint
  - Intra/inter-subject variability, axis tilting during motion
  - Allowing rotations and translations of elbow axis in frontal and horizontal planes
- Double-shell structured links
  - External shells
    - Double-wall structure in carbon fiber
    - Integrate housings for the aluminum frames of the 4-DOF passive mechanism
  - Internal shells
    - Bi-layer (EVA foam + Poly Propylene)
    - Thermo-shaped on a plaster cast of the user's limb
- Bio-inspired antagonistic actuation



Lateral view

Front view



Roccella et al., patent no. WO2009016478
Lenzi et al., ICRA, 2011
Lenzi et al., Biological Cybernetics, 2011
Vitiello et al., IEEE TRO, 2013

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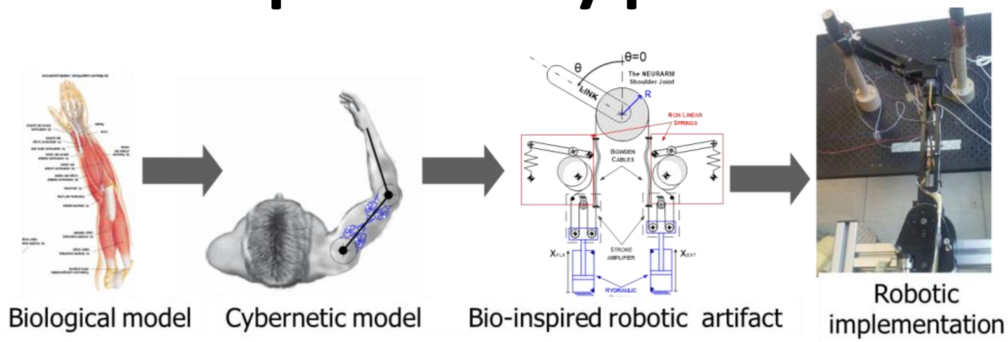

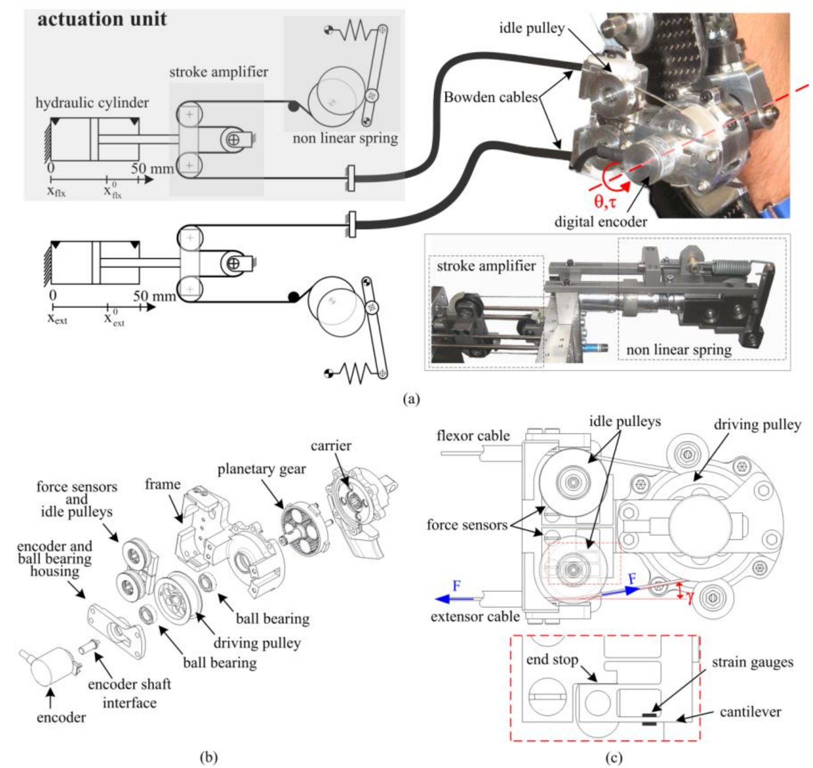

Roccella et al., patent no. WO2009016478
Lenzi et al., ICRA, 2011
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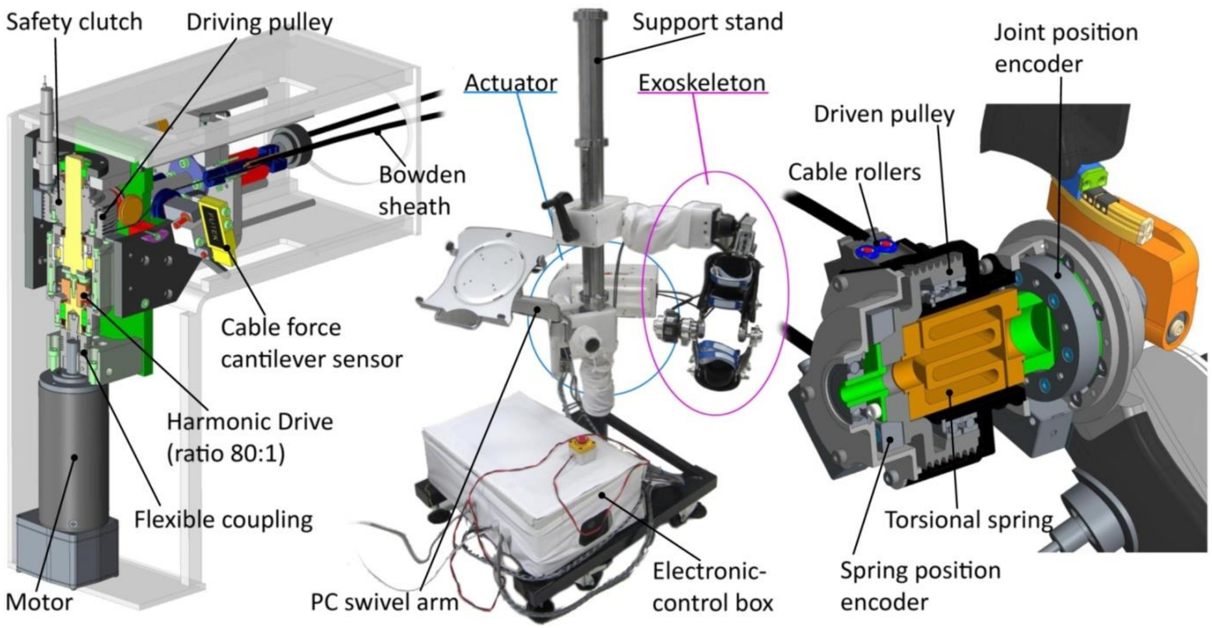
NEUROExos – Clinical deployment

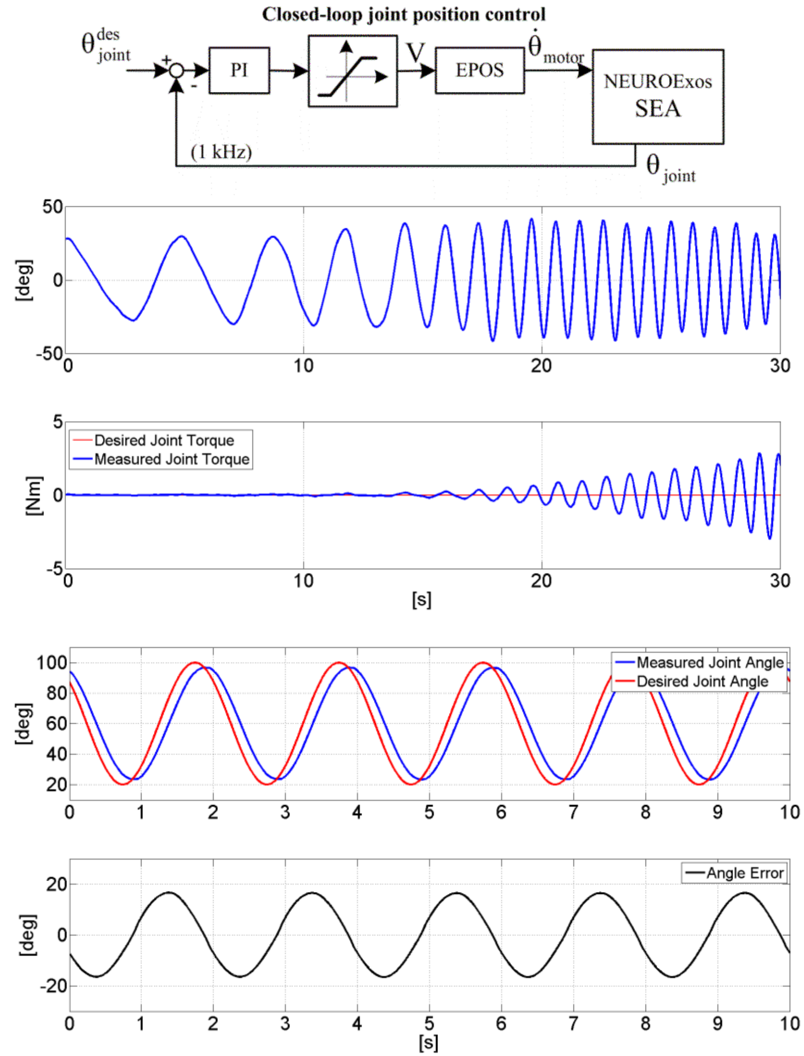
- Mobile stand
  - Adjustments and regulations
  - Compliance with room and patient's condition
- Remote actuator
  - Motor-gear, harmonic drive
  - Safety clutch
  - Bowden-cable stage
  - Torsional spring (SEA)
  - Max. Torque: 35 N·m
- Two control strategies:
  - Passive compliance control, for robot-in-charge therapy
  - Torque control, for patient-in-charge therapy
- Class IIa Medical Device
  - **IEC EN 60601-1:2007**
  - **EN ISO 14971:2012**



Cempini et al., EMBC 2013
Giovacchini et al., patent no. WO20150001469, 8 Jan 2015
Vitiello et al., TMECH, under review

NEUROExos – Clinical deployment

- Position control of the SEA output angle
- Low-output impedance torque control
  - 1-10 Nm/rad over a frequency spectrum of 0.3-1.3 Hz
  - Minimum output impedance: 1 Nm/rad @0.3 Hz
  - Maximum output impedance: 100 Nm/rad (spring stiffness), when switched-off – **at worst, patient interacts with a human-like joint stiffness**
- Maximum continuous torque: 30 Nm
- Maximum velocity under position control: 250 deg/s
- Safety loops at HW and SW levels



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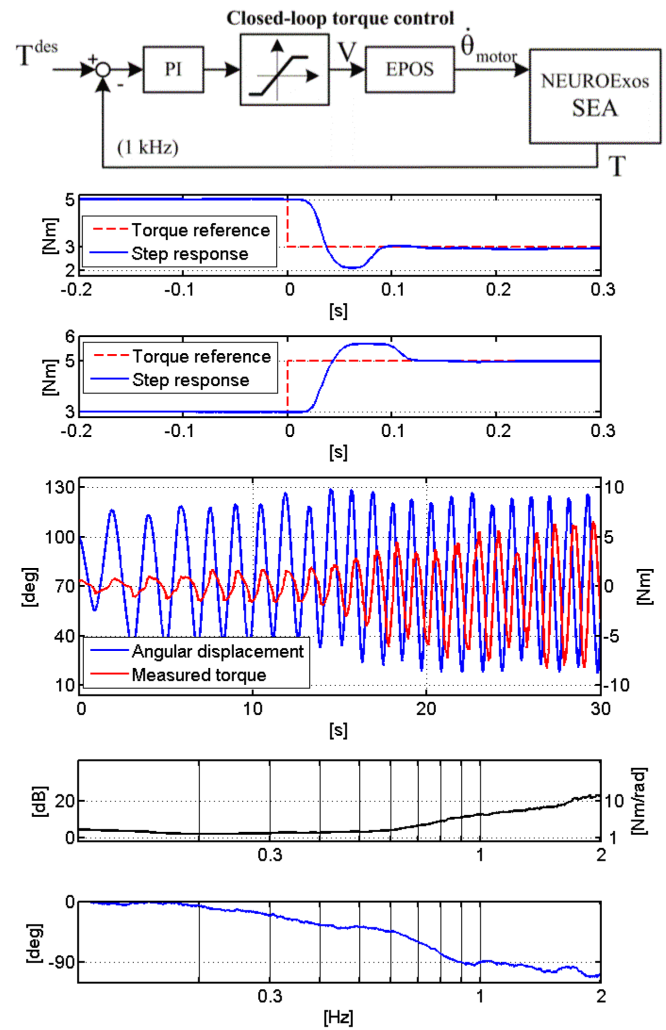

Cempini et al., EMBC 2013
Giovacchini et al., patent no. WO20150001469, 8 Jan 2015
Vitiello et al., TMECH, under review

NEUROExos – Clinical deployment

Rehabilitation treatment

Cempini et al., EMBC 2013
Giovacchini et al., patent no. WO20150001469, 8 Jan 2015
Vitiello et al., TMECH, under review

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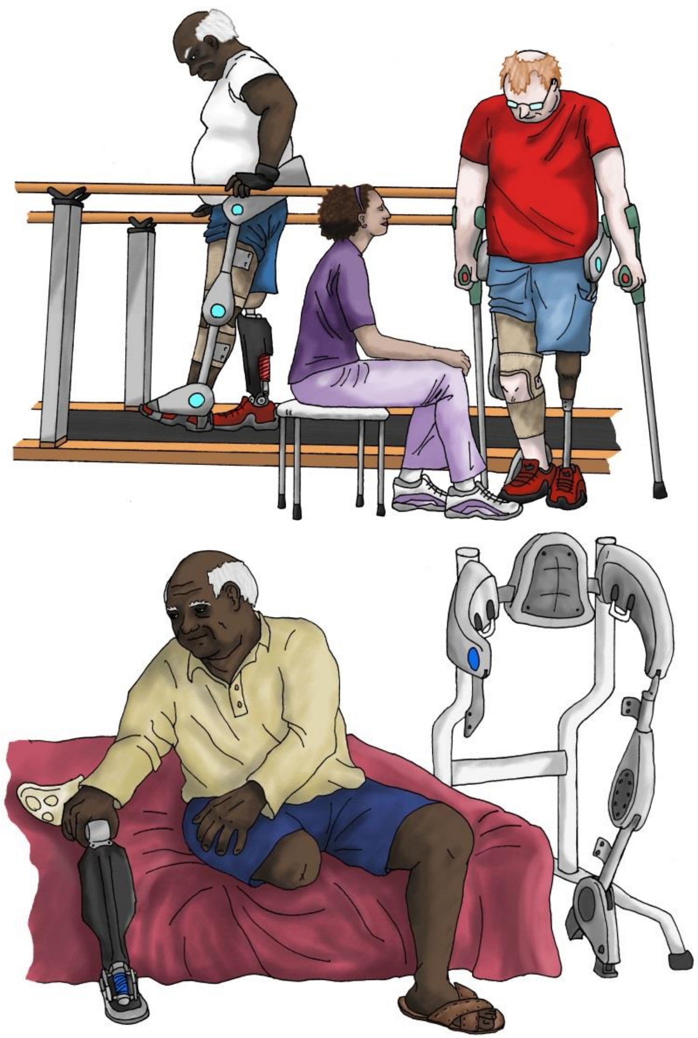
- **Lower limb: CYBERLEGs project**
- Conclusions

CYBERLEGs long-term vision



Market needs

- 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

- **GOAL, a new set of wearable robotic (orthotic and prosthetic) technologies**
  - **to help amputees to recover a more efficient gait/locomotion**
  - **intuitive/user friendly (low cognitive load)**

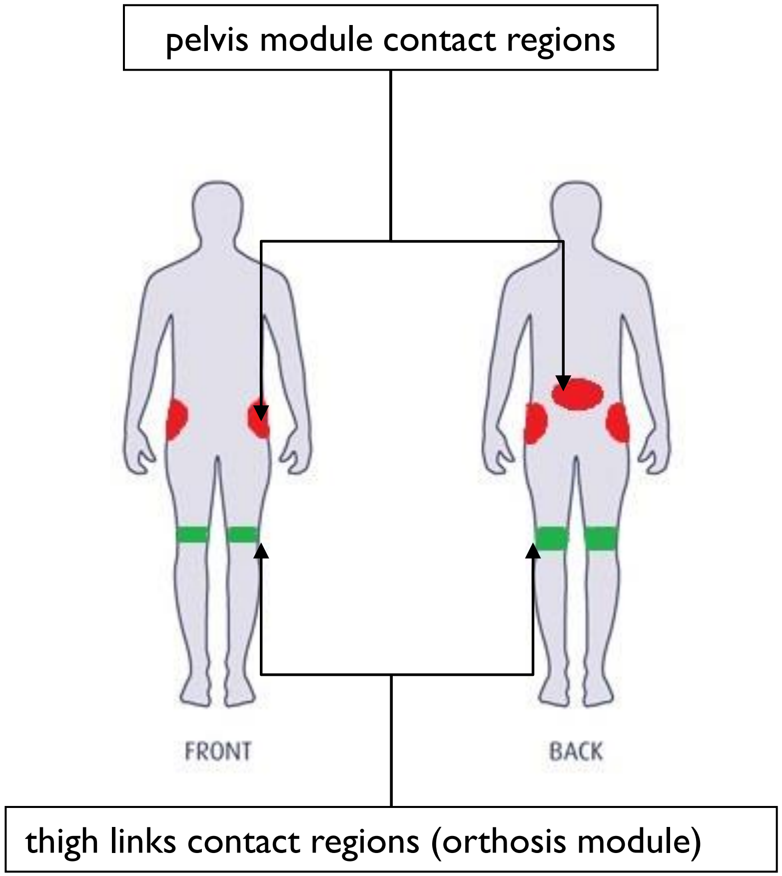
CYBERLEGs www.cyberlegs.eu

Patent pending

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

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

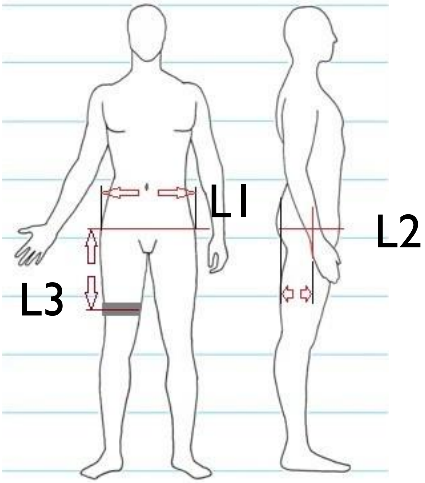


F.Giovacchini, et al., *Robotics and Autonomous Systems,* 2014.

CYBERLEGs Project has received funding from the European Community's Seventh Framework Programme (FP7/2007-2013) under grant agreement num. 287894

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



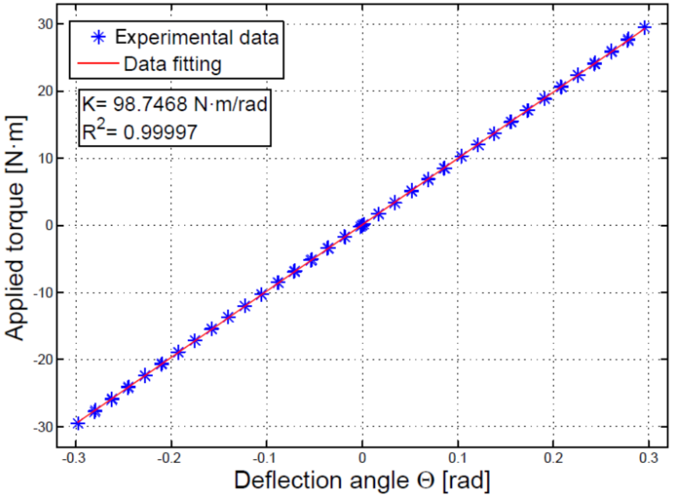
- Maximum weight: **<5 kg** (w/o batteries/control unit)
- Maximum assistance: **50%** normal-cadence torque
  - Peak hip flexion-extension torque: **35 Nm**
- Link inertia: **<10%** of human thigh inertia
- Target user weight: **80-85kg**
- Inter-subject variability:
  - Pelvis width (**L1**): 350÷440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

CYBERLEGs Project has received funding from the European Community's Seventh Framework Programme (FP7/2007-2013) under grant agreement num. 287894

Series-elastic actuation (SEA)

- Series elastic actuation (SEA)
  - Low-output impedance over the entire frequency spectrum
  - Software controllable output impedance
- The design is centered on a custom torsional spring designed and manufactured at the SSSA
  - Enabling component for many wearable-robotics applications

Specifications	
Diameter	**35 mm**
Lenght	**55 mm**
Torsional stiffness	**~100 Nm/rad**
Max allowed torque	**~ 40 Nm**
Weight	**~ 220 g**



Patent pending
F.Giovacchini, et al., "Molla Torsionale", PCT/IB2014/062735, 2014.

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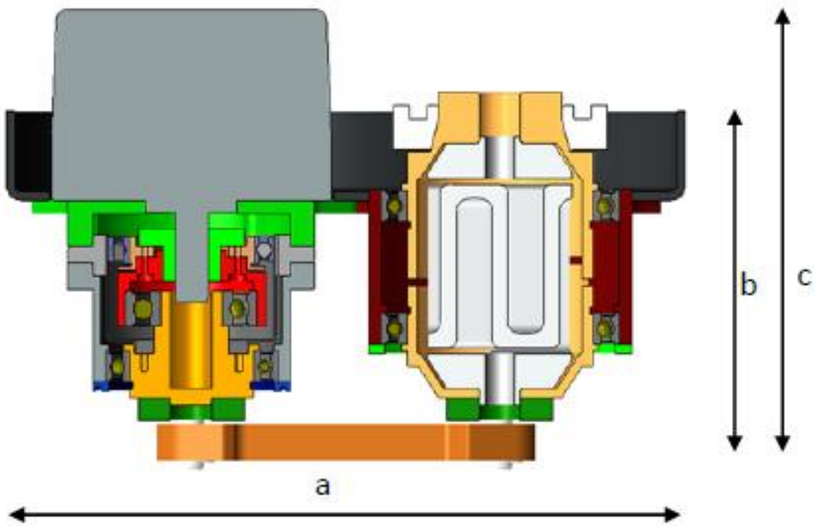
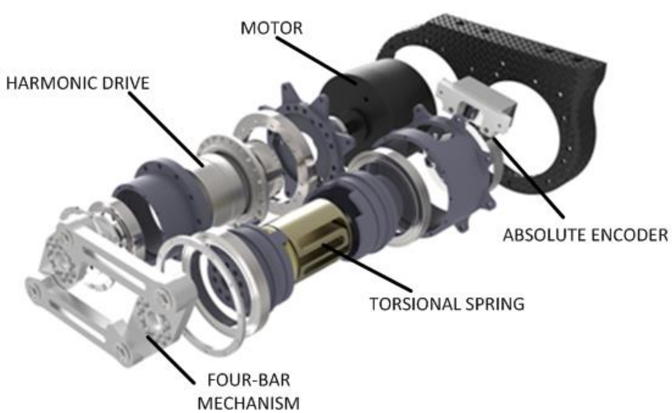
SEA: final design





PERFORMANCES

Performance at SEA output shaft	Maximum Cont Torque	27 Nm
	Maximum Peak Torque	43 Nm
	Maximum velocity	90 min^{-1}

WEIGHT

DC motor	**470g**
Harmonic Drive	100g
SEA	200g
Other components	640g
TOTAL	**1250g**

DIMENSIONS

Dimensions	
a	140 mm
b	90 mm
c	110 mm

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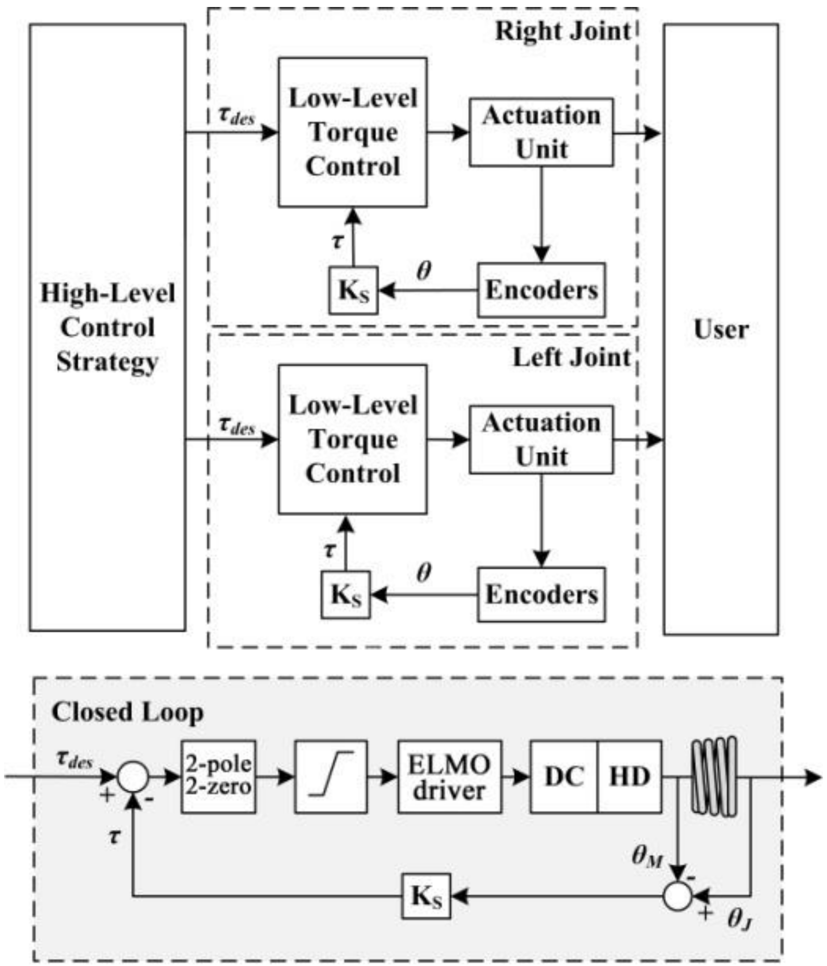
α-APO: control system (I)

- 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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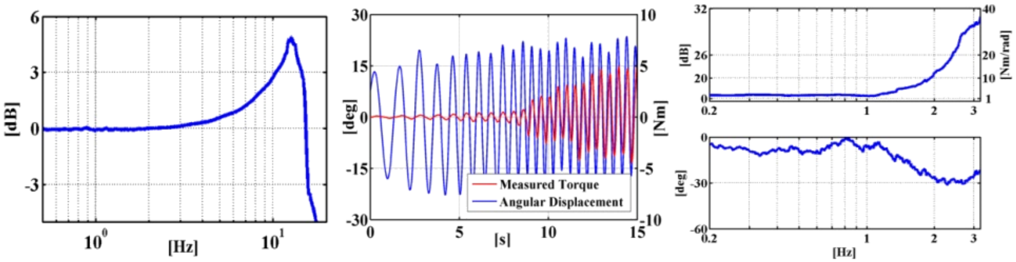
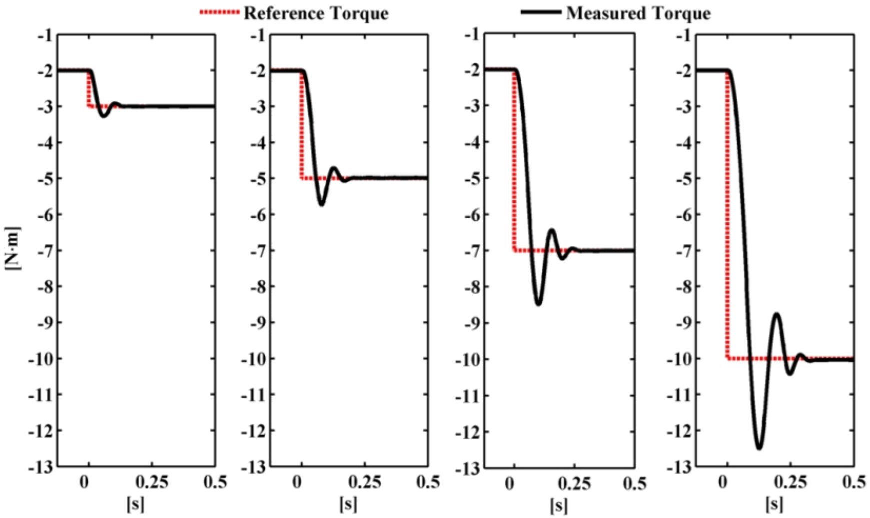
α-APO: control system (II)

- 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





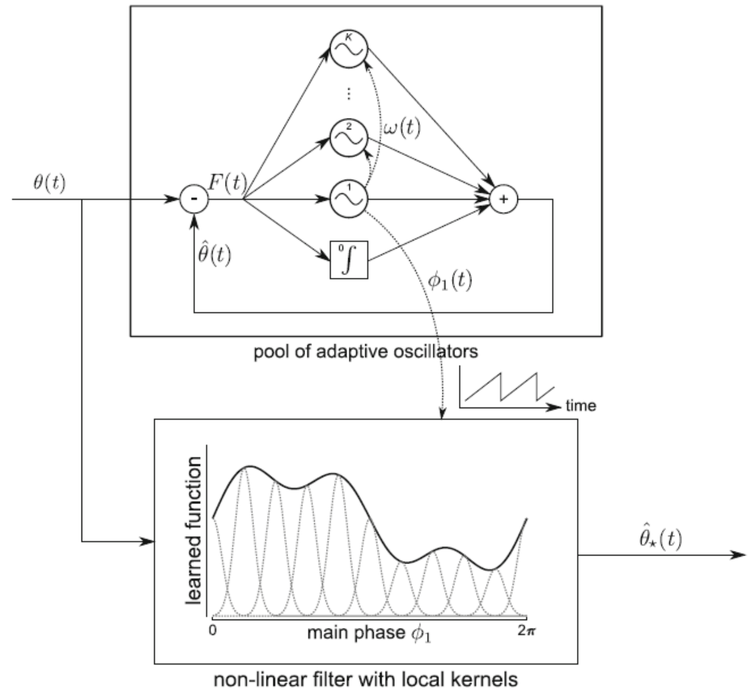
Giovacchini, et al., RAS, in press.

CYBERLEGs Project has received funding from the European Community's Seventh Framework Programme (FP7/2007-2013) under grant agreement num. 287894

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

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



Ronsse et al., MBEC, 2011

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c-HRI: AO-based assistive strategy

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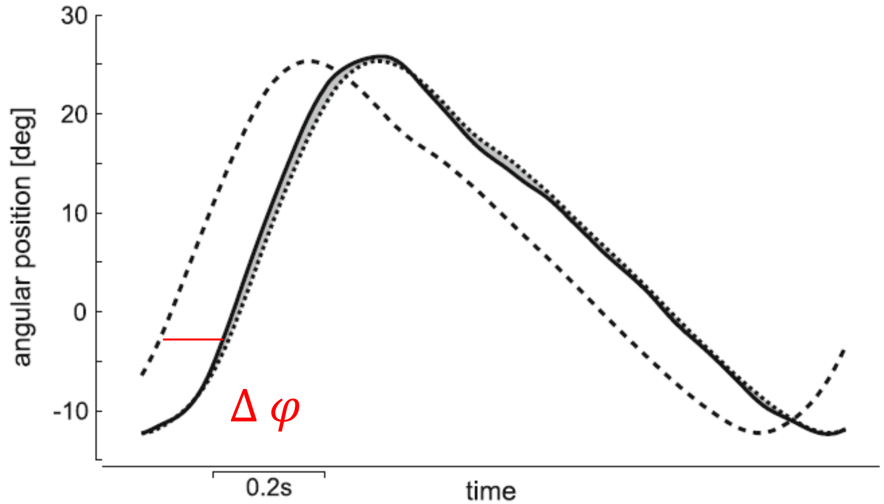
- This architecture learns **frequency** (and then the phase) and **envelop** of a quasi-periodic teaching signal, and provides a reliable prediction of the joint angle vs. gait phase within the gait cycle
- -> Estimate of both the hip joint angle $\widehat{\theta_J}(\varphi)$ and its future value at 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



Ronsse et al., MBEC, 2011

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γ-APO @ERF 2015

- CYBERLEGs was invited to present its step changes to ERF2015, Vienna, Austria
- Live demo of the new APO with:
  - Zoran Stancic (Deputy DG at EU Commission)
  - Mady Delvaux (EU Parliament)
  - EU Officers
  - 10+ EU Roboticists

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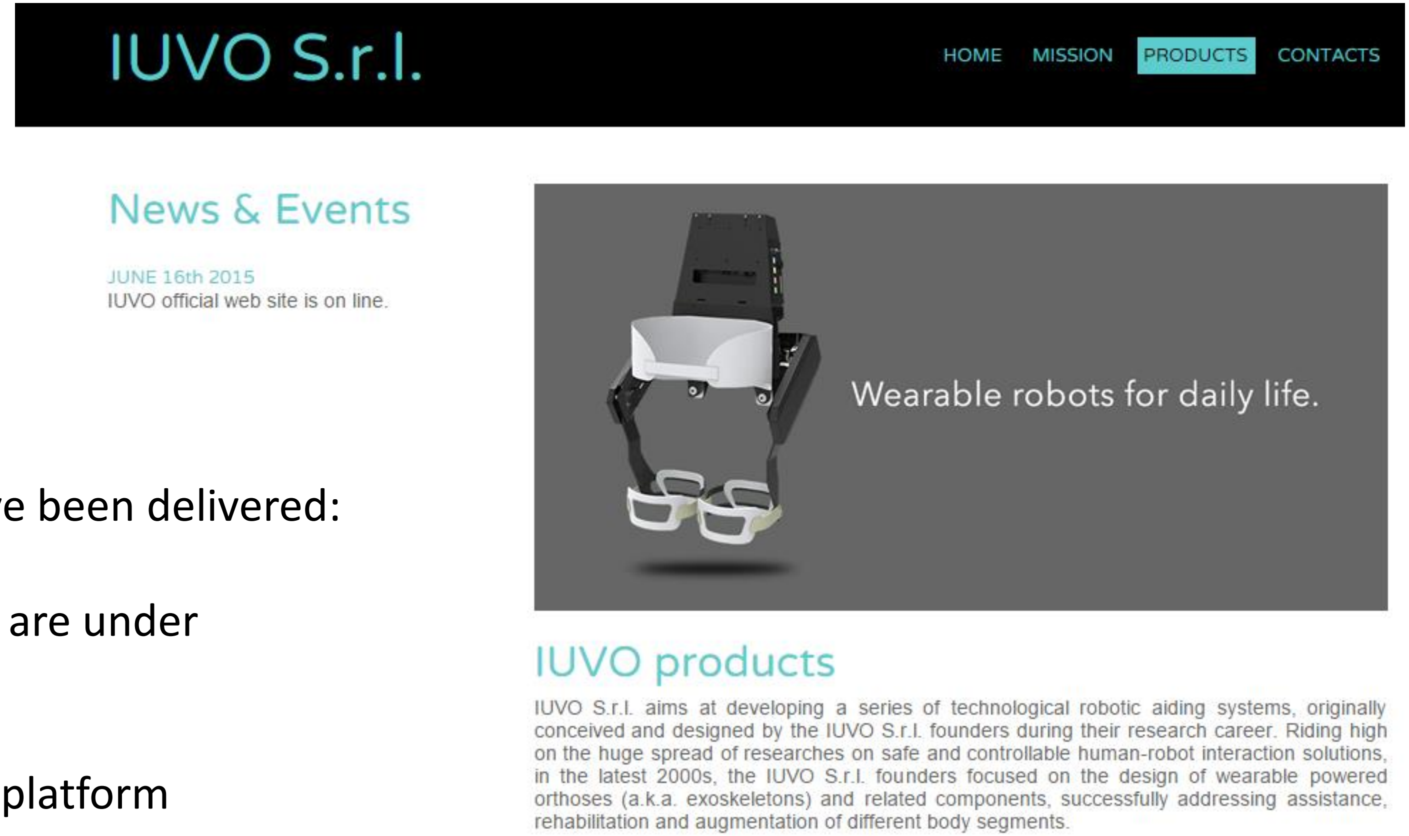
Contents

- Introduction
  - Human-exoskeleton symbiosis
  - Ergonomics in wearable robotics
- Upper limb: NEUROExos
  - NEUROExos elbow module (1 DOF)
  - NEUROExos shoulder-elbow system (4 DOF)
- Hand: HX (HandeXos)
- Lower limb: CYBERLEGs project
- Conclusions

APO is now on the market as a research prototype!



On 2015, 2 replicas have been delivered:

Two additional replicas are under preparation

Strong point: open SW platform

www.iuvo.company

Wearable Robotics Laboratory
@The BioRobotics Institute

- Dr. N**icola Vitiello** (Assistant Professor)
- Francesco **Giovacchini** (Senior researcher)
- Dr. **Marco Cempini** (Post-Doc) → moved to RIC
- Dr. **Marco Donati** (Post-Dodc)
- Simona **Crea** (Y3 PhD student)
- Mario **Cortese** (Y3 PhD student)
- Tingfang **Yan** (Y3 PhD student)
- Nicolò **D'Elia** (Y2 PhD student)
- Andrea **Parri** (Y2 PhD student)
- Andrea **Baldoni** (Y1 PhD student)
- Emilio **Trigili** (Y1 PhD student)
- Matteo **Moisé** (Senior researcher)
- Matteo **Fantozzi** (Senior researcher)
- Marco **Muscolo** (Senior researcher)
- Lorenzo **Grazi** (Junior researcher)
- Silvia **Manca** (Junior researcher)
- Dario **Marconi** (Master student)
- Elena **Martini** (Master student)
- Francesca **Spagnuolo** (Research manager)

Wearable Robotics Lab is within the Neuro-robotics research are, led by prof. **Maria Chiara Carrozza**

Thanks for the attention! Questions?
Thanks for your kind attention.
Contact: n.vitiello@sssup.it
… and you all are welcome to visit us and try our robots.