THE BIOROBOTICS INSTITUTE

Sant'Anna
School of Advanced Studies – Pisa

DETERMINISTIC6G

Dependable 6G Summer School
Sep 8th -10th , 2025
KTH, Stockholm, Sweden

Exoskeletons for assistance and rehabilitation of human motor functions

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Ageing of the population

By 2060, EU-27's population [Eurostat 2010]

Median age will be 47.6 years (from about 41 in 2010)

29.5% of the population will be 65 years of age or over, (17.4% in 2010)

The ratio of senior citizens (> 64) to working citizens (19–65) – the "old age dependency ratio" – is expected to change from 25.9% per cent in 2010 to 52.6%

Robotics technology (and **wearable robotics**) can be a solution to foster **welfare sustainability**

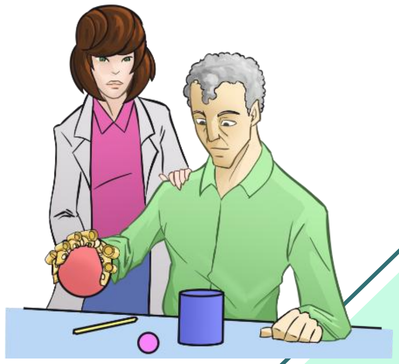
Toward sustainable and active ageing

Age-associated chronic diseases

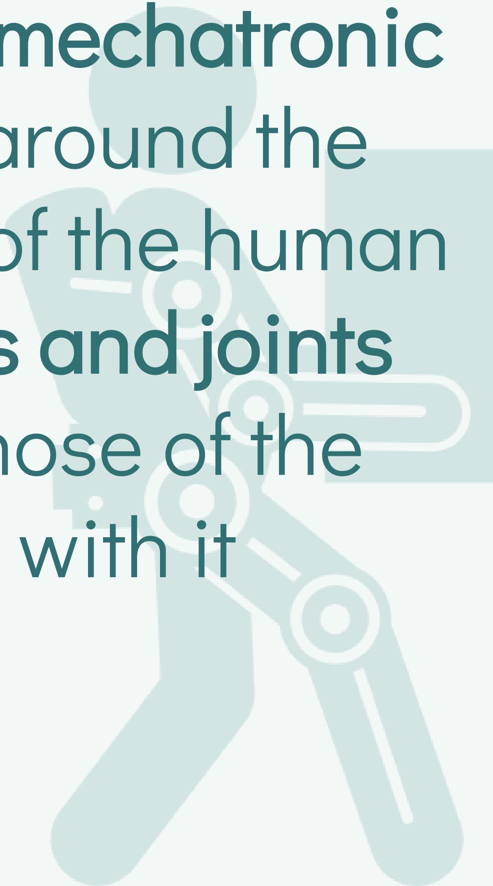
- Neurological diseases (stroke, multiple sclerosis, Parkinson's)
- Dysvascular amputations (e.g., diabetes)
- Work-related musculoskeletal disorders

Wearable robotics for sustainable and active ageing:

- Rehabilitation and daily-life assistance of people affected by chronic diseases
- Active engagement of healthy elderly in the society, with technologies capable to preserve workers health and medical conditions



Wearable robots are **mechatronic systems** designed around the shape and functions of the human body, with **segments and joints** correspondent to those of the person **coupled** with it



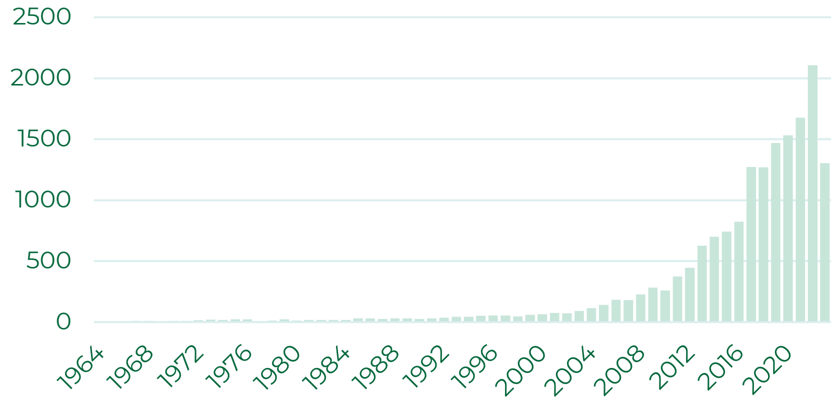
Pons, José L. *Wearable robots: biomechatronic exoskeletons.* John Wiley & Sons, 2008

Source: Scopus

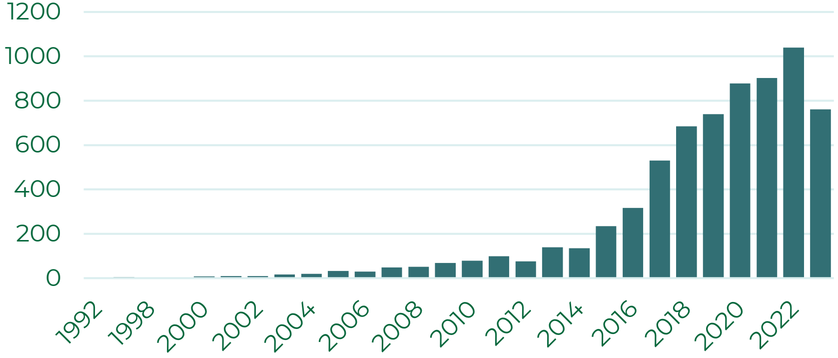
Wearable robotics

A fast growing scientific research field

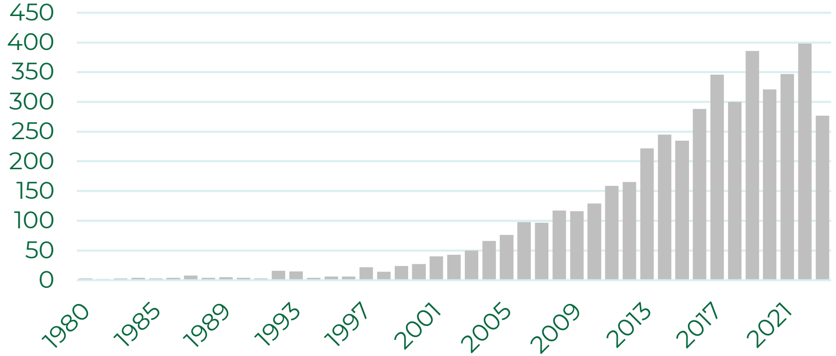
Scientific publications on "*exoskeletons*"



Scientific production on "*wearable robotics*"



Scientific publications on "*robotic prostheses*"

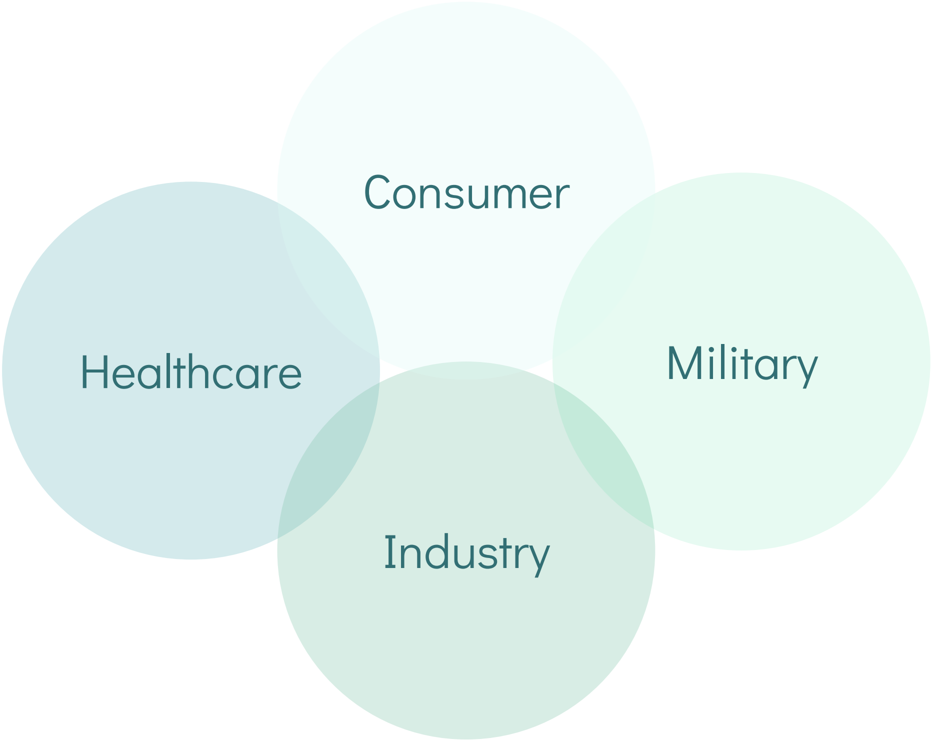


Exoskeletons

Application domains

Exoskeletons

Application domains

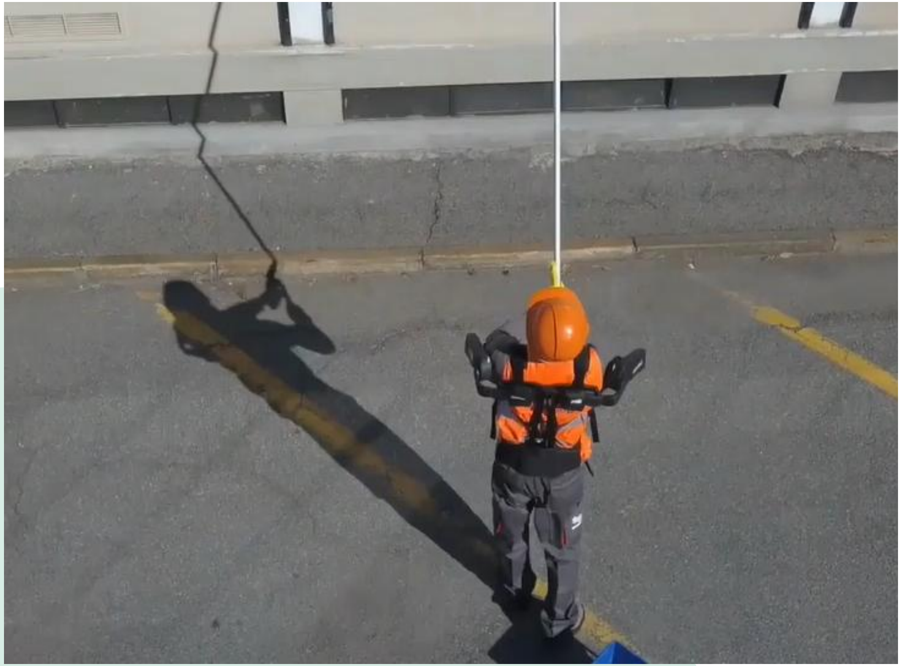


Monica L., et al. (2020) *Occupational exoskeletons: Wearable robotic devices and preventing work-related musculoskeletal disorders in the workplace of the future*, pp. 1–12.

Occupational exoskeleton (OES): a definition

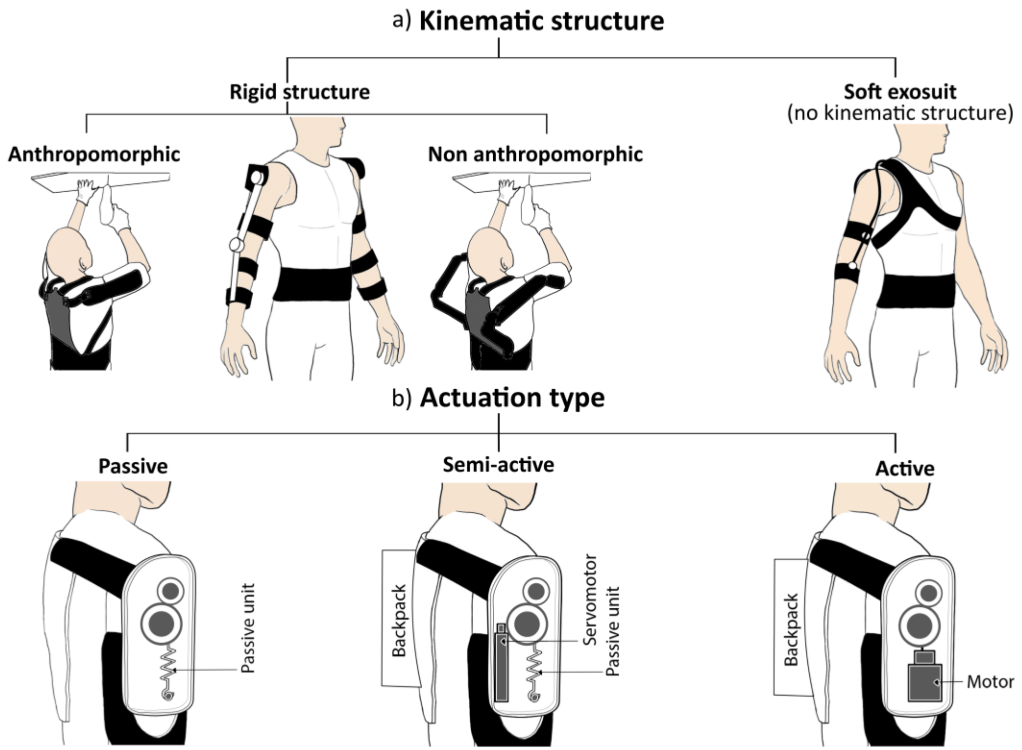
Wearable assistive devices intended **"to reduce the physical load on workers carrying out demanding activities in several occupational sectors."**

In the long term, these technologies are expected to improve the working conditions of the operators and help prevent work-related musculoskeletal disorders, particularly when other organizational measures are not feasible.



Industry

Crea, S., et al. (2021). *Occupational exoskeletons: A roadmap toward large-scale adoption. Methodology and challenges of bringing exoskeletons to workplaces*. Wearable Technologies, 2, E11.

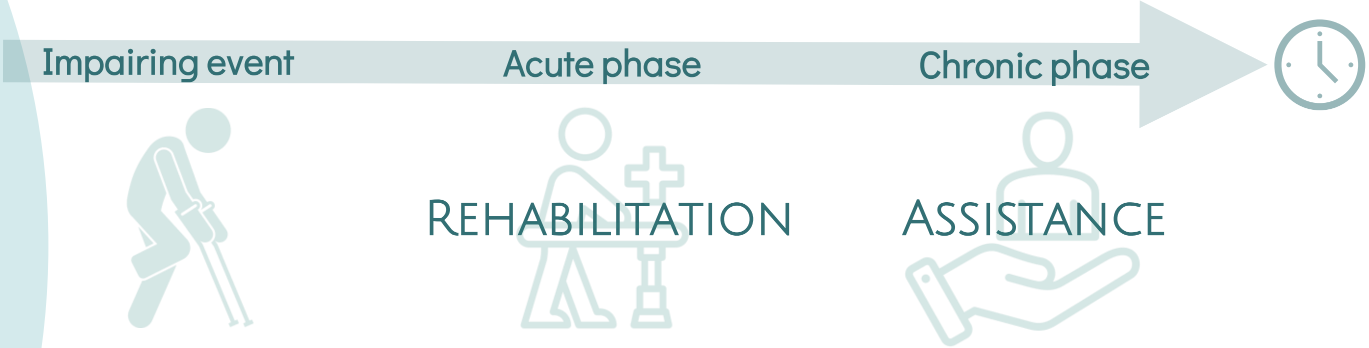


Occupational exoskeletons can be classified based on their (i) **kinematic structure** and (ii) **type of actuation** and (iii) **anatomical site** of interest

INDUSTRY

HEALTHCARE

After an impairing event, exoskeletons can be used to amplify and restore users' residual movement capabilities and functionalities



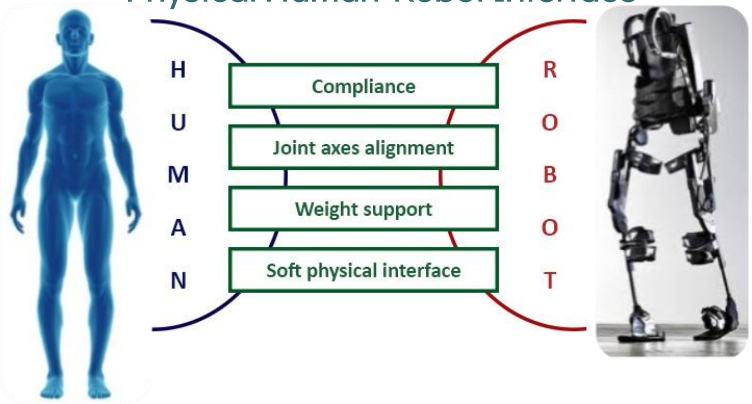
Exoskeletons

Ergonomic design

Ergonomic design of wearable robots

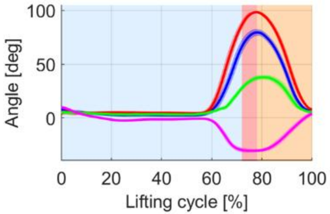
Challenge: Human-Robot symbiosis
Cognitive Human-Robot Interface

Physical Human-Robot Interface



Interfaces to detect user’s intention

Movement classification

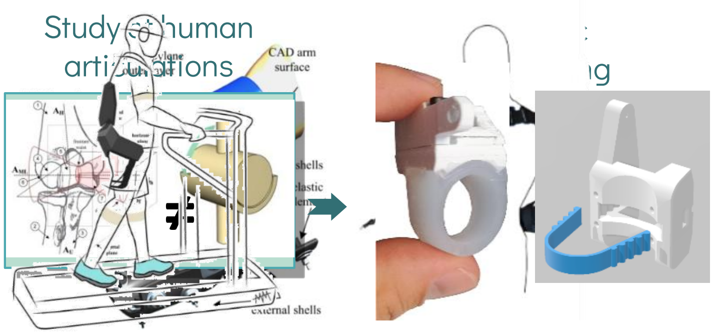


Kinematic design

Mass distribution

Tailoring

Study of human articulations



Exoskeletons

Ergonomic design

Five pillars of ergonomics

Kinematic design
How to couple human and robotic chains

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

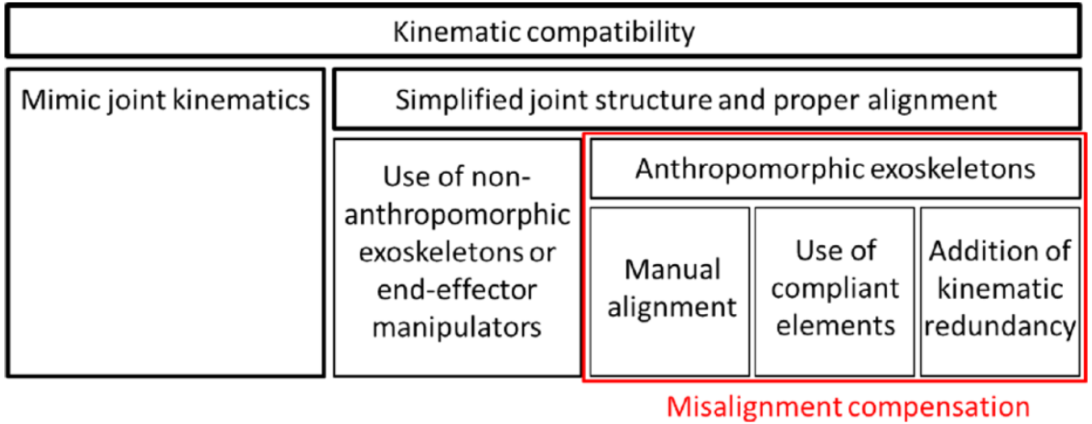
Intuitiveness
How to make the robot understanding your intentions

Mass distribution
How to reduce and allocate weight

Tailoring
How to customize the robot to user needs

KINEMATIC DESIGN

How to couple human and robotic chains



We refer to **kinematic compatibility** as the correct alignment of the axes of rotation of the robot and the human

It is crucial to ensure the correct **transfer of torque** from the exoskeleton to the wearer. If these are not properly aligned, parasitic forces and torques are induced, which may cause **discomfort or pain** and may potentially even lead to long term injury, or dislocation of the joint by frequent use of the device.

Näf, M. B., et al. "*Misalignment compensation for full human-exoskeleton kinematic compatibility: State of the art and evaluation.*" Applied Mechanics Reviews 70.5 (2018).

Kinematic Design

How to couple human and robotic chains

Fully **mimicking** the kinematics of the anatomical joint requires exact **knowledge of the joint's instantaneous axes of rotation** at any given time during motion.

Since human joints are covered with a multitude of tissues, it is **difficult** to determine the exact location of the joint rotation axes.

Substantial **inter- and intra-patient differences** further decrease the accuracy of the estimation methods, making it impossible to obtain an exact model of anatomical joint kinematics.

Kinematic design

How to couple human and robotic chains

Anthropomorphic exoskeletons require misalignment compensation techniques to guarantee high-quality interactions

The rotation of an exoskeleton joint, which is misaligned with respect to a human joint, is only possible due to the presence of soft tissues and cartilages that can withstand large deformations.

In such a situation, the forced translation will result in large depressions of the soft tissue between the exoskeleton and the human skeleton.

Stienen, A. et al. "*Self-aligning exoskeleton axes through decoupling of joint rotations and translations.*" IEEE Transactions on Robotics 25.3 (2009): 628-633.

Kinematic Design

How to couple human and robotic chains

The total misalignment between an exoskeleton and its user is usually a combination of four separate effects

Kinematic mismatch → number of DOFs (e.g., shoulder)

Migration of the instantaneous center of rotation → small translations in human (e.g. knee, elbow)

Initial offset → likely to increase with movement

Movement mismatch → interface migration

KINEMATIC DESIGN

How to couple human and robotic chains

Different misalignment compensation techniques were introduced in the literature for anthropomorphic exoskeletons

Misalignment compensation techniques						
Manual alignment	Use of compliant elements		Addition of kinematic redundancy			
	Brace/frame level	Joint level	RRP	RPP	RRR	other

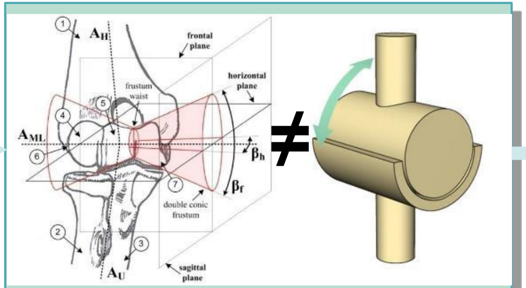
Näf, M. B., et al. "*Misalignment compensation for full human-exoskeleton kinematic compatibility: State of the art and evaluation.*" Applied Mechanics Reviews 70.5 (2018).

ITERATIVE PROCESS!

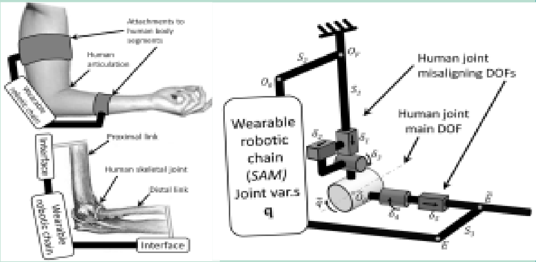
Kinematic design

How to couple human and robotic chains

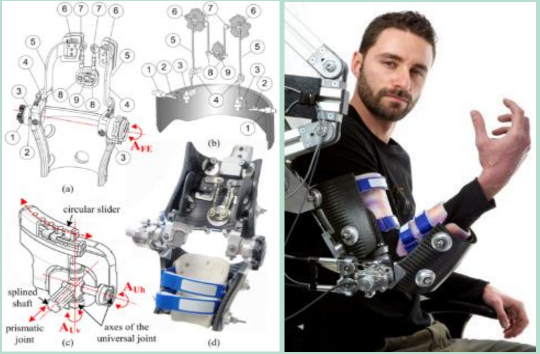
Study of human articulations



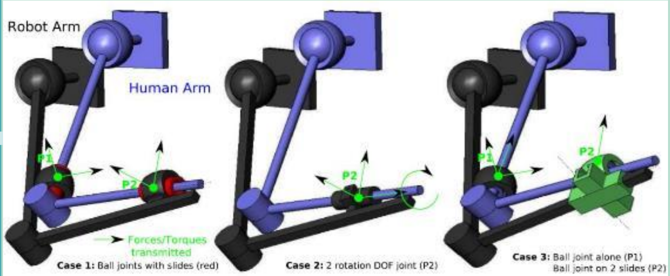
HR kinematic chains modeling



Implementation and validation



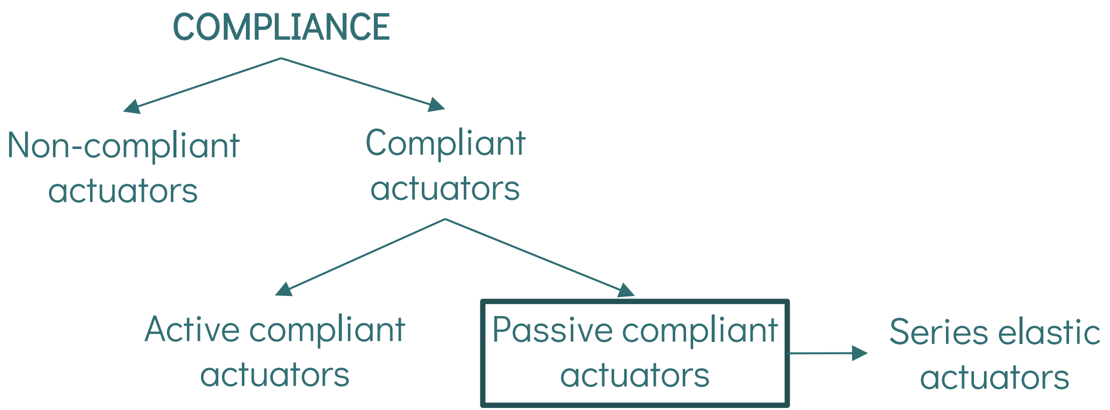
Interface kinematic design



OUTPUT IMPEDANCE

How to make the robot "transparent" to user residual capabilities

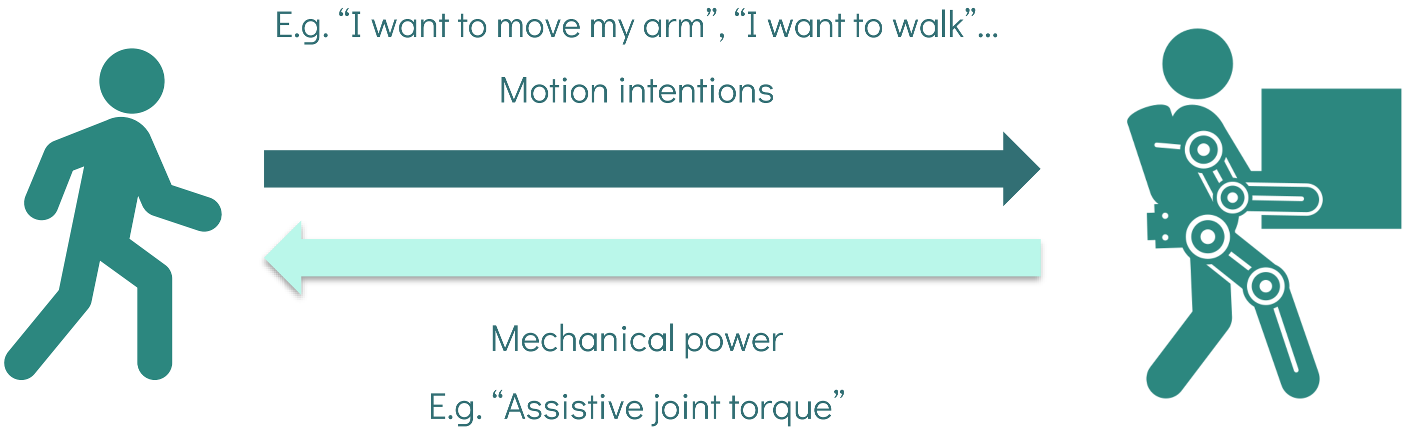
A "cooperative" wearable robot must be perceived as an extension of wearer's body and it must be completely transparent to the user residual movement ability (i.e., minimum to null output impedance)



INTUITIVENESS

How to make the robot understanding your intentions

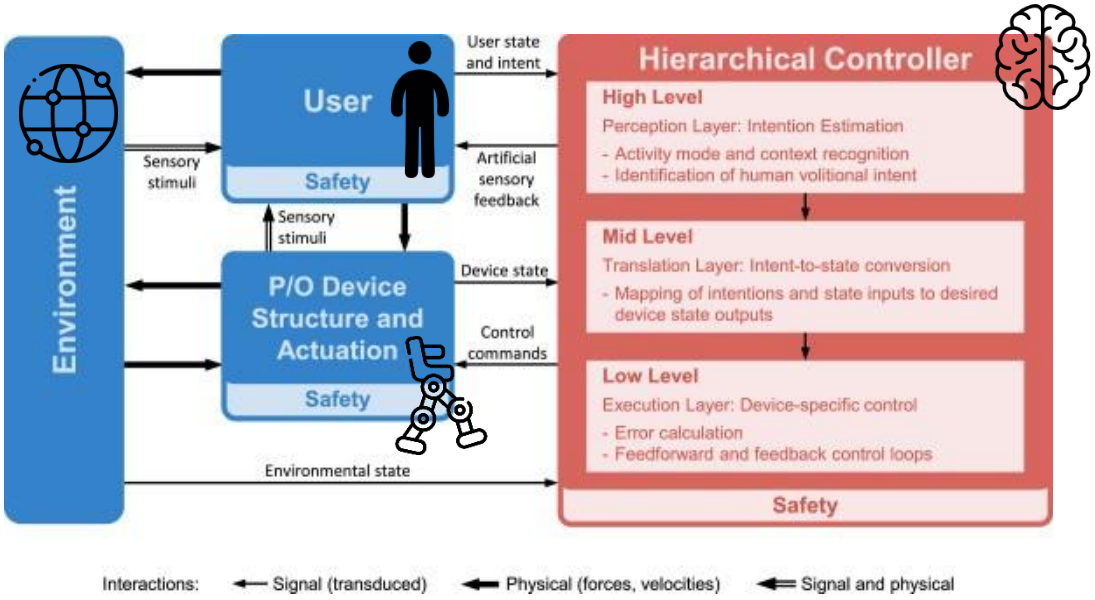
The system should understand the user's **movement intention**: a control layer interprets the sensory information and decides when and how to deliver mechanical power to the user to implement an "assistive strategy"



INTUITIVENESS

How to make the robot understanding your intentions

"The robot should "intend" the human desired intentions without involving cognitively the user in the decisional process ensuring high success reliability"



Tucker, M.R., et al. *Control strategies for active lower extremity prosthetics and orthotics: a review.* J NeuroEngineering Rehabil 12, 1

Mass distribution

How to reduce and allocate weight

Adding masses far away negatively affects the metabolic consumption. Different approaches can be adopted to enhance the mass distribution:

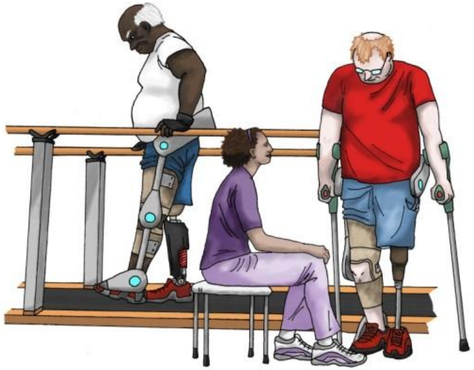
- Small distal masses can increase step length (due to inertia) and reduce step height (due to weight)
- Lightweight materials
- Integrated power/control electronics, minimized wiring
- Actuation units located away from the moving parts
- Cable/linkages transmission
- Even mass distribution around the natural COM

TAILORING

How to customize the robot to user needs

Inter-subject variability can be faced adopting adjustable and replaceable modules for anthropometric tuning and tailored customized orthoses

Moreover, an extra effort should be put on enhancing the cosmetic appearance of the exoskeleton



WRLab

20+ projects
10+ platforms
20+ researchers









Lower-limb exoskeletons

The case study of the Active Pelvis Orthosis (APO)

How to personalize gait rehabilitation in ecological environment?

Accurate human-robot synchronization

Tailored robotic assistance

CASE STUDY – APO

ALPHA-APO

BETA-APO

GAMMA-APO

2012

2017

The Active Pelvis Orthosis (**APO**) is an exoskeleton for active assistance of the **hip flexion/extension**

Series elastic actuation having peak torque ~20 Nm and parasitic torques <0.5 Nm under 1 Hz (enhanced "transparent mode")

Passive degree of freedom for hip abduction/adduction

The APOs is portable (since Beta-APO) and weighs ~9 kg for Beta-APO and 6.5 kg for Gamma-APO

Case study – Locomotion mode recognition

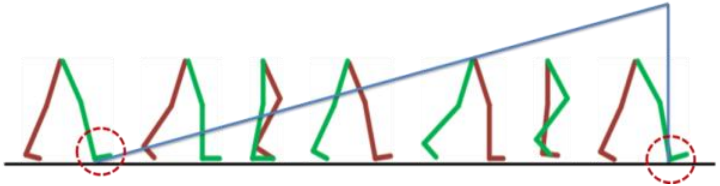
Beta-APO

An intention detection strategy was implemented to recognize the locomotion mode, using kinematics data in a “fuzzy” logic-based algorithm

Accuracy of 99.4% computed on > 10000 steps performed by six subjects

A. Parri *et al.*, "*Real-Time Hybrid Locomotion Mode Recognition for Lower Limb Wearable Robots*," in IEEE/ASME Transactions on Mechatronics, vol. 22, no. 6, Dec. 2017

Case study – gait phase estimate

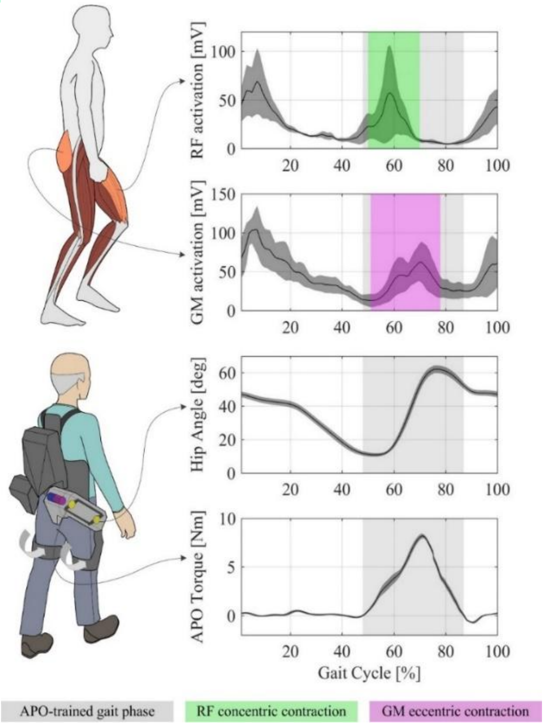


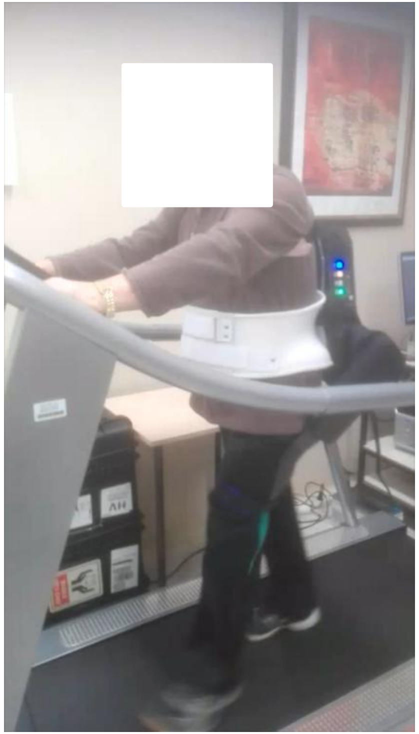
A reliable real-time estimate of the **gait phase** is key to generate assistive profiles which are synchronous with the locomotion.

The APO implements adaptive oscillators (AOs), which are mathematical tools that synchronize with the phase and frequency of a periodic input signal (e.g., the hip angle). The AOs allow a real-time estimate of the gait phase and the prediction of the hip angle trajectory.

Yan, T., et al. "*An oscillator-based smooth real-time estimate of gait phase for wearable robotics.*" Autonomous Robots 41 (2017): 759-774.

CASE STUDY – GAIT PHASE ESTIMATE





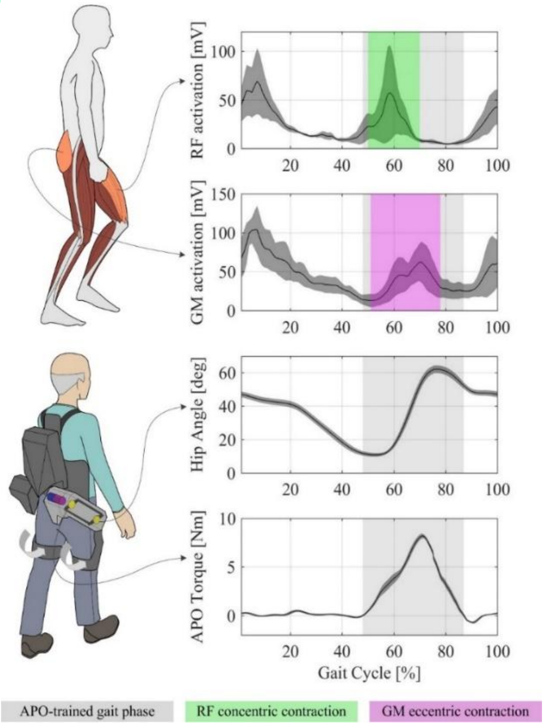
The gait phase and the hip angle estimates provided by the AOs allow the implementation of different assistive strategies

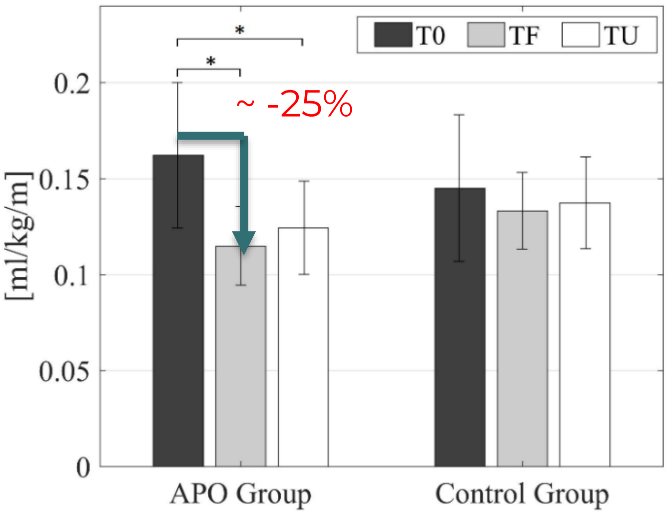
Hip joint torque feed forward

Virtual stiffness

Martini, E. et al. "*Gait training using a robotic hip exoskeleton improves metabolic gait efficiency in the elderly.*" Scientific Reports, 2019.

CASE STUDY – GAIT PHASE ESTIMATE



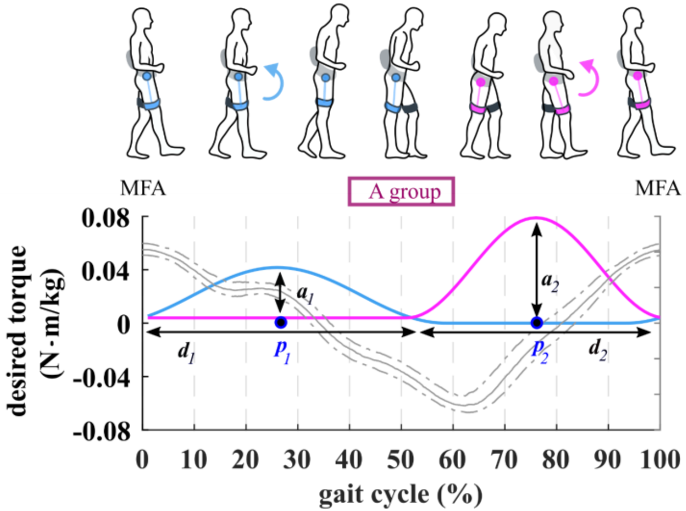


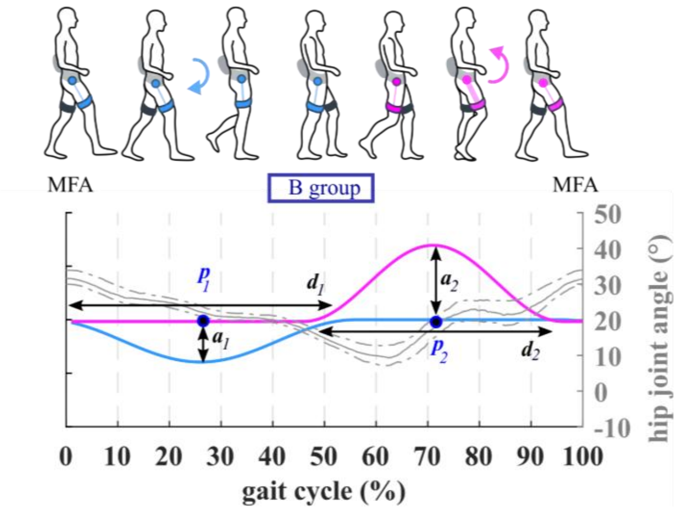
The APO group showed significant reduction in Metabolic Cost of Transport at post-training (TF) and at one-month follow-up (TU)

Martini, E. et al. "*Gait training using a robotic hip exoskeleton improves metabolic gait efficiency in the elderly.*" Scientific Reports, 2019.

CASE STUDY – GAIT PHASE ESTIMATE

A Group: Knee hyperxtension, B Group: hif flexion deficit





Livolsi et al., Sci Rep, 2022

UPPER-LIMB EXOSKELETONS

The case study of the NeuroExos Elbow Module (NEEM) and NeuroExos Shoulder-Elbow Module (NESM)

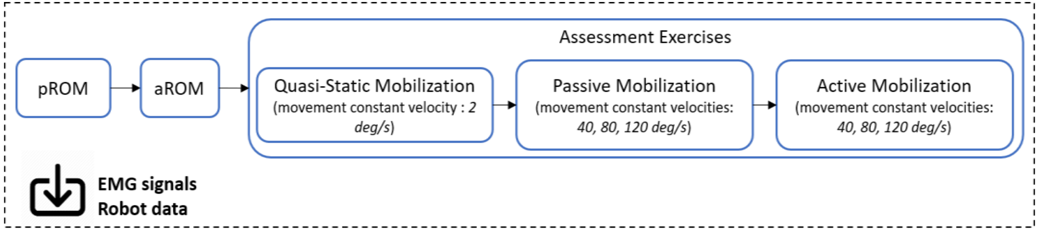
Case study – NEEM

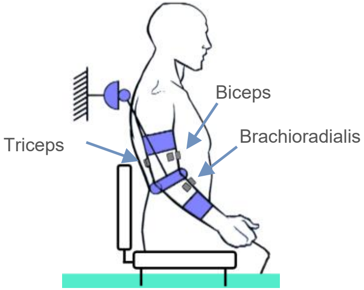
- The NeuroExos Elbow Module (NEEM) is an active exoskeleton for the assistance of the elbow flexion/extension
- The active joint has a SEA architecture having peak torque of 30 Nm

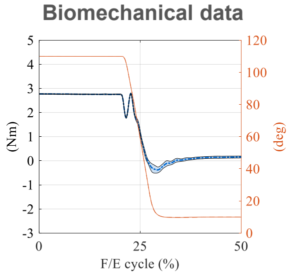
- Tested on 17 participants during 10 daily rehabilitation sessions for the treatment of elbow spasticity
- The NEEM is currently tested in an experimental protocol for the assessment of elbow spasticity

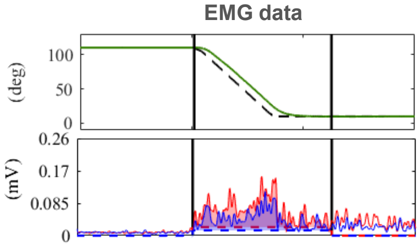
Vitiello, N., et al. "*Functional Design of a Powered Elbow Orthosis Toward its Clinical Employment.*" IEEE transactions Mechatronics, 2016

CASE STUDY – EVALUATION OF ELBOW SPASTICITY





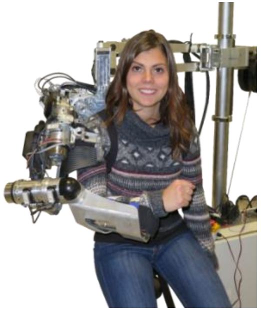




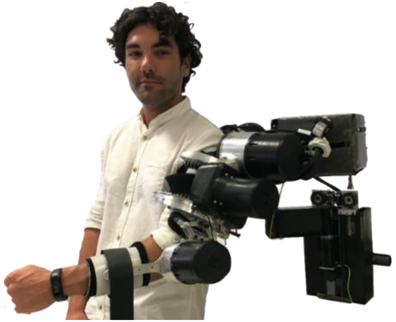
Pilla, A., et al. "*Robotic rehabilitation and multimodal instrumented assessment of post-stroke elbow motor functions—a randomized controlled trial protocol.*" Frontiers in Neurology 11 (2020)

CASE STUDY – NESM

NESM-ALPHA



NESM-BETA



NESM-GAMMA

2015 — 2019

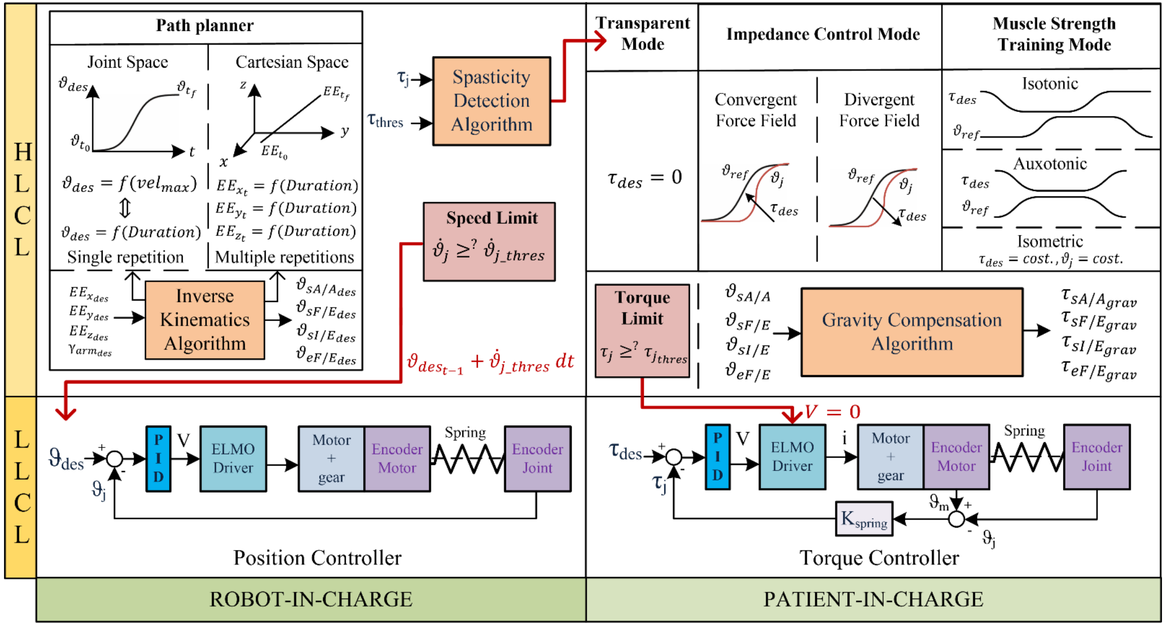
The NeuroExos Shoulder-Elbow exoskeleton (**NESM**) is an exoskeleton for active assistance of the shoulder (3 DOFs) and the elbow (1 DOF)

Series elastic actuation having peak torque ~30 Nm (shoulder) and ~15 Nm (elbow) and "transparent" behavior via gravity compensation

Passive DOFs for self-alignment to the shoulder and for trunk compensatory movements

Flipping mechanism (from NESM-beta)

CASE STUDY – NESM CONTROL ARCHITECTURE



- **Gravity compensation** algorithm to compensate the exoskeleton's weight
- Implementation of different rehabilitative exercises based on torque control (**patient-in-charge**) or position control (**robot-in-charge**)

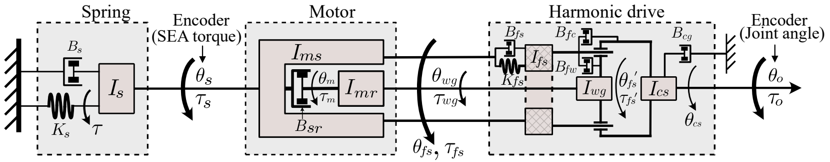
Trigili E., et al. "*Design and experimental characterization of a shoulder-elbow exoskeleton with compliant joints for post-stroke rehabilitation.*" IEEE/ASME Transactions on Mechatronics 24.4 (2019)

NESM-GAMMA

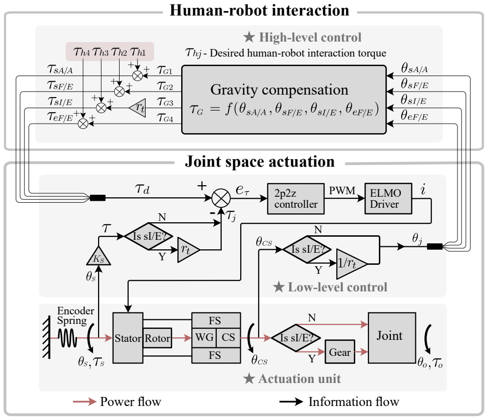
Pan, J., et al. "*NESM-γ: An upper-limb exoskeleton with compliant actuators for clinical deployment.*" IEEE Robotics and Automation Letters 7.3 (2022).

NESM-GAMMA

Compliance by mean of mechatronics …



Lumped-element linear model of the RFSEA



PATIENT-IN-CHARGE

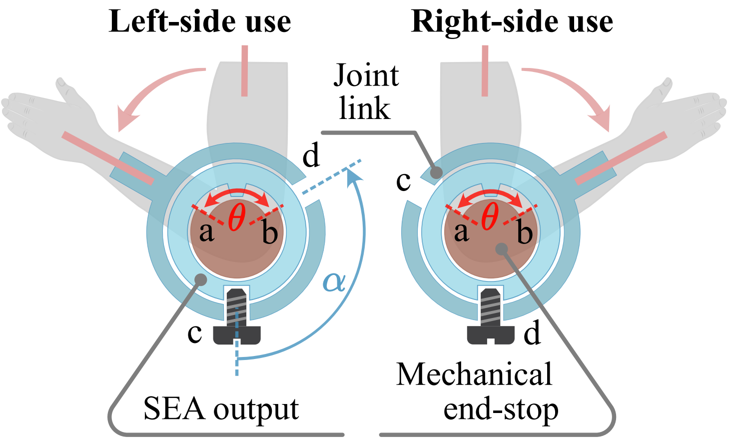
… and control

Pan et al., IEEE RAL, 2022

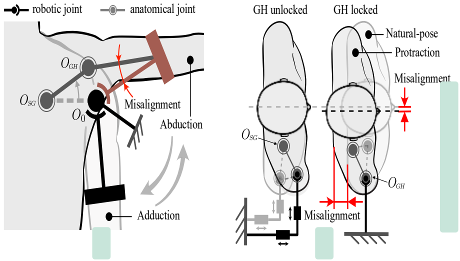
NESM-γ: ONE DEVICE, BOTH HEMIPARETIC SIDES

Pan et al., IEEE RAL, 2022

Design for either left or side use



Focus on NESM-γ shoulder kinematics



How we designed it

REHYB

Pan et al., IEEE TNSRE, *2023*

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25. Simone Prisinzano (Junior researcher)
26. Berkem Vural (Junior researcher)
27. Dr. Chiara Livolsi (collaborator)