Development of a knee prosthesis powered by electro-hydrostatic actuation

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Doctorate Program Goal

- Goal:

"Analyze *active* lower-limb prosthetic devices and try to present a novel solution for such systems from a *mechanical design perspective*"

- In Italy → **11'639** lower limb amputations per year
- Amputation → great **impairment** to quality of life
  - 67% suffer from Phantom-limb pain
  - 20.6%-60.3% suffer from depressions
  - 25%-57% suffer from anxiety
  - +280% oxygen consumption in above-knee amputation
- The existing devices are not yet **adequate**
  - 33.87% abandonment rate
  - Difficulties for the user to adapt to such devices
  - Mostly rely on passive or semi-active solutions not-capable of exerting active power

Knee Prostheses – State-of-the-art

Intermediate Solution

- Medium functionality
- Light-medium weight
- Optimized Energy Consumption

Semi-Active Prostheses
Electronically-Controlled Damper

- Low functionality
- Light-weight (1.5 – 2 kg)
- Low Energy Consumption
- Most adopted

➢ **Efficiency**

➢ **Integration**

➢ **Back-drivability**

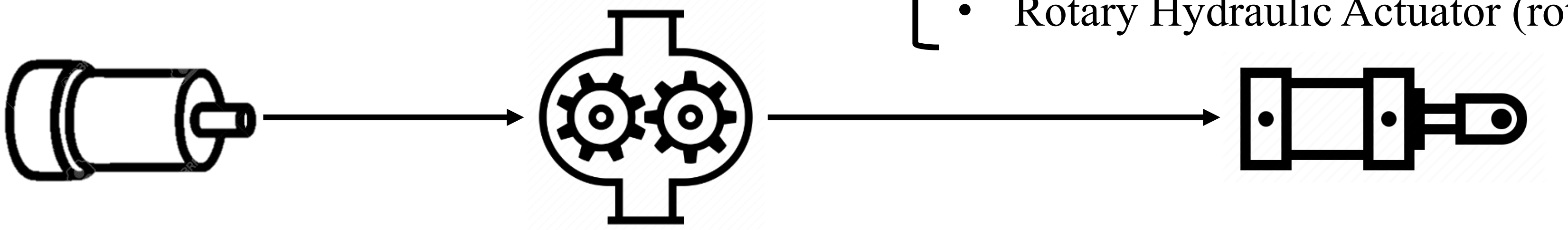
Fully-Active Prostheses
Electro-mechanical Actuation

- High functionality
- Heavy (3.5 – 4 kg)
- High Energy Consumption
- Most abandoned

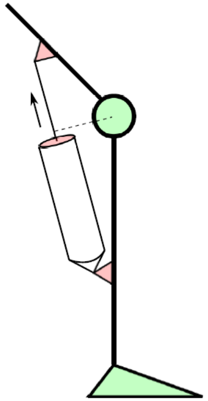
Proposed Architecture: Electro-hydrostatic Actuation (EHA)

- Alternative to classical electro-mechanical actuation

- Architecture:
  - Electrical Motor → Hydraulic Pump →
    - Linear Hydraulic Cylinder (linear-EHA)
    - Rotary Hydraulic Actuator (rotary-EHA)



Linear Actuation



- Main Advantages (known from literature):
  - Good controllability
  - High back-drivability
  - Good power-to-weight ratio

- Better Mass Distribution
- Angle-Dependent – Transmission Ratio

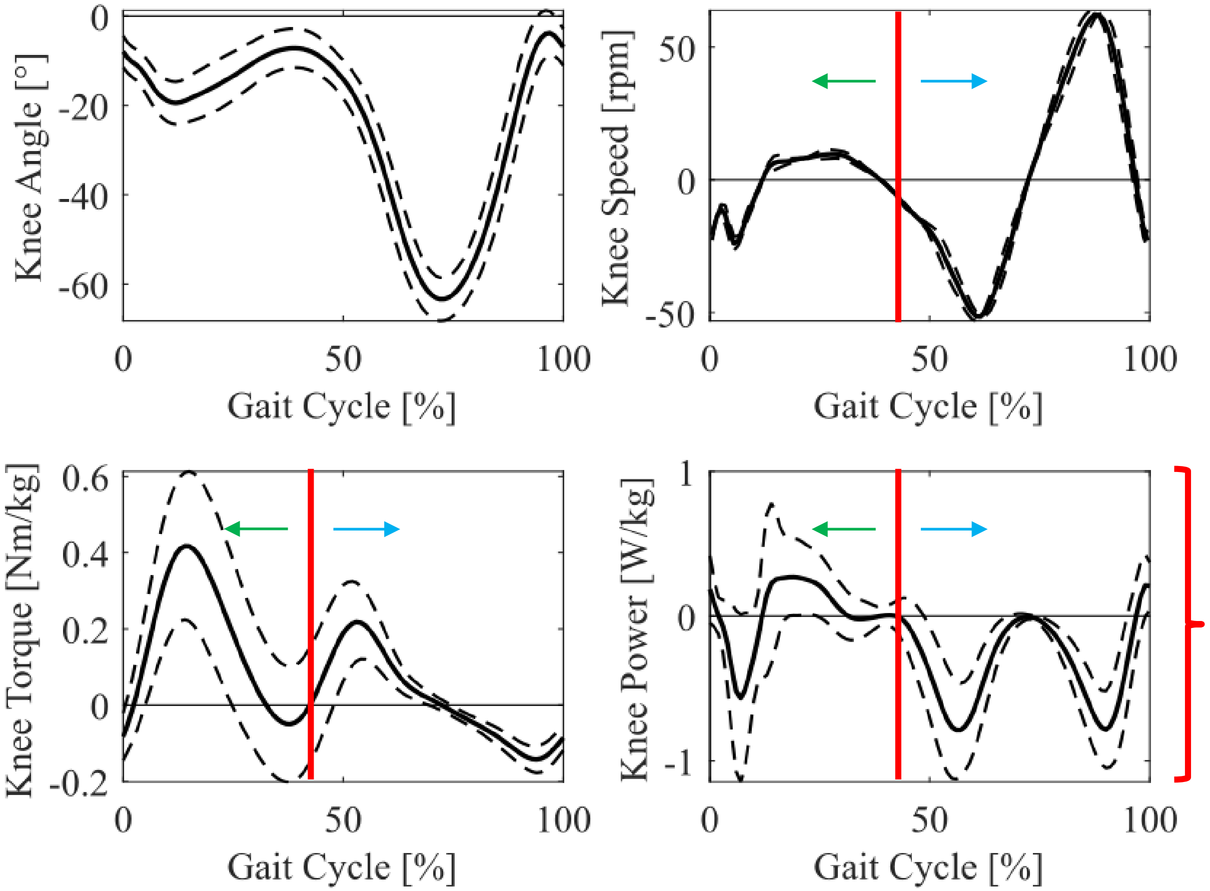
Knee Biomechanics

- Actuator Designed to satisfy **Level Walking** Requirements

High Torque – Low Speed   Low Torque – High Speed

Range of Motion (ROM) ≥ 65°

Selected ROM: 110°



Knee Works Mainly as a Brake:

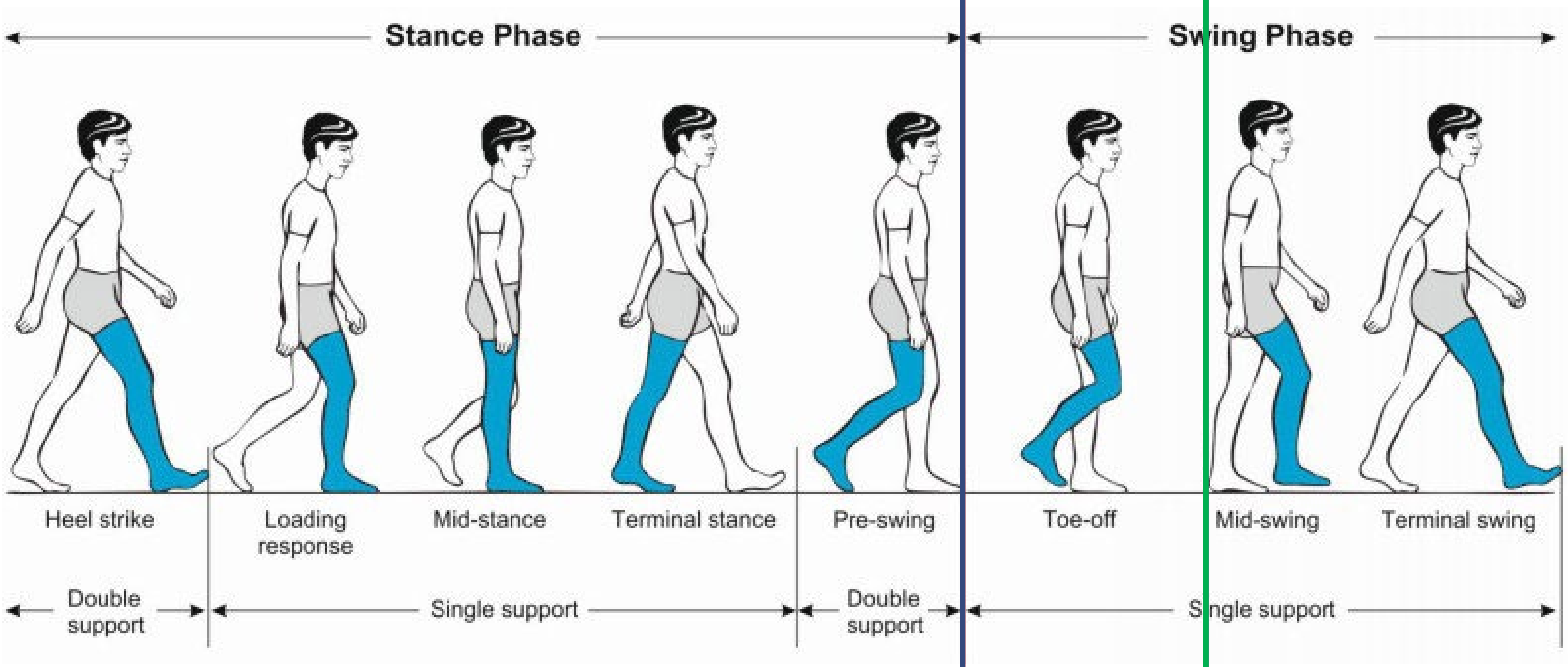
- Negative Mean Power

Power Regeneration Possibility

Gait Cycle – Level Walking

Mostly Active behavior
Knee behaves as a Spring-Damper system → **Admittance Control**

Passive braking behavior
Knee extends the lower leg → **Regenerative braking**



Partially Active behavior
Knee flexes the lower leg → **Position Control**

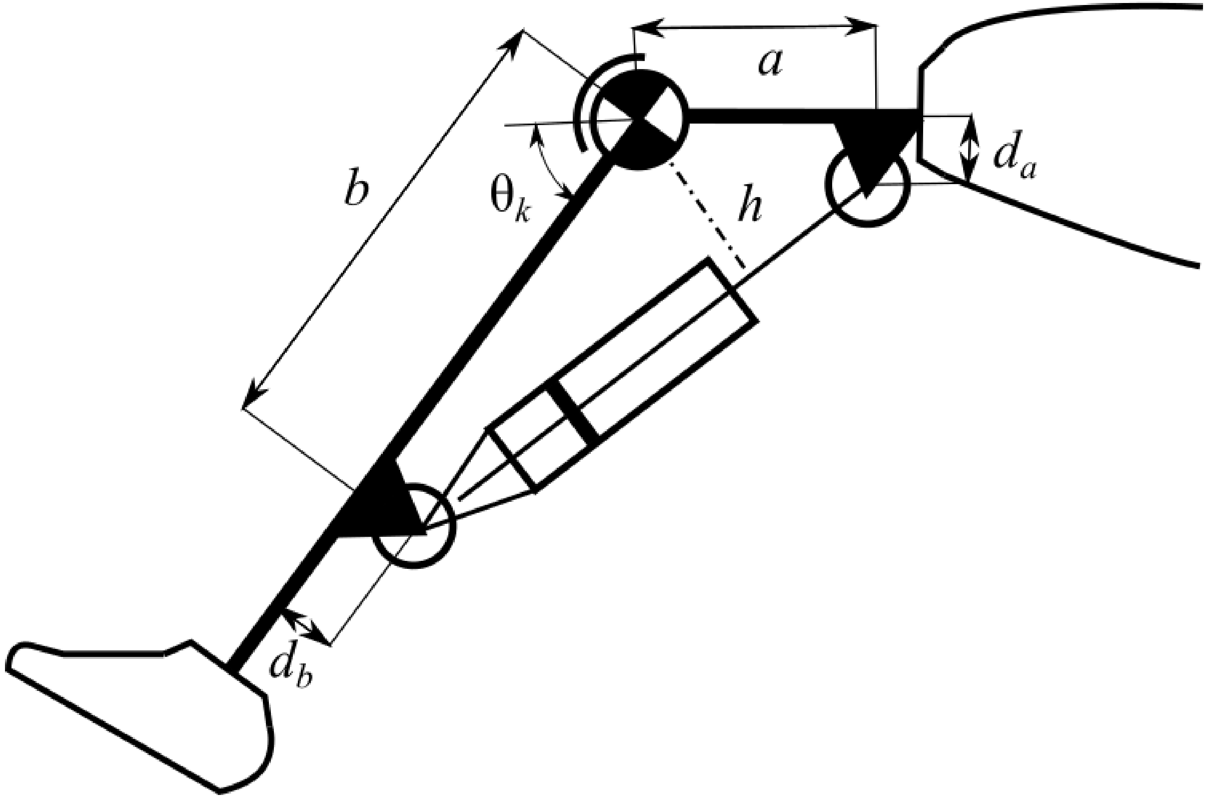
Actuation Kinematics

- Articular Actuation → Mimicking Muscle Working Principle

- Linear-Rotary Conversion:
  - $h(\theta_k, a, d_a, b, d_b) = \frac{T_k}{F} = \frac{v}{\omega_k}$

    ↓

    Variable Transmission Ratio
  - **Geometric** Parameters: a, d_a, b, d_b
    - Selected wrt geometric constraints
  - **Physical** Quantity → Knee Angle θ_k



Development Process

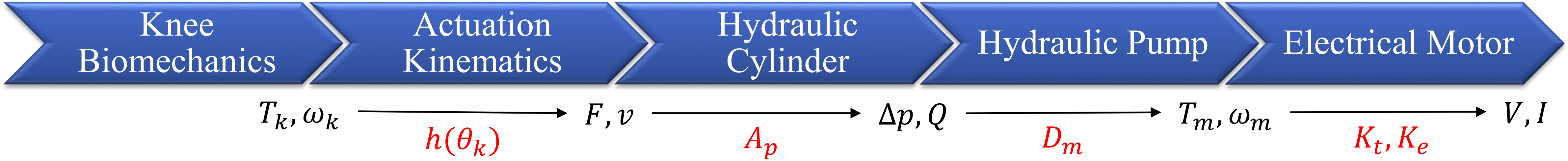
- During the doctorate program, 2 prototypes have been developed:
  - **Test-rig Prototype**
    - Based on commercial-off-the-shelf (COTS) components
    - *Goal* → validate the linear EHA as a feasible actuator for knee prostheses without taking care of geometric and weight constraints
  - **Fully-integrated Prototype**
    - Based on fully custom designed components
    - *Goal* → enhance the actuator back-drivability and performance while satisfying the integration constraints in terms of size and weight

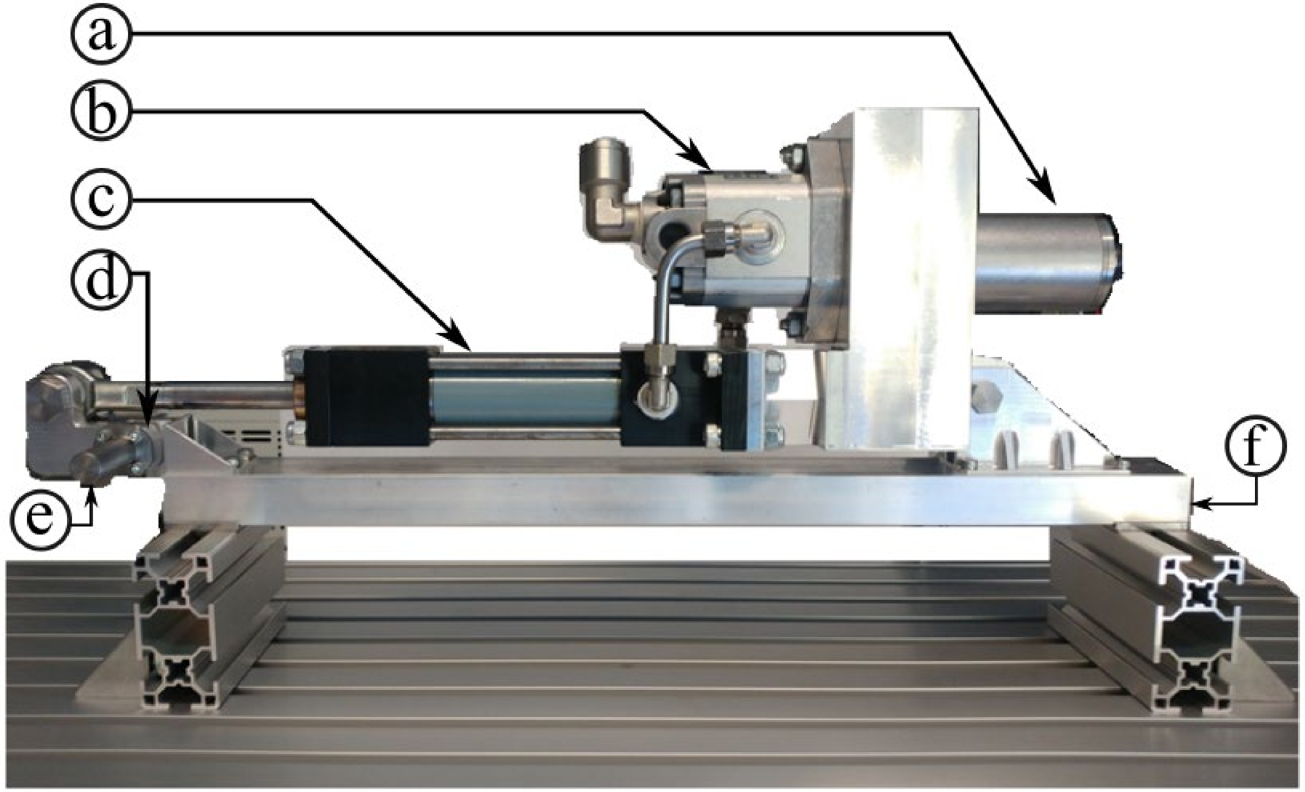
Test-rig EHA Prototype[1]

- Design & Experimental Validation

Tessari, F., Galluzzi, R., Tonoli, A., Amati, N., Laffranchi, M., De Michieli, L., (October, 2020) "Analysis, Development and Evaluation of Electro-Hydrostatic Technology for Lower Limb Prostheses Applications" *IEEE Proceedings of International Conference on Intelligent Robots and Systems (IROS)* – ACCEPTED & UNDER PUBLICATION

Assembled COTS l-EHA

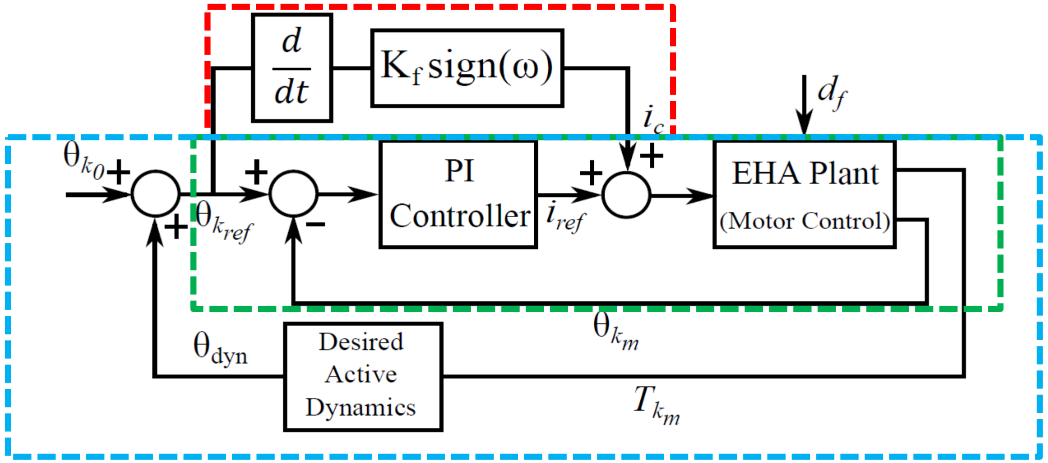




a) **Electrical Motor:** Maxon EC-i 40
b) **Hydraulic Pump:** Bucher APR05/0.75
c) **Hydraluic Cylinder:** FluidoSistem 25/12P
d) Knee Joint
e) Thigh-Connector
f) Shin/Pylon

Implemented Control Strategy

- On the low-control level → A **current** control loop has been implement on the electrical motor

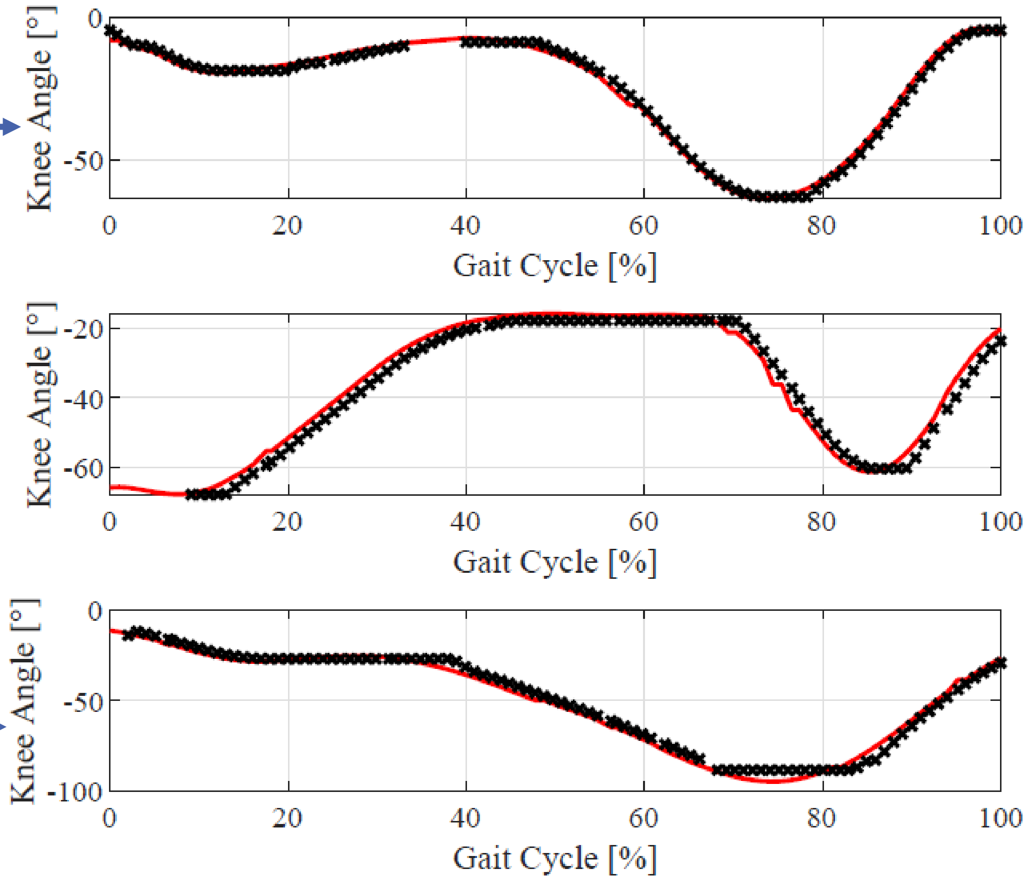


- On the high-control level:
  - A **position tracking** control
    - Useful to asses the capability of the designed device
    - Required for the admittance control
  - An **admittance** control
    - Particularly suited for *natural walking and gait coordination enhancement*
    - Reduced number of control parameters

- Moreover → a **feed-forward friction compensation** to compensate for elevated hydraulic cylinder *friction, stick-slip and stiction* effects

Position Tracking – Results

- 3 Different Gaits have been tested:
  - Level Walking
  - Stair Ascending
  - Stair Descending



- Results shows **accurate** position tracking capabilities
  - $1.5° \leq |RMSE_{max}| \leq 3.4°$

Admittance Control

- **Admittance Control →** Imposes a dynamic trajectory to the position control loop that is function of an *imposed mechanical behavior* (inertia, damping, stiffness)

$$\theta_{k_{ref}} = \theta_{k_0} + \theta_{dyn}$$

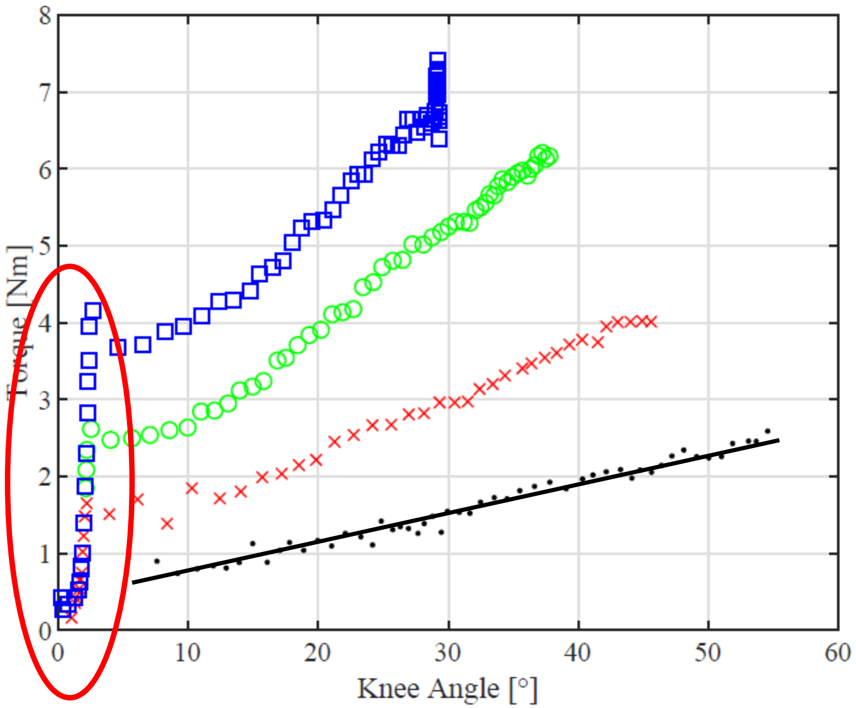
$$\theta_{dyn} = \frac{T_{k_m}}{J_{k_{des}} s^2 + \beta_{k_{des}} s + k_{k_{des}}}$$

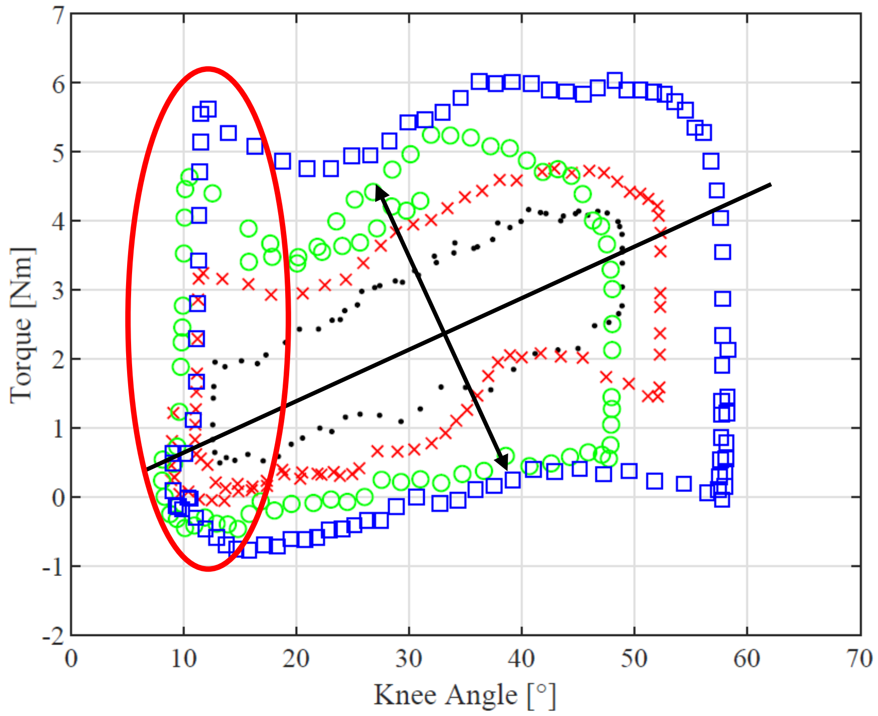
- In the specific case we focused on a **spring-damper dynamics** $(\boldsymbol{\beta_{k_{des}}}, \boldsymbol{K_{k_{des}}})$

$$\theta_{dyn} = \frac{T_{k_m}}{\beta_{k_{des}} s + k_{k_{des}}}$$

Admittance Control – Results

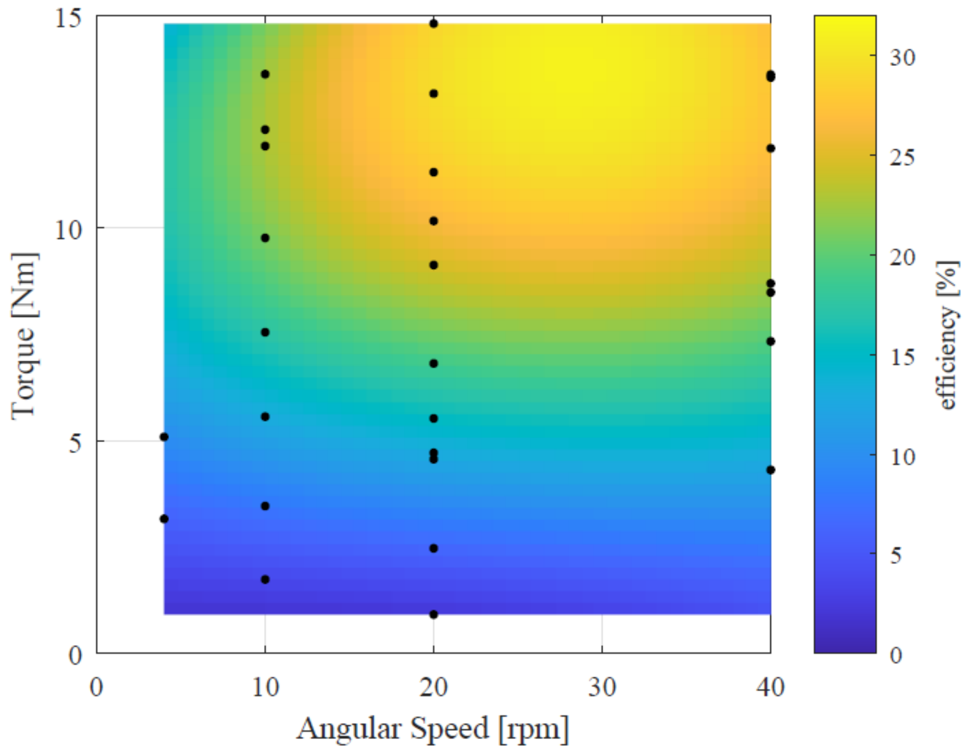
- 2 Test campaigns→
  - $\beta = const. \wedge k = k_i, i = 1, \ldots, n$
  - $k = const. \wedge \beta = \beta_i, i = 1, \ldots, n$





Prototype Efficiency Mapping

- An experimental efficiency map has been evaluated
  - Coupling the Prototype to a Dynamic Load



- The efficiency is calculated as:

$$\eta = \frac{P_{out}}{P_{in}} = \frac{T_k \cdot \omega_k}{V_{bus} \cdot I_{bus}}$$

- Results are compared to an electro-mechanical actuation with equivalent transmission-ratio
  - Comparison showed a **slightly higher** efficiency of EHA

- Unfortunately, the **frictions** were too high to operate the developed EHA as brake/damper → impossible energy harvesting

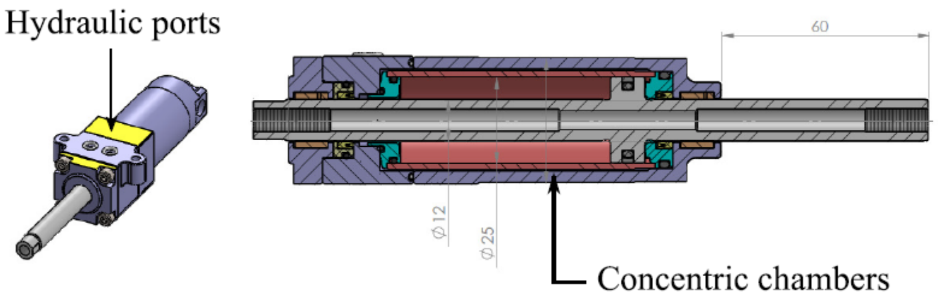
Fully-integrated EHA Prototype[2]

Design & Experimental Validation

- Tessari, F., Galluzzi, R., Tonoli, A., Amati, N., Laffranchi, M., De Michieli, L., (October, 2020) "Design and Testing of a Fully-Integrated Electro-Hydrostatic Actuator for Powered Knee Prosthesis" *Springer Proceedings of International Symposium on Wearable Robotics (WeRob2020)* – ACCEPTED & UNDER PUBLICATION
- Tessari, F., Galluzzi, R., Tonoli, A., Amati, N., Milandri, G., Laffranchi, M., De Michieli, L., (December, 2020) "An Integrated, Back-Drivable Electro-Hydrostatic Actuator for a Knee Prosthesis" *IEEE Proceedings of International Conference on Biomedical Robotics and Biomechatroncis (BioRob)* – ACCEPTED & UNDER PUBLICATION

Hydraulic Cylinder – Design

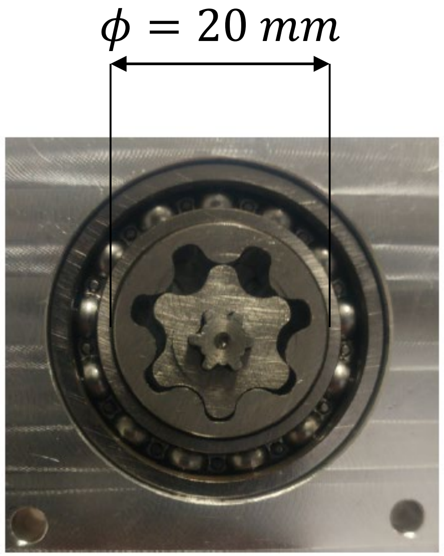
- Architecture → passing-shaft
  - No need of accumulators

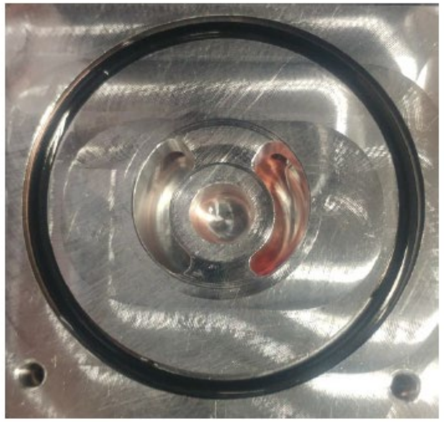


- Same A_p, D, d were maintained

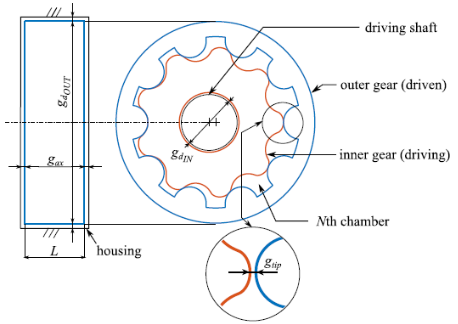
- Design Upgrades
  - To enhance **integration**:
    - Concentric chambers → Reduced radial size
    - Adjacent hydraulic ports → Minimized hydraulic circuitry
  - To enhance **performance**:
    - Utilization of high-performance PTFE seals → Reduced frictional effects

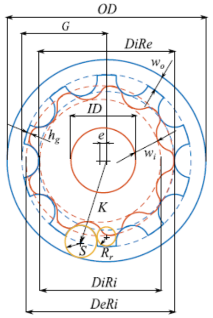
Hydraulic Pump – Design

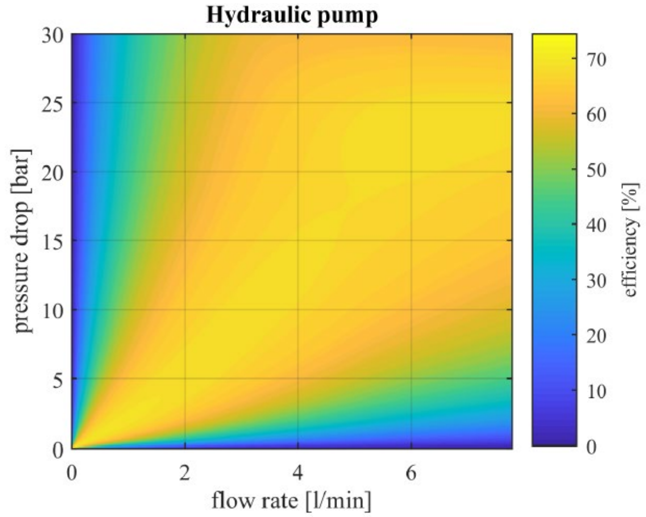




- Same Volumetric Displacement → $D_m = 0.75 \frac{cc}{rev}$
- Pump Architecture → Custom **Gerotor** Pump
  - **Lower noise** compared to external gear pump
  - **More compact** compared to external gear pump
- Dedicated design methodology to enhance[1]:
  - Volumetric Efficiency







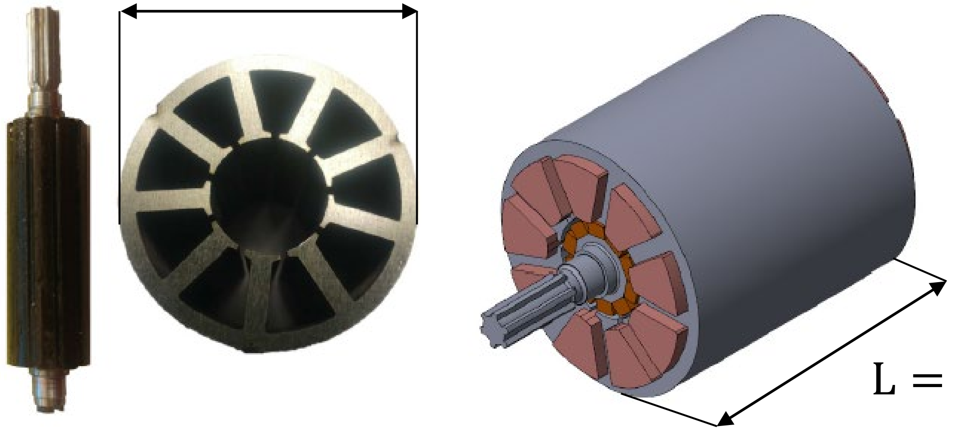
Tessari, F., Galluzzi, R., and Amati, N. (November 6, 2019). "Efficiency-Driven Design Methodology of Gerotor Hydraulic Units." ASME. *J. Mech. Des*. doi: https://doi.org/10.1115/1.4045421

Electrical Motor – Design

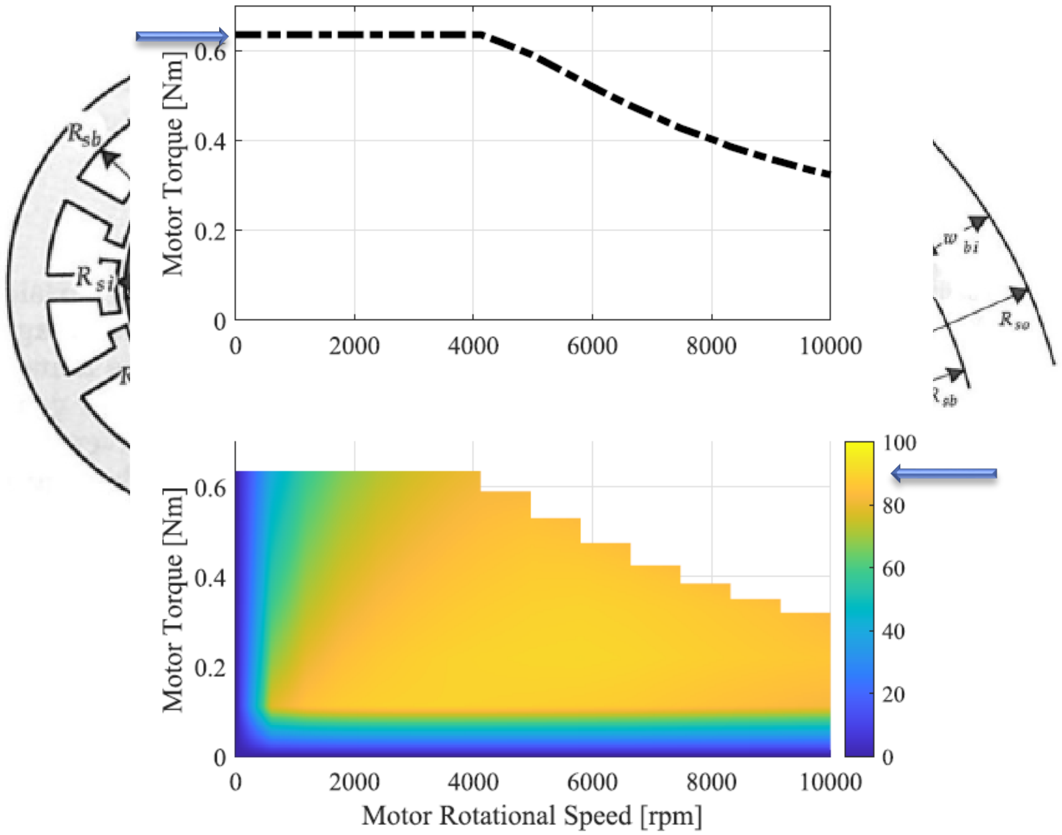
- Design a custom PMSM capable of satisfying the Knee Requirements

- Motor design methodology:
  1. Analytical modelling (Matlab)
  2. Magnetic optimization (Comsol)
  3. Electrical simulation (FluxMotor)

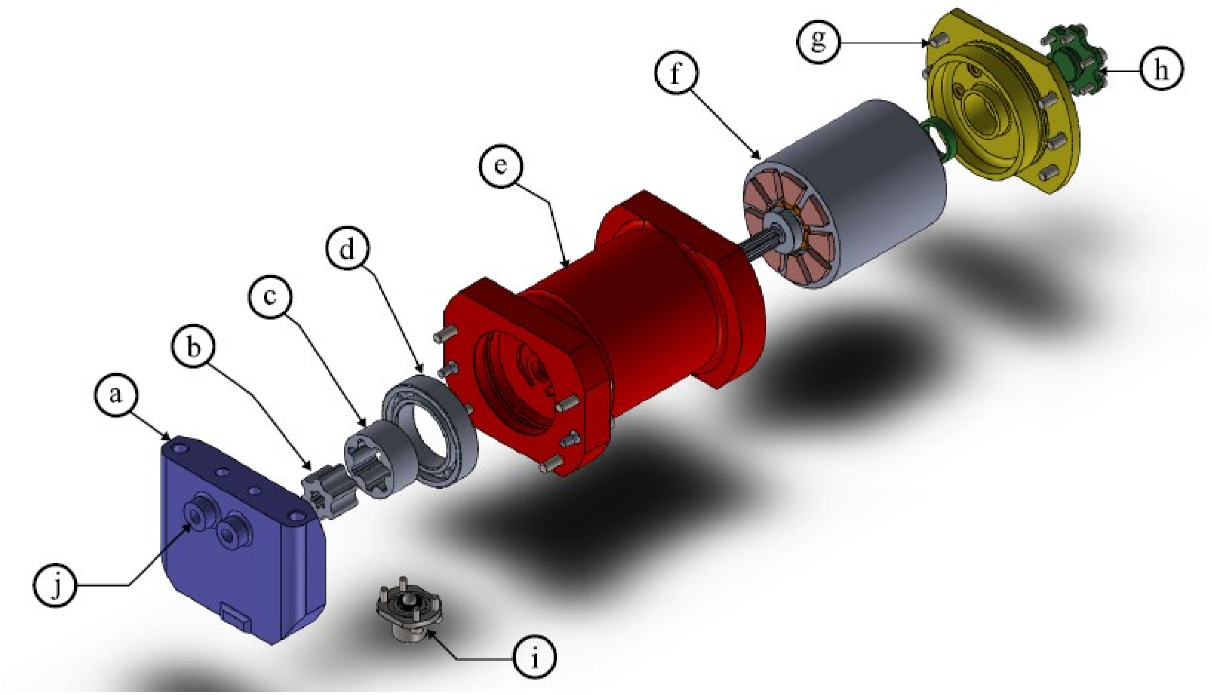
$\Phi = 39\,mm$



$L = 43\,mm$



Assembled Fully-Integrated I-EHA

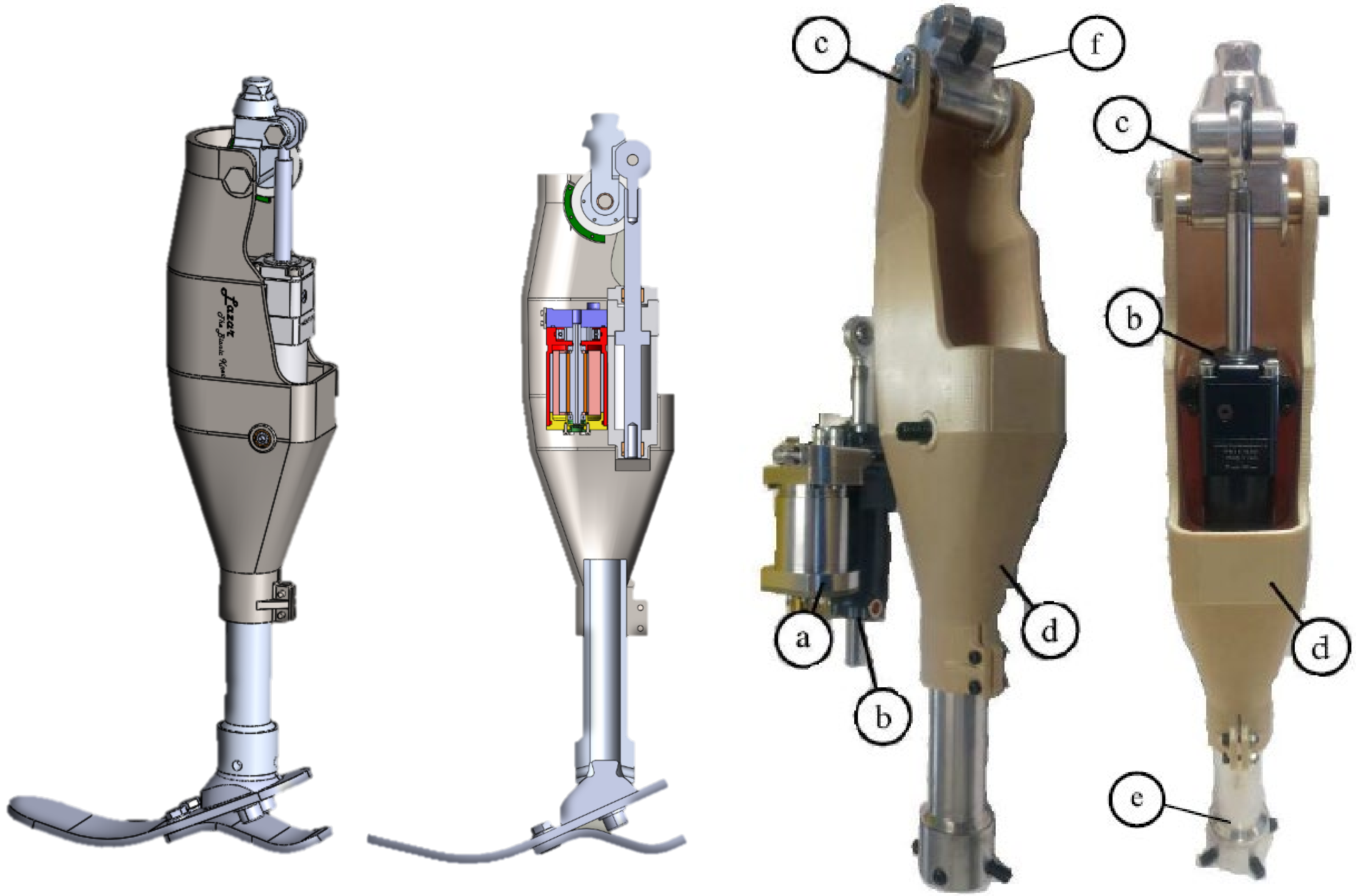


$V = 123.5 \times 91 \times 60 mm^3$
$\mathrm{M} = 1.2\ kg$

a) Pump cover.
b) Inner gear.
c) Outer gear.
d) Pump ball bearing.
e) Case.
f) Electrical Motor.
g) Anodized Actuator Plug.
h) Motor Hall Sensors Housing.
i) Pre-loading valve.
j) Pressure sensors ports.

a) Case
b) Electrical Motor
c) Hydraulic Pump
d) Hydraluic Cylinder

Assembled Fully-Integrated Prosthetic Knee



a) Motor-Pump Group
b) Hydraulic Actuator
c) Knee Joint
d) Actuator Chassis
e) Pylon connector
f) Thigh connector

Designed to reach:

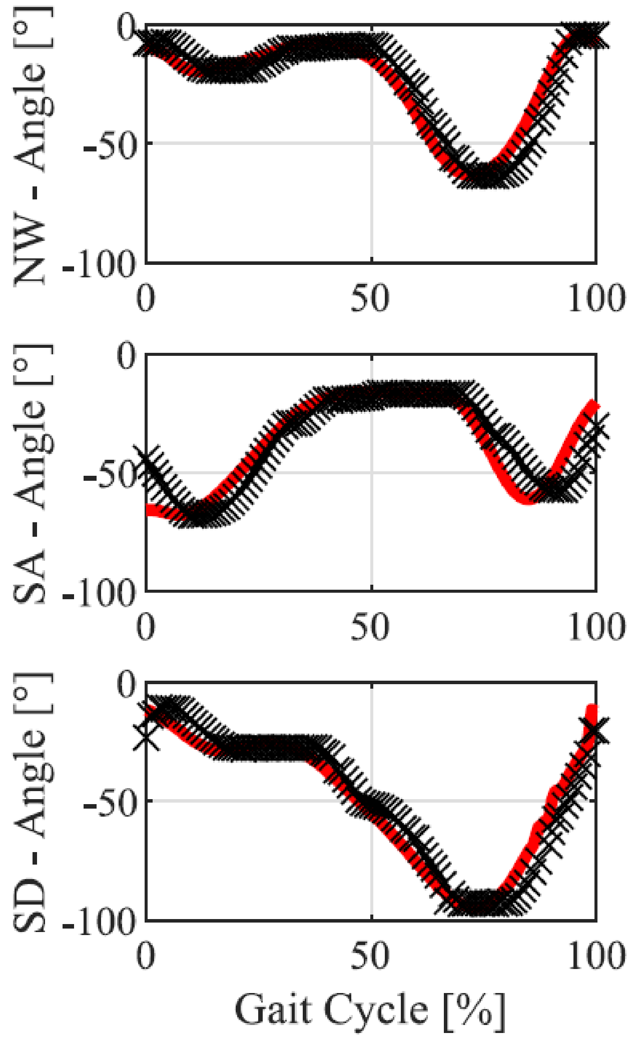
$T_{max} \approx 45\ Nm$

$\omega_{max} \approx 60\ rpm$

(to satisfy level walking requirements)

Position Tracking – Results

- 3 Different Gaits have been tested:
  - Level Walking
  - Stair Ascending
  - Stair Descending

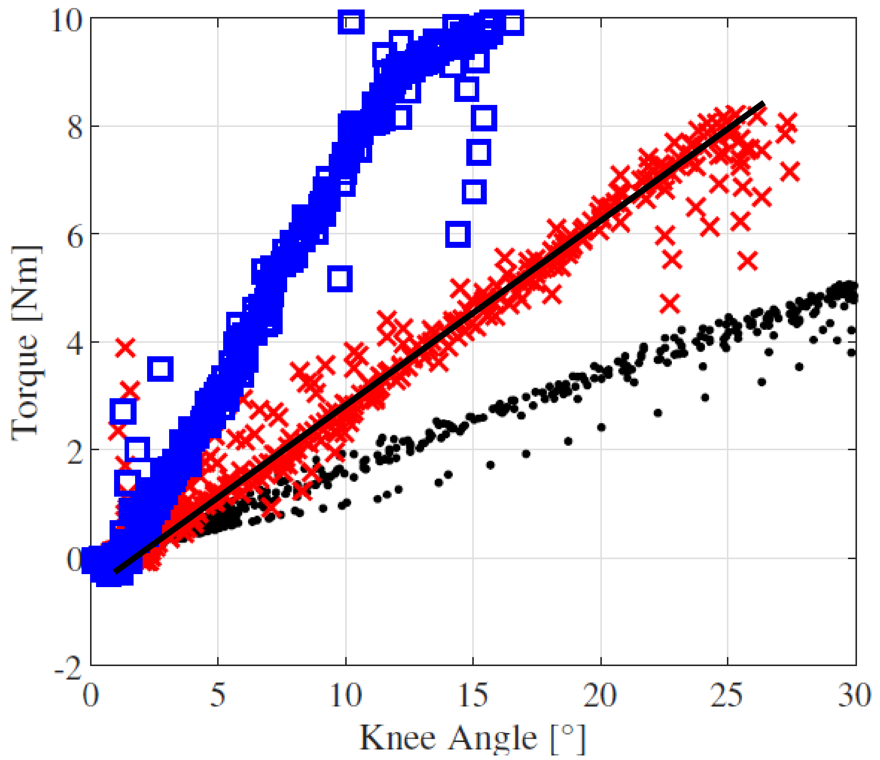


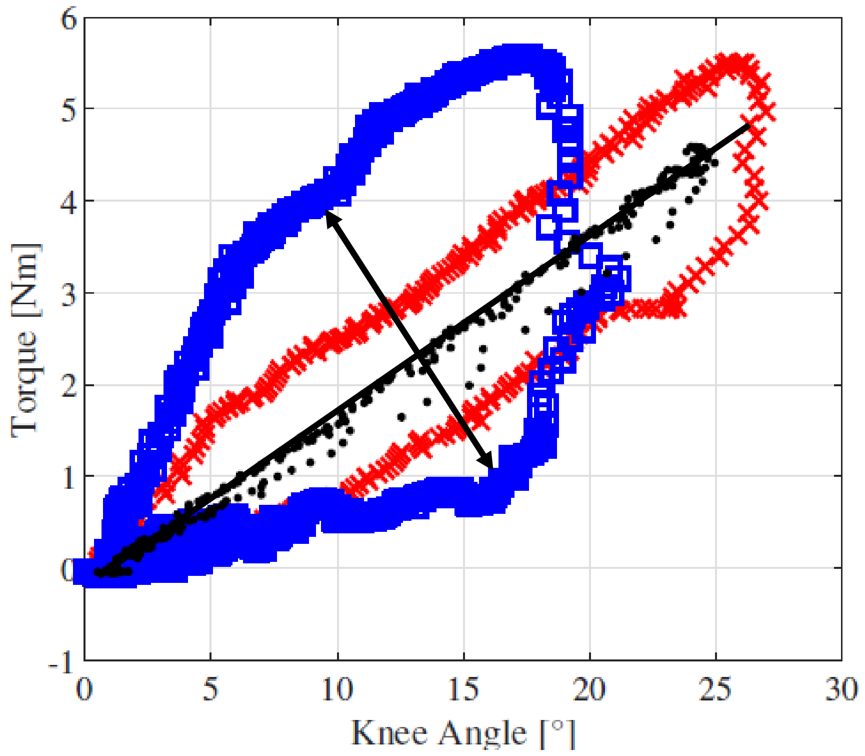
- Results shows **accurate** position tracking capabilities
  - $5.5° \leq |RMSE_{max}| \leq 7.4°$

Worse with respect to first prototype → due to leakage in the hydraulic unit

Admittance Control – Results

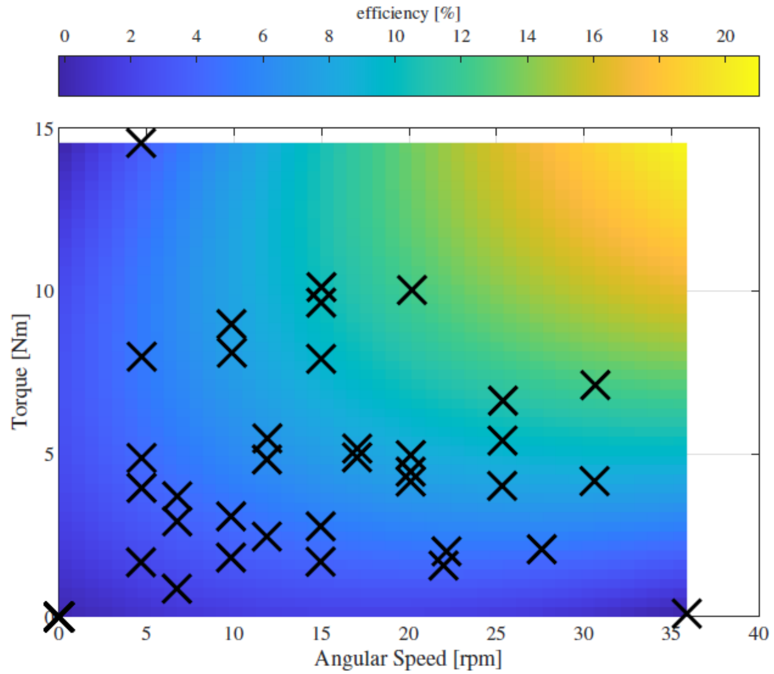
- 2 Test campaigns→
  - $\beta = const. \wedge k = k_i \, , i = 1, \dots, n$
  - $k = const. \wedge \beta = \beta_i \, , i = 1, \dots, n$





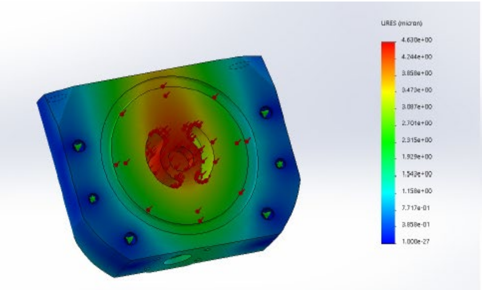
Efficiency Mapping

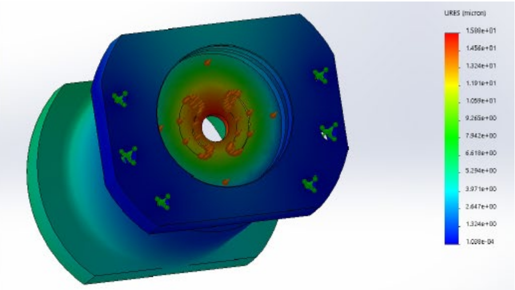
- Similarly to the test-rig EHA, the efficiency map as an actuator has been experimentally computed



- A worsening of the performance is observable
  - Peak efficiency @ (15 Nm, 35 rpm) dropped:
    - η: 30% → 21%

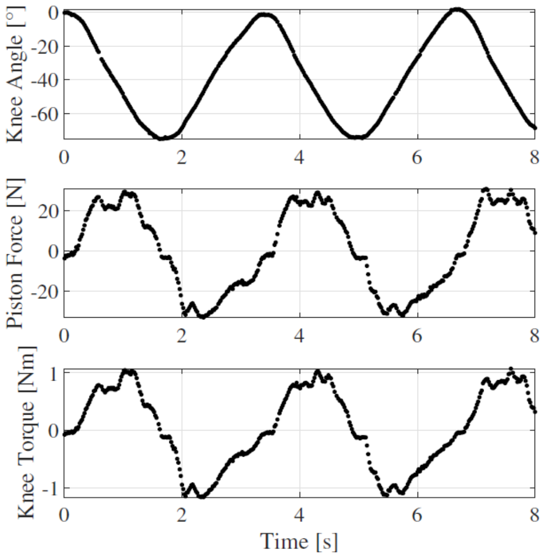
- Source of the performance loss:
  - Un-modeled deformation of the pump housing
    - leading to an almost *doubled pump axial clearance*
      - *Breaking down volumetric efficiency* of the pump





Regenerative Braking

- The fully-integrated EHA demonstrated to be **highly back-drivable**
  - $T_{bd} \leq 1\ Nm\ @\ \omega_k = 7.5\ rpm$

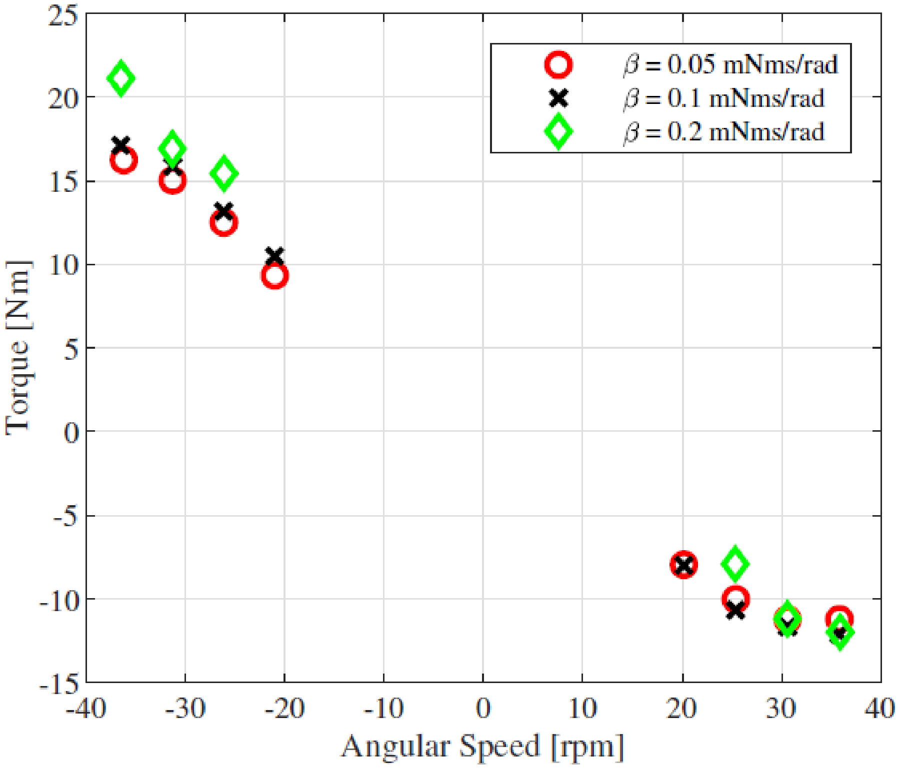


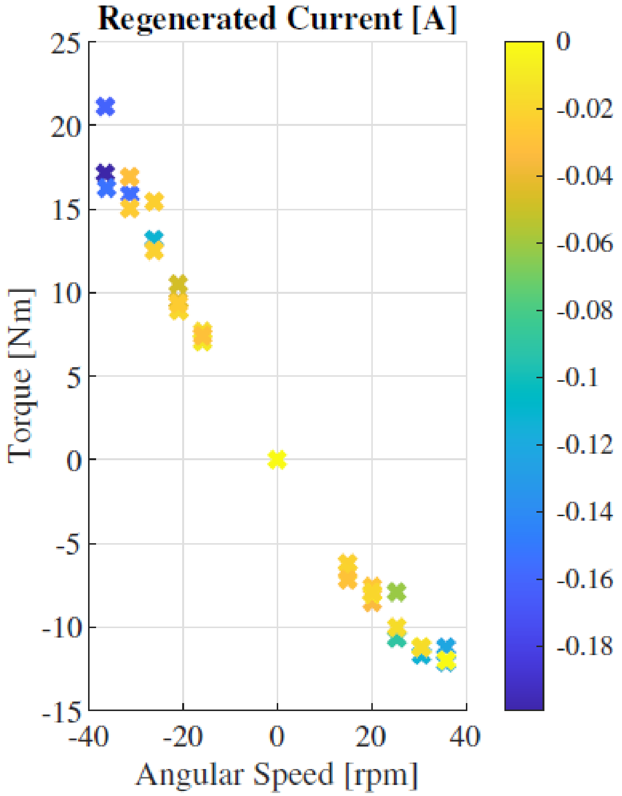
- As a consequence, regenerative braking control technique have been implemented
  - It consists on imposing a current proportional to the rotating speed of the motor and opposite in sign

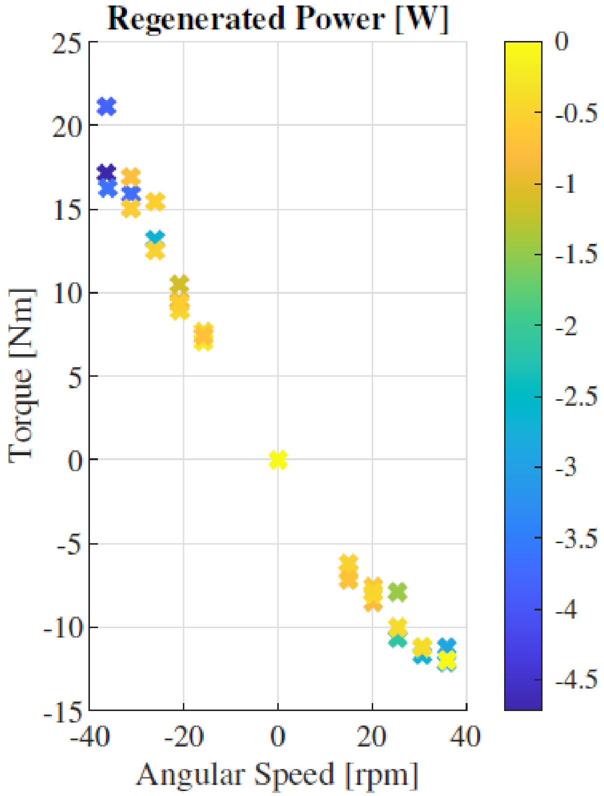
$$i_{ref} = -\frac{1}{K_T}\beta_{reg}\omega_{m_m}$$

Regenerative Braking – Results

- Different damping coefficients β_{reg} have been tested → for each of them the regenerated current I_{reg} and power P_{reg} have been computed







Conclusions

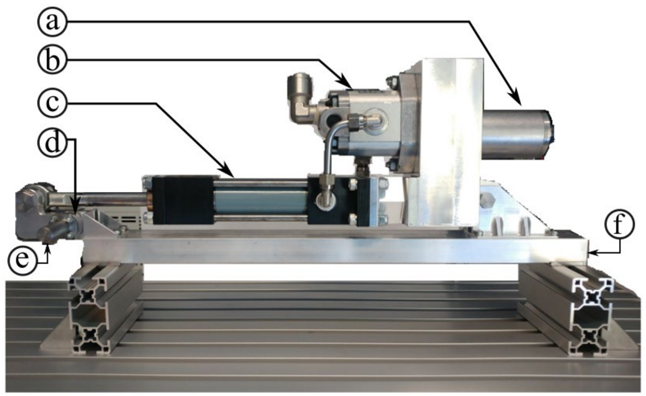
Intermediate Solution

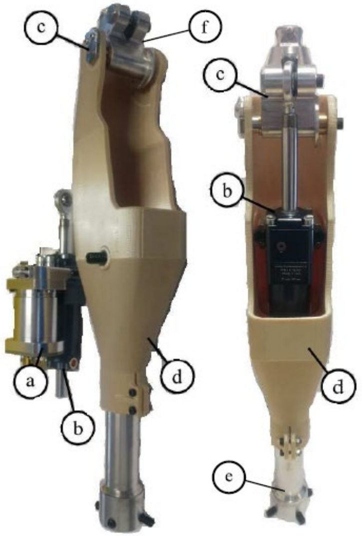
- Medium functionality
- Light-medium weight
- Optimized Energy Consumption

- **Efficiency**
  - Comparable/Better Perf.
- **Integration**
  - Compact & Light-weight
- **Back-drivability**
  - Controllability & Reg. Braking

- The resulting **EHA prototypes** demonstrated to be able to satisfy the starting goals.

- Specifically:
  - **1st Prototype**
  - **2nd Prototype**





Future Developments

- An **upgraded version** of the fully-integrated EHA is **under development** on the basis of the presented results

- The developed actuator will be tested in the next months in the **real-case scenario** on a sensorized tread-mill to investigate its capabilities also in the field of application

- “Human” level control strategies are under investigation to guarantee a better **human-machine interaction**

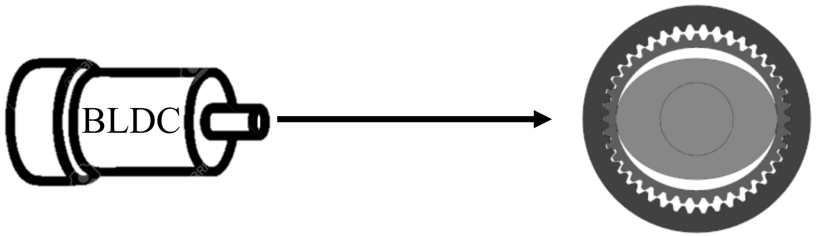
Thanks for your attention!

Back-Up Slides

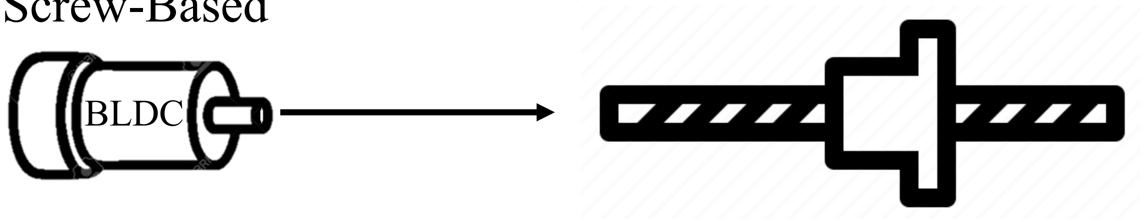
- Support Material

Active Prostheses – State-of-the-art

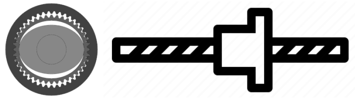
- The analysis of the state-of-the-art of active knee prostheses – both commercial products and research prototypes – shows a particular focus on:
  - **Electro-mechanical actuation**
    - Specifically two main trends can be observed
      - Gear-Based



      - Screw-Based



Active Prostheses – State-of-the-art

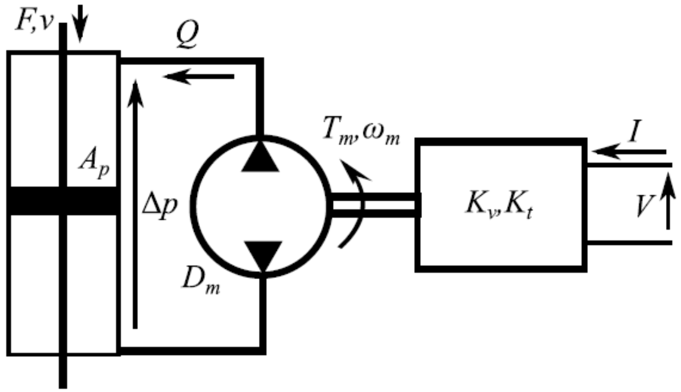
- The analysis of the state-of-the-art of active knee prostheses – both commercial products and research prototypes – shows a particular focus on:
  - **Electro-mechanical actuation → Gear-based & Screw-Based** 

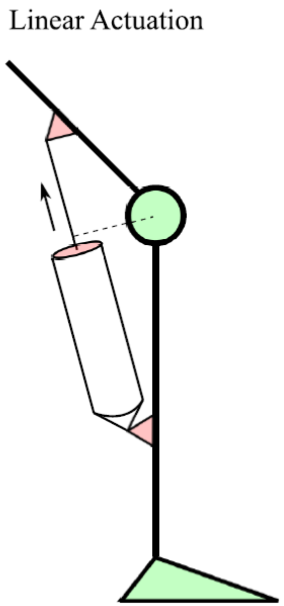
- The resulting devices are often **bulky**, **non-integrated** and **poorly efficient**

- The design is mainly focused on reaching Torque-Speed requirements without considering:
  - **Integration →** the prosthesis must be *light-weight* while contained within the *anthropometric geometrical constraints* of a physiological lower leg
  - **Back-drivability →** a back-drivable prosthesis would guarantee a much better *human-machine interaction*, as well as, control of the device
  - **Efficiency →** a higher efficiency will lead to *lower energetic consumption* of the prosthesis, and thus a *longer autonomy* of the system

Design Approach

- **Linear** EHA has been chosen due to **2** main advantages:
  - Better Mass Distribution
  - Variable (Angle-Dependent) Transmission Ratio



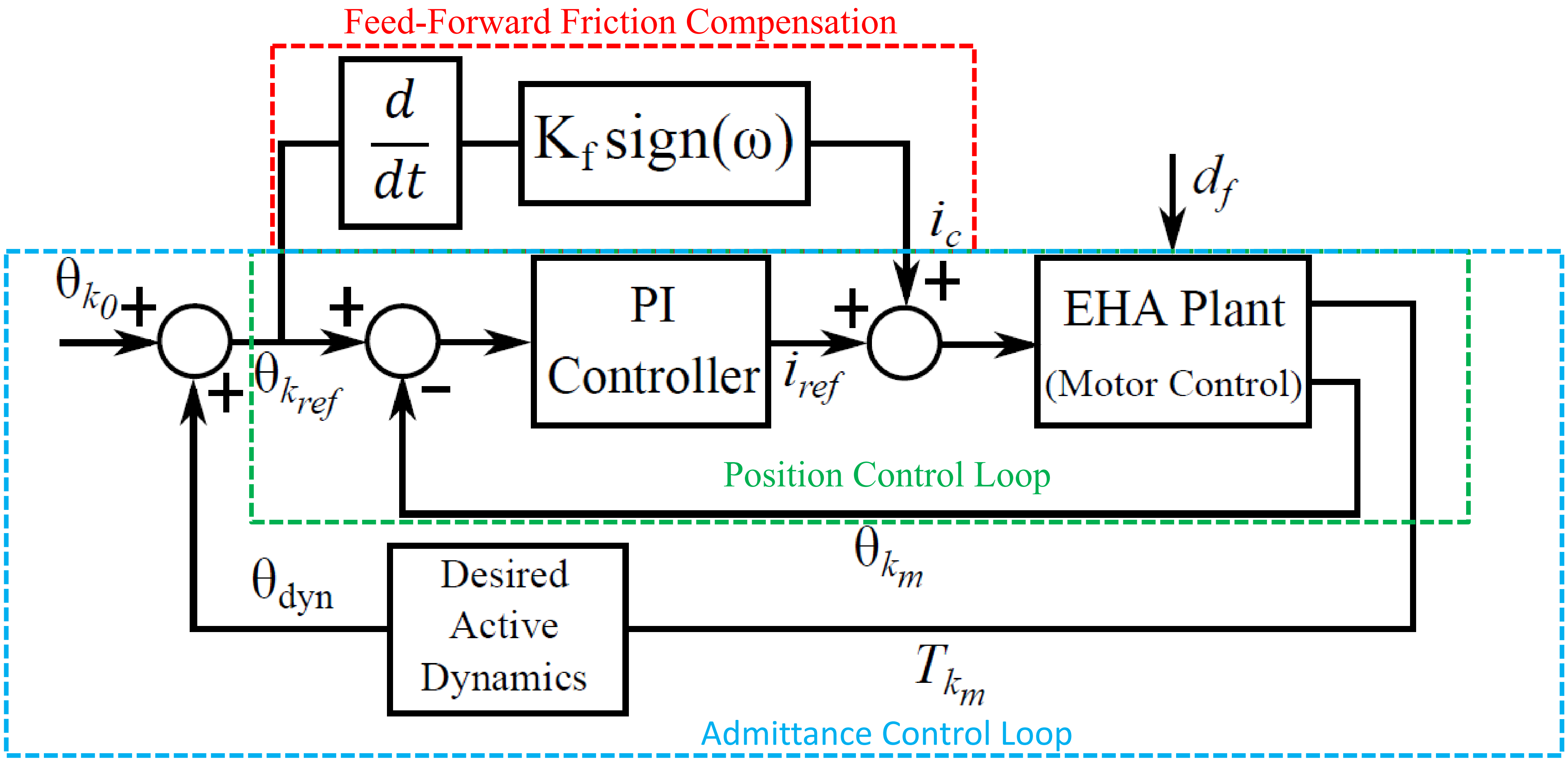


- **Top-Down** Design Strategy →

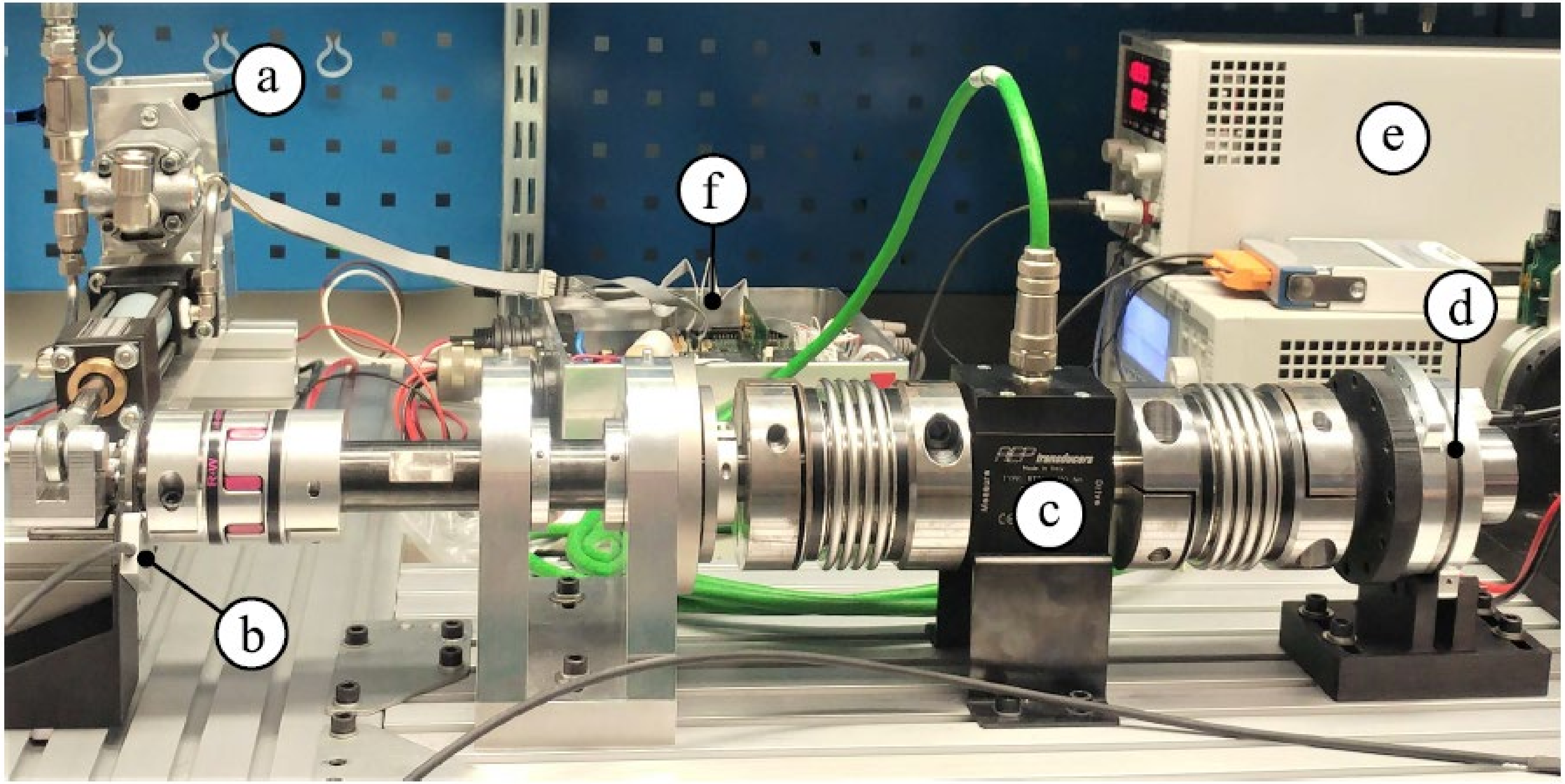
  from Biomechanial Knee Requirements to Sub-component Specifications

Knee Biomechanics → Actuation Kinematics → Hydraulic Cylinder → Hydraulic Pump → Electrical Motor

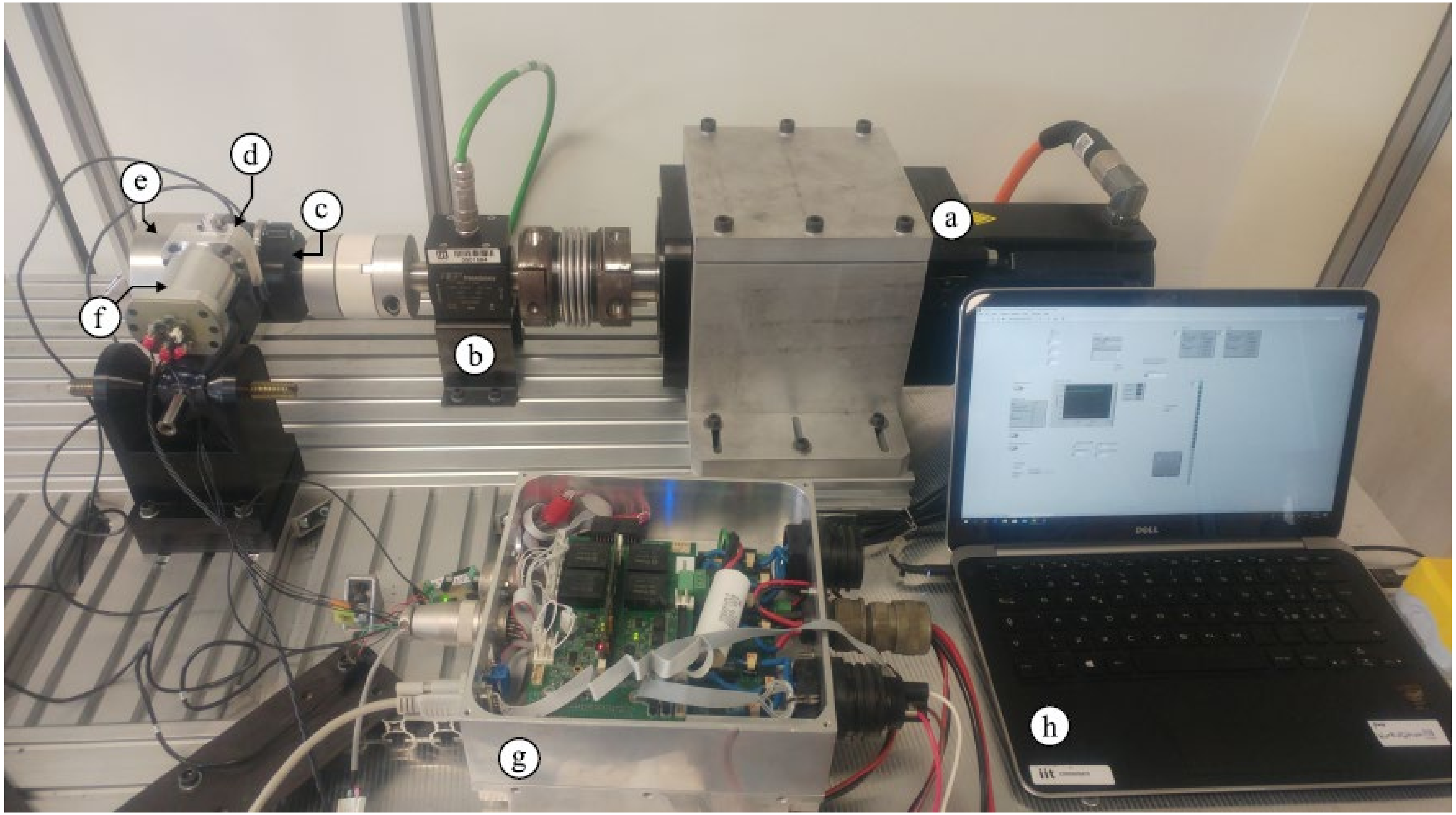
Control Strategy Block Scheme



Test Bench



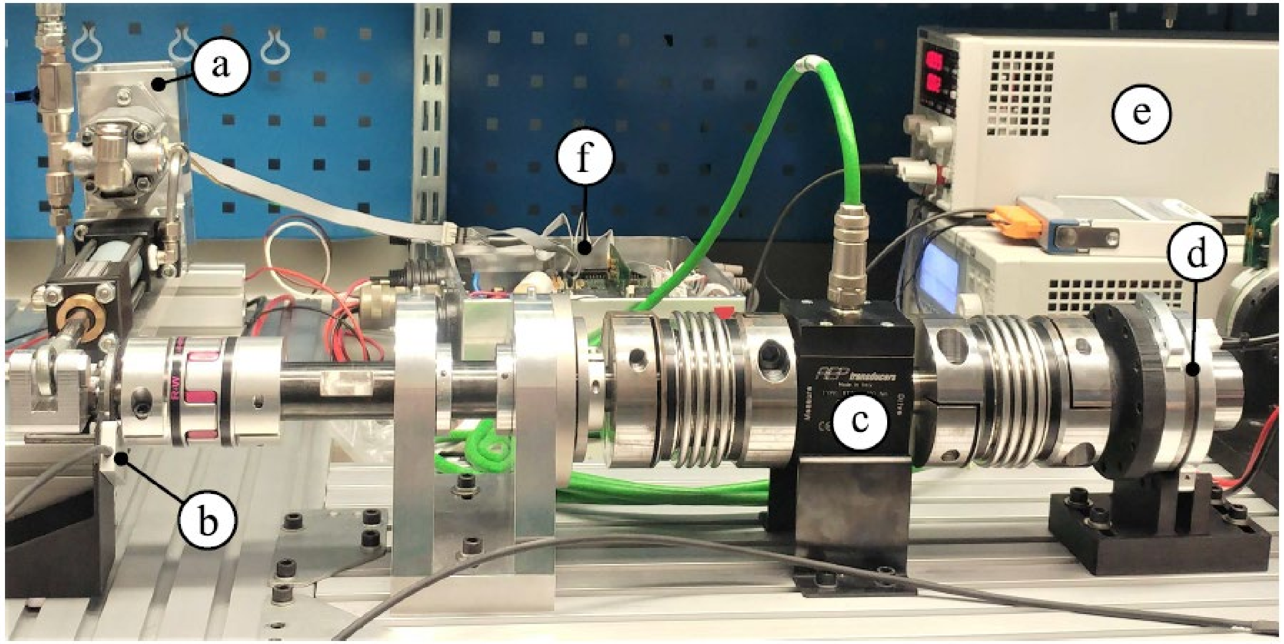
Test Bench



Test Bench & Sensors

- To implement the different control strategies
  - Digital Hall Sensors → for the Electrical Motor Control
  - Analogue Encoder → for the Knee Angular Position Control
  - Torque Transducer → for the Knee Force-based Control

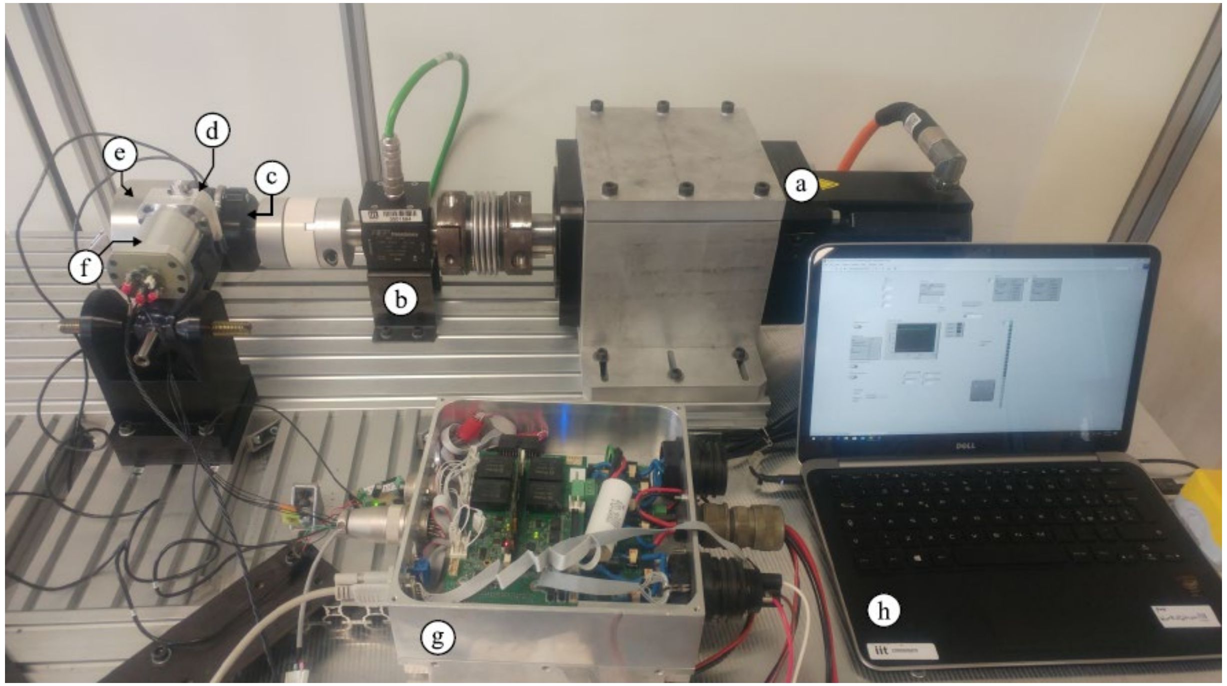
- Resulting Test Bench
  a) EHA Prototype
  b) Knee Encoder
  c) Torque Transducer
  d) Load Drive
  e) Power Supply
  f) Control and Power Stage



Test Bench

- To implement the different control strategies
  - Analogue Hall Sensors → for the Electrical Motor Control
  - Analogue Encoder → for the Knee Angular Position Control
  - Torque Transducer → for the Knee Force-based Control

- Resulting Test Bench
  a) Load Drive
  b) Torque Transducer
  c) Knee Joint
  d) Pressure gauges
  e) Knee Encoder
  f) Fully-integrated EHA
  g) Control & Power Stage
  h) Test bench computer main controller



Conclusions

- The doctorate path led to the design of 2 electro-hydrostatic actuators:
  - The **test-rig prototype**
    - Demonstrated to represent a valid substitute to classical electro-mechanical actuation showing ***comparable efficiency*** performance, while showing ***good controllability***
    - On the other hand, the lack of components integration and optimization, led to a bulky and non-backdrivable device
  - The **fully-integrated prototype**
    - Showed that a dedicated process of components customization and integration, actually guarantees a much more ***integrated***, ***light-weight*** and ***back-drivable*** device. The developed actuator is highly controllable and its back-drivability allows ***energy harvesting*** during gait.
    - Some limitations have been found in the ***pump housing design***, which broke down the efficiency performance. However, a set of possible solutions is already under analysis to compensate it.