Energy efficient actuators for biomechanical applications

From accurate models to energy-efficient concepts

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R&MM Research Group

Variable Impedance Actuators

Pneumatic muscles, MACCEPA, SPEA, self-healing

Safety
Energy efficiency
High torques

Cognitive and physical human-robot interaction

Coworkers for manufacturing, bipeds, social robots for robot assisted therapy, bipeds, rehabilitation and assistive exoskeletons, prostheses

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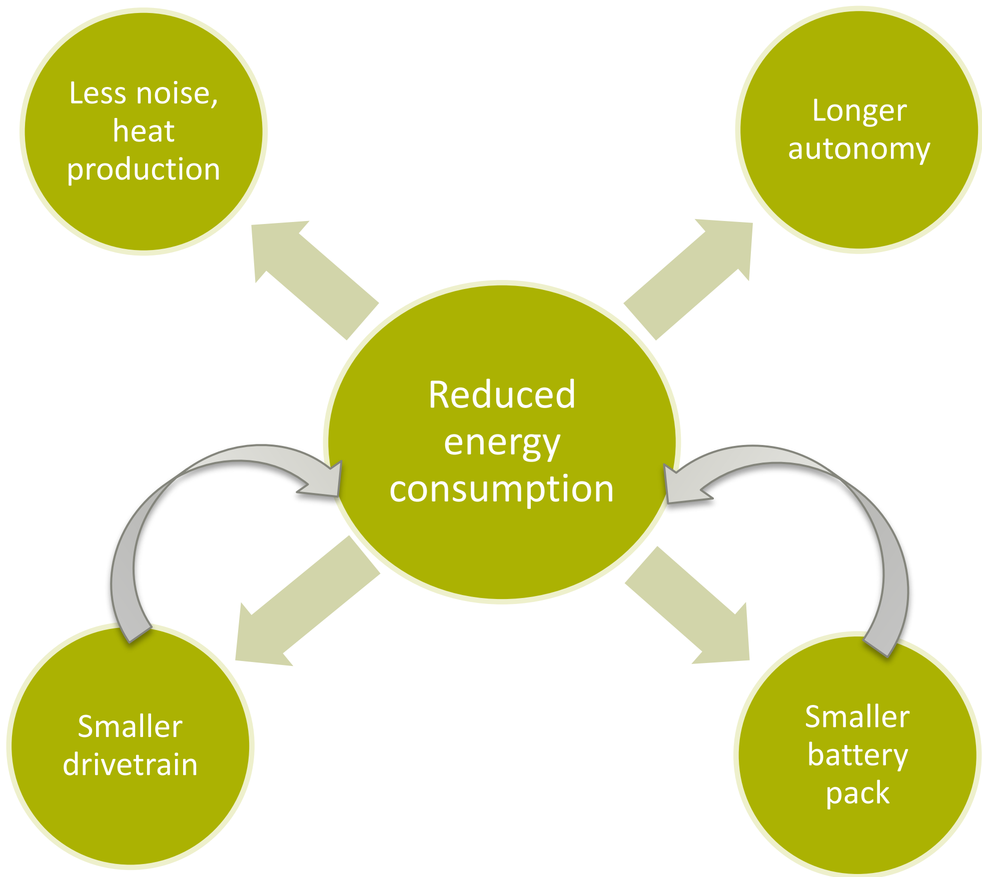
Why study energy efficiency?



Optimizing for efficiency

Energy efficient design can be achieved by minimizing

$$C = \int |P_{mech}| dt$$

$$= \int |T \cdot \omega| dt$$

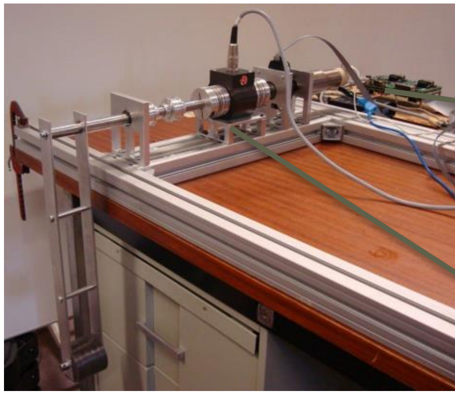
Power flow through drivetrain

(i.e. by minimizing the ~~mechanical energy consumption~~)

How does this relate to E_{elec}?

Experimental verification

Case study: pendulum



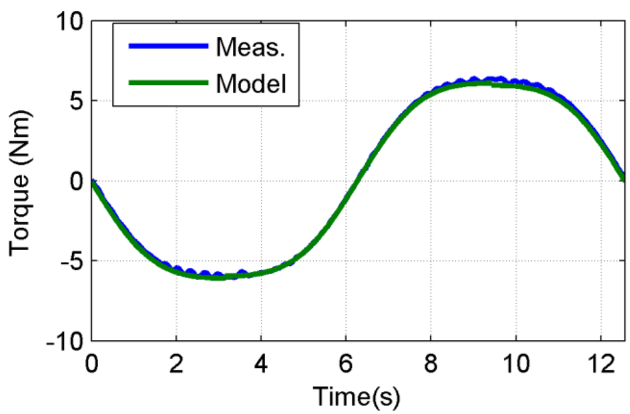
Elec. power measurement (controller input)

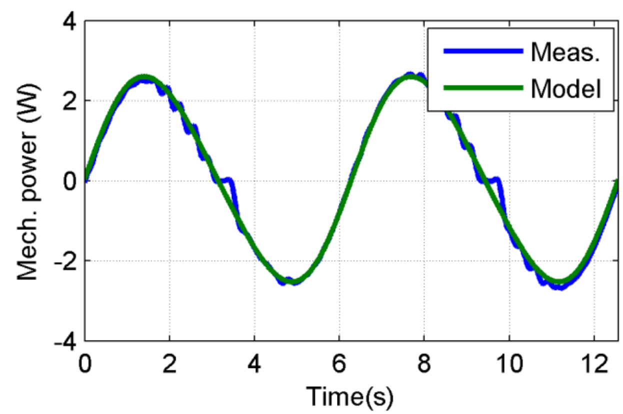
Mech. power measurement

Imposed trajectory

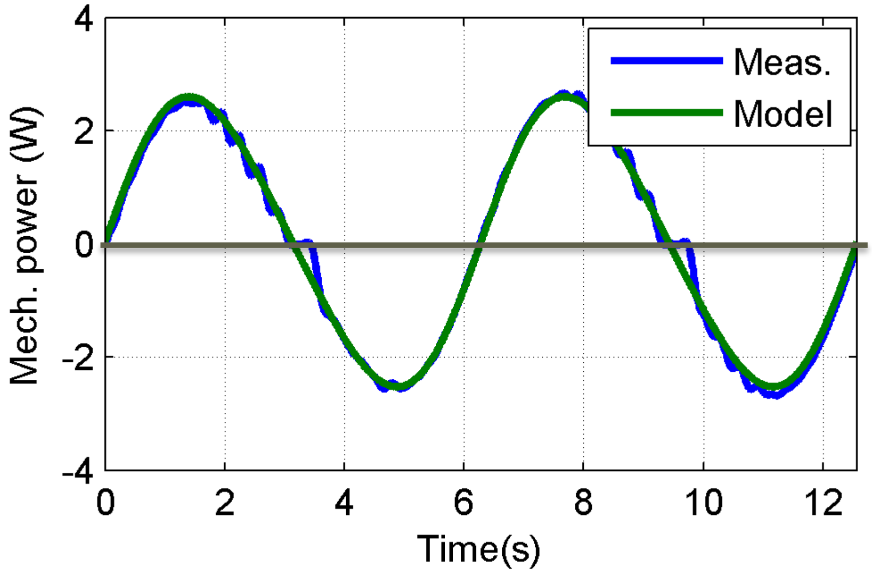
$$\theta = \theta_0 \sin(\omega t)$$

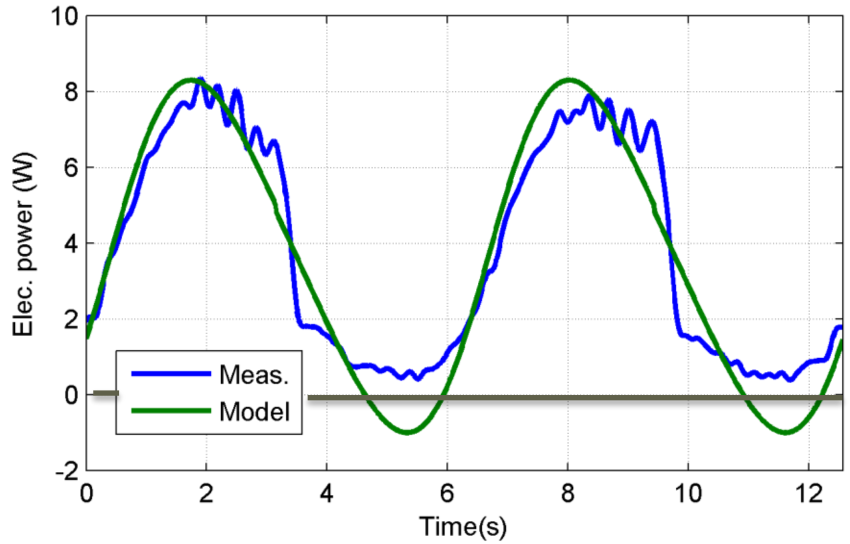
Torque and mechanical power





Mechanical vs. Electrical power





- High losses in powertrain
- Symmetry lost
- Simple model incorrect...

$$P_{elec} = \frac{1}{\eta_g \eta_m} P_{mech}$$

Electrical power

Loss mechanisms / drivetrain dynamics matter!

- Gearbox: $P_{loss} \sim T\dot{\theta}$
- Motor: $P_{loss} \sim T^2, \dot{\theta}^2, \dot{\theta}$
- Friction: $P_{loss} \sim \dot{\theta}^2, \dot{\theta}$
- Controller losses: ?
- Motor inertia

$$P_{elec} \not\sim P_{mech}$$

Verstraten et al., ***Modeling and design of geared DC motors for energy efficiency: Comparison between theory and experiments*****, Mechatronics (2015)**

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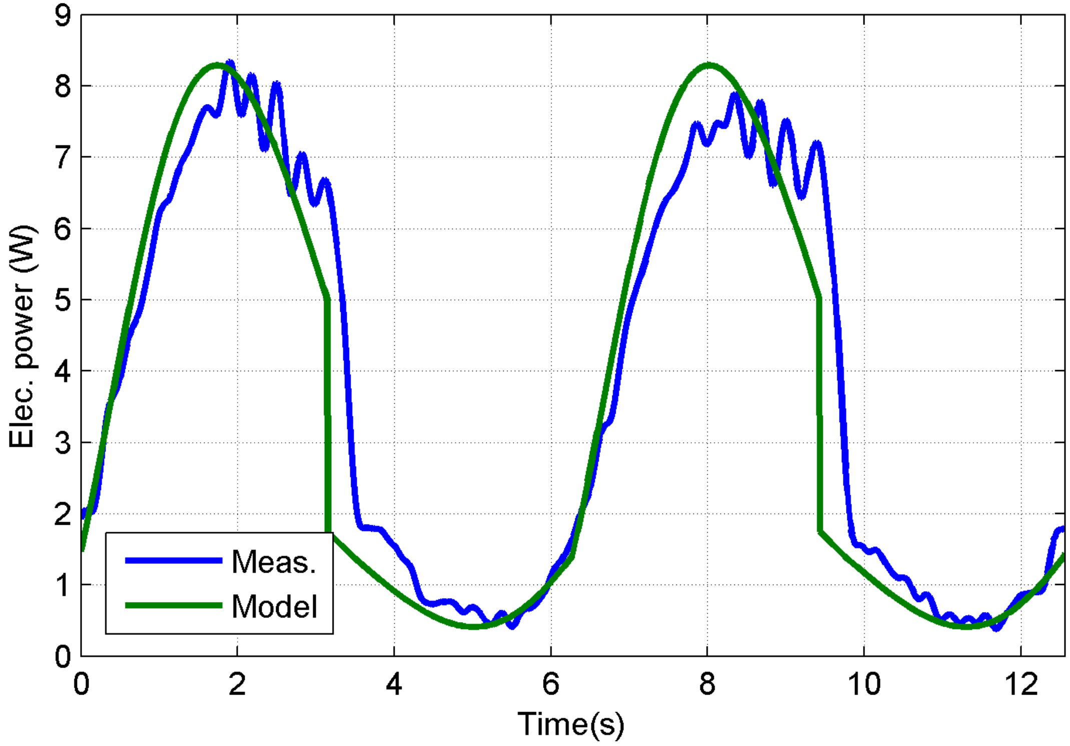
Electrical power

An improved model



Verstraten et al., *Energy Consumption of Geared DC Motors: Comparing Modeling Approaches*, IEEE Robotics and Automation Letters (2016)

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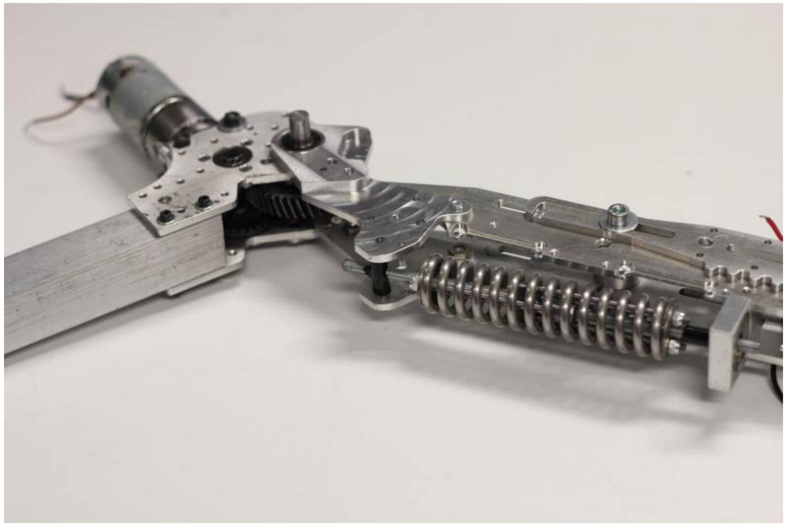
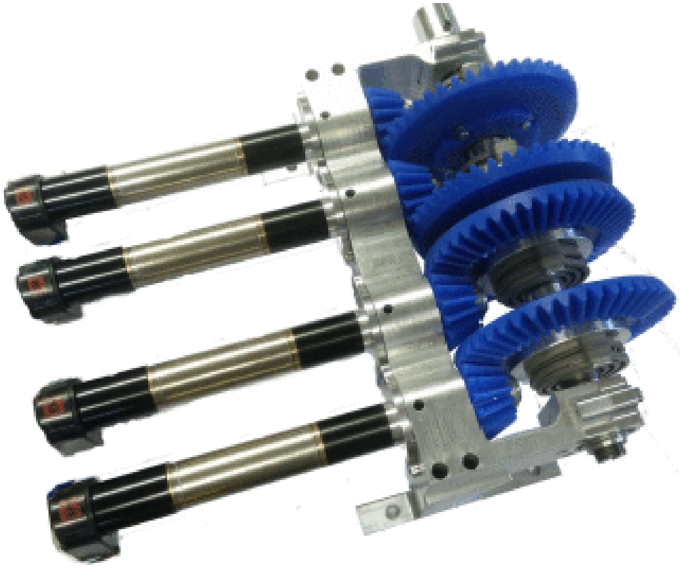
How to improve efficiency

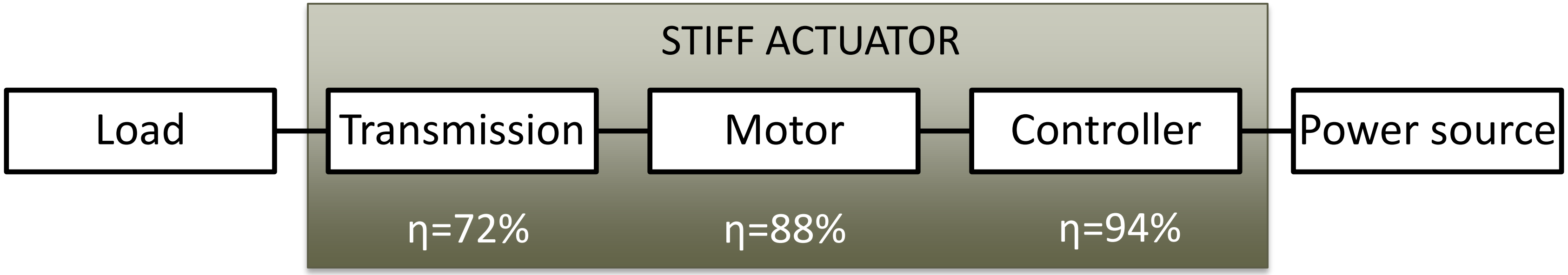
Two concepts





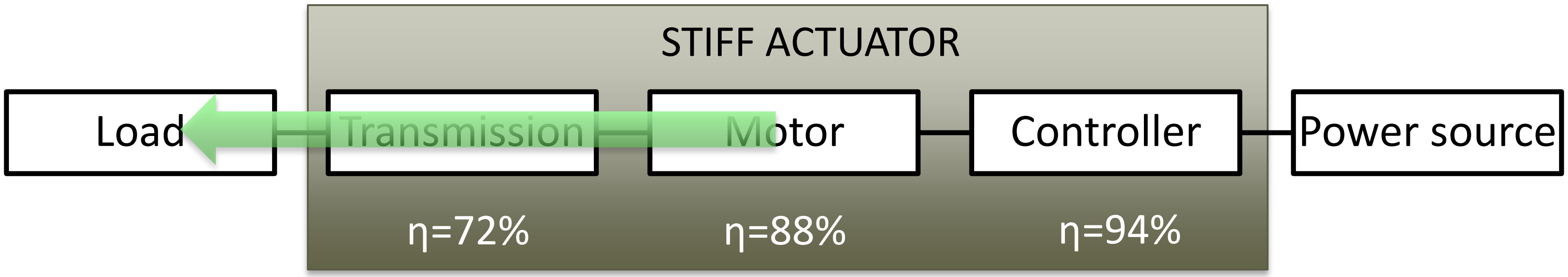
Compliance **Redundance**

Rigid actuator



Rigid actuator

Steady state - motor



Forward drive:

$$T_{motor} = \frac{1}{\eta_g n} T_{load} \quad (P_{load} > 0\,)$$

$$\rightarrow\ |P_{load}| < |P_{motor}|\ ✓$$

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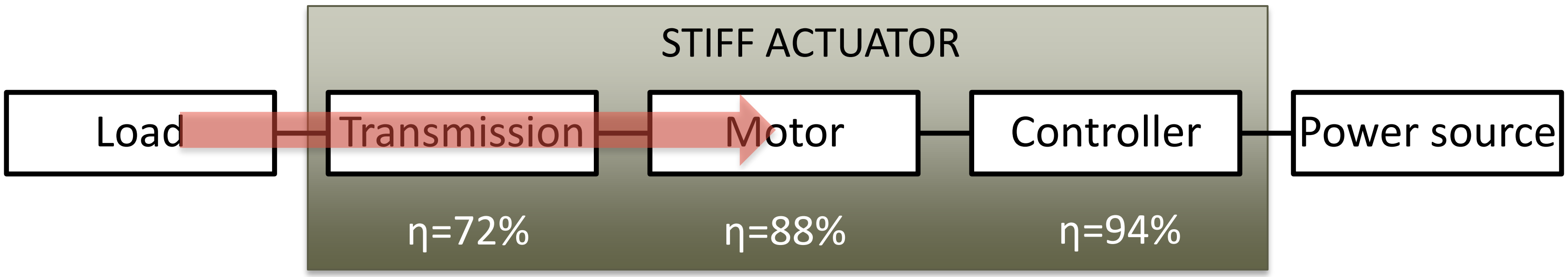
Rigid actuator

Steady state - generator



Forward drive:

$$T_{motor} = \frac{1}{\eta_g n} T_{load} \quad (P_{load} > 0\,)$$

Reverse drive:

$$T_{motor} = \frac{\eta_g}{n} T_{load} \quad (P_{load} < 0\,)$$

$\rightarrow\ |P_{load}| > |P_{motor}|$ ✓

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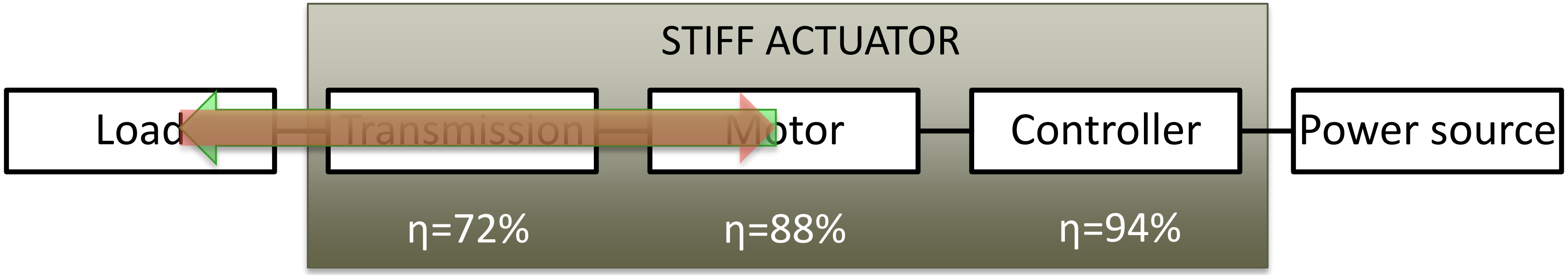
Rigid actuator

Dynamic



Dynamic applications:

$$\begin{cases} T_{motor} = \dfrac{1}{\eta_g n} T_{load} & (P_{load} > 0) \\ T_{motor} = \dfrac{\eta_g}{n} T_{load} & (P_{load} < 0) \end{cases}$$

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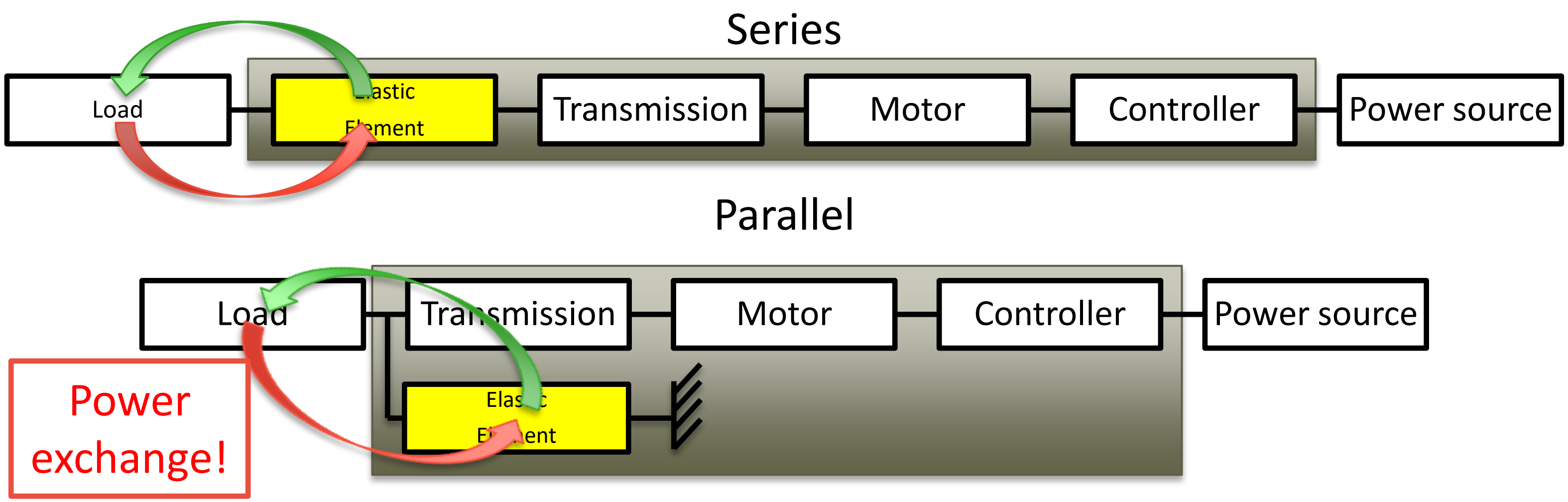
Improving efficiency: compliance

Bypass the lossy components

Introduce an energy storage buffer at the output!



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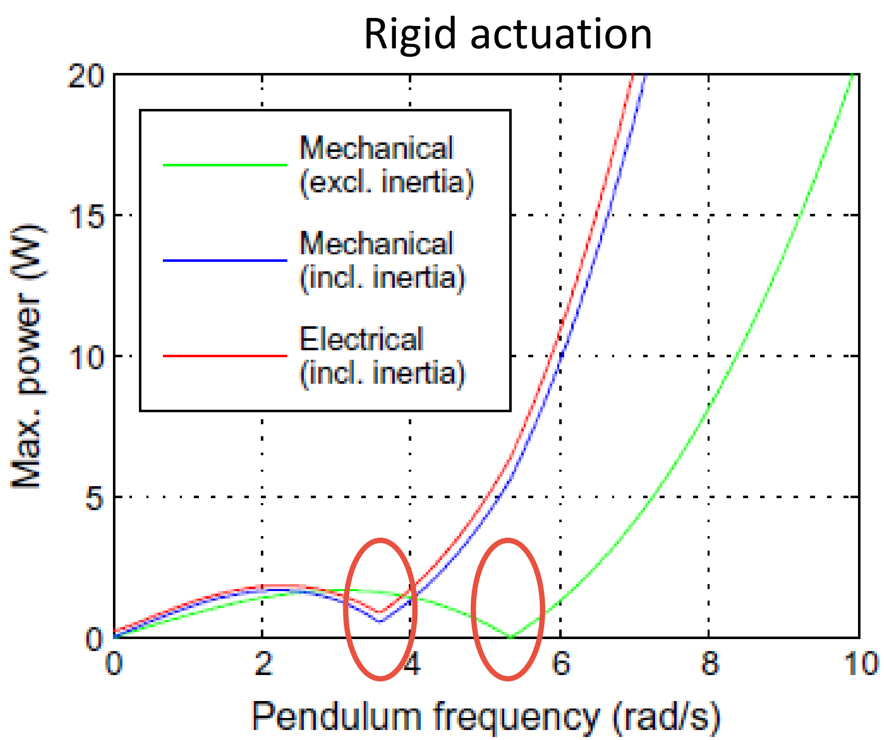
Efficiency & Natural Dynamics

Resonance:

- T = 0

$$P = \color{red}{\boldsymbol{T}}\omega = 0$$

- At least one



Verstraten et al., ***Modeling and design of geared DC motors for energy efficiency: Comparison between theory and experiments*****, Mechatronics (2015)**

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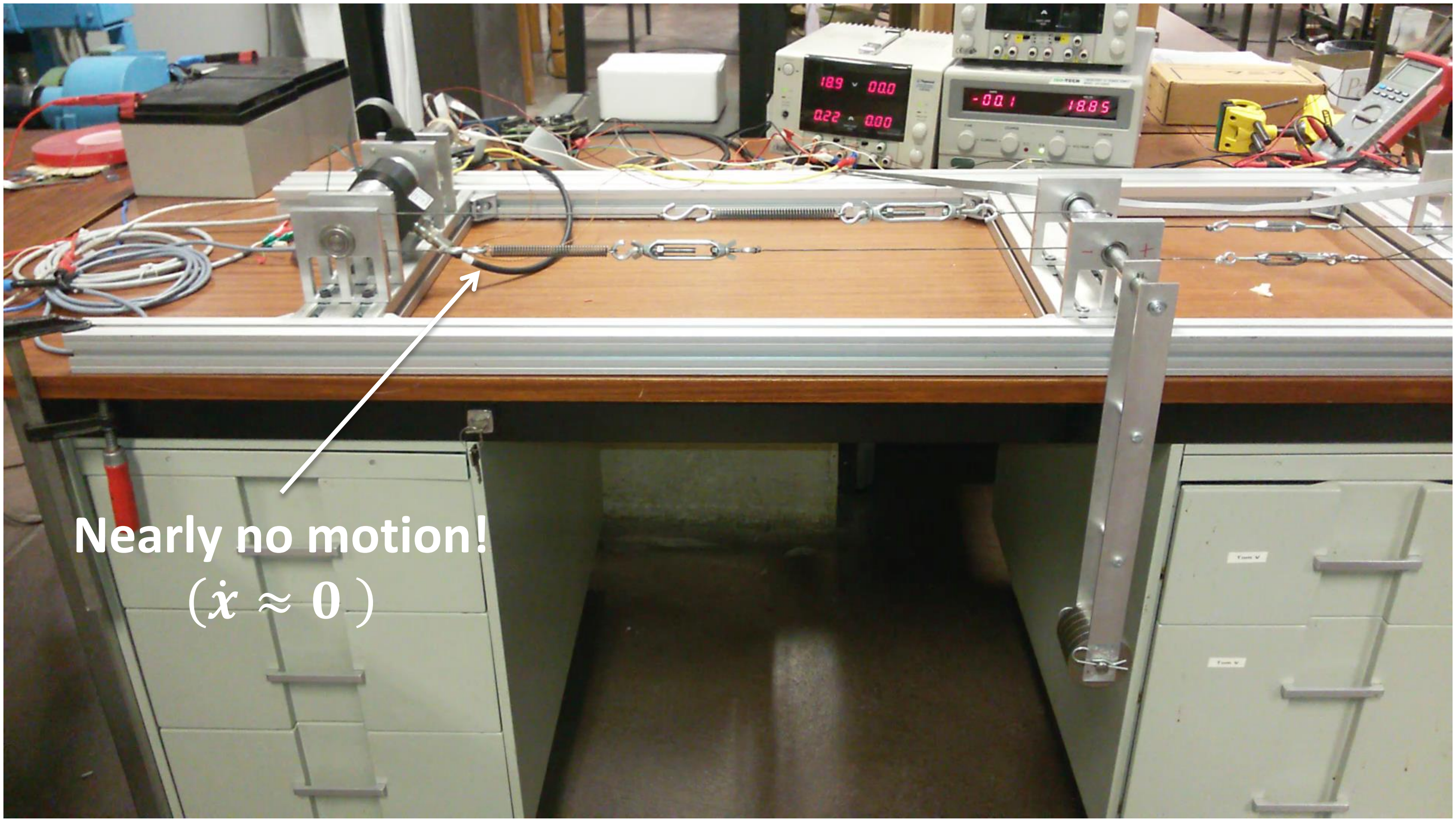
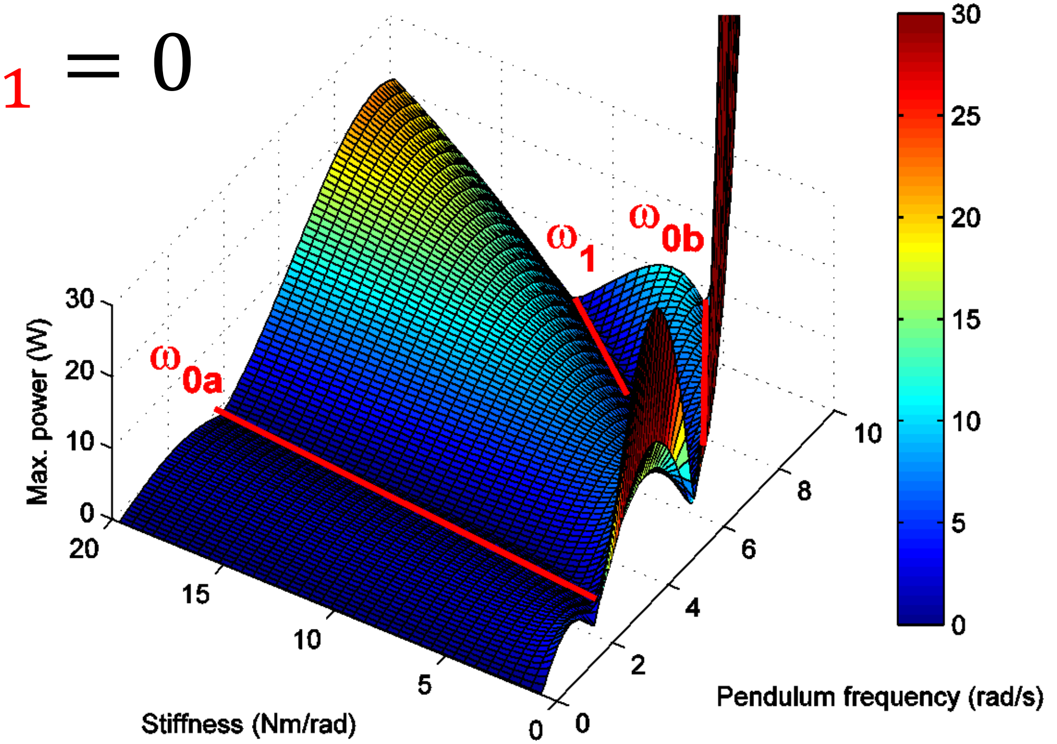
Antiresonance



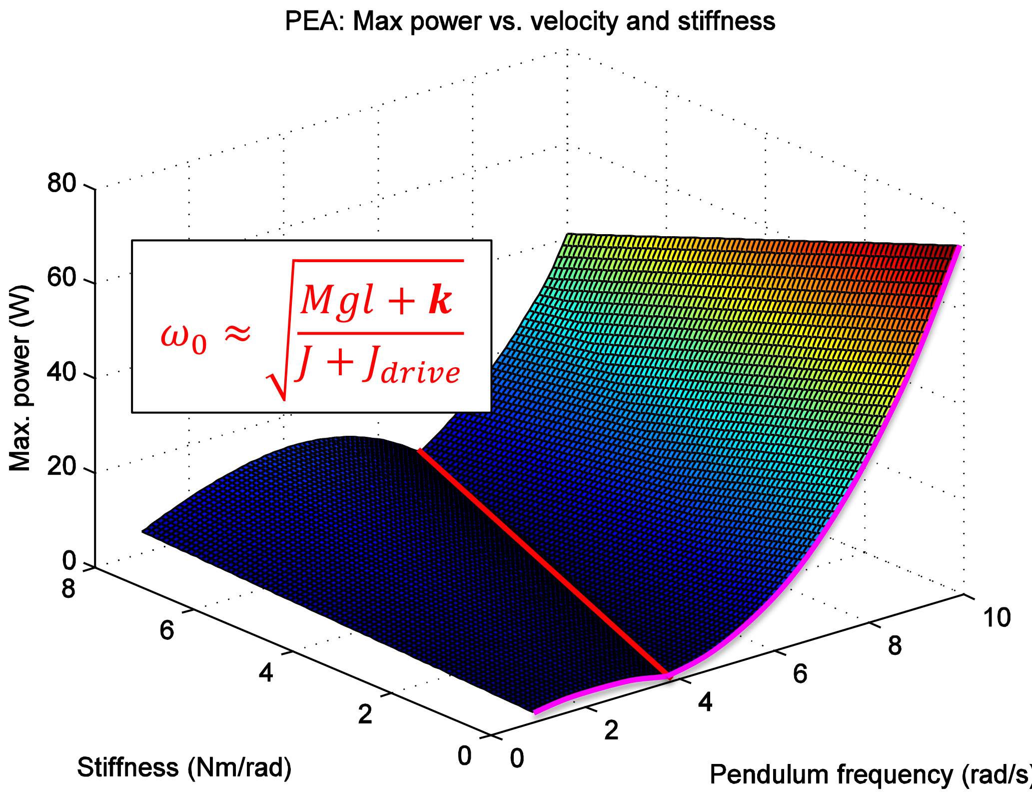
Series Elastic Actuation

Antiresonance:

$$P = T\omega_1 = 0$$



Parallel Elastic Actuation



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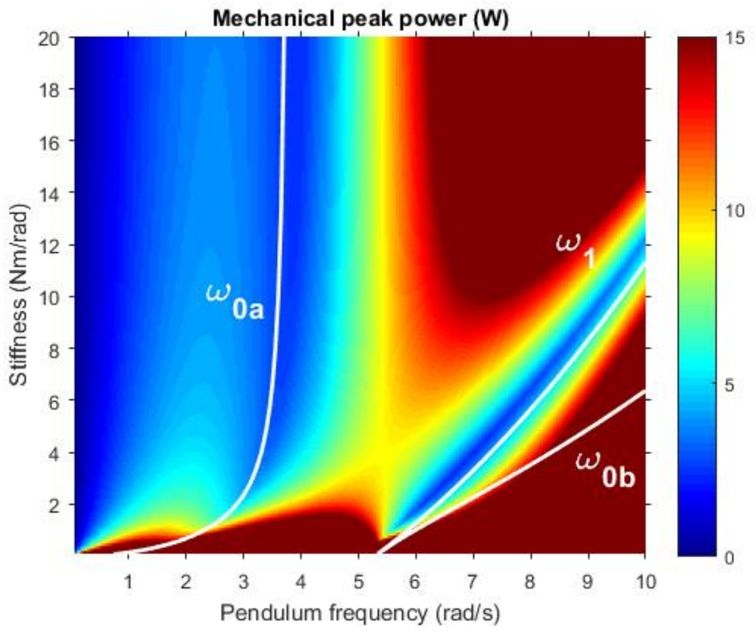
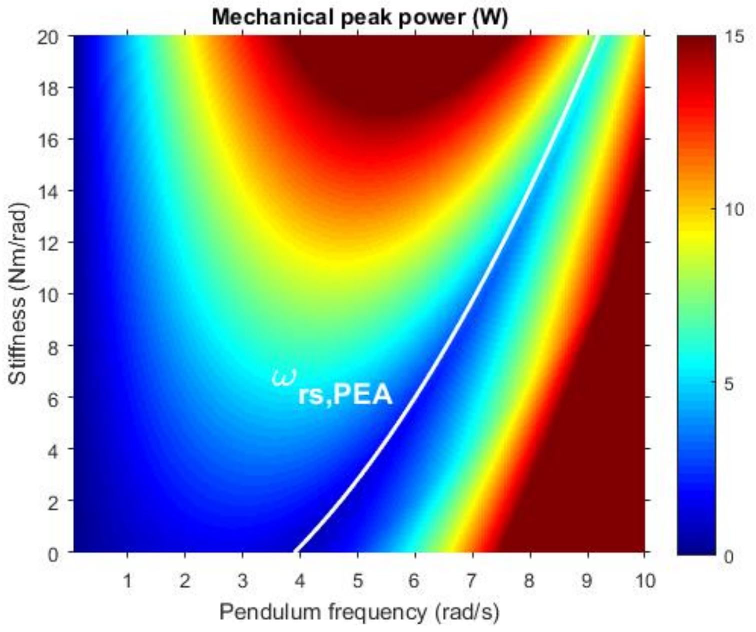
Series or Parallel?
Mechanical peak power

Series



Parallel



Verstraten et al., ***Series and parallel elastic actuation: impact of natural dynamics on power and energy consumption*****, Mechanism and Machine Theory (2016)**

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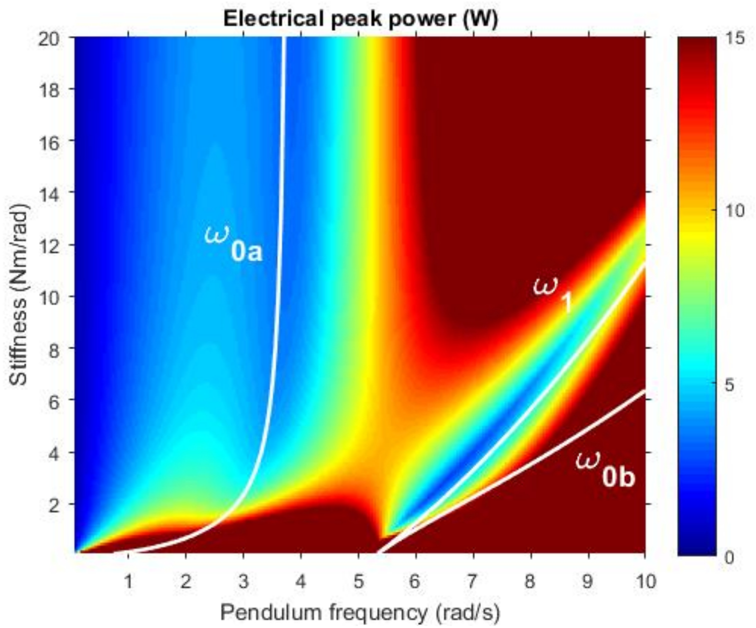
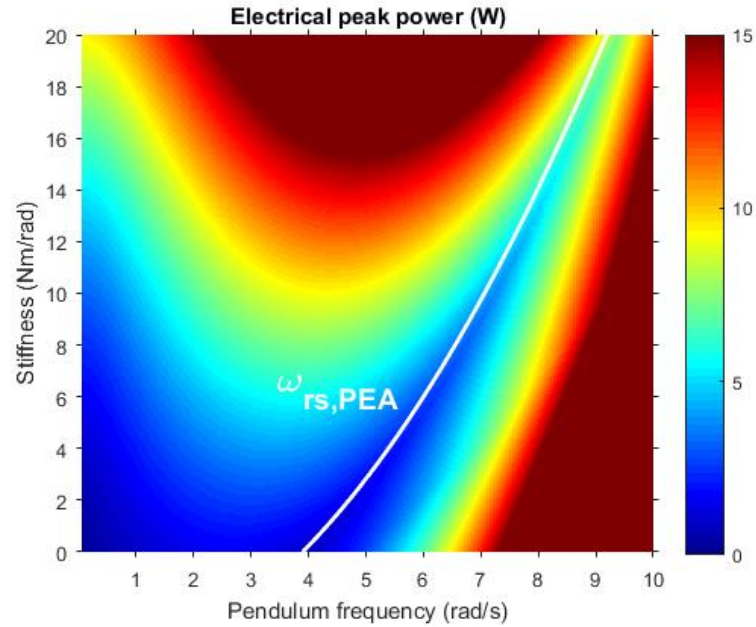
Series or Parallel?
Electrical peak power

Series



Parallel



Verstraten et al., ***Series and parallel elastic actuation: impact of natural dynamics on power and energy consumption*****, Mechanism and Machine Theory (2016)**

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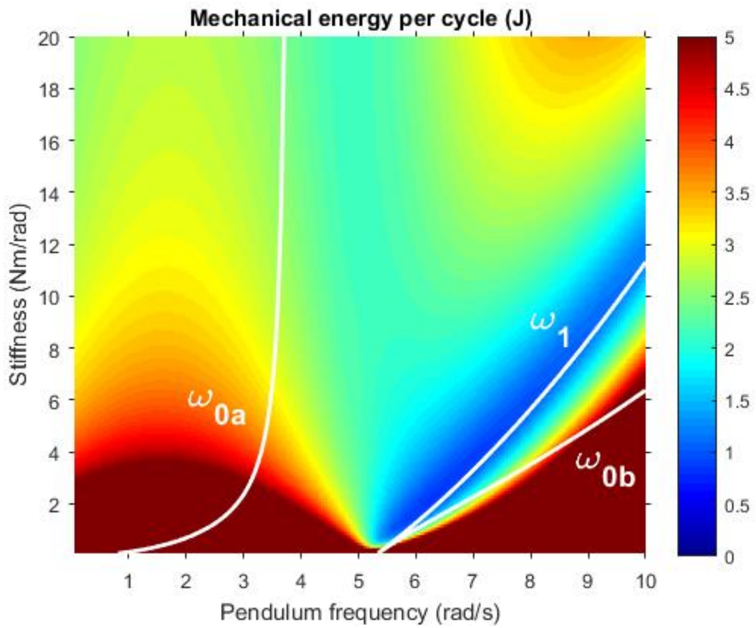
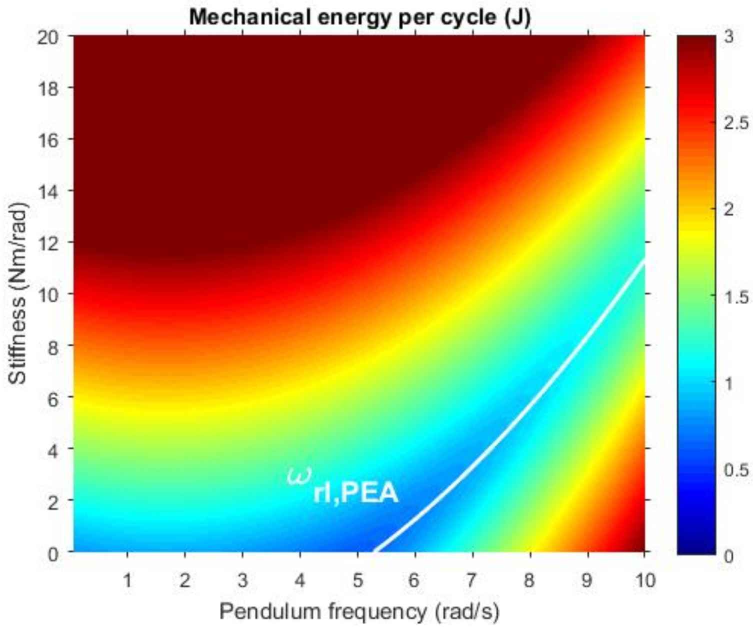
Series or Parallel?
Mechanical energy

Series



Parallel



Verstraten et al., *Series and parallel elastic actuation: impact of natural dynamics on power and energy consumption*, Mechanism and Machine Theory (2016)

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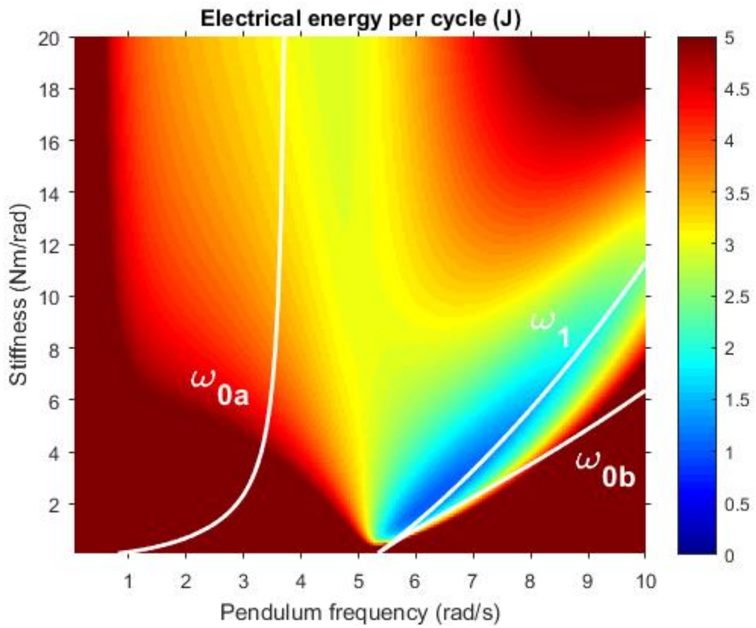
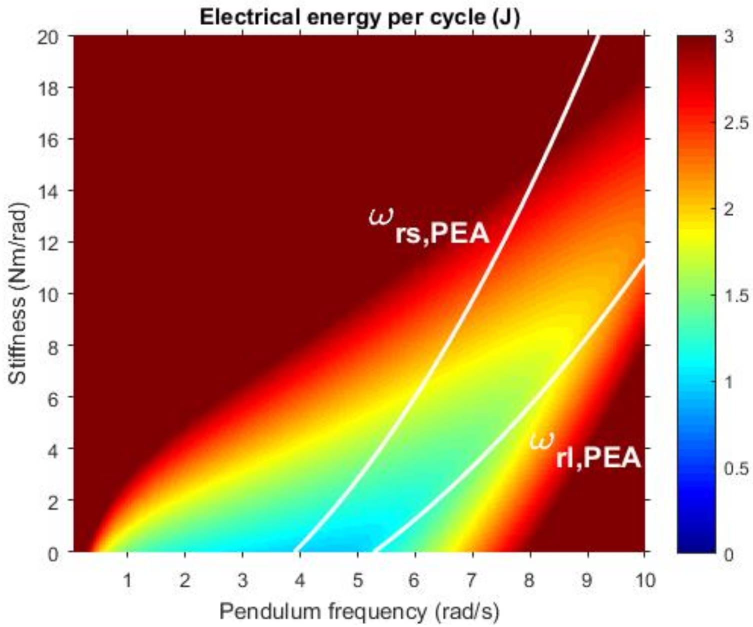
Series or Parallel?
Electrical energy

Series



Parallel



Verstraten et al., ***Series and parallel elastic actuation: impact of natural dynamics on power and energy consumption*****, Mechanism and Machine Theory (2016)**

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Series or Parallel?

Addition of offset: $$\theta = \theta_0 \sin(\omega t) + \theta_1$$

Additional static torque!

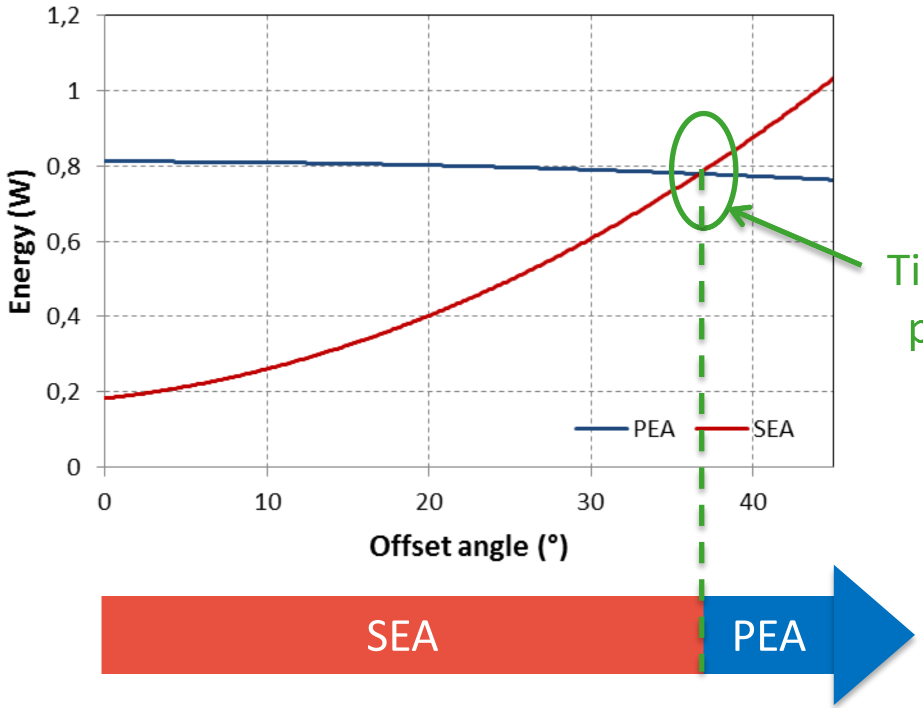
- **PEA**: compensation by setting equilibrium angle

$$\theta_{eq} = \frac{\mathrm{Mgl}\,\sin(\theta_1)}{k_p} + \theta_1$$

- **SEA**: cannot compensate!

Series or Parallel?
With offset

Energy consumption with optimal stiffness tuning:



Beckerle et al., Series and Parallel Elastic Actuation: Influence of Operating Positions on Design and Control, IEEE/ASME Transactions on Mechatronics (2017)

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Series or Parallel?

Series

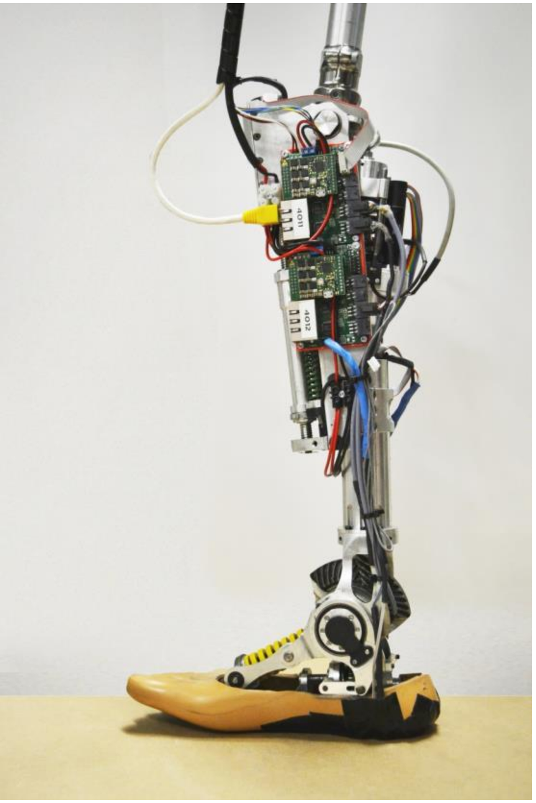
- Decoupling of motor and load (additional DOF)
  = increased **safety**
- Load force = motor force
- Extra **antiresonance** frequency (+resonance)
- Reduction of motor **speed and torque**
- Cannot cancel static torque

Parallel

- No decoupling of motor and load
  = no increase in safety
- Load pos. = motor pos.
- Shift of **resonance** frequency
- Only reduction of **motor torque**
- Can **cancel static torque**

Application to prosthetics

AMP-foot 4



CYBERLEGs Beta-prosthesis

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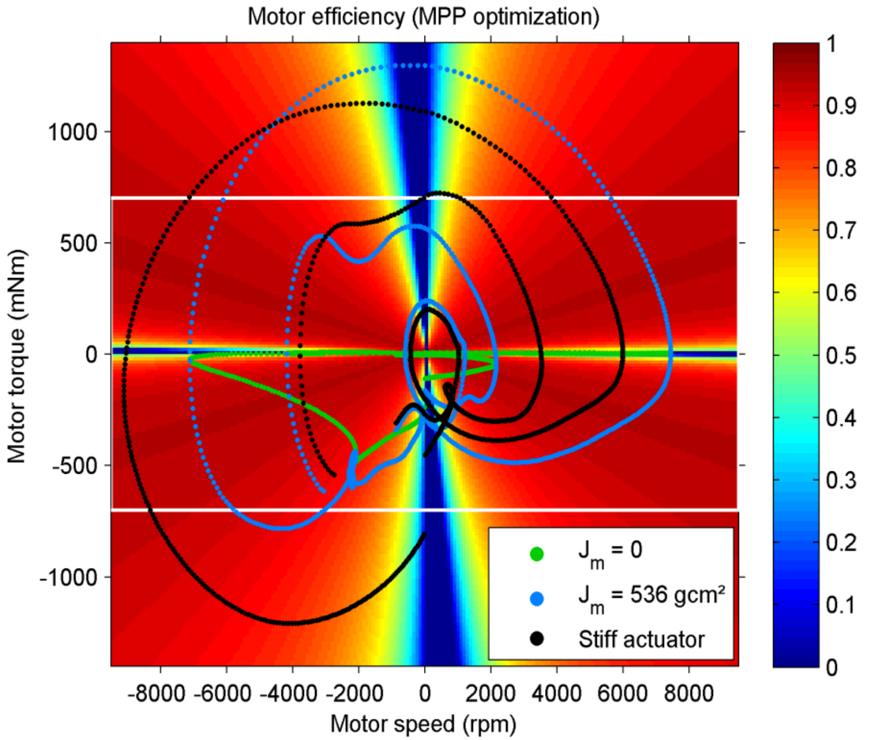
Application to prosthetics

Inertia has a huge impact!



Verstraten et al., ***On the Importance of a Motor Model for the Optimization of SEA-driven Prosthetic Ankles,*** **Wearable Robotics (WeRob) 2016**

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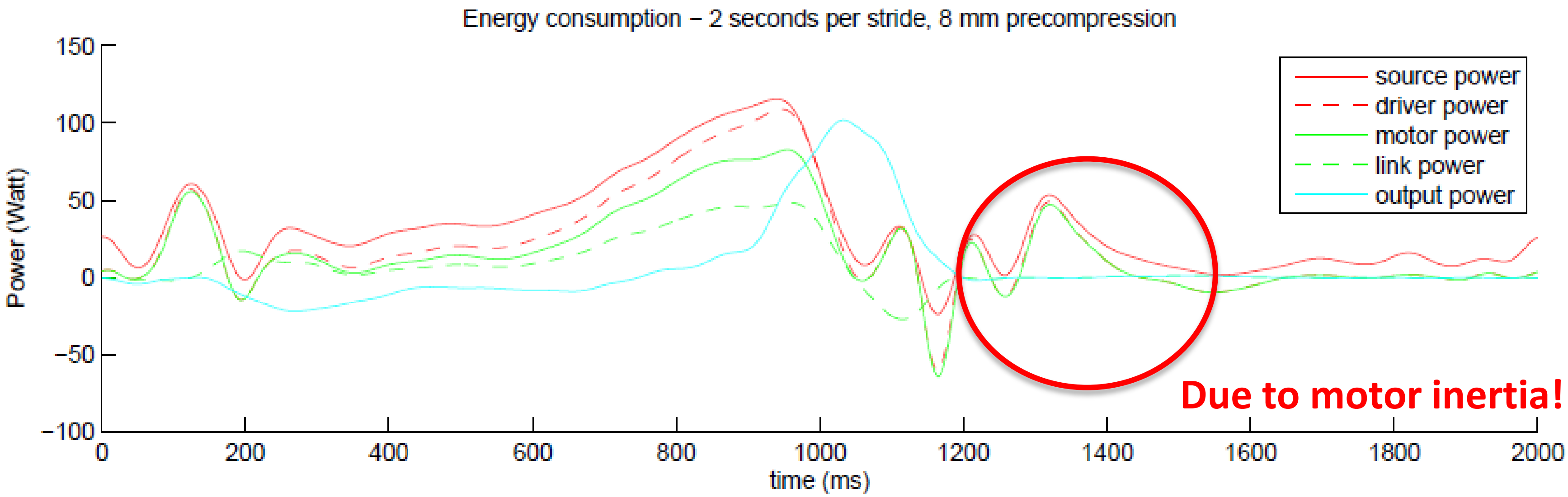
Application to prosthetics

Measurements on Cyberlegs prosthesis



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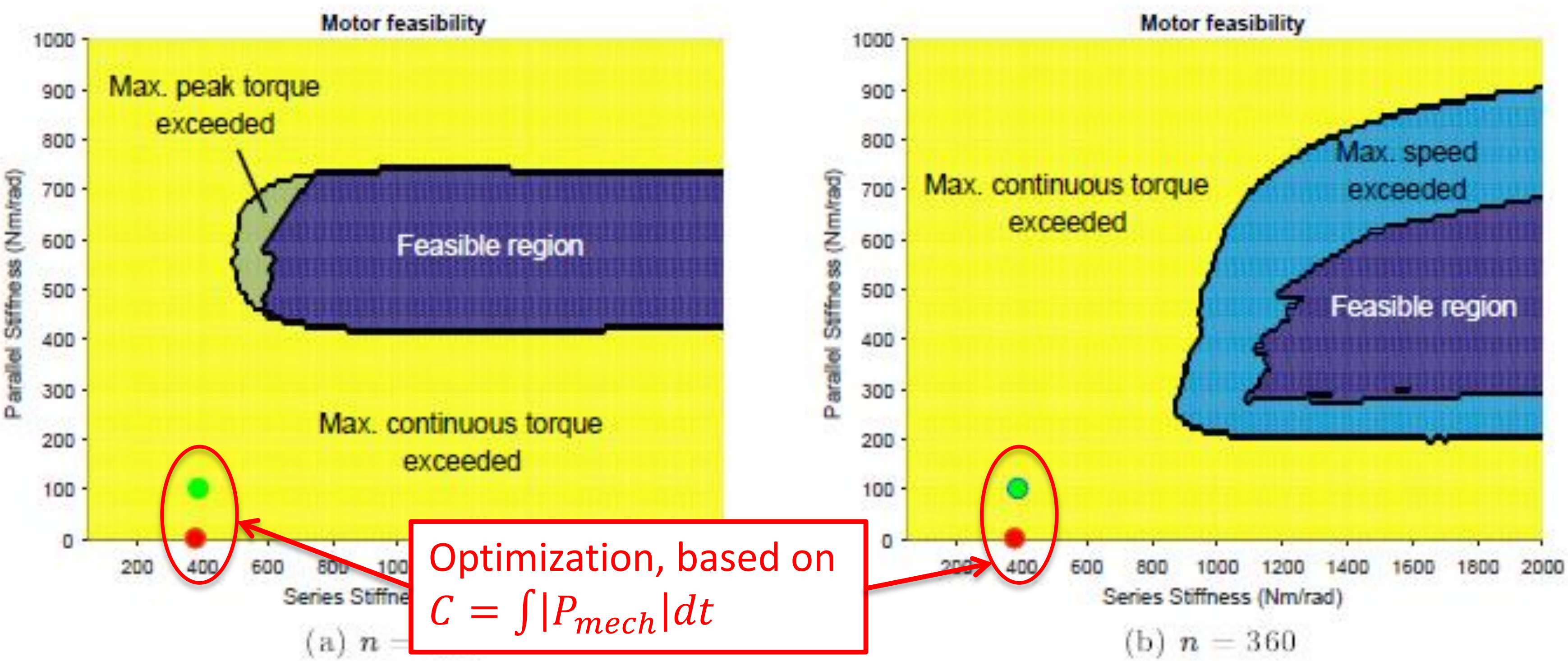
Application to prosthetics

Motor limitations influence spring selection



Verstraten et al., *Optimizing the Power and Energy Consumption of Powered Prosthetic Ankles with Series and Parallel Elasticity*, M&MT (under review)

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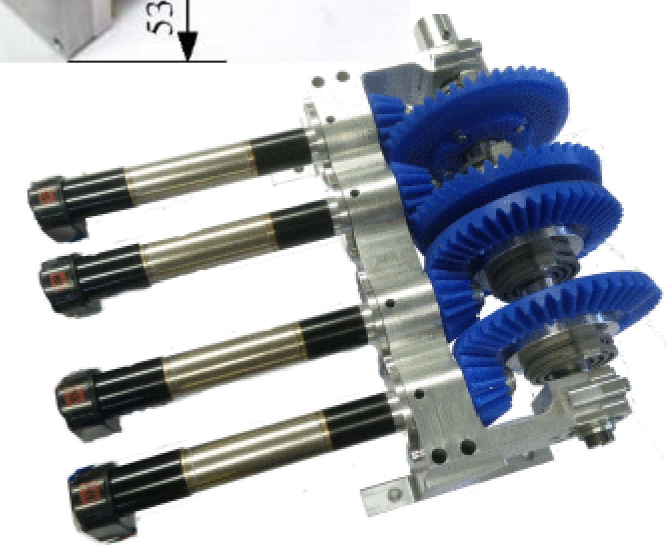
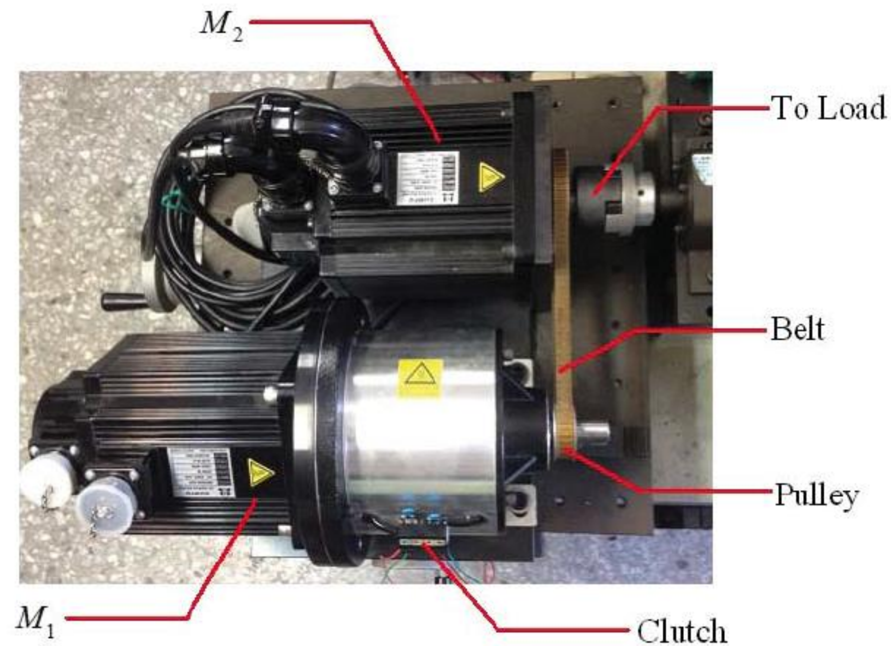
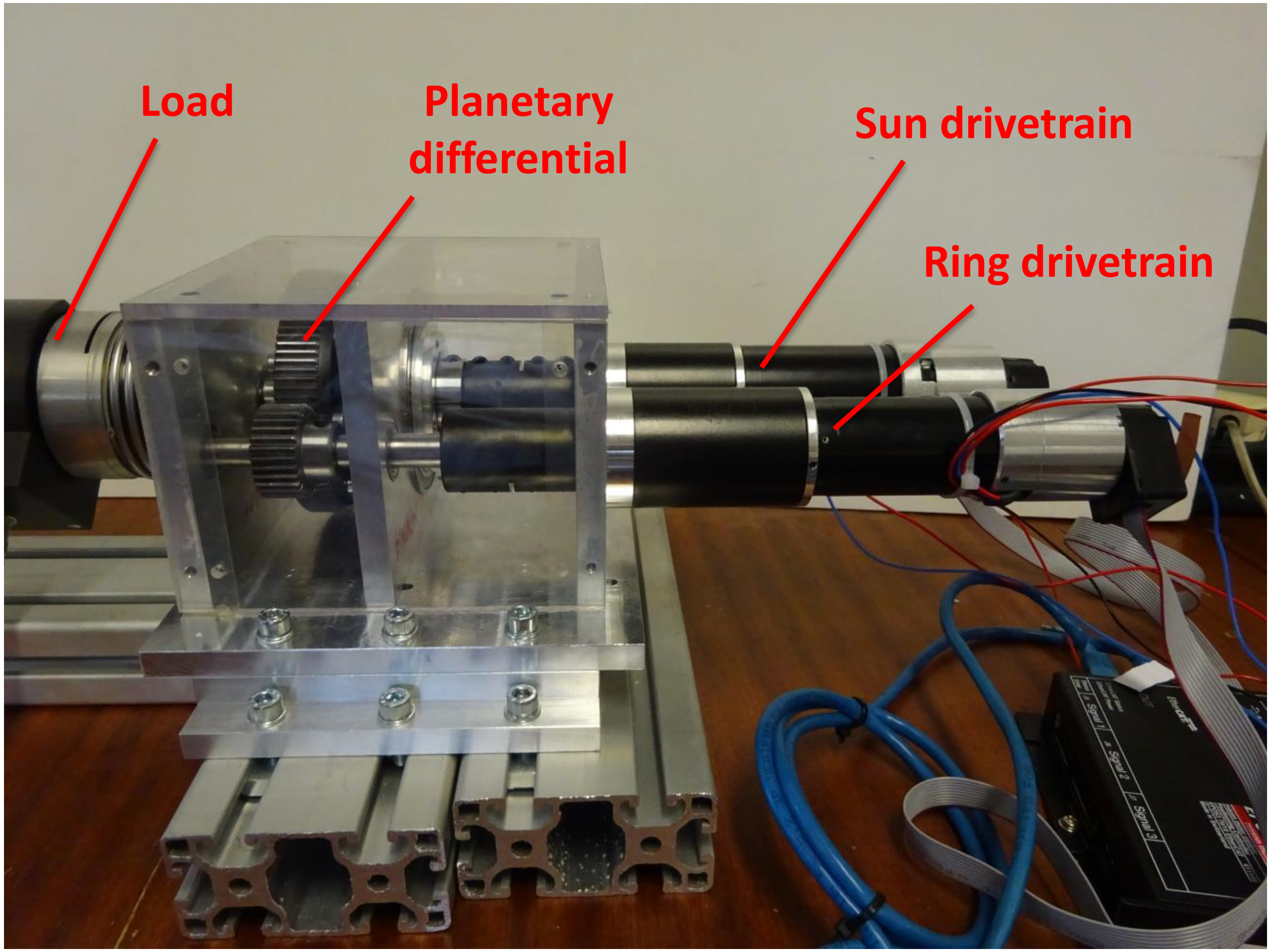
Improving efficiency: Redundance





Dual-motor actuator (DuPG)



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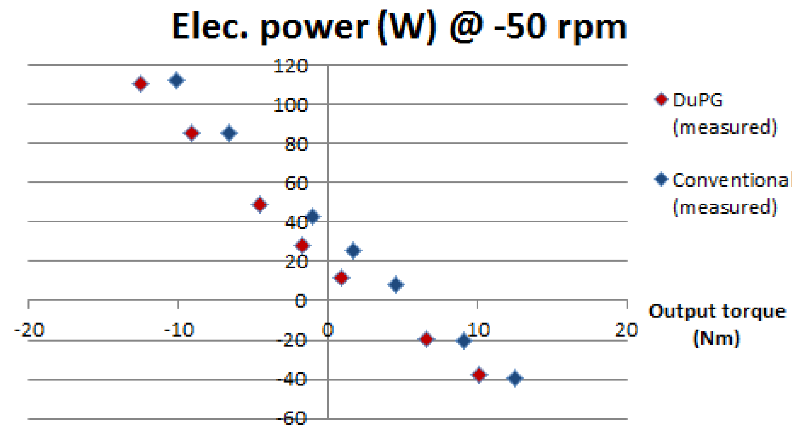
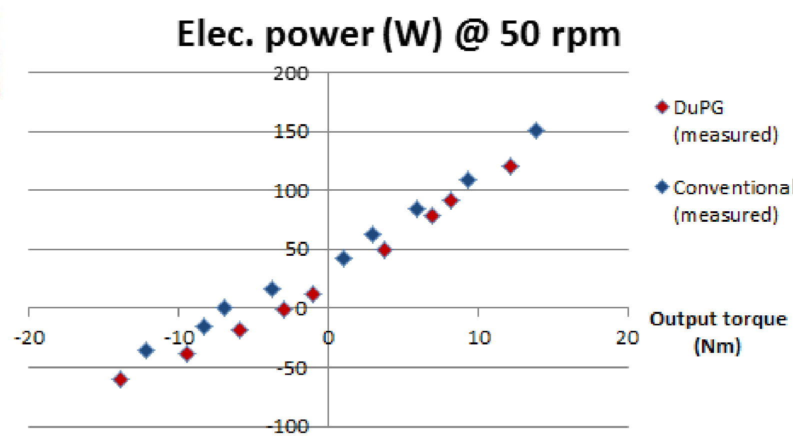
Improving efficiency: DuPG

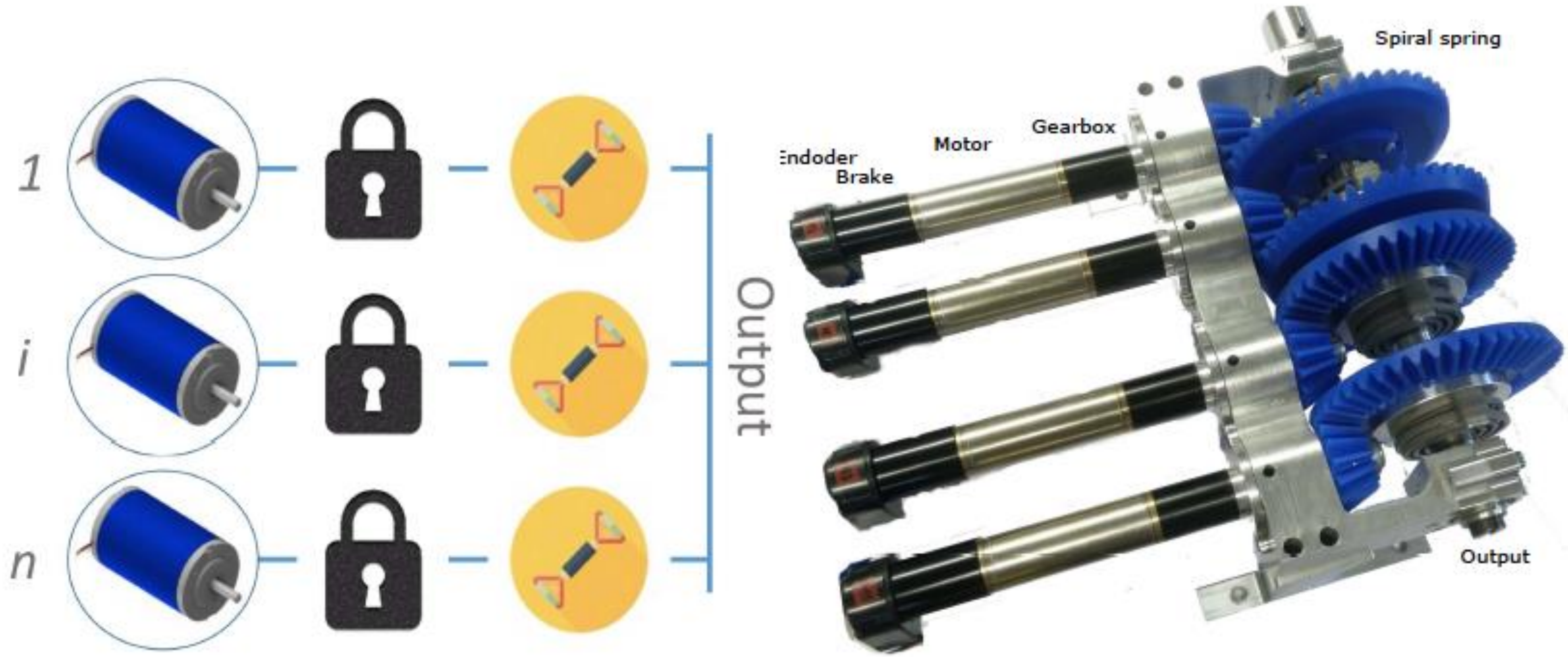
- Designed to replace conventional actuator
- Results:
  - Lower energy consumption
  - 40% weight reduction
  - 56% volume reduction





+SPEA

Combining redundance and compliance



(a) +SPEA schematic (b) +SPEA prototype

Mathijssen et al., *Drastic actuator energy requirement reduction by symbiosis of parallel motors, springs and locking mechanisms*, ICRA 2016

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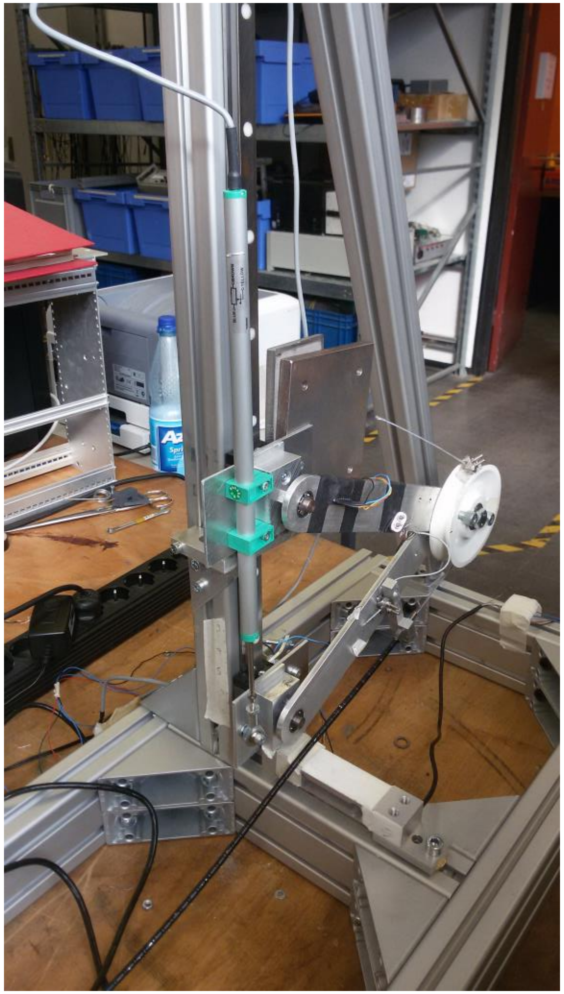
Marco Hopper II



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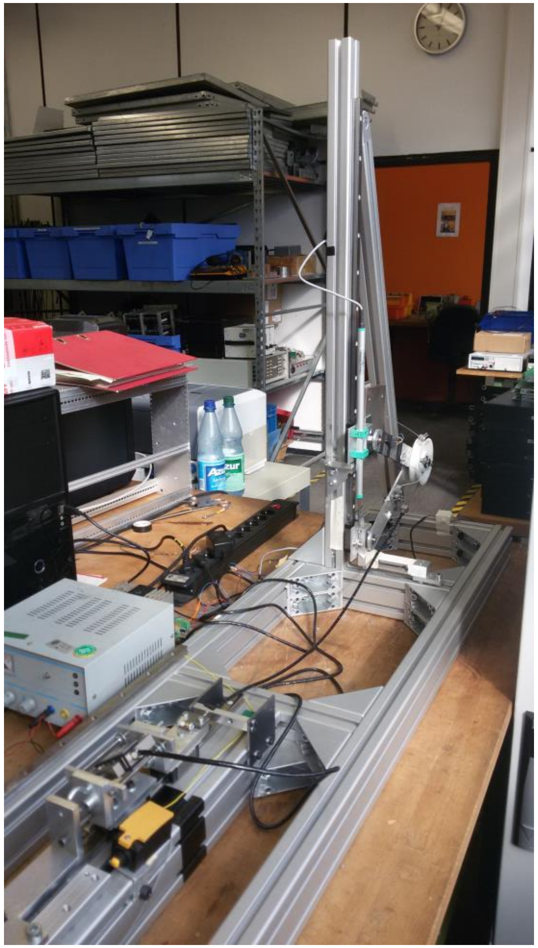
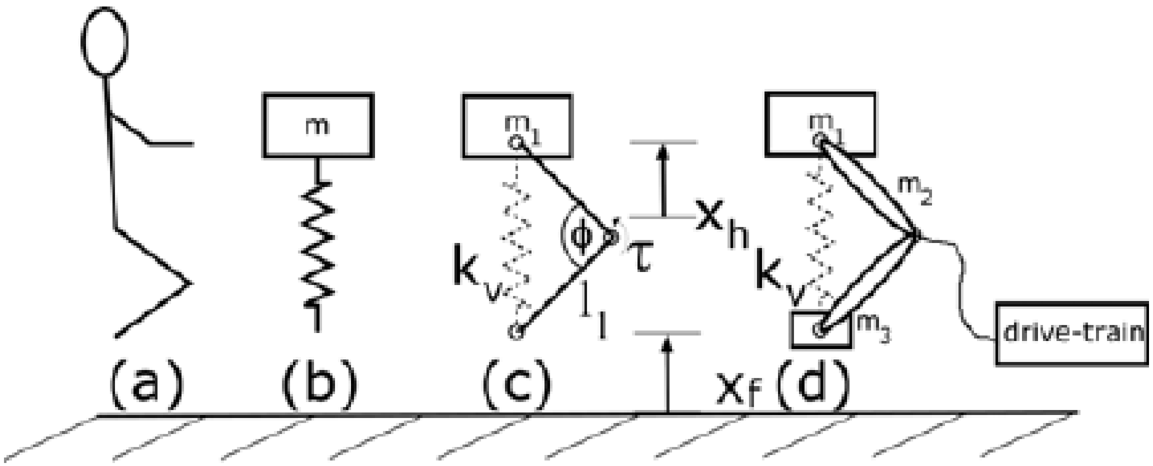
Marco Hopper II



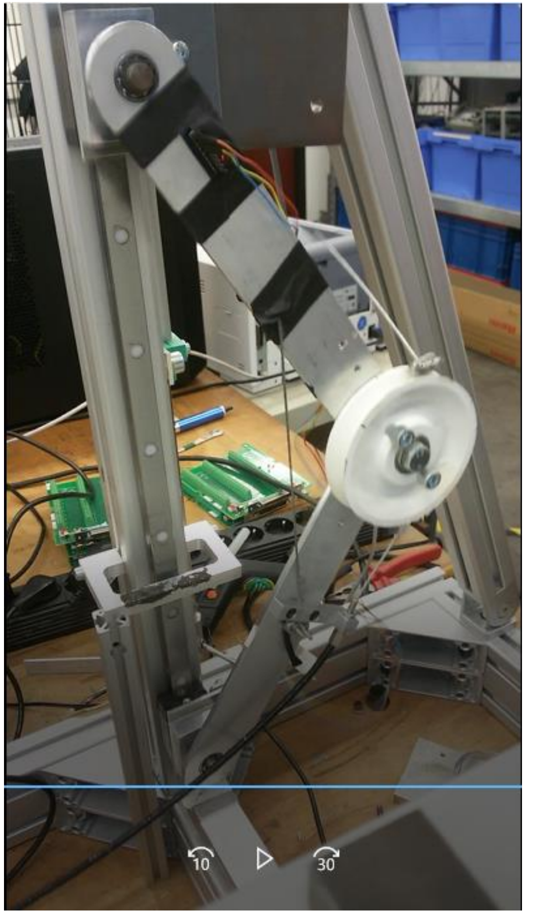
- Leg with 2 segments (shank/thigh)
- Hip/foot: linear motion
- Actuation:
  - Motor
  - Planetary gearbox
  - Spindle
  - Bowden cable
  - Pulley (knee)

Virtual Model control

Concept:
- Cancel system dynamics
- Replace with spring-mass dynamics
- Tune stiffness of virtual spring



Video - February 2017



Improvements to setup

- IMU => potentiometer
- Friction compensation
- State machine:
  - Extension
  - Flight
  - Compression
- More complex state transitions
- Improved “zero force mode” in flight

Video – March 2017

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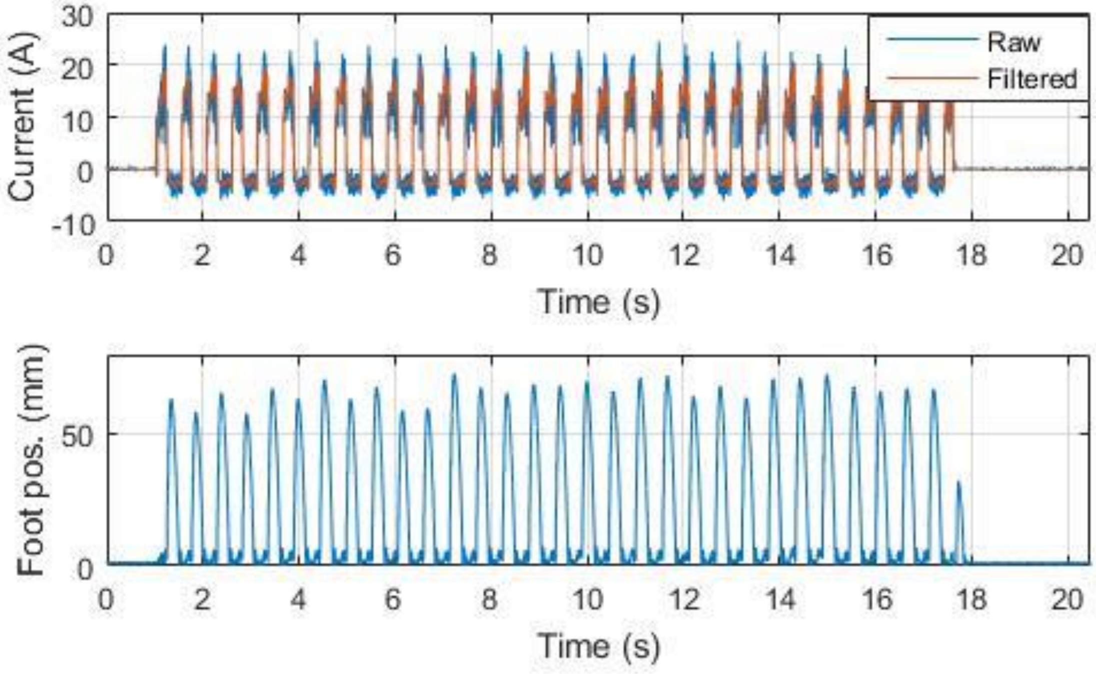
Rigid actuation

- Stable hopping height: 6 cm
- Increased frequency



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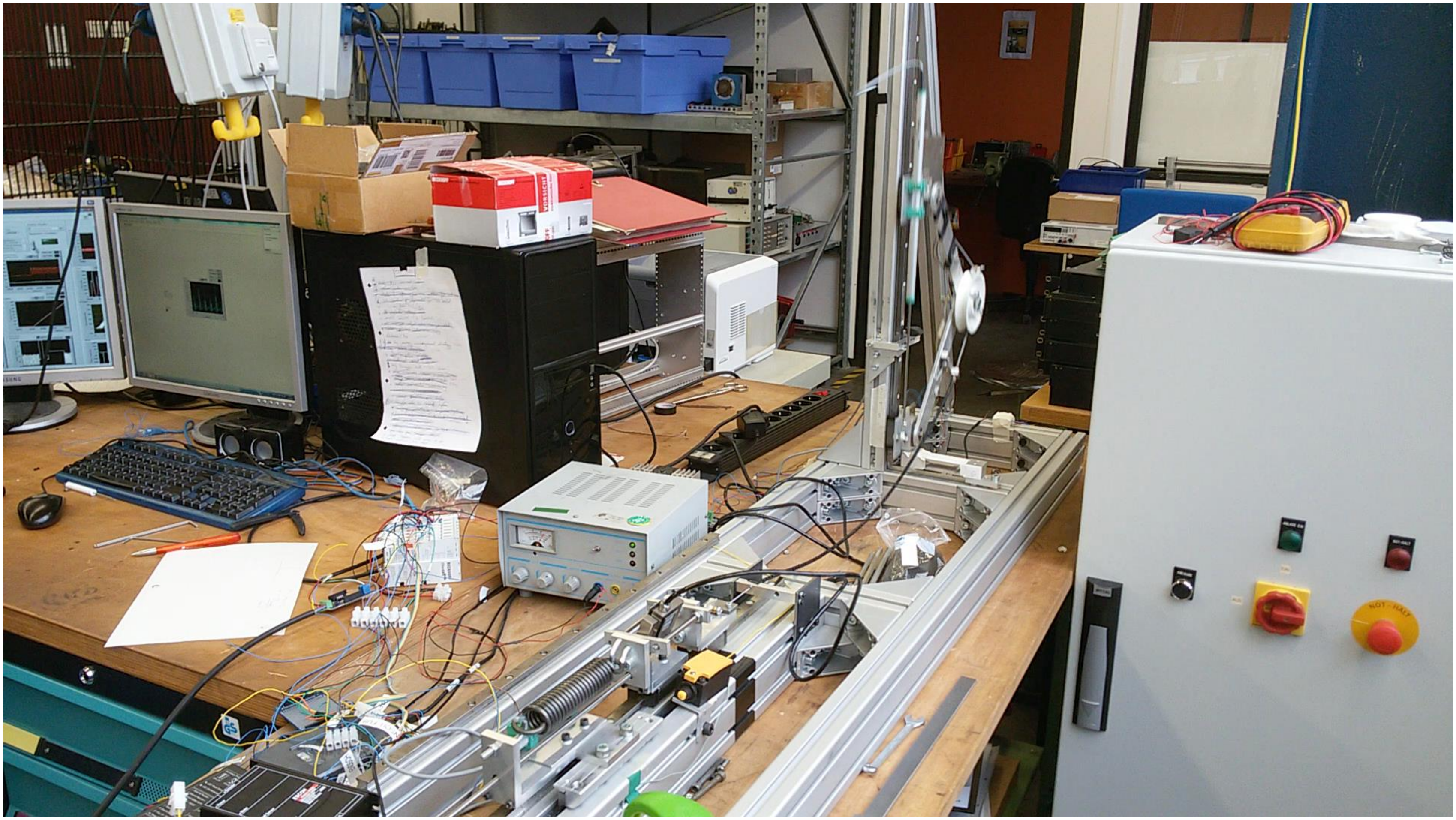
With series spring



With series spring

First (visual) observations:

- Better stability
- Smaller impact forces
- Lower ΔW
- Lower hopping frequency
- Stable hopping height: 3-4 cm

Future work

SEA-driven hopper

- Increase hopping height
- Compare electrical energy consumption with rigid actuation

DuPG-driven hopper

- Show feasibility on setup
- Measure energy consumption

Thank you for listening!

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