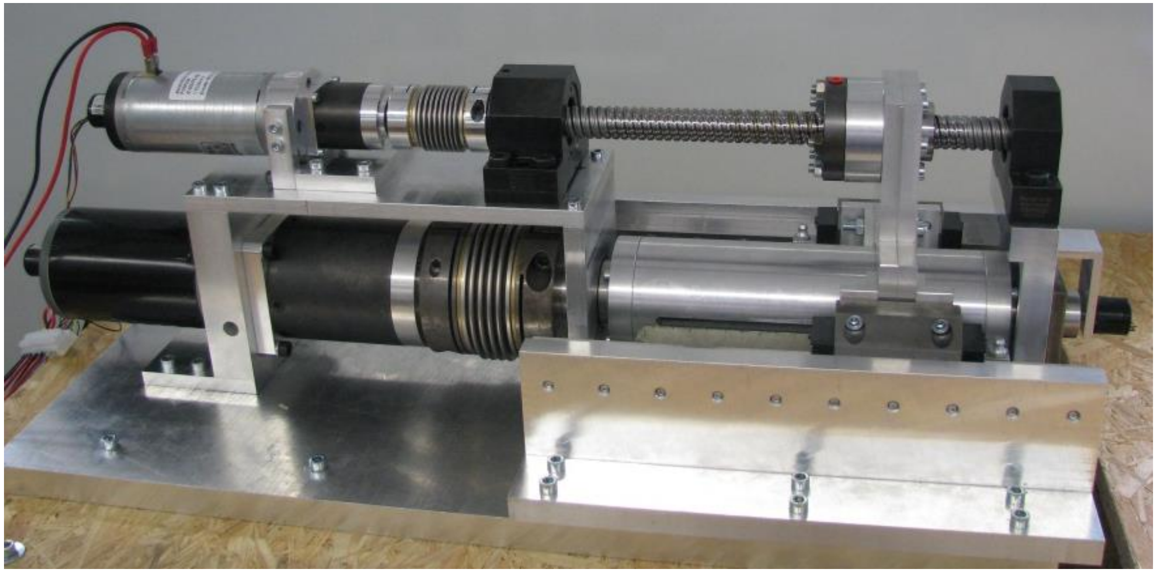
Elastic Actuators for Efficient Robot Motion



Philipp Beckerle, Institute for Mechatronic Systems, TU Darmstadt, Germany

Outline

- Why elastic actuation?
- Possible actuator designs
- Variable torsion stiffness actuator
- Exemplary application: Knee prosthesis
- Project ideas

Why elastic actuation?

Motivation

Requirements in working environments

- Classical: Fast and precise motion

→ High joint stiffness beneficial

- Trend: (Safe!) human-robot collaboration

→ Low joint stiffness beneficial

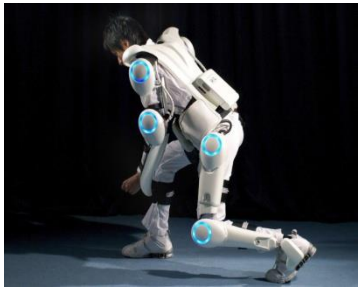
www.logismarket.de

www.assemblymag.com

Requirements in assistive robotics:

- Energy efficiency
- Shock absorption

→ Variable joint stiffness beneficial



www.cyberdyne.jp

www.tum.de

www.endolite.de

Why elastic actuation?

Powered lower limb prosthetics

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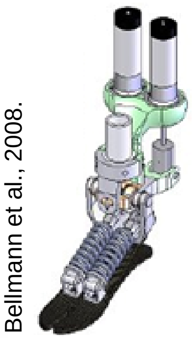
State-of-the-art

- Powered knee and ankle devices
- Elastic actuation and mechanical transfer of energy between joints

Current potentials

- Improvement of energy balance and flexibility

www.ossur.com



Bellmann et al., 2008.

Lawson et al., 2013.

Au et al., 2009.

Geeroms et al., 2013.

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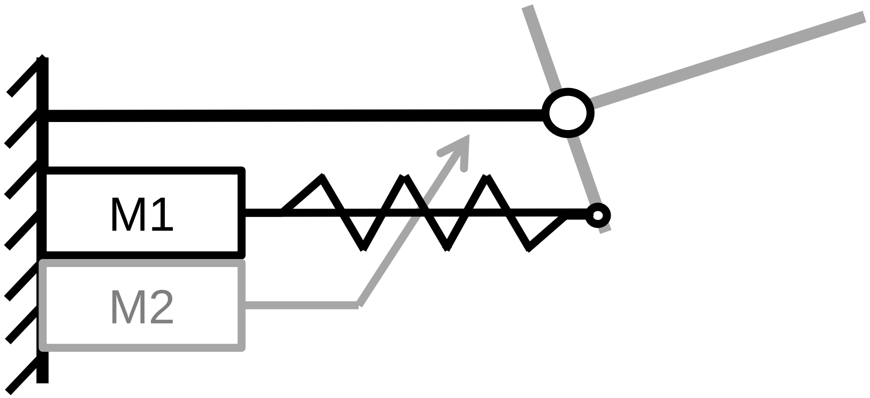
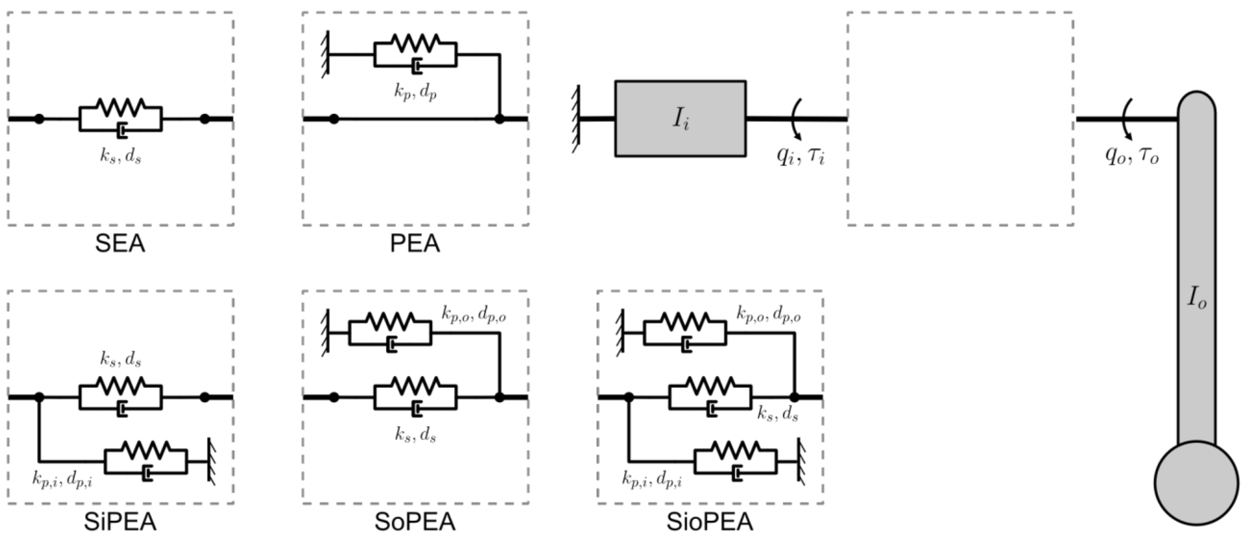
Basic concept and configurations



- Link is driven via elastic element by motor 1
- Motor 2 is used to vary the stiffness charactersistics



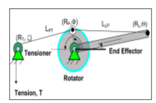
Possible actuator designs

State-of-the-art Variable Stiffness Actuation

Variable Stiffness

according to Van Ham et.al., 2009

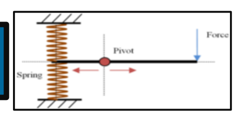
- **Equilibrium-controlled**
  - SEA
- **Mechanically-controlled**
  - MARIONET



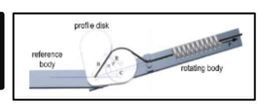
  - VS-Joint

  - PAM

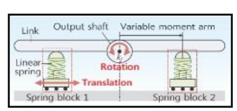
  - AwAS



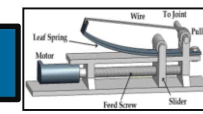
  - MACCEPA



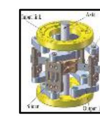
  - HDAU



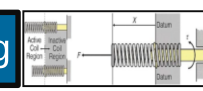
- **Antagonistic-controlled**
  - AMASC
  - PDAU
  - VSSEA
- **Structure-controlled**
  - MIA



  - VSJ



  - Jack Spring



  - **VTS**

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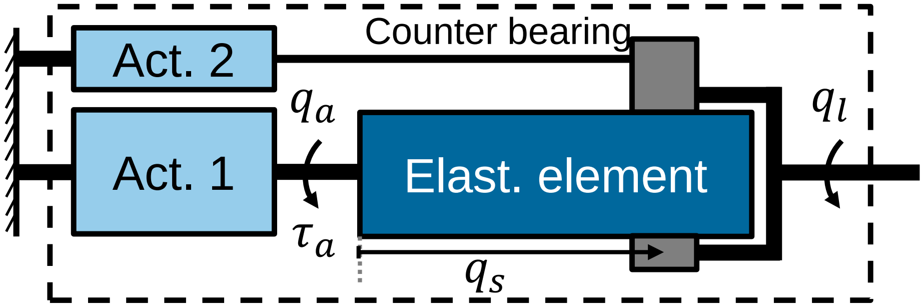
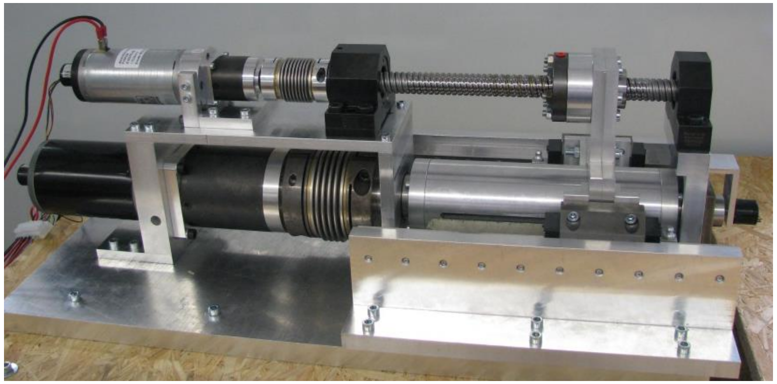
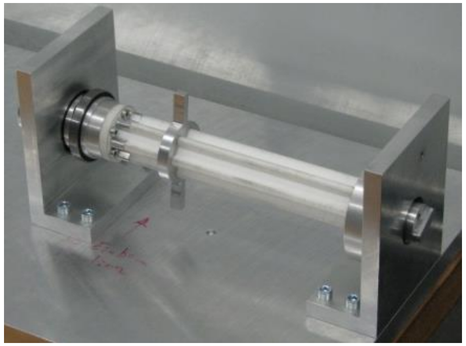
Series-elastic actuation concept

Variable torsion stiffness (VTS)





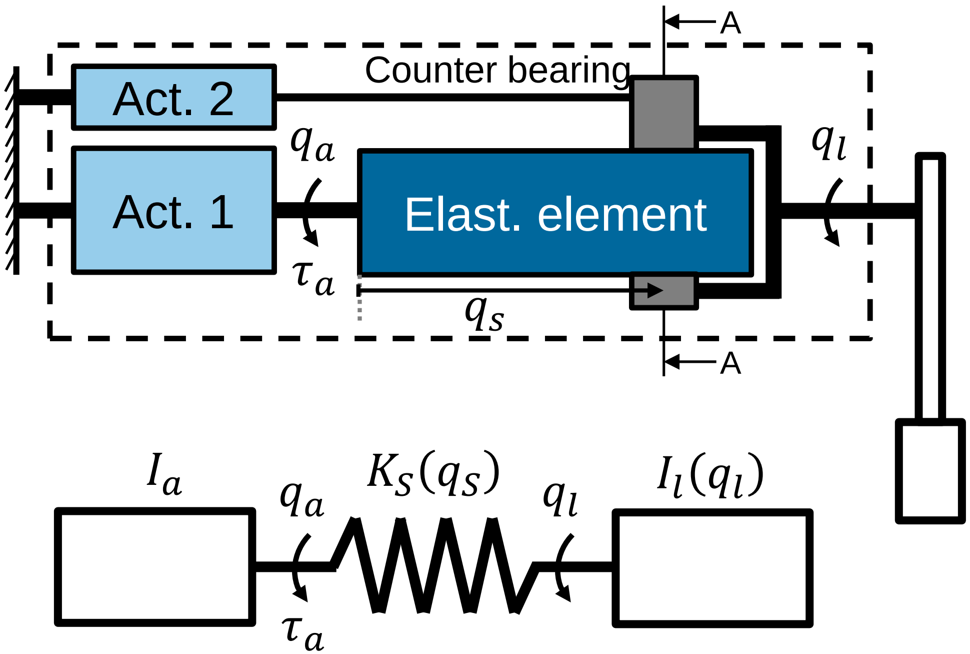
- Actuator 1 moves link via elasticity
- Actuator 2 varies stiffness $K_s(q_s) = \frac{\Gamma I_T}{q_s}$
- Pendulum load in prototype is according to a shank



Elastic acutation

Advanced modeling of transfer behavior

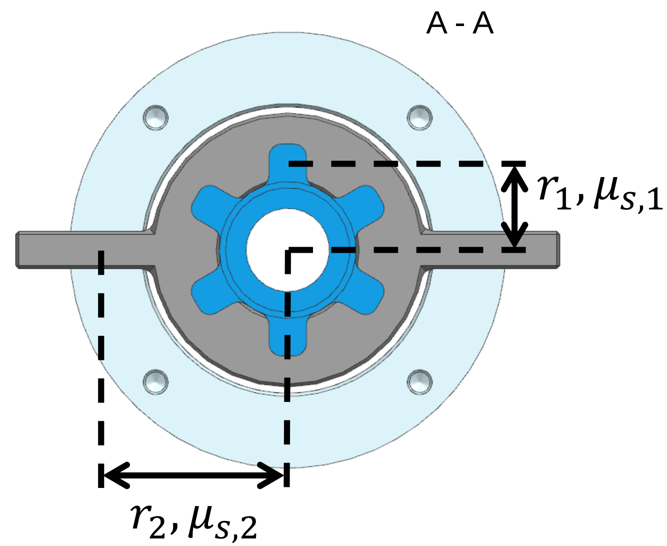
Link motion



$$I_l\ddot{q}_l + G_l(q_l) + K_s(q_s)(q_l - q_a) = 0$$

$$I_a\ddot{q}_a + K_s(q_s)(q_l - q_a) = \tau_a$$

Stiffness variation



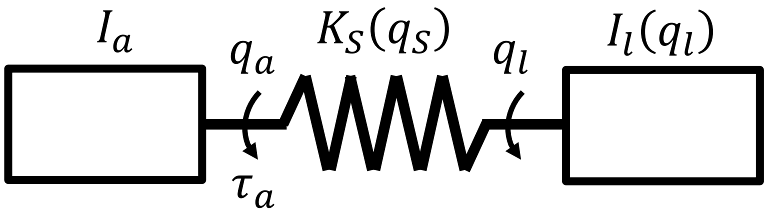
$$m_s(q_s)\ddot{q}_s = F_s - c_f|\tau_e|\,sign(\dot{q}_s)$$

$$c_f = \left(\frac{\mu_{s,1}}{r_1} + \frac{\mu_{s,2}}{r_2}\right)$$

$$\tau_e = K_s(q_s)(q_l - q_a)$$

Question

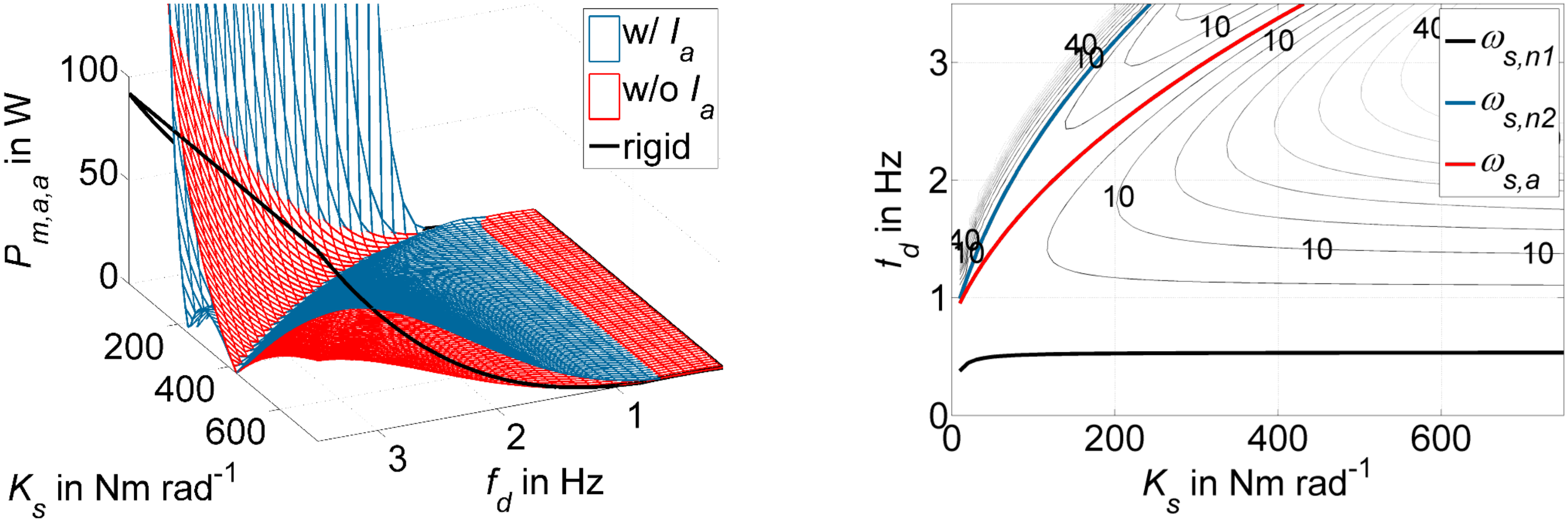
- What impacts the mechanical transfer behavior of VTS?
- What are important transfer paths?
- Could you draw the frequency response?



$$I_l\ddot{q}_l + G_l(q_l) + K_s(q_S)(q_l - q_a) = 0$$

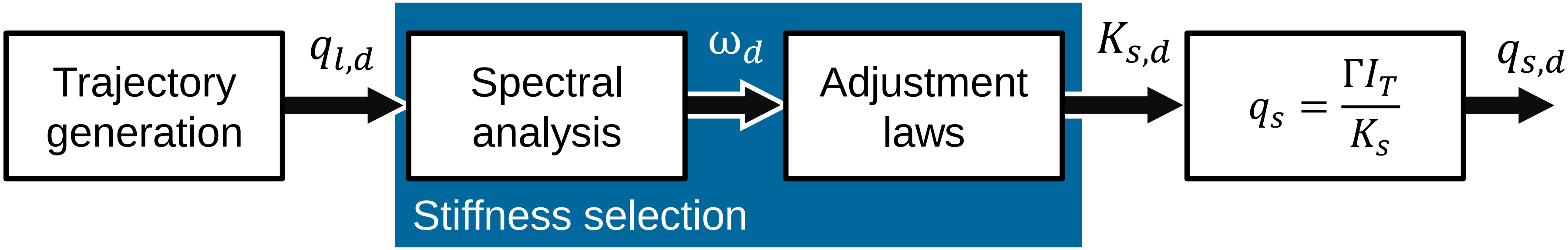
$$I_a\ddot{q}_a - K_s(q_s)(q_l - q_a) = \tau_a$$

Power consumption & natural dynamics



- Mean mechanical power consumption: $$P_{m,a,a} = \frac{1}{t_m}\int_{t_m} |\tau_a \dot{q}_a| dt$$
- Additional areas of minimum power consumption due to natural dynamics

Stiffness control strategy



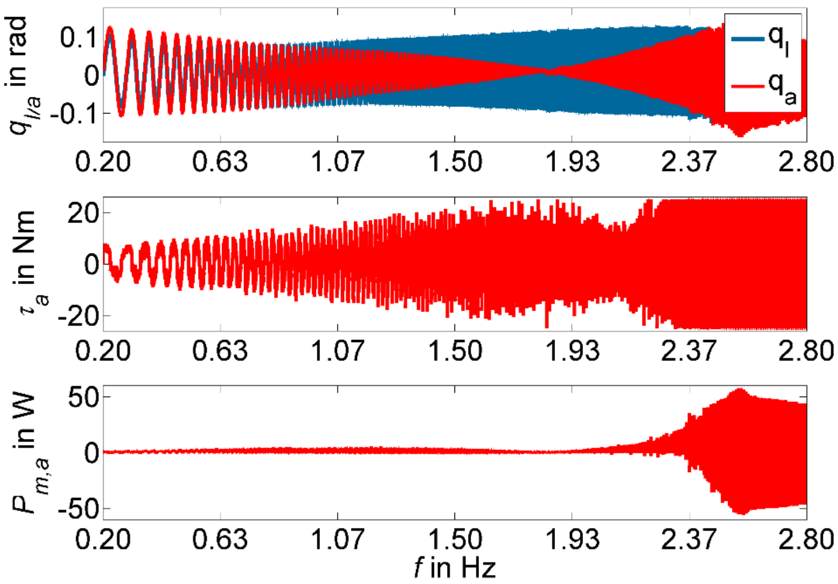
- Determination of frequency component with maximum power share
- Matching antiresonance or second natural mode by stiffness variation

$$K_{s,a}(\omega_d) = I_l \omega_d^2 - m_l g l_l \qquad K_{s,n2}(\omega_d) = \frac{I_a I_l \omega_d^4 - I_a m_l g l_l \omega_d^2}{-(I_l + I_a)\omega_d^2 + m_l g l_l}$$

- Setting counter bearing position with PI-controller

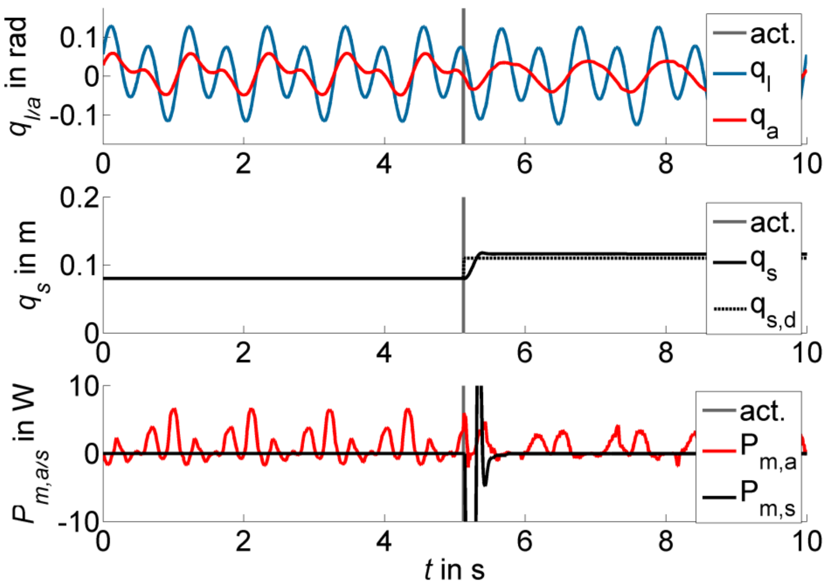
Experimental investigations

Chirp, $K_s = 75\ \mathrm{Nm\ rad^{-1}}$



- Power minimum for antiresonance
- Second natural mode does not show distinct minimum

Dual sine, K_s for antiresonance



- K_s adjusted at $t = 5\ s$
- Power of actuator 1 reduced
- Power peak at actuator 2

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Exemplary application: Knee prosthesis

HMCD-requirements & proshtetic knee concept

ACT: $\hat{v}_k, \hat{\tau}_k, \hat{P}_k$ $(1{,}3\ \mathrm{m\,s^{-1}})$

FUN: $\hat{v}_k, \hat{\tau}_k, \hat{P}_k$ $(2{,}6\ \mathrm{m\,s^{-1}})$
Variation $K_s(q_s)$

MEC: Human kinematics

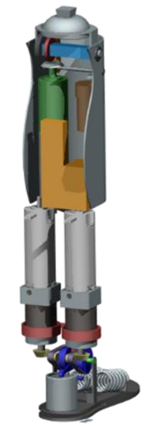
OPT: $10\ \mathrm{km}$ walking/running

WEI: $2{,}5\ \mathrm{kg}$ (comp. human)

SIZ: human dimensions

SEN: q_k, q_a, τ_a

Knee concept



- DC-Motor
- Serial, variable torsion stiffness
- Revolution joint
- Recuperation, LiPo
- 2 position encoders

Exemplary application: Knee prosthesis

Determination of gait-optimal stiffness values

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Biomechanics

q_k, τ_k Lipfert, 2010.

Inverse dynamics with stiffness iteration

$$\tau_k + K_s(q_k - q_a) = 0$$

$$I_a \ddot{q}_a + K_s(q_a - q_k) = \tau_a$$

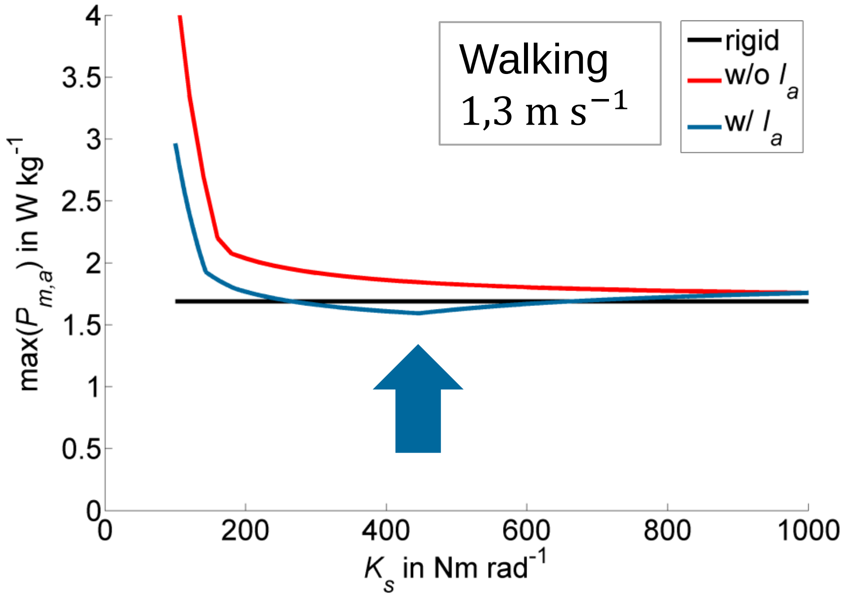
Requirements

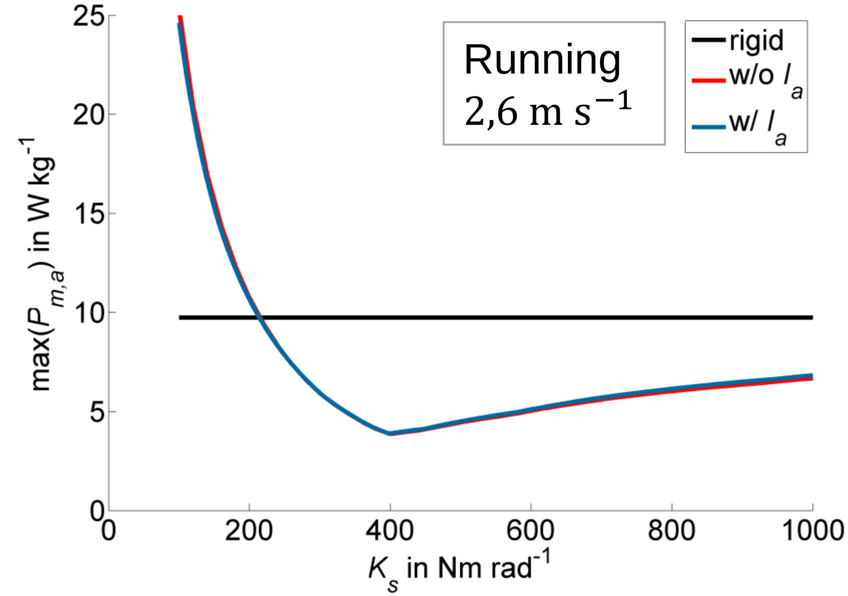
q_a, τ_a

Power minimization

$$\min_{K_s}(\max_{t_m}(P_{m,a}))$$

$$P_{m,a} = \tau_a \dot{q}_a$$





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Exemplary application: Knee prosthesis

System integration & simulation w/ prosthesis

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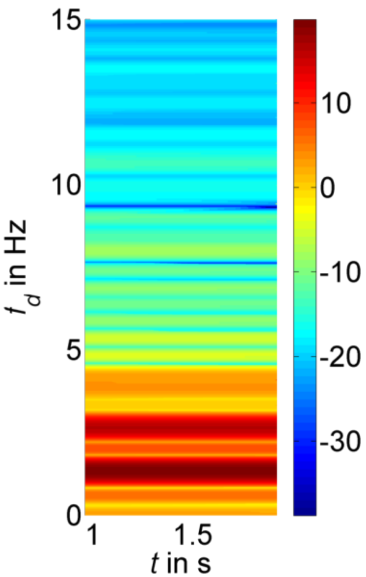
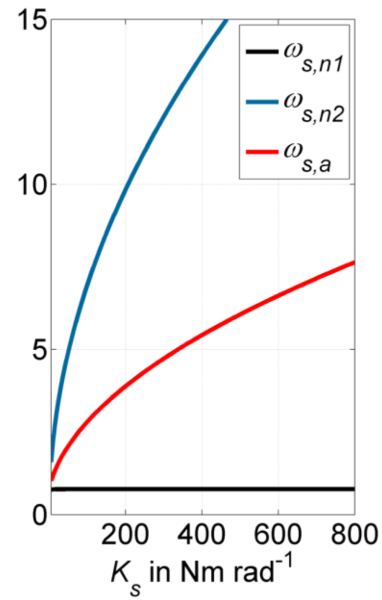
Integration actuation / controls

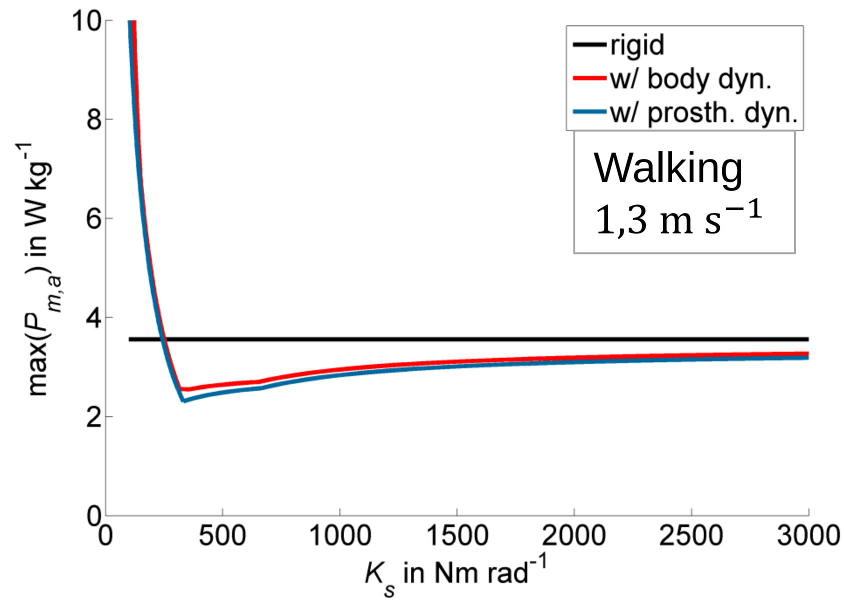




- Suitability of stiffness control

→ Major frequencies close to first natural mode (constant w.r.t. K_s)

Deviating dynamics with prosthesis



- Considers inertial parameters of prosthesis in human simulation

→ Maximum power reduced (10%)

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Project ideas

HMCD-requirements & proshtetic knee concept

- Variable stiffness control for human motions with prosthesis
  - Stiffness optimization for knee actuator during squats and hopping
  - Relation of power consumption, biomech. optimum, and natural dynamics
  - Implementation as a stiffness control algorithm for a prosthesis