User-Centered Actuation of Lower Limb Prosthetic Devices

TECHNISCHE
UNIVERSITÄT
DARMSTADT

Visiting Imperial College, London, UK

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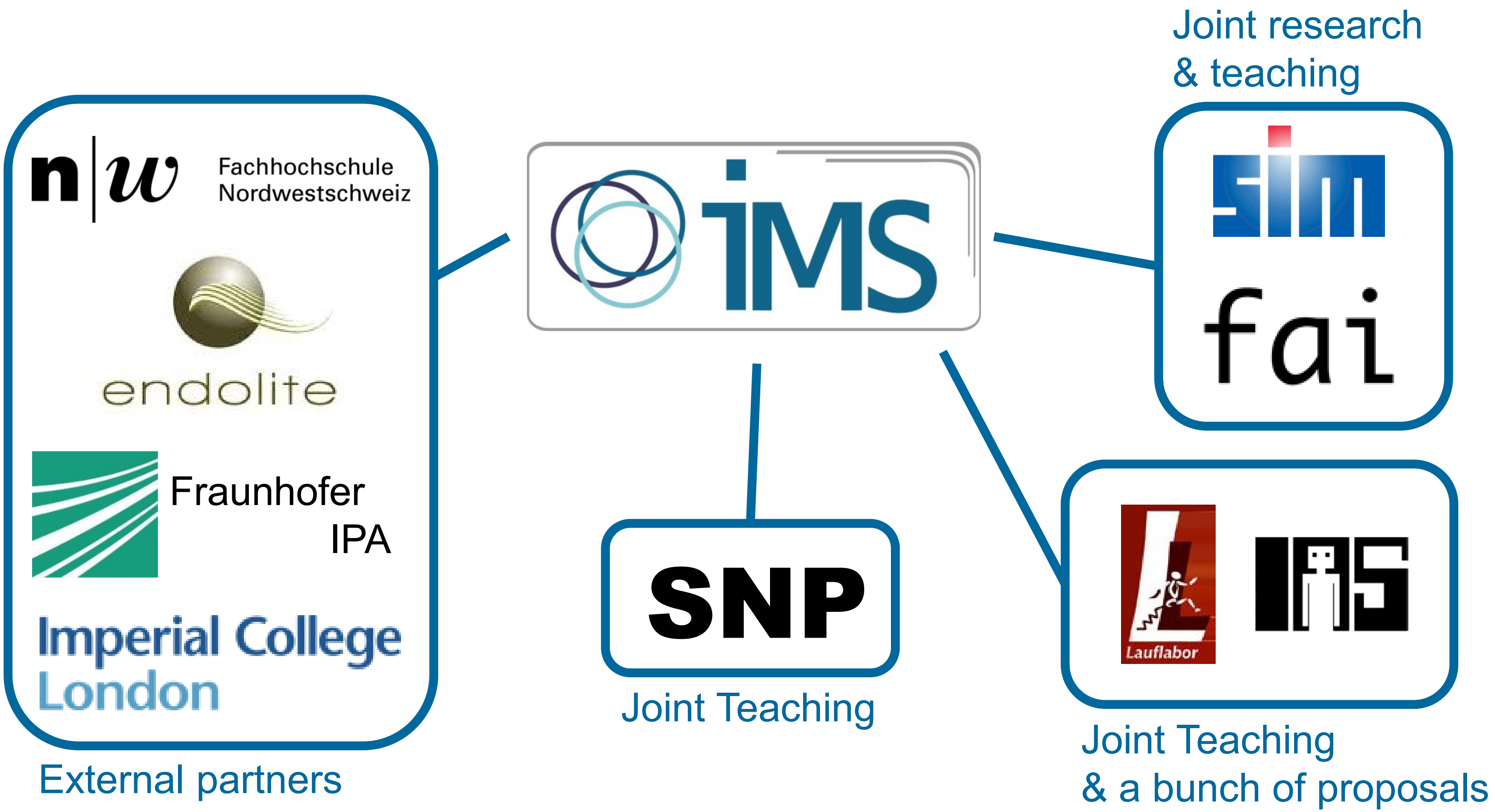
TU Darmstadt, IMS and …
our cooperations in prosthetics, robotics etc.



Joint research & teaching

External partners

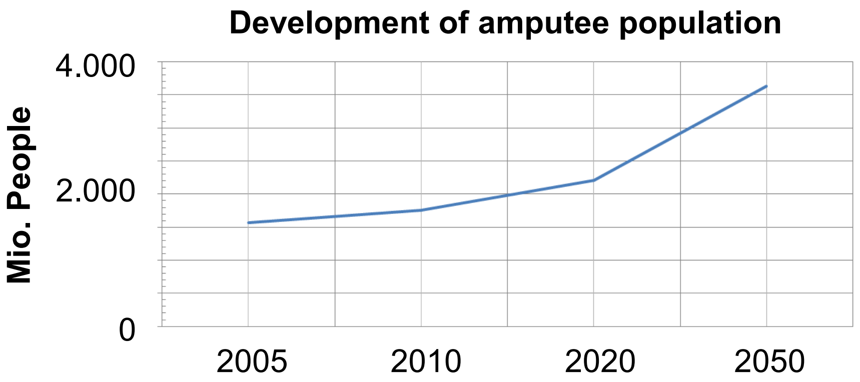
Joint Teaching

Joint Teaching
& a bunch of proposals

Outline

- Motivation & key research issues
- User-centered design approach
- Compliant actuator design
- Variable stiffness control
- Conclusion & outlook

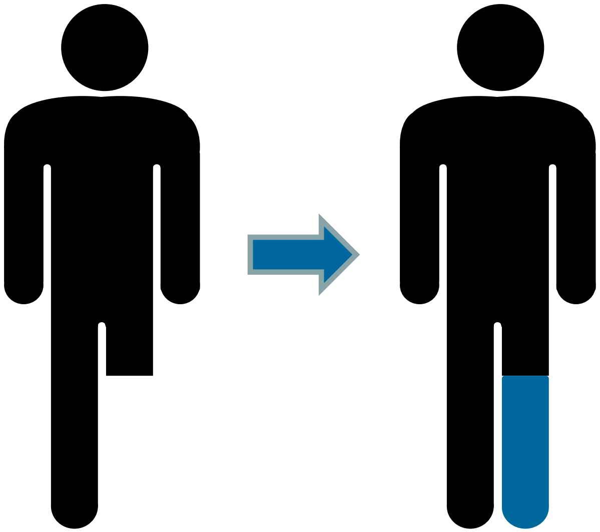
Motivation and challenge


Development of amputee population

Ziegler-Graham et al., 2008.

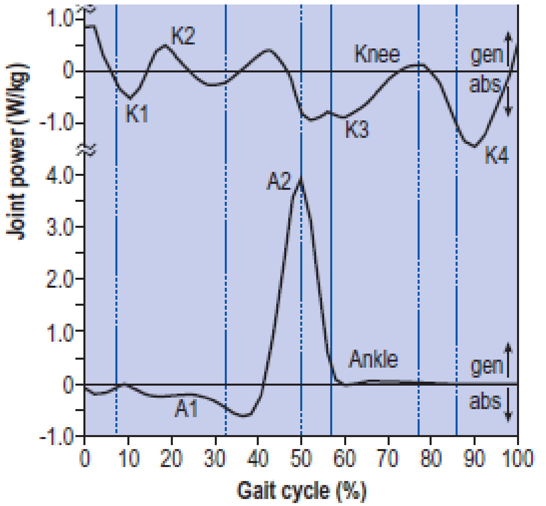
North american study:

- 1.6 million amputees in 2005
- 66% lower limb amputation
- Forecast for 2050: 3.6 million amputees

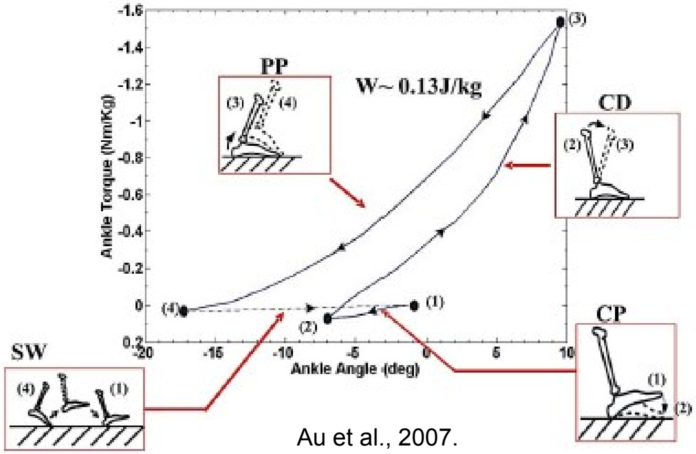


A prosthesis should copy function and appearance of a lost body part

Biomechanical and psychological factors



Whittle, 2007.



Au et al., 2007.

Biomechanical

High joint torques & powers (100Nm/250W)

Variable stiffness, nonlinear behaviour

Power dissipation and generation

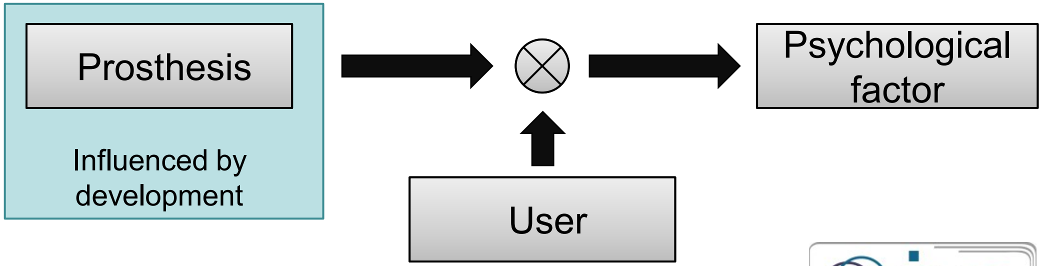
Psychological

Satisfaction (SAT): *Acceptance of dissatisfaction*

Feeling of security (FOS): *Flexibility - felt stability*

Body scheme integration (BSI): *Appearance - function*

Christ et al., 2012.



State-of-the-art
(Powered) lower limb prosthetic systems

Commercial products

- (Semi-)active knee and ankle joints
- First systemic solutions
- Series elastic ankle designs

Research approaches

- Advanced series elastic designs
- Complex mechanisms, active overall systems

Challenges

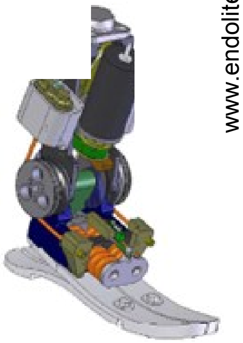
- Gait flexibility still limited (speed, direction, stairs, slopes)
- Technical concepts lack structured user-orientation
- Trade-off between active and passive dynamics
- General design methodology / assessment scores
- Realization of energy storage

genium.ottobock.com

www.ossur.com

www.endolite.de

Bellmann et al., 2008.



Au et al., 2009.

Goldfarb, 2013, vanderbilt.edu.

Geeroms et al., 2013.

Key research issues and approaches

A synergistic design requires consideration of user and prosthesis!

Development

Technical solutions are mainly designed based on biomechanical criteria.

User-Centered Design: Identification and consideration of human factors.

Technologies

Actuation tries to mimic sound biomechanics ignoring changed dynamics.

Holistic modeling including drive and gait **simulation with prosthesis**.

Stiffness is optimized to biomechanical data. Adaptation frequency unclear.

Adjustment laws considering drive dynamics.

Power analysis including model of variation mechanism.

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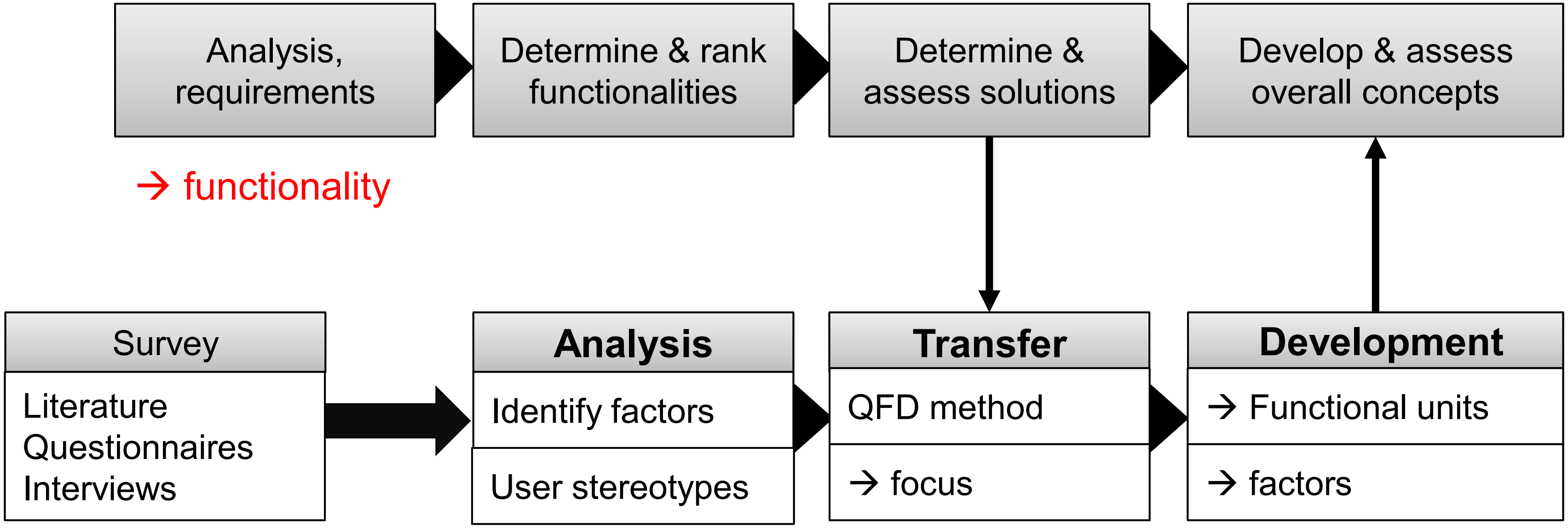
Design methodology
Integration of user experience & assessment

Objective assessment criteria based on subjective user assessment



Analysis, requirements

Determine & rank functionalities

Determine & assess solutions

Develop & assess overall concepts

→ functionality

Survey

Literature
Questionnaires
Interviews

Analysis

Identify factors

User stereotypes

Transfer

QFD method

→ focus

Development

→ Functional units

→ factors

→ usability

Windrich, 2012.
Beckerle et al., TAR 2013.

Analysis
User stereotypes and evaluation

Otto Bock

- (Female) active person
- Person w/ limited activity

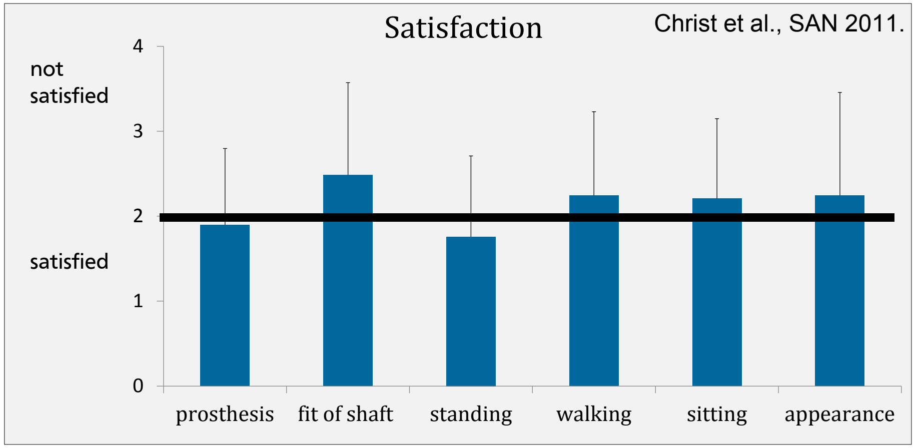
Expert study N = 20

Schürmann et al., BNF-PRM 2013.

Questionnaire optimization (85 Items)

Factor modeling:
SAT, FOS, BSI, Support (SUP), Socket (SOC), Mobility (MOB), Outer Appearance (OUT)

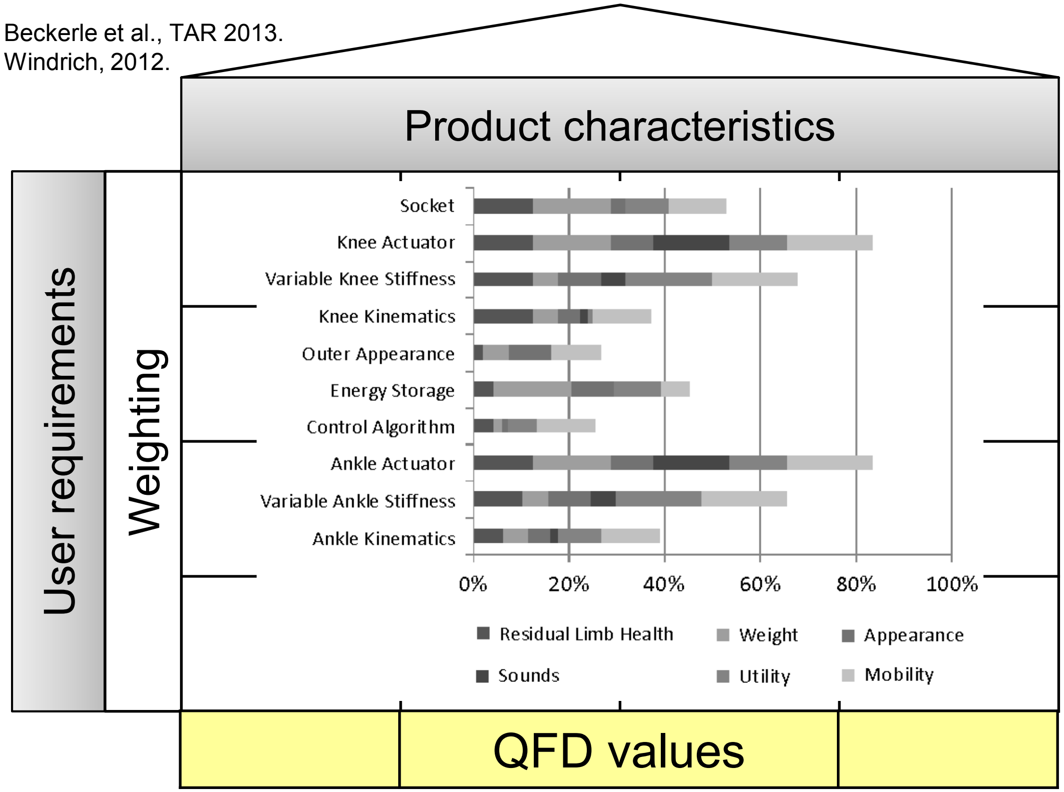
SAT	13	SUP	10
FOS	14	SOC	15
BSI	11	MOB	16
REJ	2	OUT	4



Christ et al., SAN 2011.

Transfer
Quality function deployment

Beckerle et al., TAR 2013.
Windrich, 2012.



Aim

Connect users & engineers POV

Assessment

Progressive scale (0 – 1 – 3 – 9)

Result

QFD-value = scale of influence

→ **Development focus**

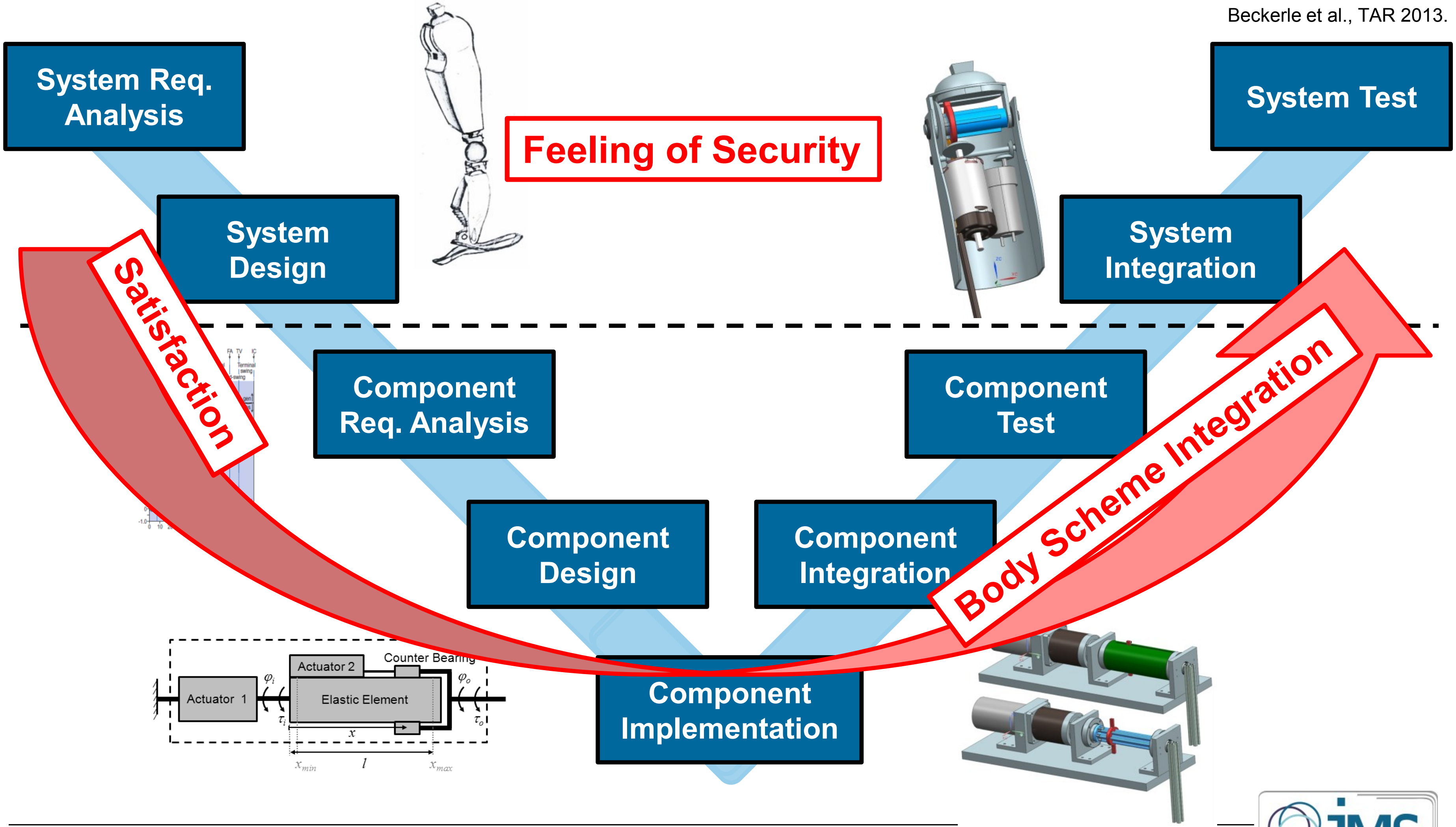
First indications regarding SAT with active prostheses based on Legro 1999

Actuators and variable stiffness are relevant, socket issues remain (underranked)

Development

System integration

Beckerle et al., TAR 2013.

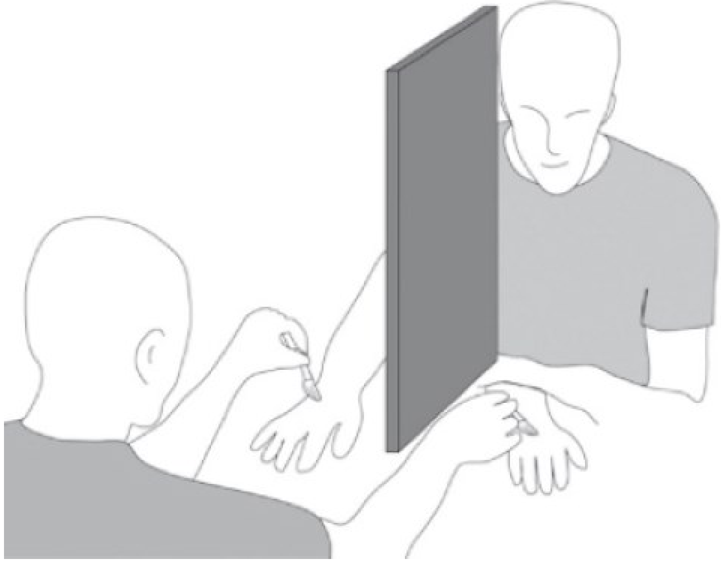


Psychological factors
Rubber Hand Illusion

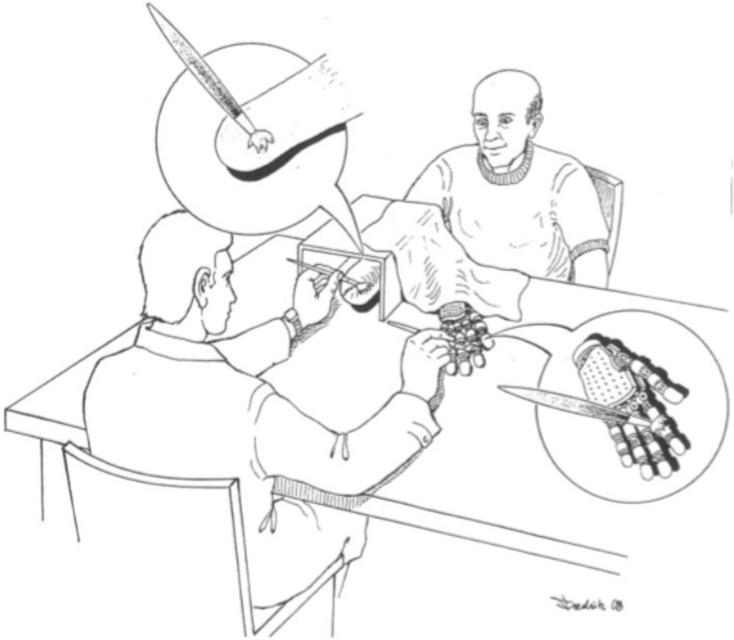
→ Illusion in which tactile sensations are referred to an alien limb

Botvinick & Cohen 1998

→ Three-way interaction between vision, touch and proprioception

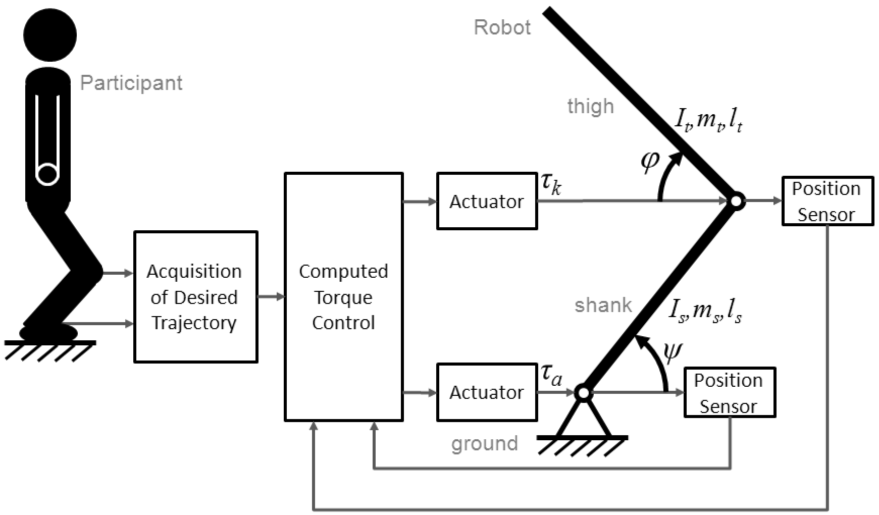


Moseley et al., 2012

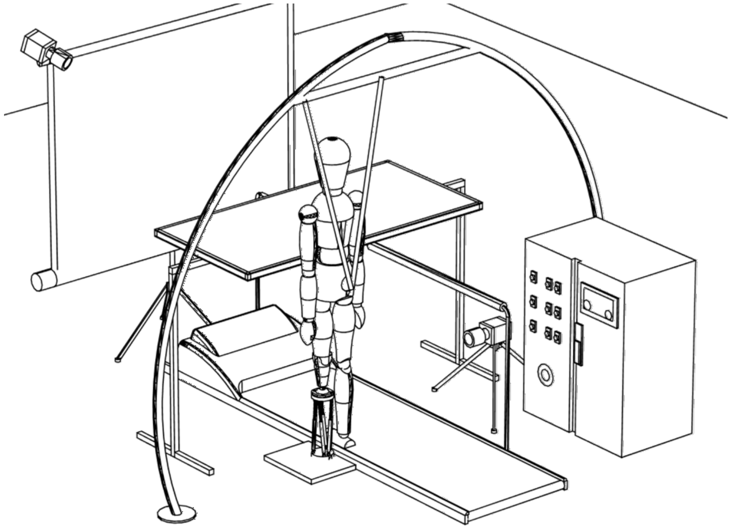


Rosén et al., 2009

Experimental approaches



Beckerle et al., SMC2012. Christ et al., BMT2012.



Christ et al., EMBC 2012. Wojtusch et al., EMBC 2012.
Beckerle et al., SMC2013.

Int^{2}Bot

➢ Robot finalized, Kinect trajectory issues

- Maintainance of BSI and interfaces

Prosthesis-User-in-the-Loop

➢ Simple prototype in development

- Simulation of gait with prosthesis

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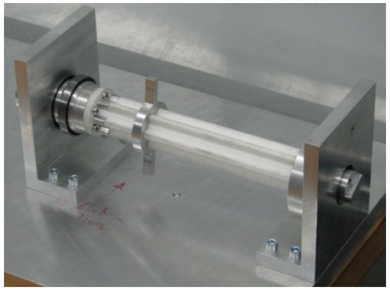
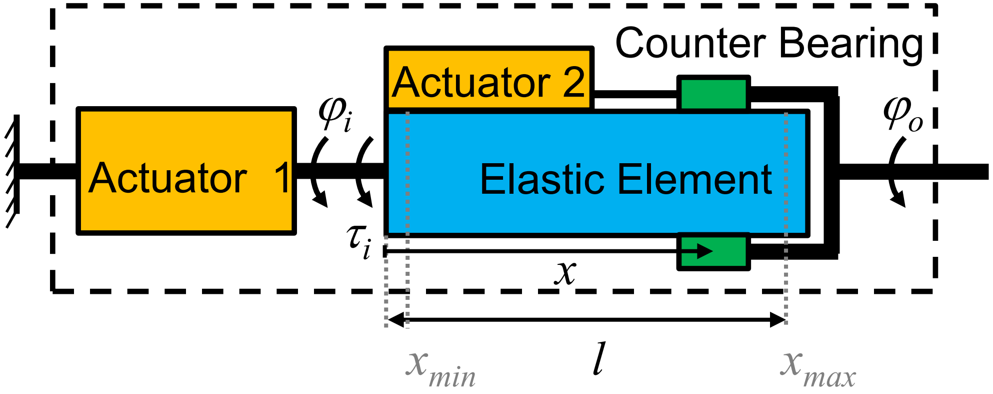
Series Elastic VTS Actuator Concept

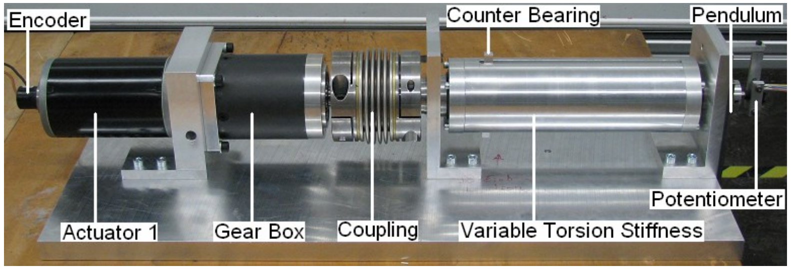
- Actuator 1 is driving the joint via Variable Torsion Stiffness
  - Elastic element in serial configuration
- Actuator 2 moves counter bearing to adjust stiffness

→ Stiffness varied as function of active elastic length



$$k_{VTS}(x) = \frac{G I_T(x)}{x}$$

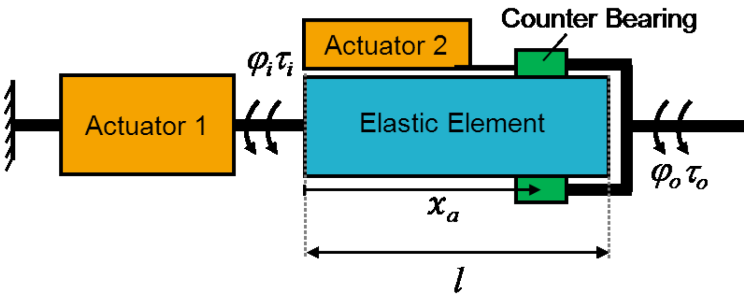


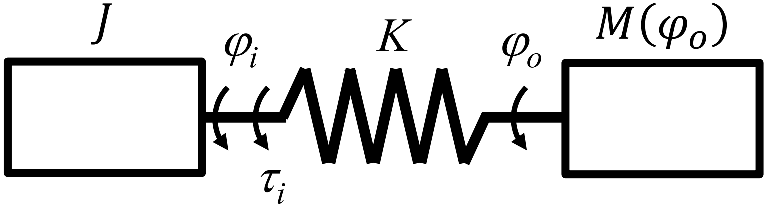


Schuy et al., Biorob2012.
Beckerle et al., AIM2013.

Modeling of VTS

Drive Train Model

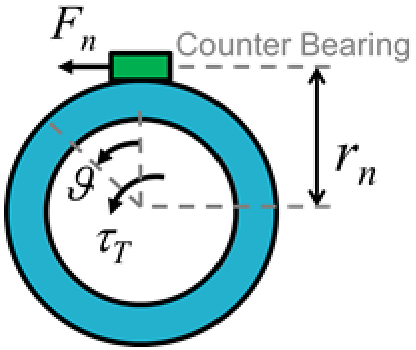




$$M(\varphi_o)\ddot{\varphi}_o + G(\varphi_o) + K(\varphi_o - \varphi_i) = 0$$
$$J\ddot{\varphi}_i - K(\varphi_o - \varphi_i) = \tau_i$$

$$C(\dot{\varphi}_o, \varphi_o) = 0$$

Stiffness Adjustment Model



$$F_f = -\mu \frac{k_{VTS}(x)}{r_n} \vartheta_x$$

Coulomb-type friction

Beckerle et al., AIM2013.

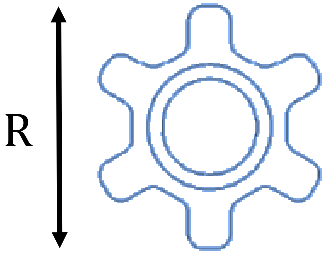
Dimensioning of elastic element in VTS

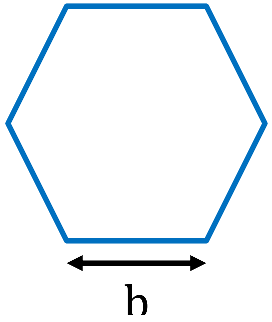
Schuy et al., Biorob2012. Beckerle et al., AMAM2013. Schuy et al., AIM2013.

Dimensioning regarding outer geometry

Tube: $R = \sqrt[4]{\frac{2\ k_{VTS,\max}\, x_{min}}{\pi\, G\, (1-\lambda^4)}}$

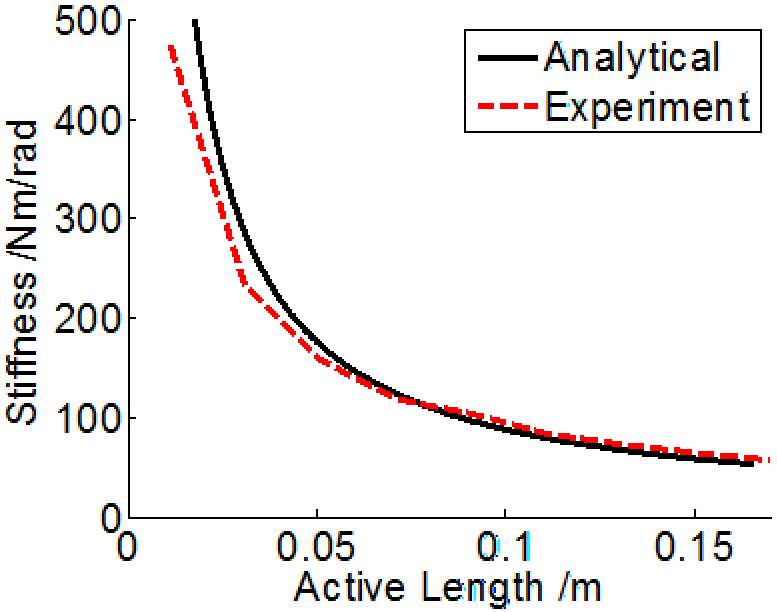
Hexagon: $b = \sqrt[4]{\frac{k_{VTS,\max}\, x_{min}}{c_g\, G}}$





Static stiffness evaluation

- Coupling and gears: $k_{cg} = \frac{k_c\ k_g}{k_c+k_g}$
- Calculation: $k_{vts} = \frac{mgl\,\sin(\varphi_o)}{\varphi_i-\varphi_o-\frac{mgl\,\sin(\varphi_o)}{k_{cg}}}$



Power analysis considering system dynamics

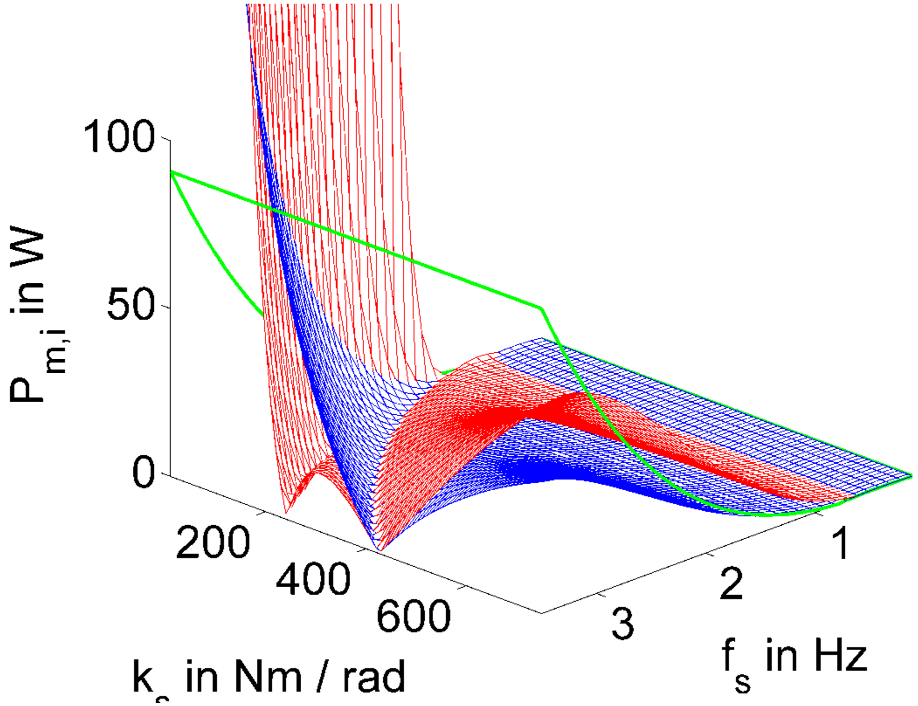
Beckerle et al., AIM2013.

$$M(\varphi_o)\ddot{\varphi}_o + G(\varphi_o) = \tau_o = K(\varphi_i - \varphi_o)$$

$$K(\varphi_i - \varphi_o) = \tau_i = \tau_o$$

$$J\ddot{\varphi}_i + K(\varphi_i - \varphi_o) = \tau_i = \tau_o$$

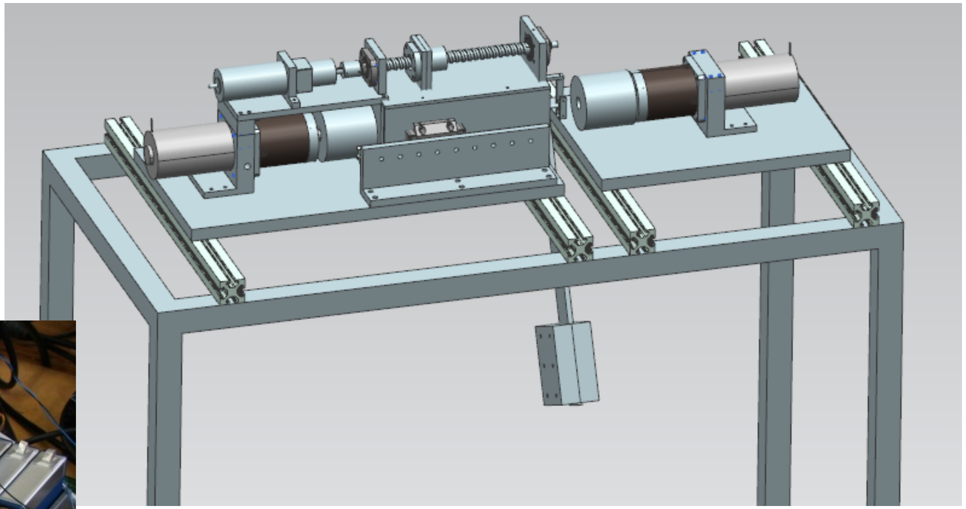
Average power: $\frac{1}{t_m}\int_{t_m} \tau_i \varphi_i \, dt$



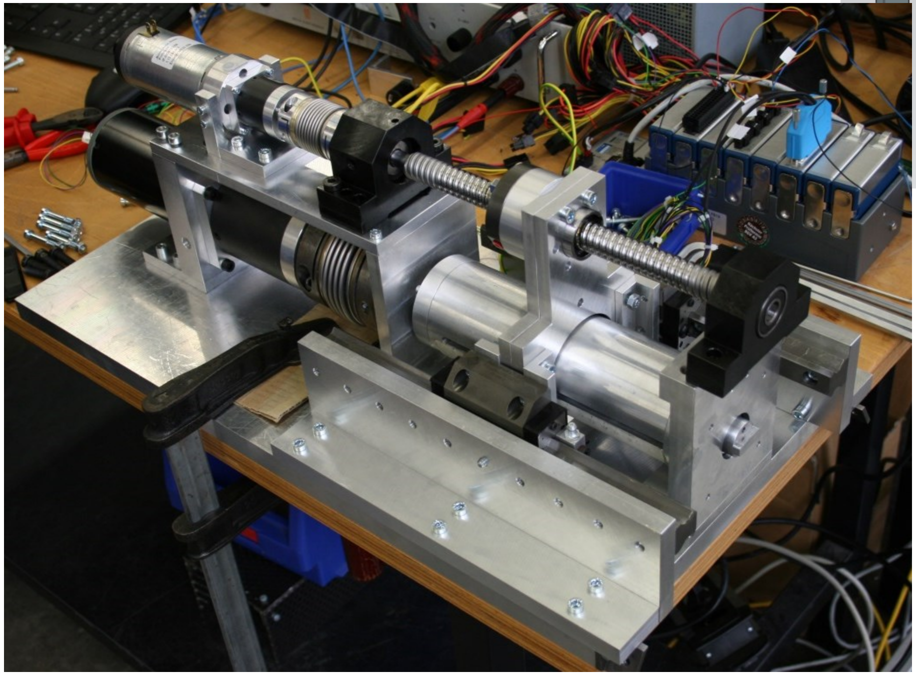
Impact on actuator design

- Areas of low power are shifted → Appropriate specification of operating range
- Addtional power minimum occurs → Increased versatility in stiffness selection

In progress: System upgrades



Automation of stiffness adjusment



Simulation of biomechnical loads

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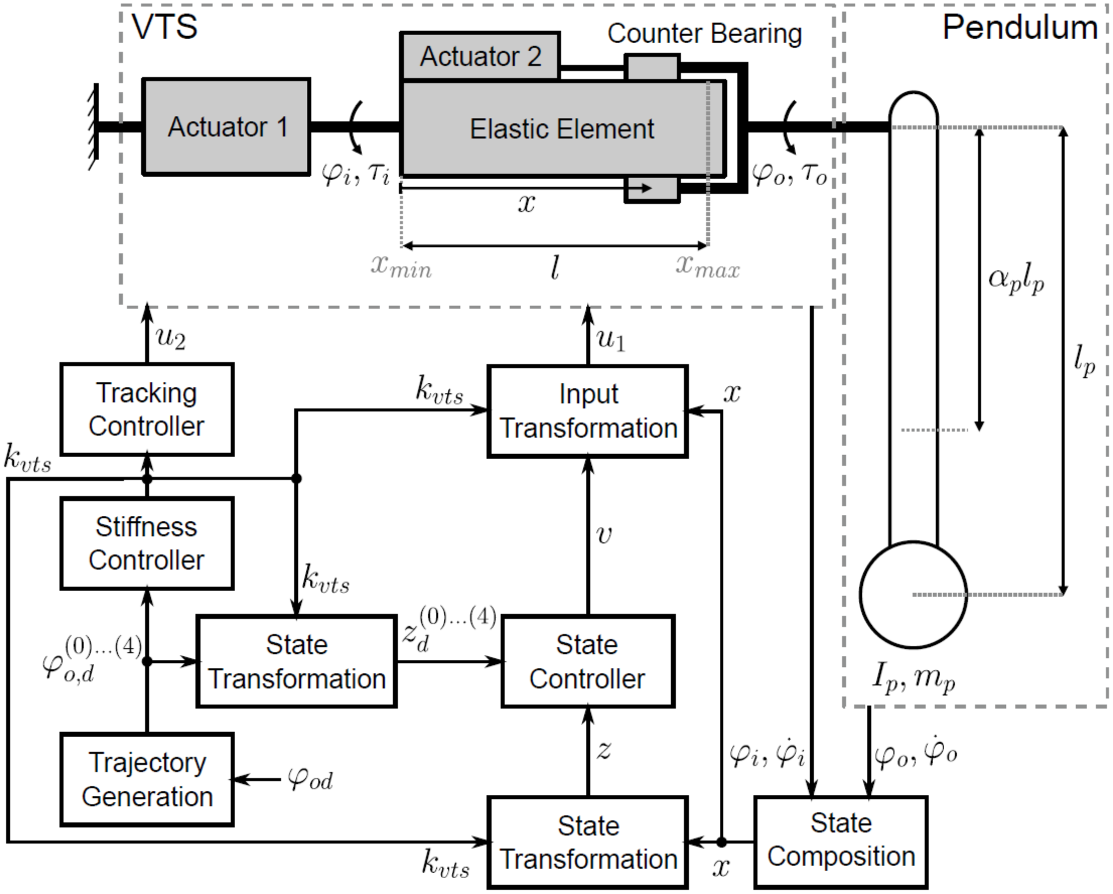
Position Control

Feedback Linearization

- Suitable for low stiffness due to Spong et al. 1989
- Stiffness adaptation considering adjustment
- Robustness extension

Alternative appraoch

- Passivity based control



Beckerle et al., AIM2013.

Variable stiffness control strategy (1)

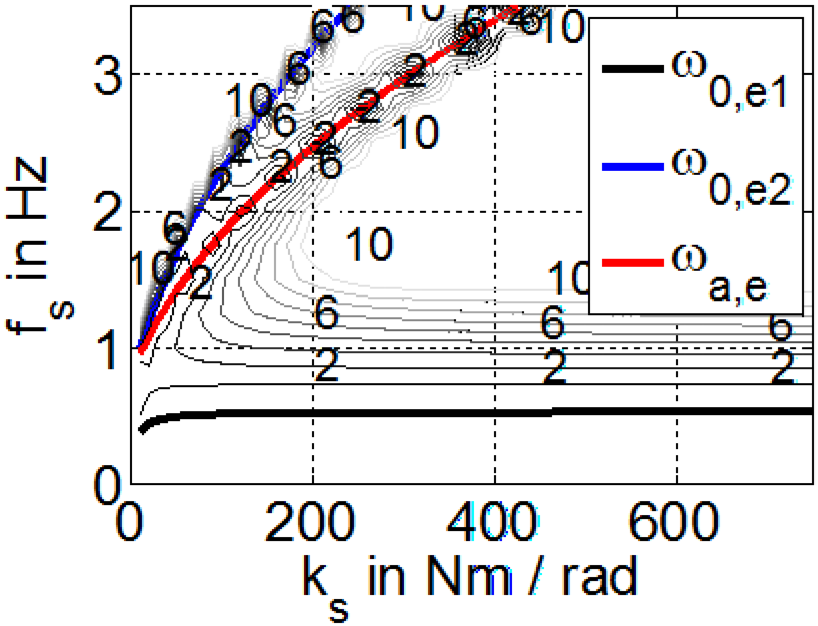
Linearized transfer functions @ 0°

- Drive sided behaviour

$$\frac{\varphi_i(s)}{\tau_i(s)} = \frac{Ms^2 + K + mgl}{c_4 s^4 + c_2 s^2 + c_0}$$

- Link sided behaviour

$$\frac{\varphi_o(s)}{\tau_i(s)} = \frac{K}{c_4 s^4 + c_2 s^2 + c_0}$$



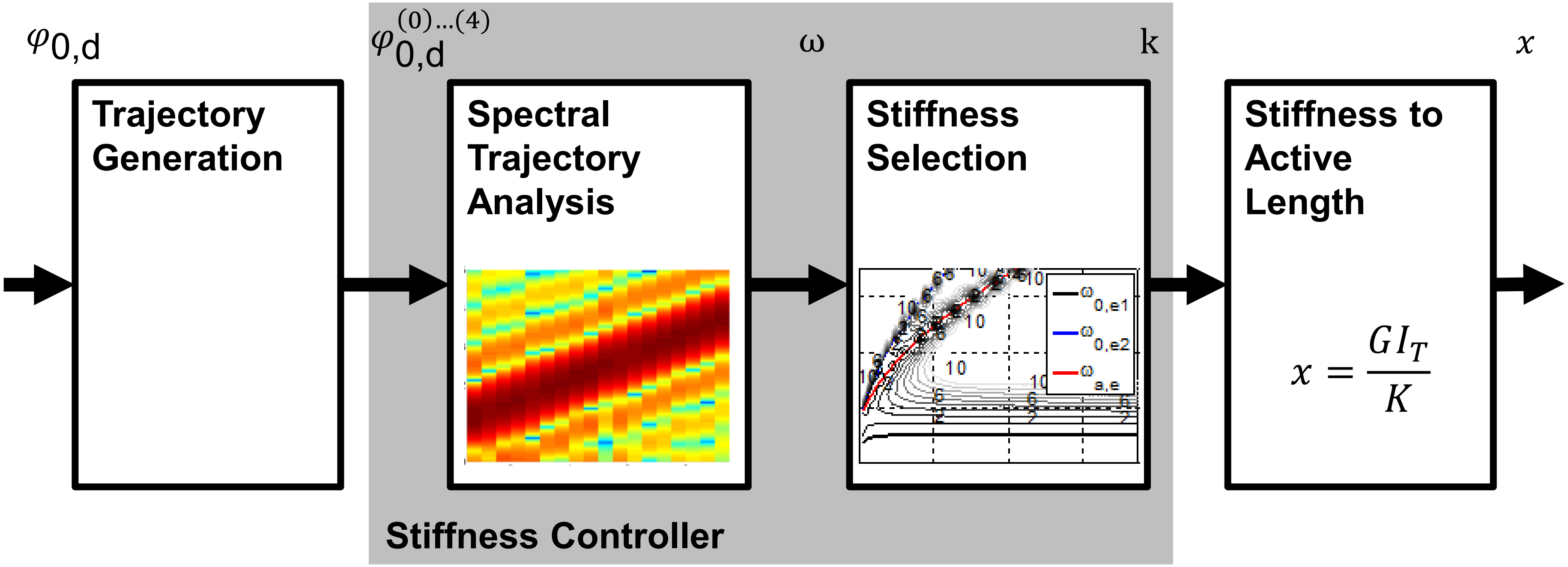
→Two natural frequencies $\omega_{0,e1/2}$ and one antiresonance mode $\omega_{a,e}$.

→Previous concepts mainly tune stiffness to $\omega_{a,e}$. Two options available:

$$K_{a,e}(\omega) = M\omega^2 - mgl \qquad K_{0,e2}(\omega) = -\frac{JM\omega^4 - Jmgl\omega^2}{-(J+M)\omega^2 + mgl}$$

Beckerle et al., AIM2013.

Variable stiffness control strategy (2)



$\varphi_{0,d}$

Trajectory Generation

$\varphi_{0,d}^{(0)\ldots(4)}$

Spectral Trajectory Analysis

ω

Stiffness Selection

k

Stiffness to Active Length

$$x = \frac{GI_T}{K}$$

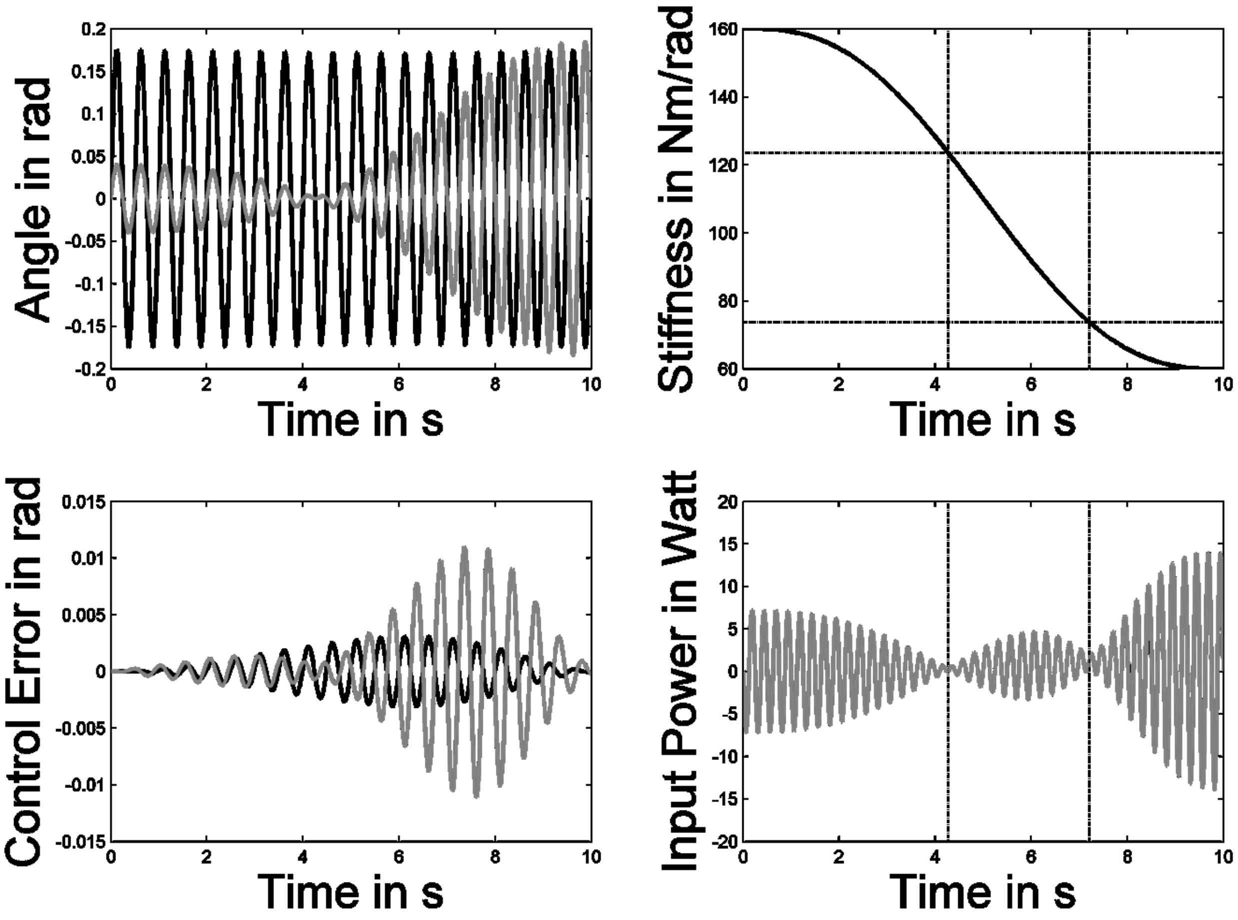
x

Stiffness Controller

- Spectral analysis with bank of Goertzel filters → major frequency component
- Stiffness selection to match natural frequency or antiresonance

Beckerle et al.,
HUMASCEND2013.

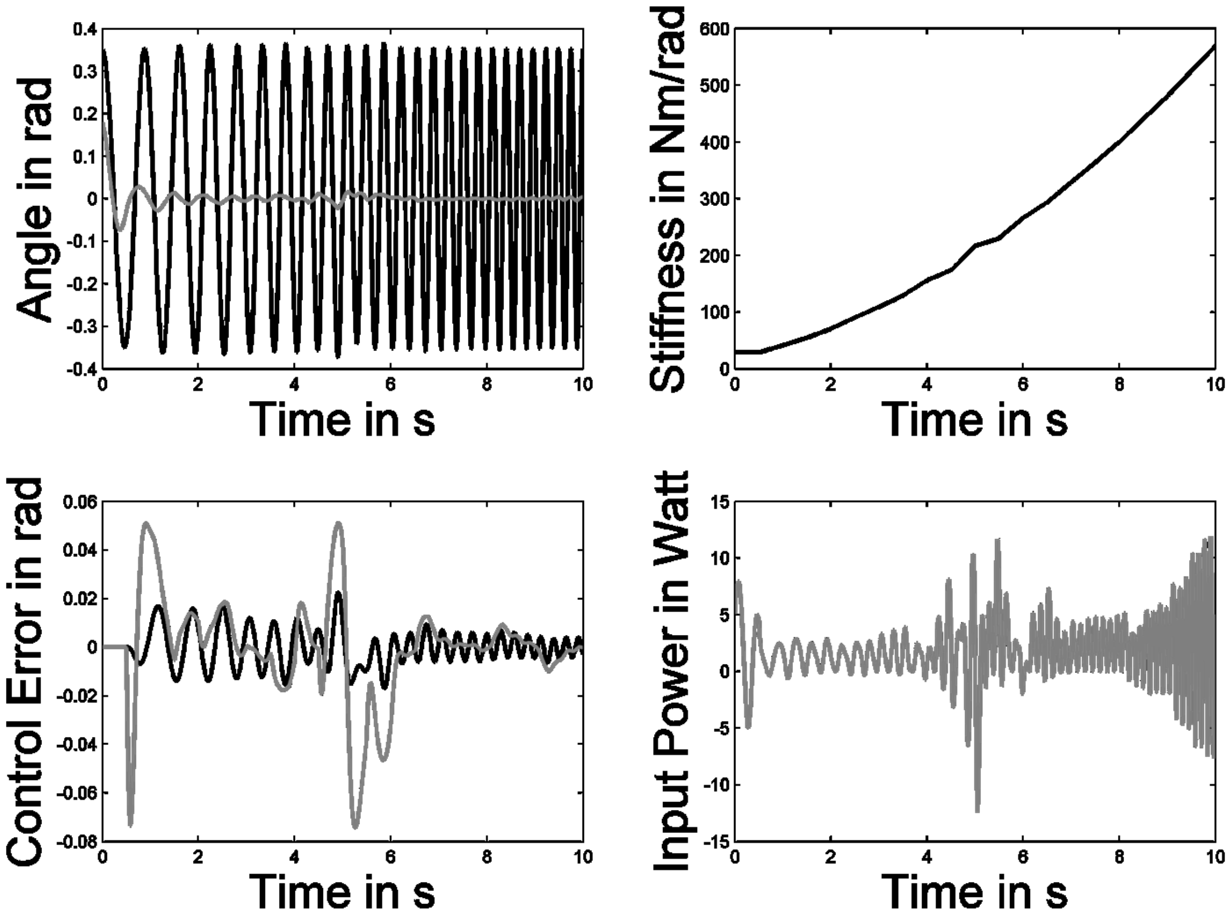
Forward Dynamics Simulation Results (1)



- Sinus 10° @ 2.0 Hz
- 160 to 60 Nm/rad
  - Antiresonance: 123.41 Nm/rad
  - 2nd natural freq.: 73.59 Nm/rad
- Control error reduced by K-adaptation
- Minimum power for antires. / 2nd natural

Beckerle et al., AIM2013.

Forward Dynamics Simulation Results (2)



- Sweep 1.0 to 4.0 Hz
- Stiffness adjusted to
  - Antiresonance
- Increased control error for transient K
- Power increased for transient K and unexact extrapolation

Beckerle et al., AIM2013.
Beckerle et al., HUMASCEND2013.

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Conclusion & Outlook

Framework for User-Centered Design

Approach based on **QFD and V-model** prepared.

Relevant human factors: SAT, FOS, BSI, SUP, SOC, MOB, OUT.

Open: Final QFD regarding development focus. Int²Bot experiments.

Development

Actuator design

Different specification of **operating range** to minimize power consumption.

Open: Gait simulation with prosthesis to estimate real biomechnical loads..

Variable Stiffness Control

More versatile adjustment by laws considering drive dynamics.

Open: Power analysis with extended model. Experiments with VTS.

Technologies

Thank you

Janis Wojtusch
(Computer Science)

Jochen Schuy
(Mech. Engineering)

Oliver Christ
(Psychology)

Questions? → Feel free to ask!