Cooperative and Interactive Control Approaches in Biomedical Engineering Systems

Günther Schmidt
Thomas Fuhr and Robert Riener
Interactive Systems and Control Group (ISAC)

Institute of Automatic Control Engineering, Technische Universität München
Univ.-Professor Dr.-Ing. Dr.-Ing. h.c. Günther Schmidt

Abstract

Systems of modern biomedical engineering are characterized by a growing content of functions depending on concepts and techniques taken from well-proven approaches in fields such as systems, control, and automation. In this presentation we will discuss in some detail two projects, where an artificial control system is physically coupled with a human being.

The first project is concerned with a *cooperative, feedback controlled neuroprosthesis* for motion restitution of patients with a spinal cord injury. Key of this system is a multi-layer hybrid (discrete event – continuous) control approach. The second project focuses an *interactive model-based control approach* for the design and operation of multimodal (involving many human senses) knee joint simulator for ‘hands-on’ training of medical students in orthopaedics. The system comprises an industrial robot, a force/torque sensor, and multi-DoF biomechanical knee models. For both examples, conceptual details as well a experimental results will be presented.

Interaction of Human and Artificial System

Control and Automation in Medicine

Organ Function Replacement Systems
Life sustaining/improving

- Mechanical Ventilators
- Dialysers
- Cardiac Pacemakers
- Neuroprosthesis (WALK)

Support Systems
Physicians, Patients, Health Care Staff

- Surgical Field Robots
- Intelligent Wheelchairs
- Rehab. Robots (Arm, Leg)

Educational and Training Systems

- Anesthesia Simulator
- Laparoscopy Simulator
- Knee Simulator (VOR)

Laboratory Automation Systems

- Analytics (chem./biochem.)
- Imaging Techniques (MRI, CT, US)
- Data Acquisition (ECG, EEG)

Definitions

Context: ***Human-Centered Controls/Robotics***

- **Cooperativity**

  Human operator is supported by the technical system in executing his/her intentions, but is not enforced to do so.

- **Interactivity**

  Exchange of Information and Energy between human and technical system is determined by the human.

Research Project #1

Cooperative Gait Neuroprosthesis

Fuhr, T.; Quintern, J; Riener, R.; Schmidt, G.:
Walk with WALK! - A Cooperative, Patient-Driven Neuroprosthetic System.
IEEE Engineering in Medicine and Biology (EMB) Magazine, January/February 2008, pp. 38-48

WALK!

A Cooperative Gait Neuroprosthesis

Generation of motion patterns
relevant for locomotion
by use of
Functional Electrical Stimulation
(FES)
of paralyzed limbs

Lehrstuhl für Steuerungs- und Regelungstechnik
TUM

Neurologische Klinik
Klinikum Großhadern
LMU

Gait Neuroprosthesis

Target Group

- Patients with complete spinal cord injury (thoracic lesions)

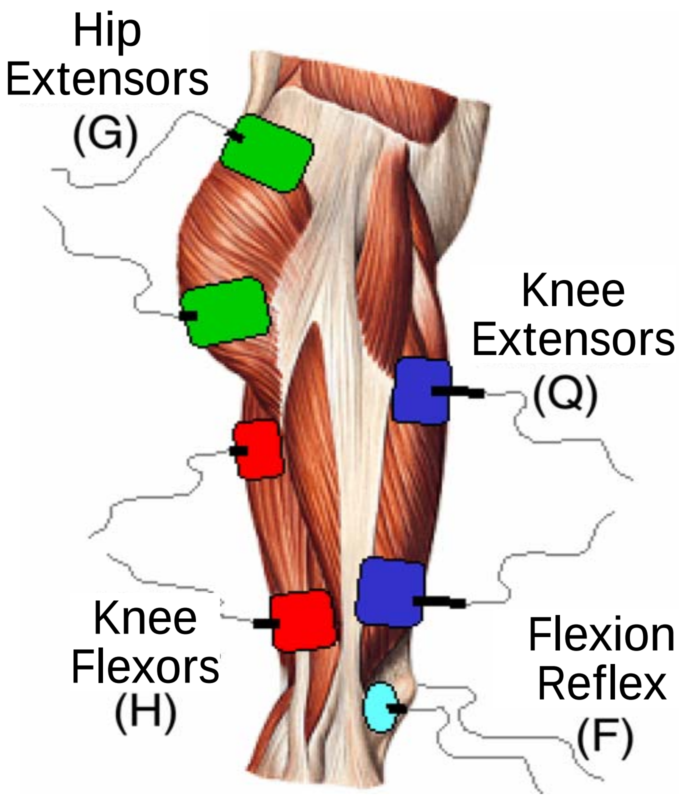
Method

- Electrical stimulation of peripheral motor neurons, surface electrodes

Relevant Motion Tasks

- **Standing:** Standing up, Standing, Sitting down
- **Gait:** Step Forward
- **Stair Climbing:** Stair ascent and descent

Muscle activation



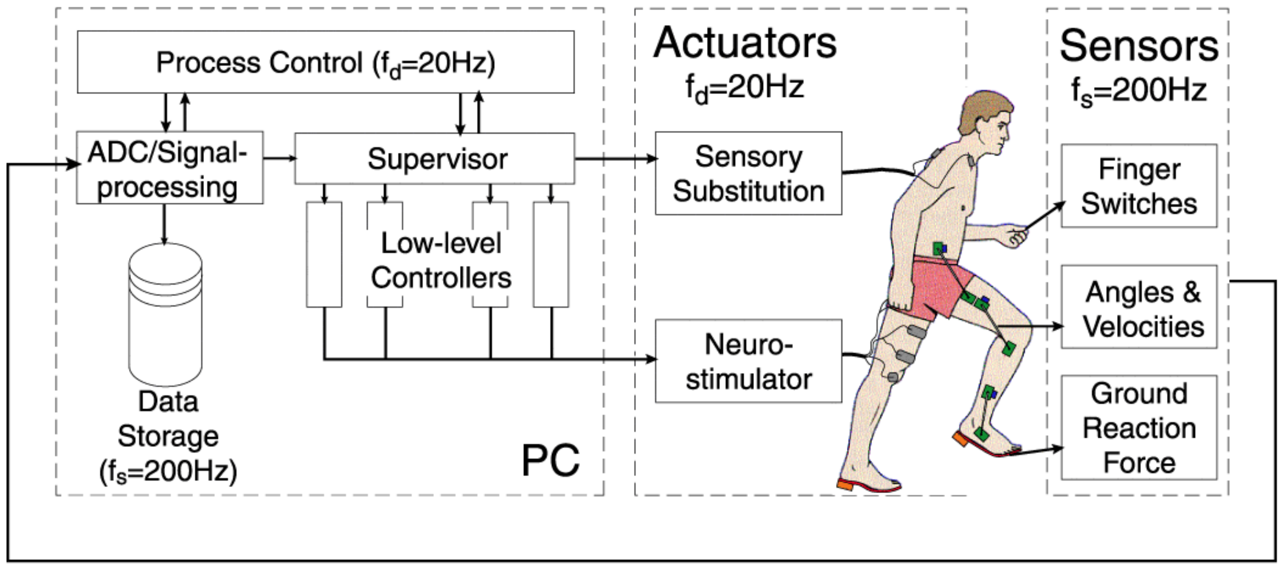
Gait Neuroprosthesis

Patient mounted sensors

- Knee angles
  and angular velocities
- Force sensing soles

WALK! System Architecture

- **Actuators**
  - Technical: neurostimulator, tactile displays
  - Biological: leg muscles, voluntary upper body contributions
- **Sensors**
  - Patient mounted sensor systems: angles, velocities, forces
- **Motion control and supervision, monitoring**
  - Feedback control system, signal processing and data acquisition, user interface



Control System Challenges

Plant: *Human Motor System*

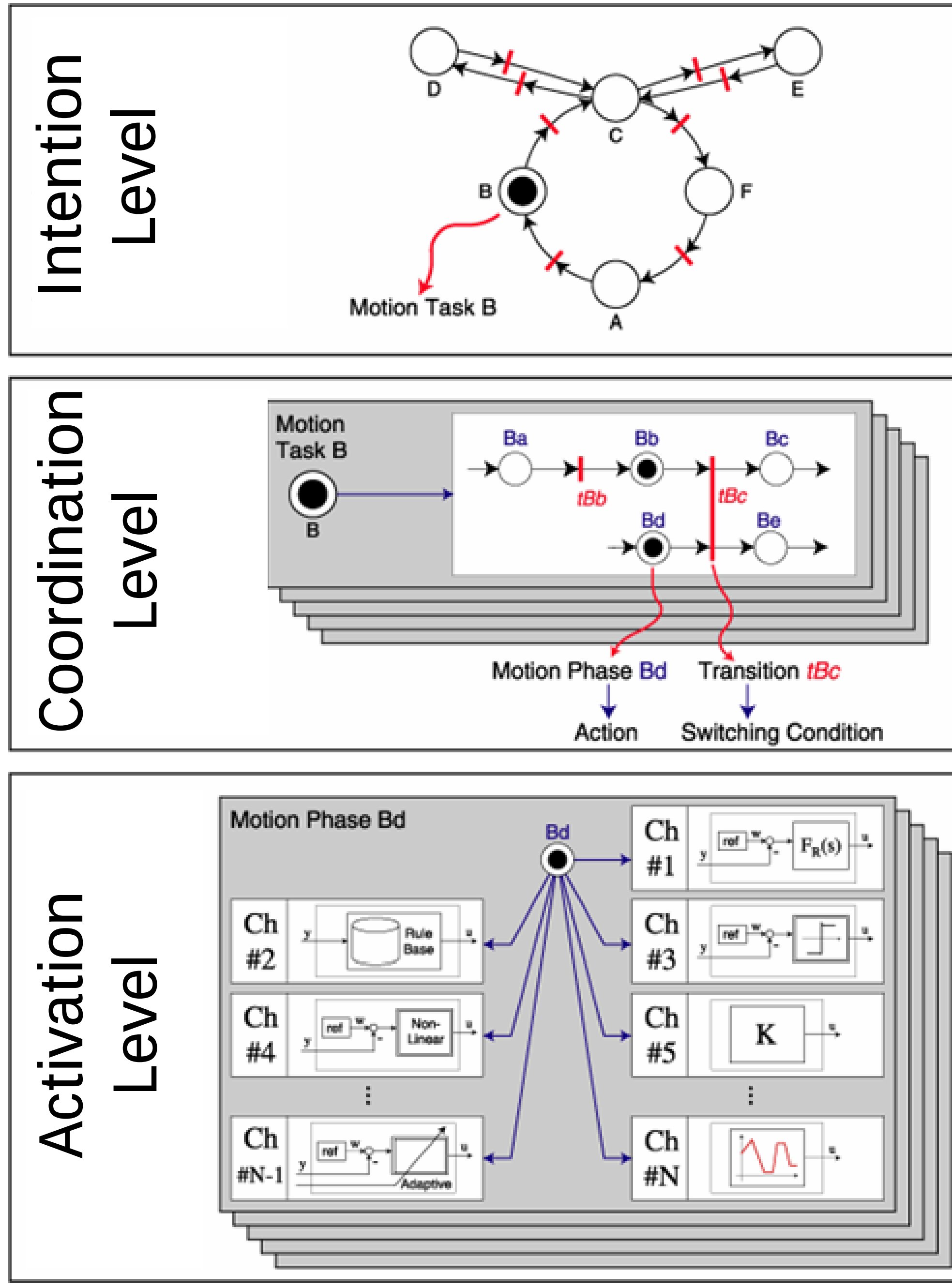
- Nonlinear, time-variant: muscle fatigue
- Underactuated: few, coupled stimulation channels
- Unknown plant characteristics
- Competition with voluntary (upper body forces) + non-voluntary control effects
- Control sampling rate: 20 Hz, due to stimulation rate limits

Requirements:

- Cooperativity: neuroprosthesis supports patient
- Maximum safety and reliability
- Minimum complexity

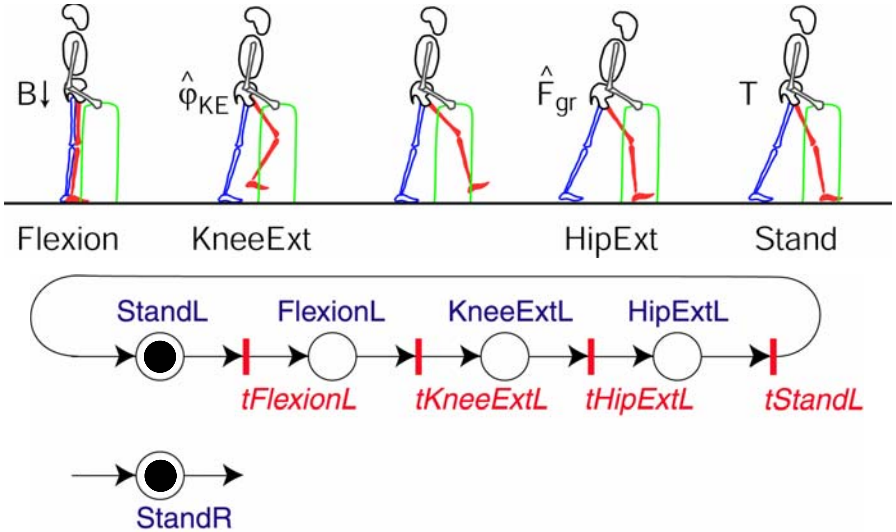
Hierarchical Hybrid Control Architecture

- Intention level
  - Selection of motion task for a specific motion
- Coordination level
  - Discrete event specification of motion tasks by means of a set of motion phases
- Activation level
  - Muscle activation via low-level open-loop and closed-loop controllers

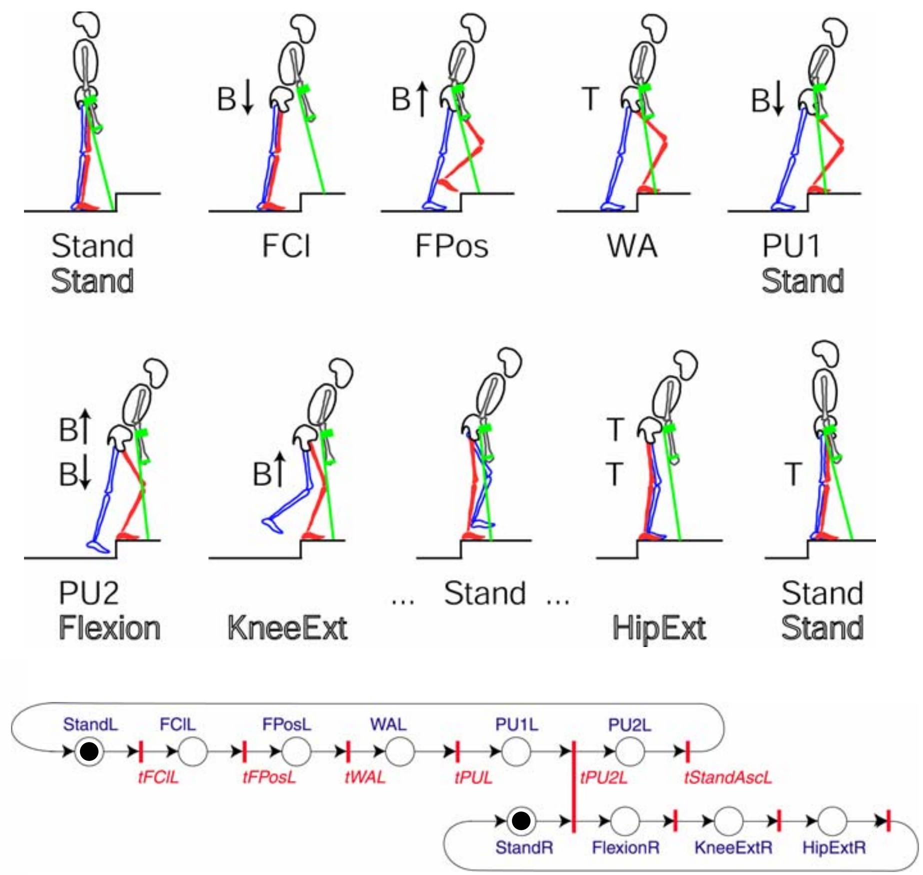


Motion Task Synthesis

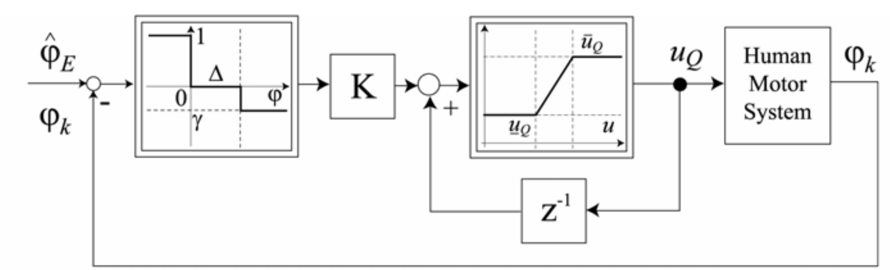
Step



Stair Ascent



Example: Knee Extension Controller



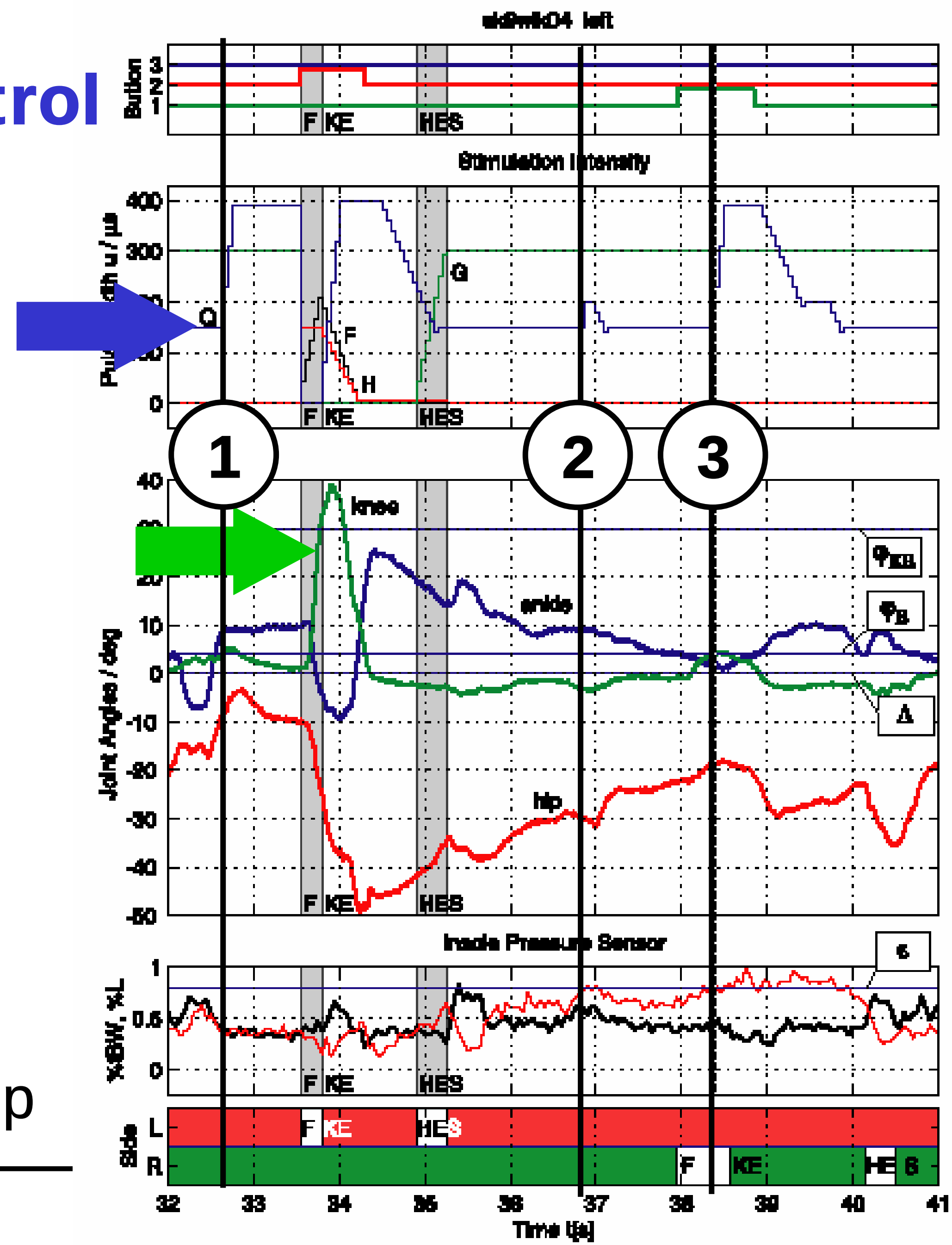
Knee Extension Control

Closed-loop control of knee extensor activation (Q):

(1) Unloaded swing leg is slightly flexed prior to step

(2) Stand leg supports > 75% of body load

(3) Knee is slightly flexed during contralateral step



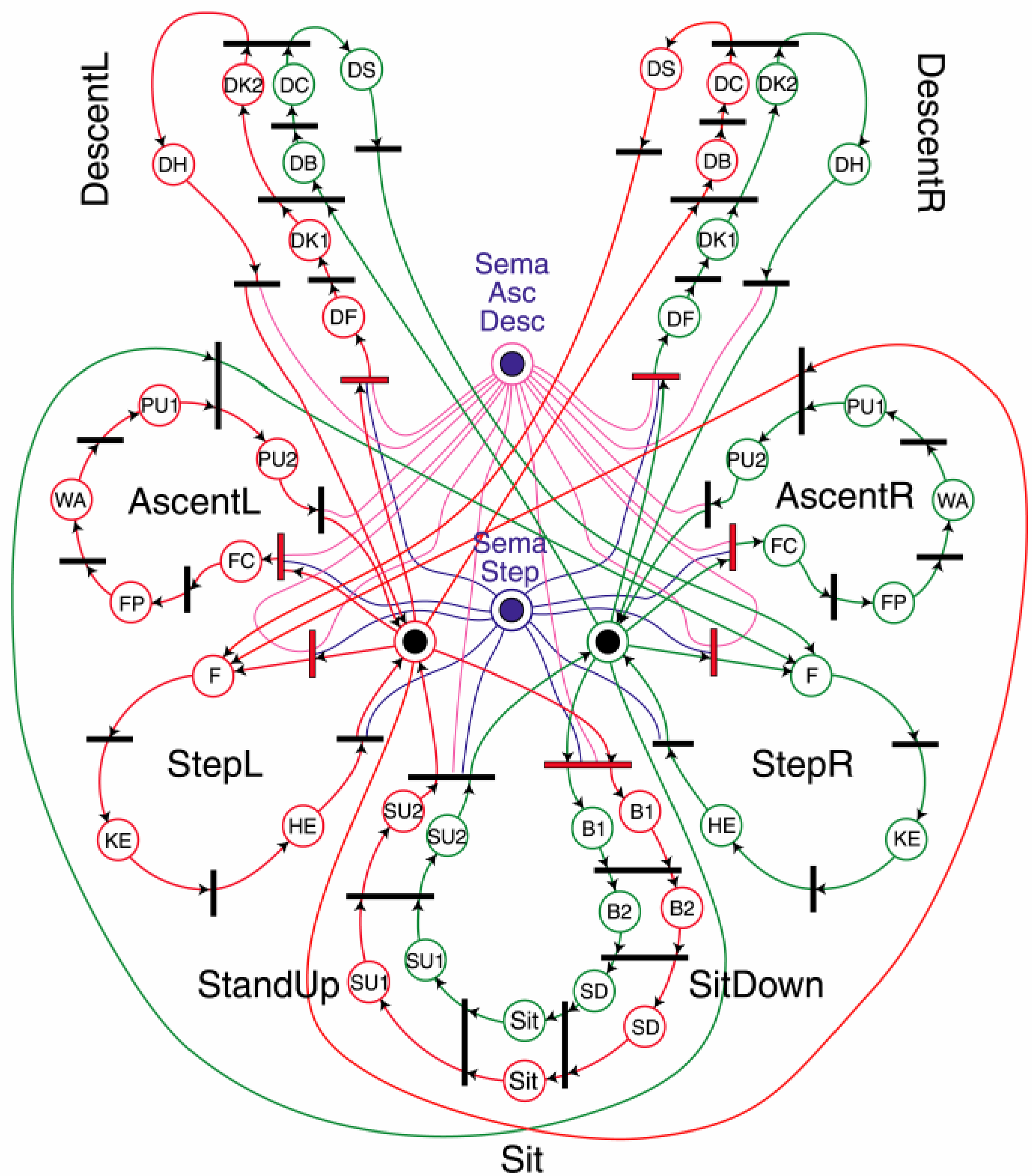
WALK!

Supervisor

- CIPN Model
- Resulting from fusion of intention level and coordination level

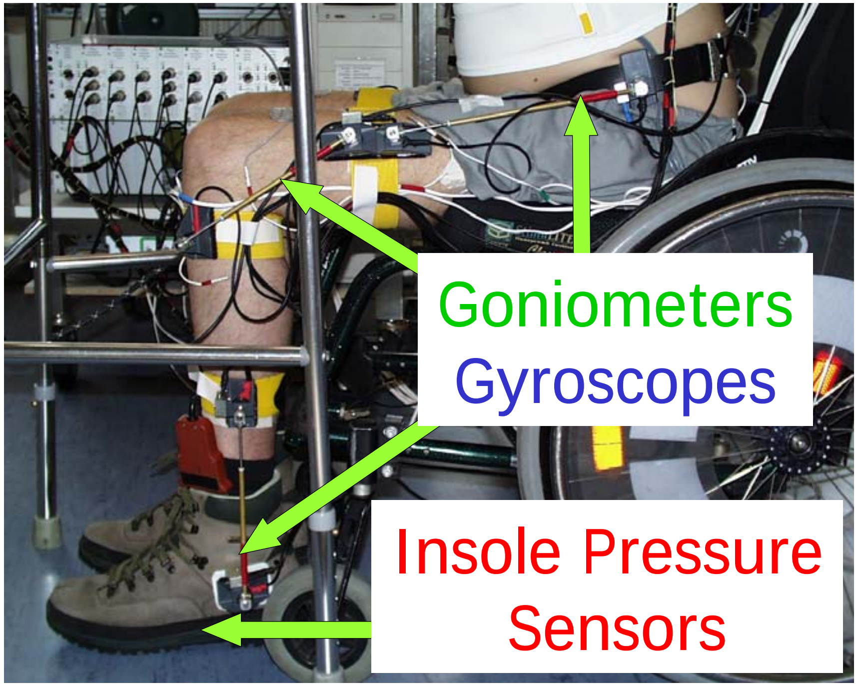
Elements

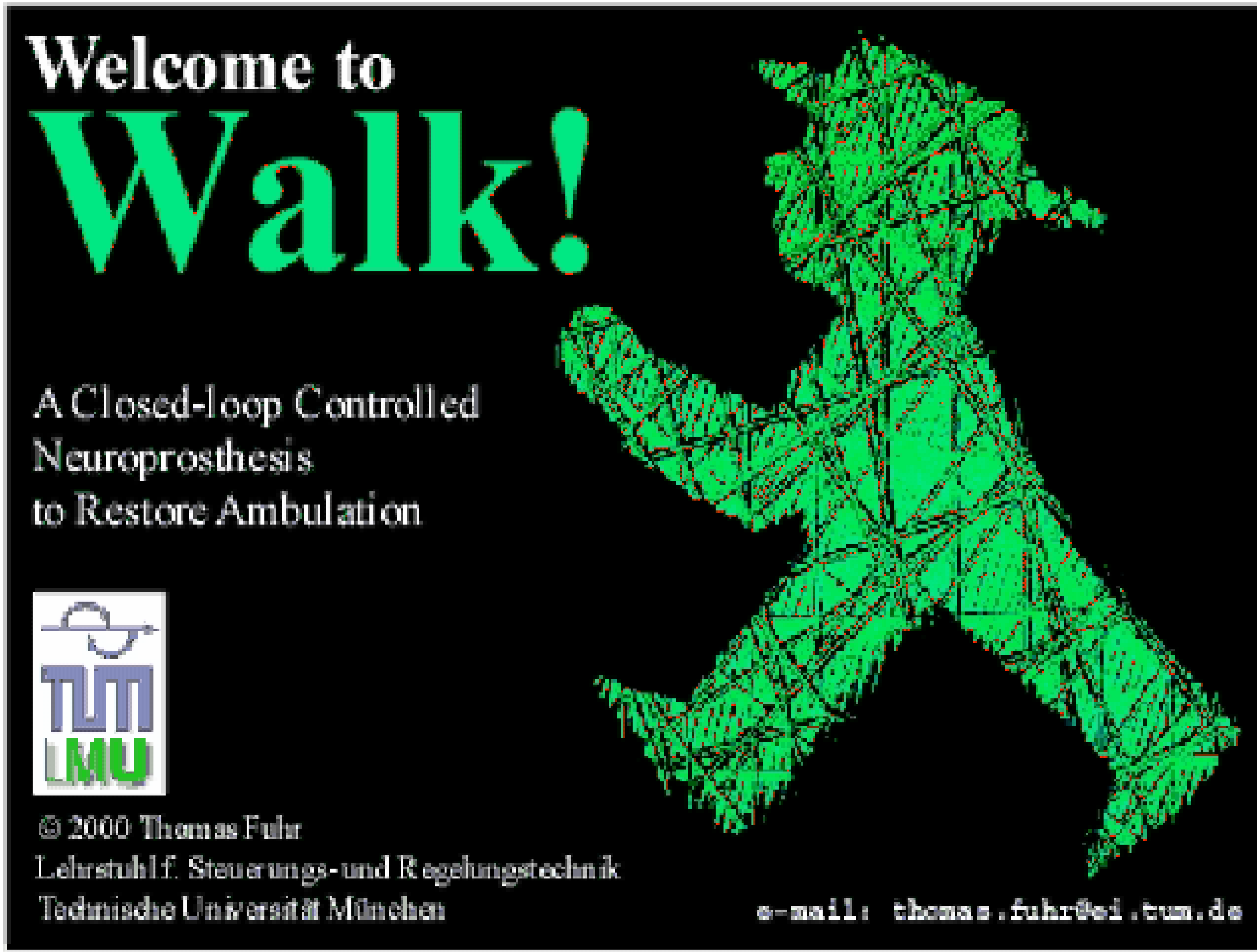
- Sensor or switch-triggered transitions
- Actions represented by places
- Lower-level controllers



Cooperative Neuroprosthesis WALK!

- Neurostimulator (ProStim8, FRA)
- Multisensory system
- Sensory substitution system
- Process supervision & control



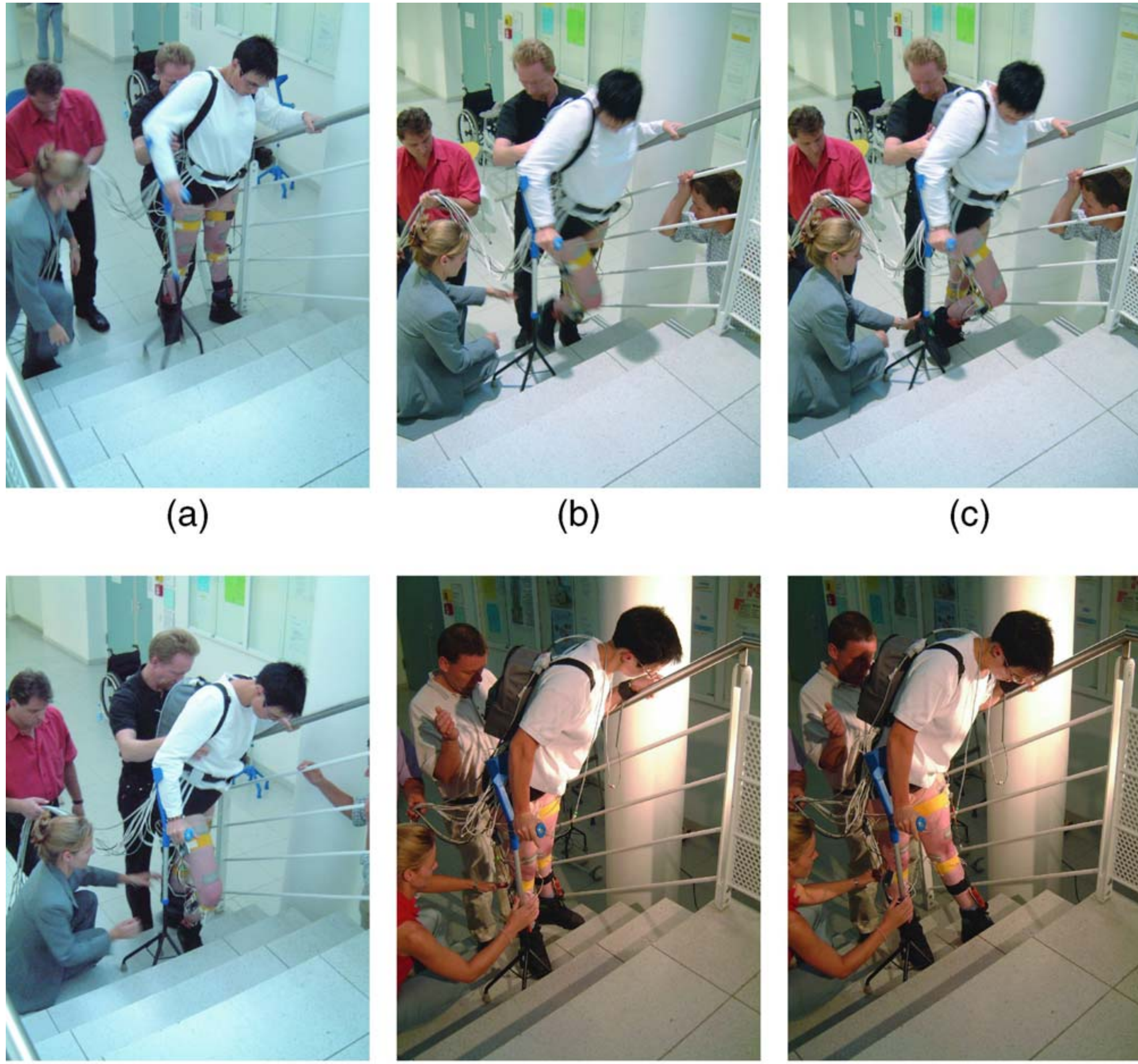

Welcome to
Walk!
A Closed-loop Controlled
Neuroprosthesis
to Restore Ambulation
© 2000 Thomas Fuhr
Lehrstuhl f. Steuerungs- und Regelungstechnik
Technische Universität München
e-mail: thomas.fuhr@ei.tum.de

WALK!

Stair ascending with closed-loop controlled neuroprosthesis

Step height Platform: 12.0 & 16.5 cm

Step height Staircase: 17.0 cm



(a) (b) (c)

(d) (e) (f)

Ascending a Staircase with WALK!

Résumé

- Prerequisite of cooperativity
  - Merging of methods from area of systems & control, biomechatronics and IT
- Cooperativity of a neuroprosthesis
  - Improves control of movements
  - Releases patients from tasks that can be automatized
  - Reduces muscle fatigue and stimulation intensity
  - Improves patient’s quality of life

Research Project #2

VR Knee Joint Simulator

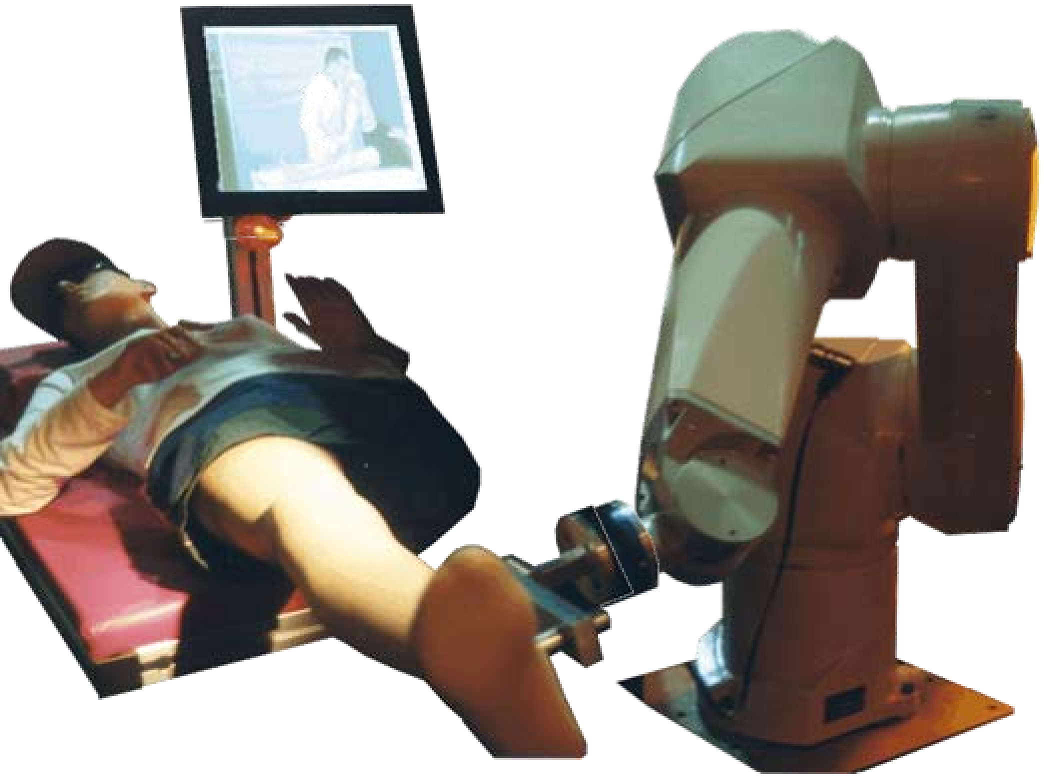
Riener, R., Hoogen, J., Burgkart, R., Buss, M., Schmidt, G.:
Development of a Multi-modal Virtual Human Knee Joint for Education and Training Orthopaedics.
Technology and Informatics, 81,
Medicine Meets Virtual Reality 2001, pp. 410-416.

Hoogen, J.; Schmidt, G.; Riener, R.:
Haptic Environment for Analysis of Smooth Arm Movements.
Proc. of the 11th International Conference on Advanced Robotics, ICAR2003.
Univ. of Coimbra, Portugal, pp. 173-178

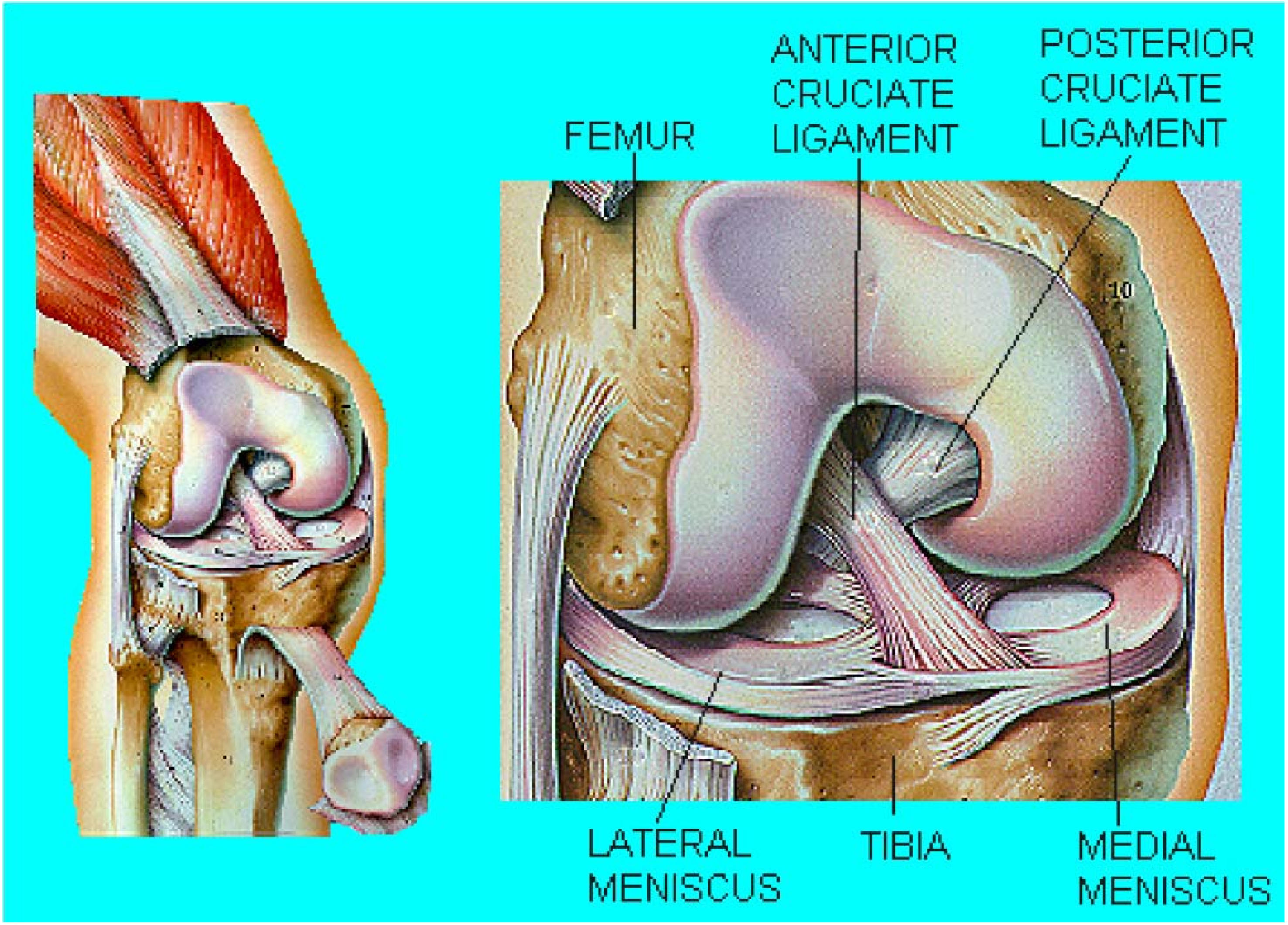
VOR

Virtual Orthopedic Reality

Multimodal simulator
for intensive and realistic
medical education
and training of clinical
diagnosis methods



Anatomy of the Knee Joint



New Methods in Orthopedic Education

- Joint diagnosis requires high level of experience and sensitivity
- Training with patients is cumbersome, time consuming and expensive
- Result of survey with > 50 orthopedic doctors:

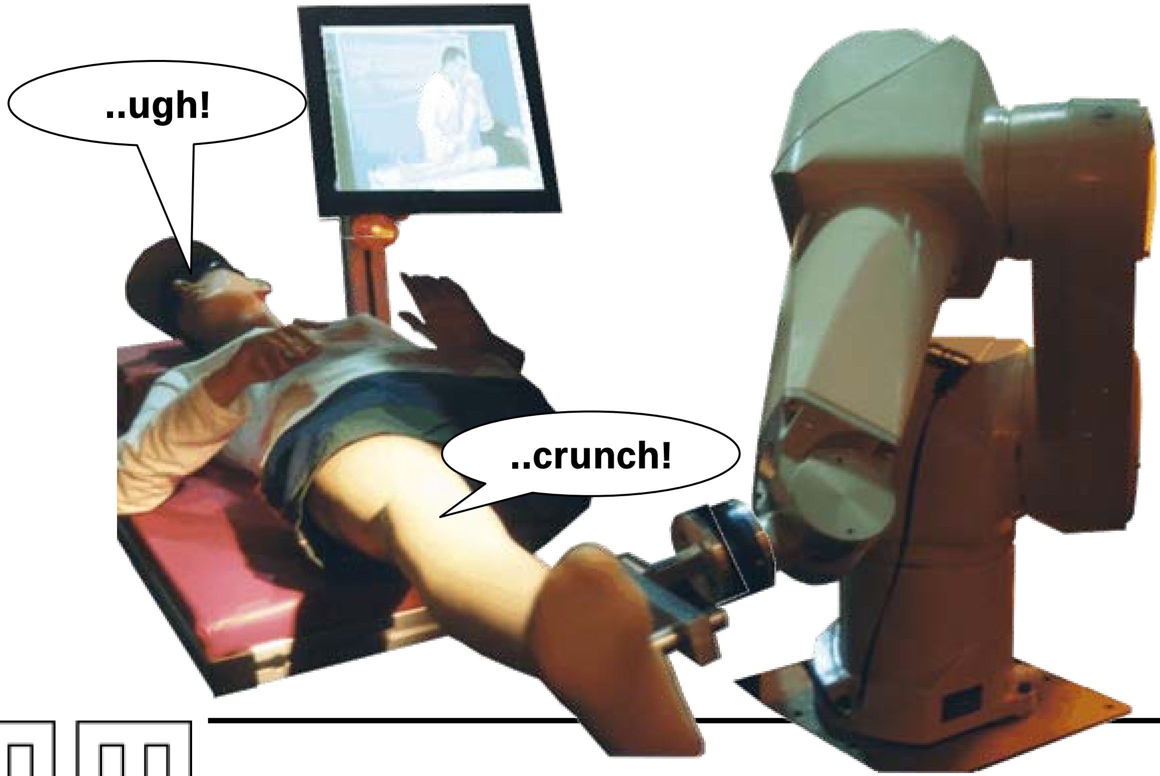
  " …. training methods need to be improved …. "

McMurray Test
for diagnosis of
meniscus injuries

The Munich Knee Simulator

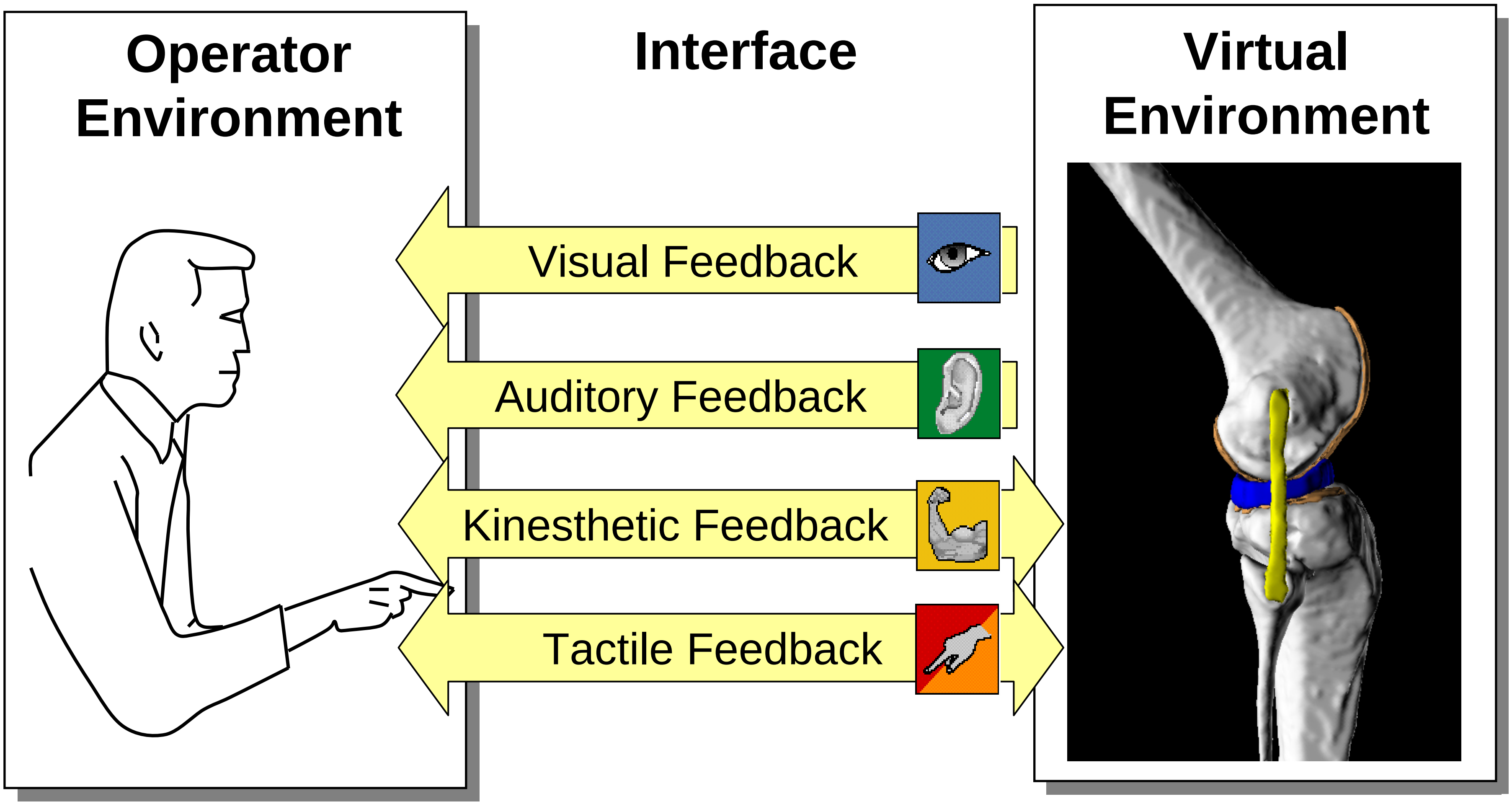
... a *multimodal* platform for the interactive training

- Industrial robot with F/T sensor for *kinesthetic* feedback (highly dynamic)



- Artificial leg for *tactile* feedback
- Realistic examination environment
- *Visual* feedback
- *Auditory* feedback

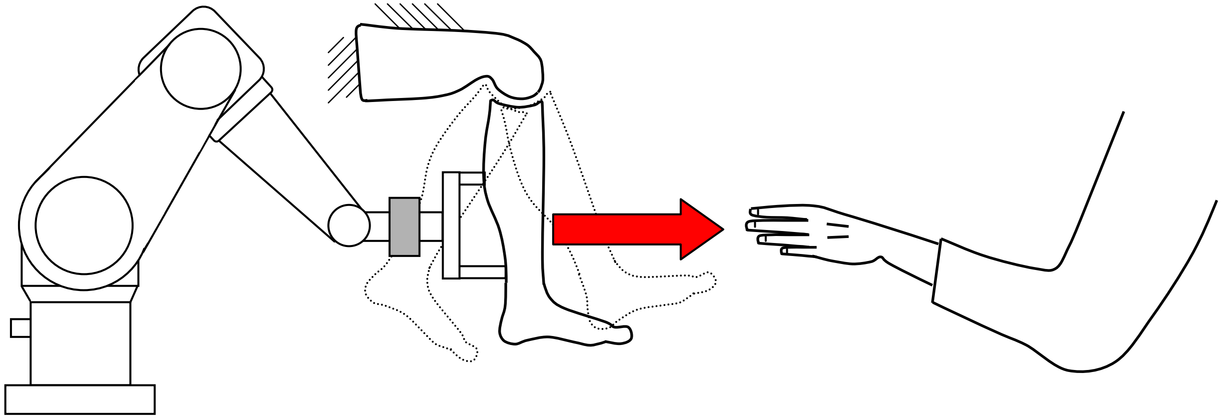
Principle of Multimodal VR



Operational Modes

#1 Teaching Mode: Artificial leg performs desired motion

- Operator learns appropriate test movements in 6 DoFs through motion playback

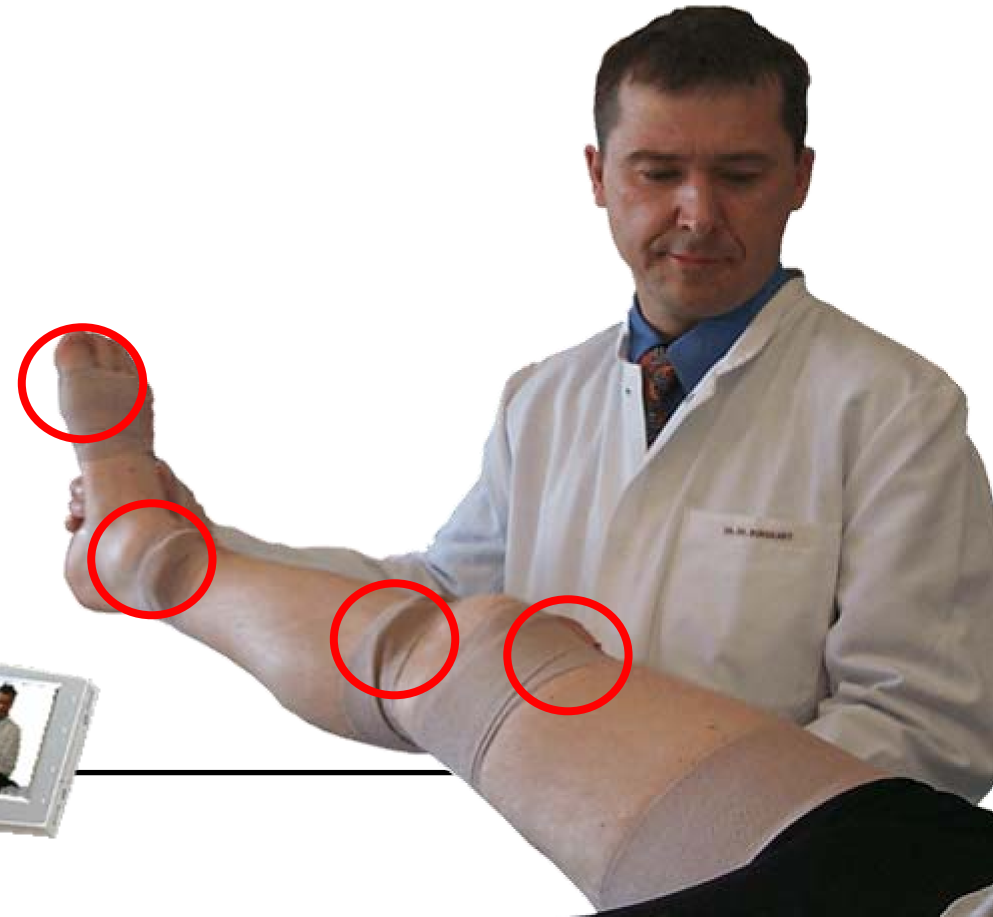


Data Acquisition for Teaching Mode

Analysis of 60 functional tests, executed by an experienced orthopedician

Motion tracking system

- 3 video cameras
- 4 electromagnetic position sensors



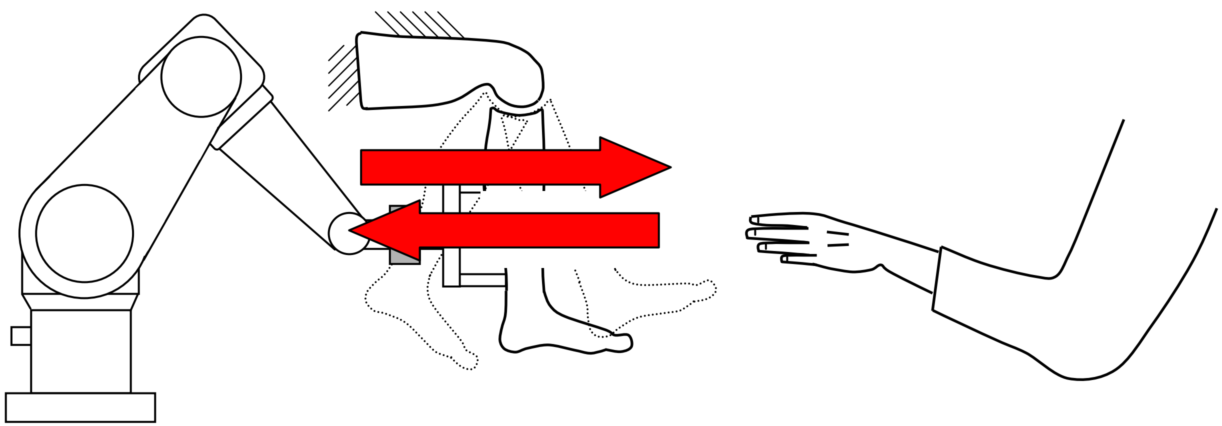
Operational Modes

#1 Teaching Mode: Aritificial leg performs desired motion

➢ Operator learns appropriate test movements in 6 DoFs

#2 Interactive Mode: Artificial leg reacts to operator interaction

➢ Operator perceives (simulated) physiological/pathological properties of knee joint mechanics in 6 DoFs

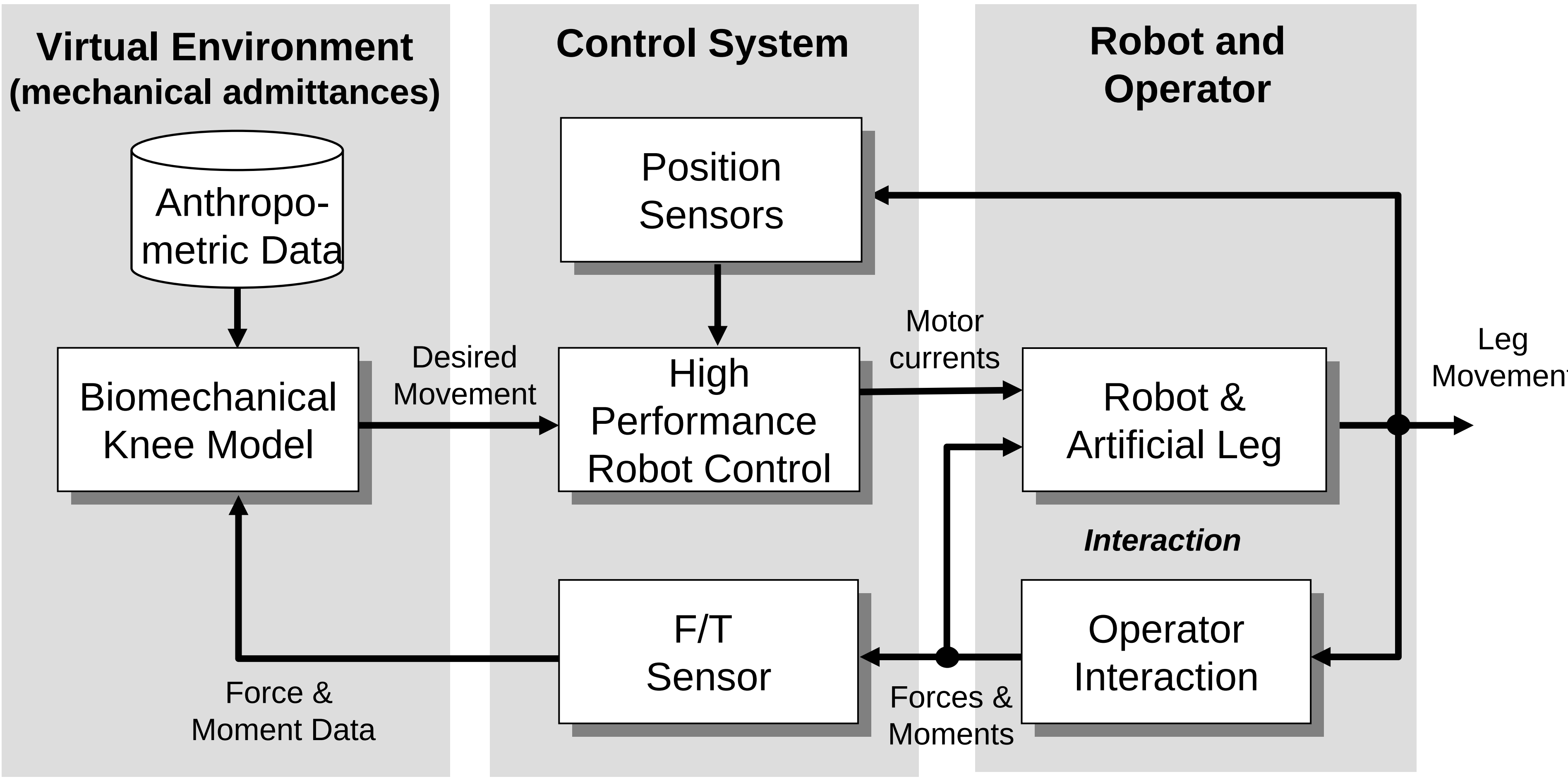


Interactive Mode A

Patella tendon reflex

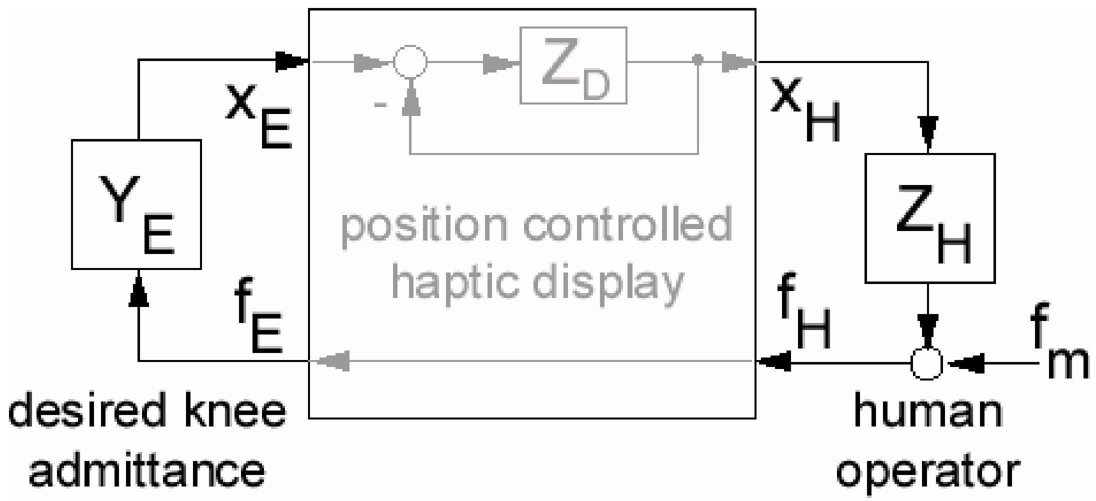
Interactive Mode B

Admittance control enables force reflection in 6 DoFs



Network Model of Kinesthetics

- Impedance $f(t) = Z(x(t))$
- Admittance $x(t) = Y(f(t))$
- e.g. linear: $x(s) = \frac{1}{ms^2 + ds + k} \cdot f(s)$



- Control Objectives : Stability & Transparency

i.e. $f_H = f_E$ & $x_H = x_E$

Admittance Control System and Robot Kinetics

Robot Model $\quad M(q)\ddot{q} + F(\dot{q}) + G(q) = \tau_A - J^T f_H$

+

Control Law $\quad \tau_A = r + k$

Model-based Compensator

$$k = \hat{F}(\dot{q}) + \hat{G}_g(q) + \hat{G}_s(q_2) + J^T f_S$$

$$\hat{F}_i(\dot{q}_i) = c_v \dot{q}_i + c_c sign(\dot{q}_i) \ , \ \ f_S = f_H$$

SFB/FF Controller

$$r = \hat{M}(\ddot{q}_d + K_v(\dot{q}_d - \dot{q}) + K_p(q_d - q))$$

Kinematics

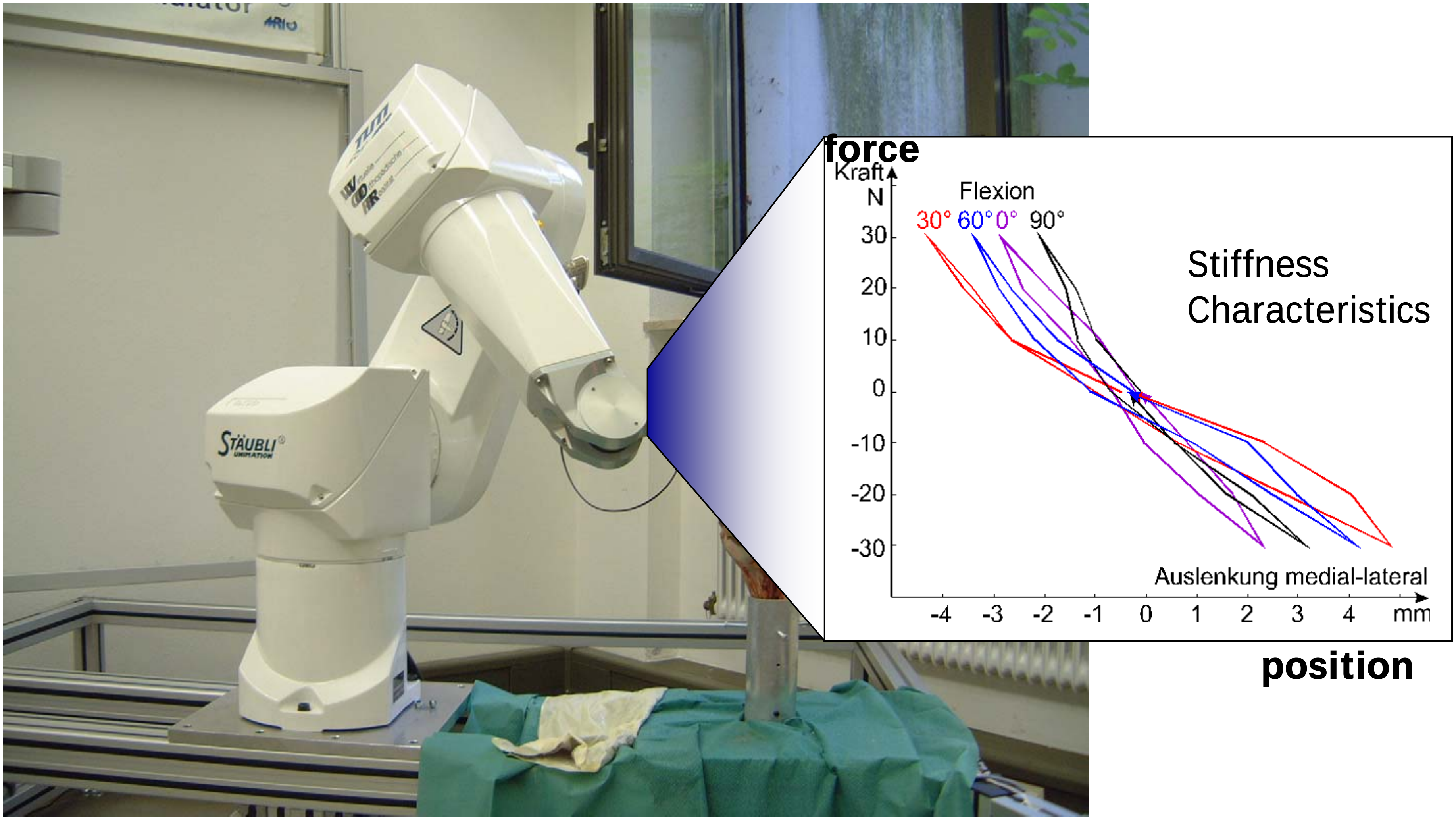
$$[q_d, \ \dot{q}_d, \ \ddot{q}_d] = InvKin[x_d, \ \dot{x}_d, \ \ddot{x}_d]$$

Biomechanics

$$x_d = x_E = Y(f_E)$$

Prototype of the Knee Simulator

Acquisition of Biomechanical Knee Data



Résumé

- Prerequisite of interactivity:
  - Merging of methods from area of systems & control, biomechatronics and IT, VR

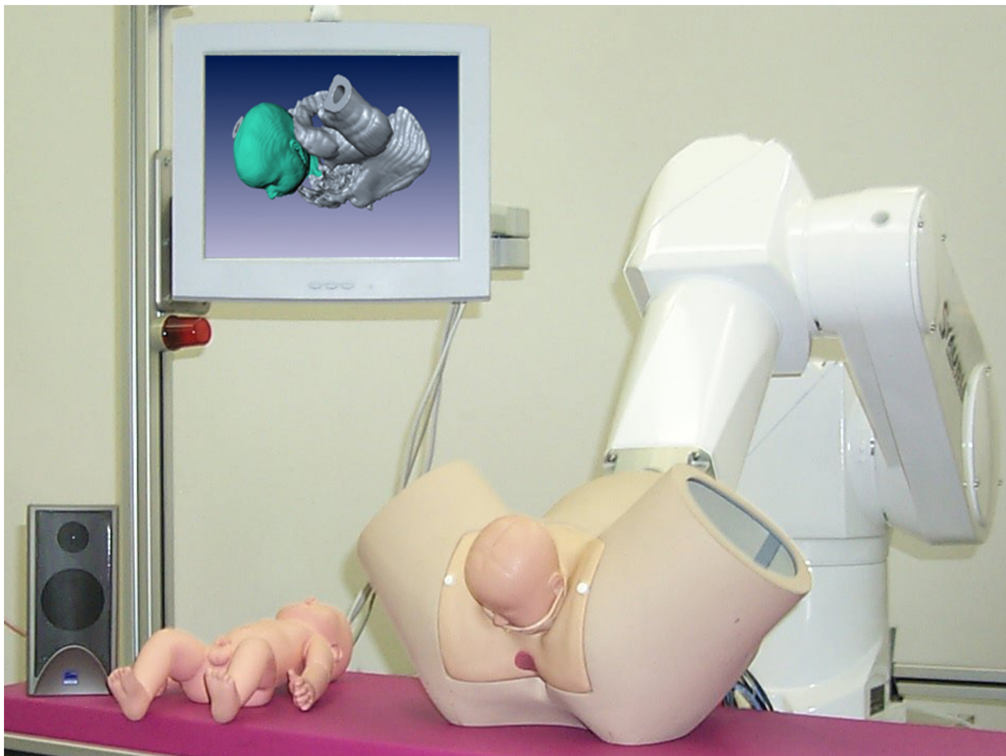
- Interactivity of the knee simulator supports
  - realistic, multimodal simulation of knee pathologies
  - more intensive and practical medical training

Outlook

Transfer of technological know-how into related application fields, e.g. ....

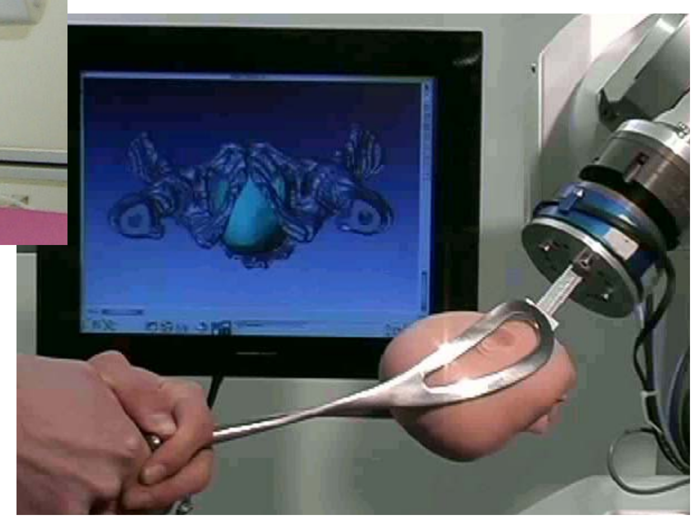
Delivery Training Simulator

for medical students and midwives



Cooperation partners at TUM

- LSR: R. Riener, F. Frey
- Orthopedic Clinic: R. Burgkart, T. Obst
- Clinic for Gynaecology: E. Ruckhäberle, K. Schneider



Baby passing through cervix without and with doctor‘s intervention

Conclusions from both Projects

- Prerequisite for achieving cooperativity or interactivity:
  - Blending of methods from areas of automation, systems & control, biomechatronics, VR and IT
- Cooperativity of a neuroprosthesis
  - Improves control of movements
  - Releases patients from tasks that can be automated
  - Reduces muscle fatigue and stimulation intensity, ...
- Interactivity of the knee simulator supports
  - Realistic, multimodal simulation of knee pathologies
  - More intensive and practical medical training

Thank you

for your attention