ETHZ Summer School on Soft Robotics

Soft human-robot interaction: the example of rehabilitation robotics

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RELAB
REHABILITATION ENGINEERING LAB

IRIS
Institute of Robotics and Intelligent Systems

RITZ
Rehabilitation Initiative & Technology Center Zurich

Neural Plasticity and Repair
National Center of Competence in Research

My background

2005

MSc Microengineering,
EPF Lausanne

PhD in Mechanical Engineering,
National University of Singapore

2007

Exchange in Simon Fraser University, Vancouver

2008

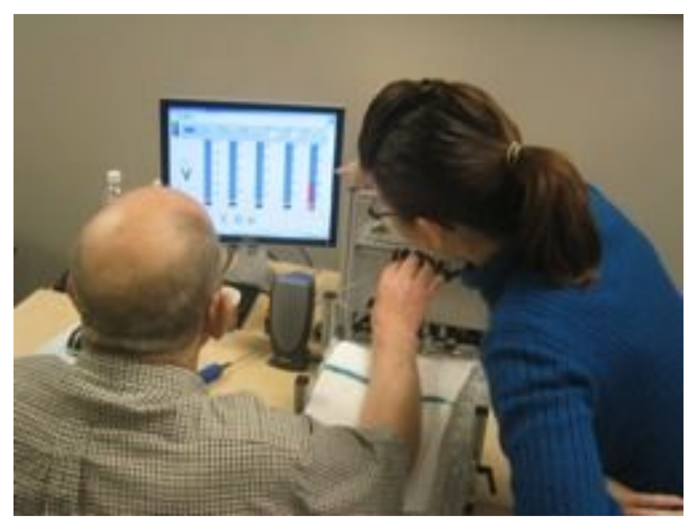
Visiting researcher in Tan Tock Seng Rehabilitation Center, Singapore

2009

Research associate, Rehabilitation Engineering Lab, ETH Zurich








Contents

- **Part 1 (10h15-11h15)**

  1) Physical Human-Robot Interaction

  2) Human factors

  3) Evaluation metrics

  4) The example of rehabilitation robotics

  5) Take home messages

Softness in robotics

...in the mechanical design

...in the materials

?

...in the electronic components

...in the control of the physical human-robot interaction

What is this?

Isaac Asimov
"I, Robot", 1941
http://wikipedia.org

"The Laws of physical Human-Robot Interaction:

1. *A robot **may not injure** a human being or, through inaction, allow a human being to come to harm.*
2. *A robot must **obey any orders** given to it by human beings, except where such orders would conflict with the First Law.*
3. *A robot must **protect its own existence** as long as such protection does not conflict with the First or Second Law."*

Physical Human-Robot Interaction

How to follow the "laws"?

http://robot925.blogspot.ch/2011/03/robotics.html

http://www.prisma.unina.it/isero2/session3.html

http://spectrum.ieee.org/

avoid with "hardware"

avoid with "software"

"soft" direct interaction

Physical Human-Robot Interaction

RI MAN, RIKEN

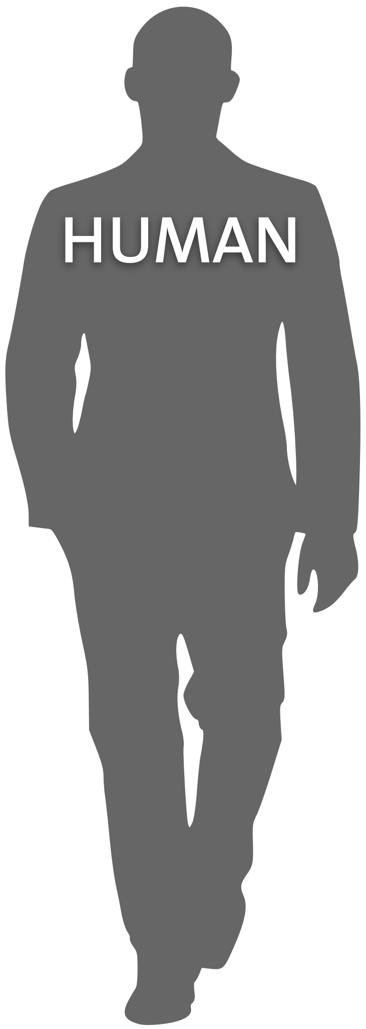
daVinci robot, Intuitive Surgical

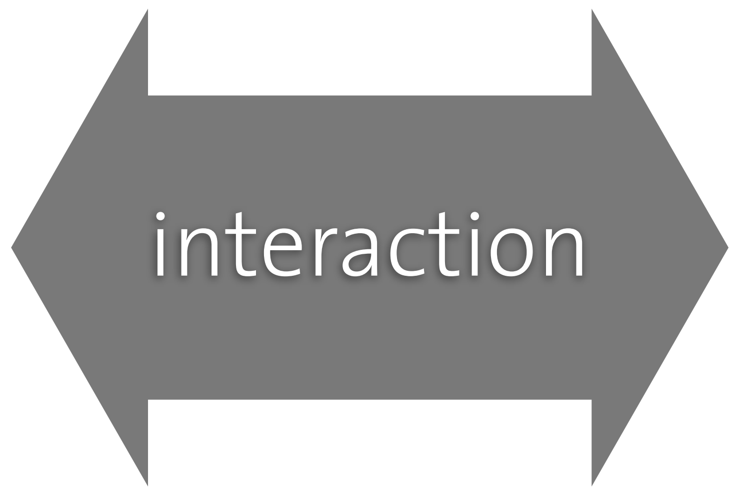
Paro

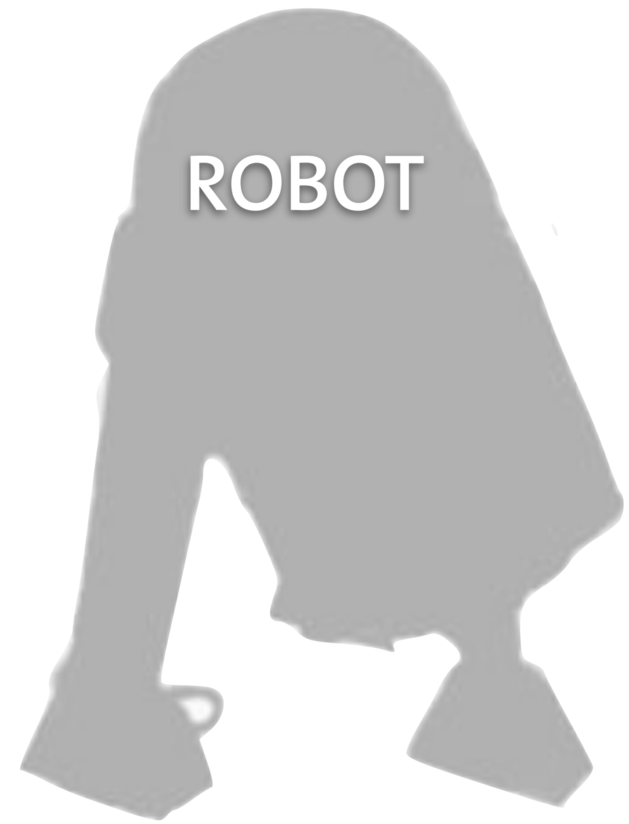
Haptic simulator for coloscopy, LSRO EPFL

Arm exoskeleton ARMin, SMS lab, ETHZ

Human-Robot Interaction







- defined system!
- needs
- limitations

- realistic
- safe
- provide an advantage

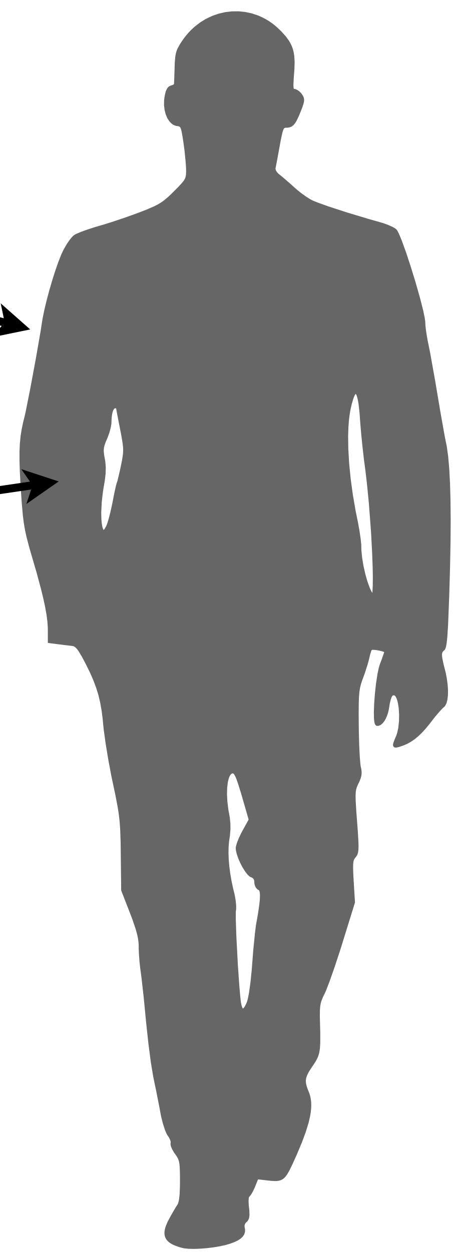
- flexible system
- virtually no limitations…

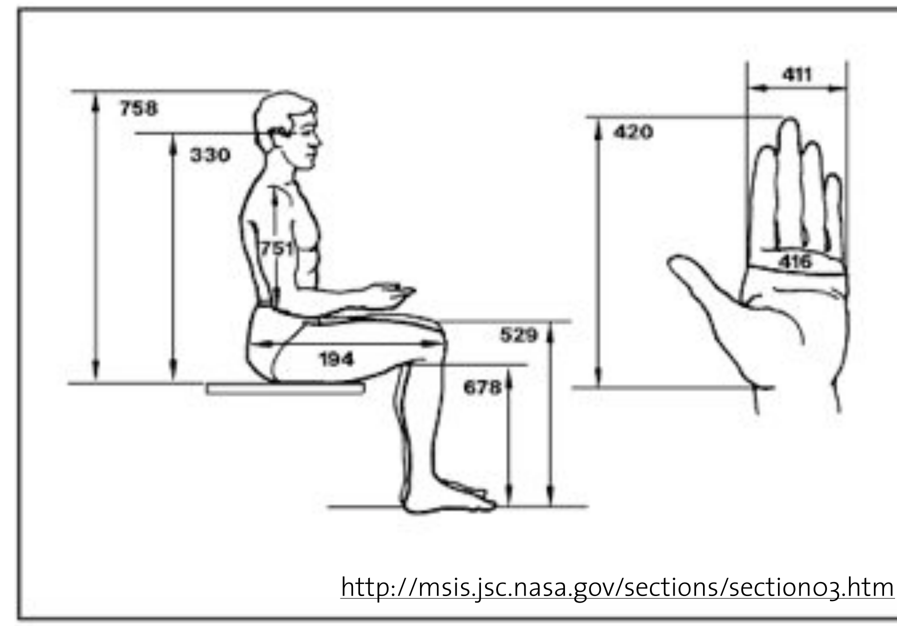
Human factors

Understand the human

anthropometrics

range of motion





http://msis.jsc.nasa.gov/sections/section03.htm

goniometer

Human factors

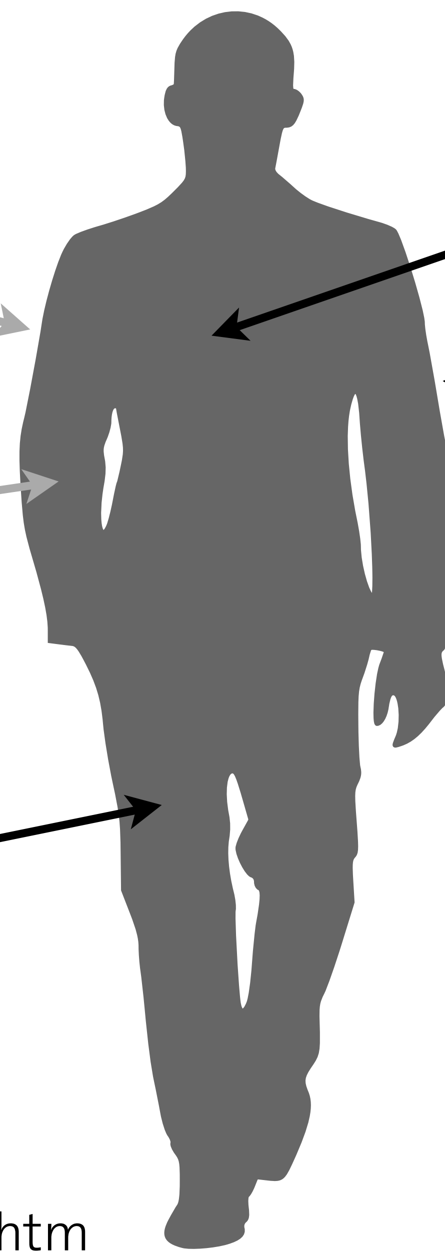
Understand the human

anthropometrics

movement bandwidth

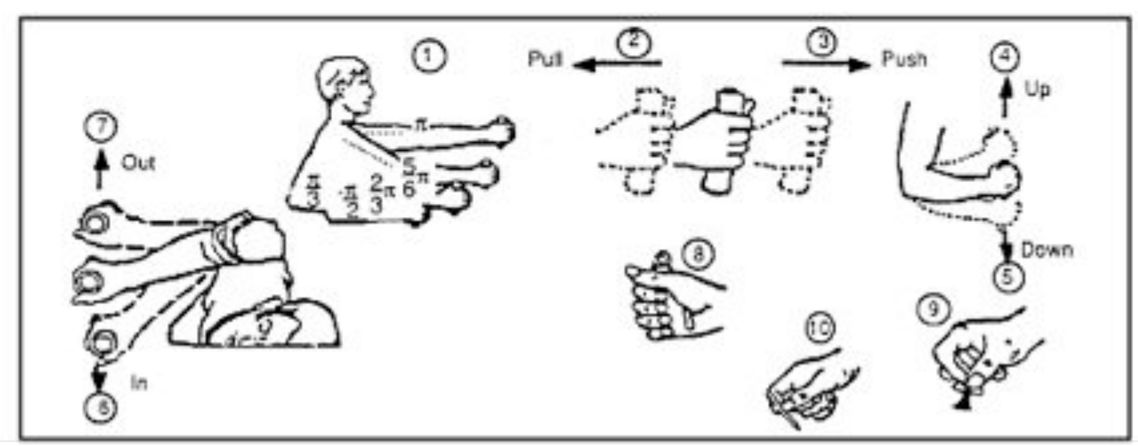
joint impedance
(mostly stiffness)

range of motion

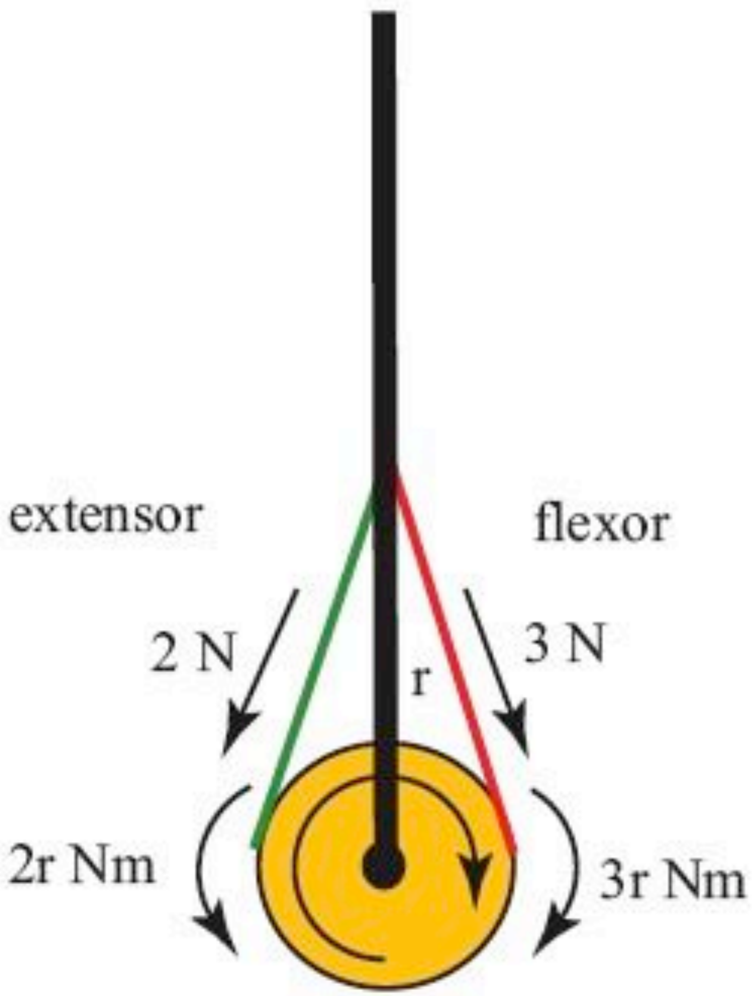


joint force/torque

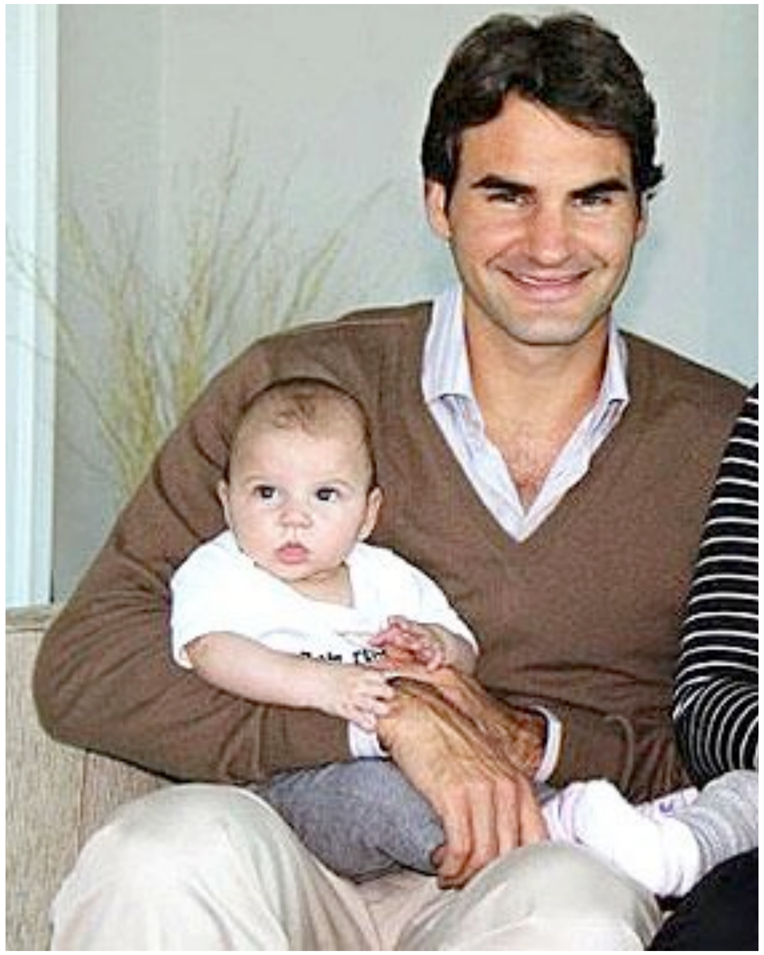
NASA website:
http://msis.jsc.nasa.gov/sections/section03.htm



Muscle biomechanics

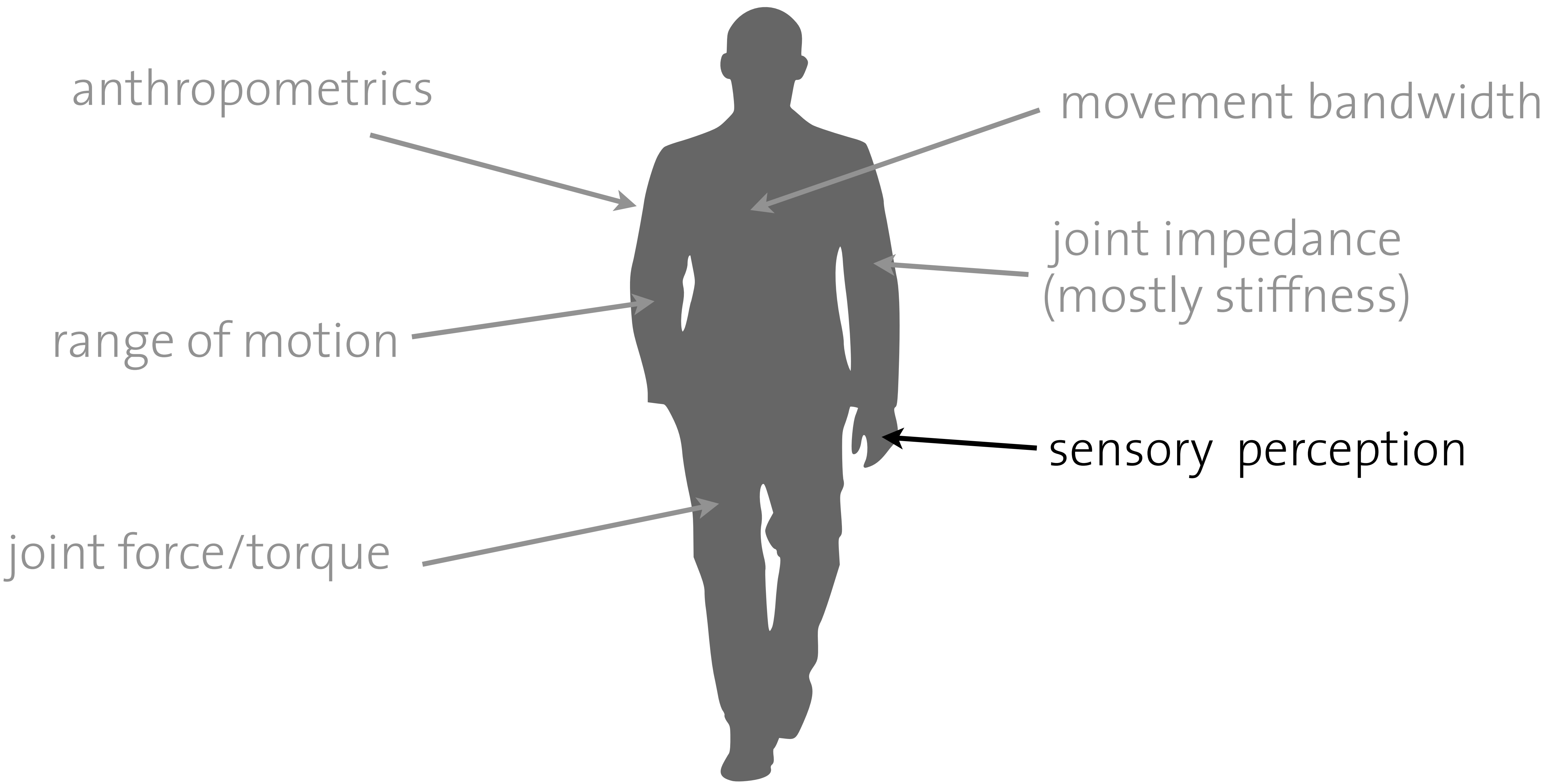


Human factors



Human factors

Understand the human



Human factors

Sensory (Aristotle, five senses):

- see, visual perception
- hear, auditory perception
- smell, olfactory perception
- taste, gustatory perception
- touch, haptic perception

Modern Physiology:

- sense of temperature, thermoception
- sense of pain, nociception
- sense of balance
- self perception, proprioception

Human factors

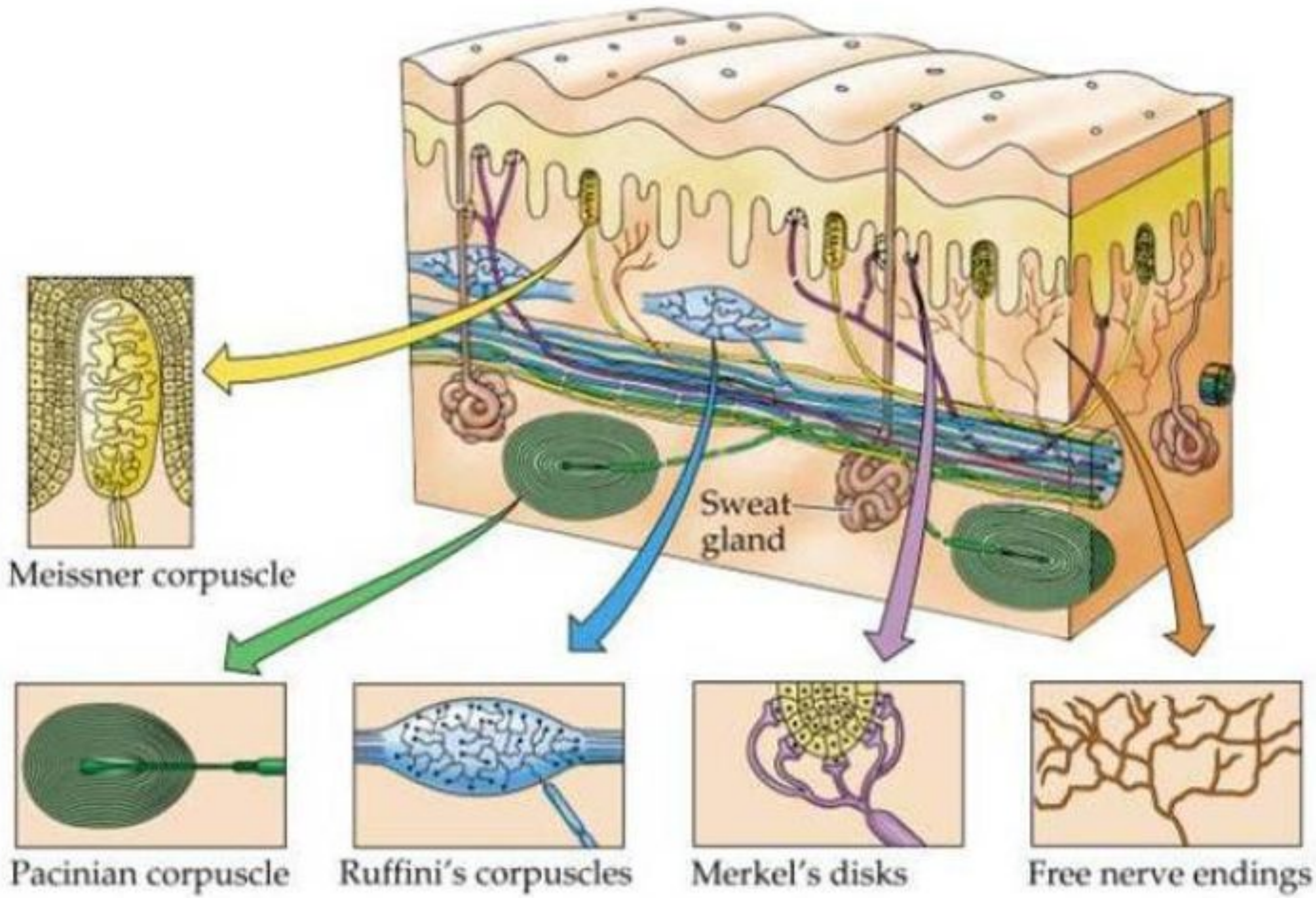
Vision vs Haptics:
the hand is quicker than the eye…

	Information capacity (bits/sec)	Temporal acuity
Fingertip	10^2	5 ms
Ear	10^4	0.01 ms
Eye	10^6-10^9	25 ms

adapted from L. Jones, Human Factors and Haptic Interfaces

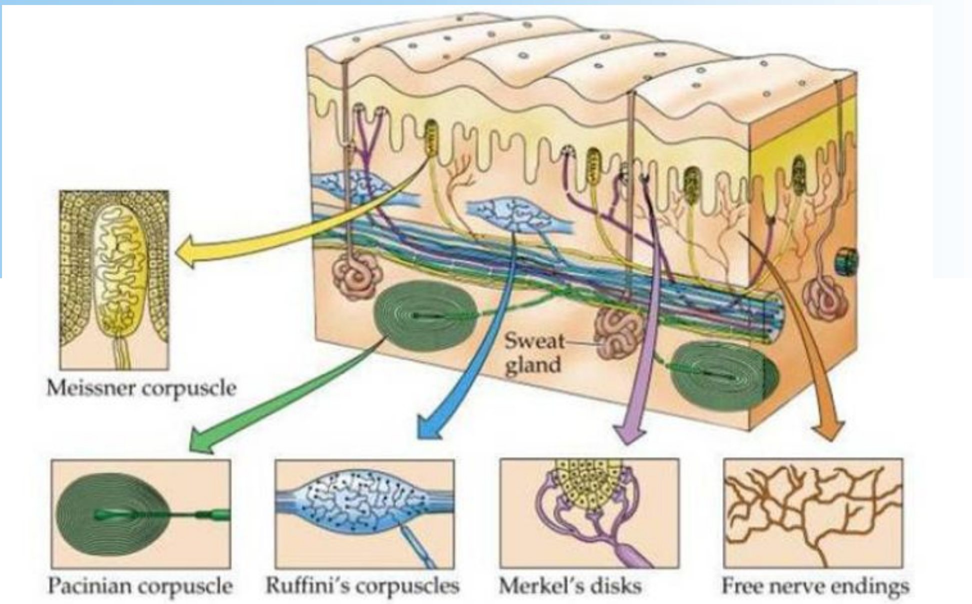
Human factors

Cutaneous receptors



Human factors

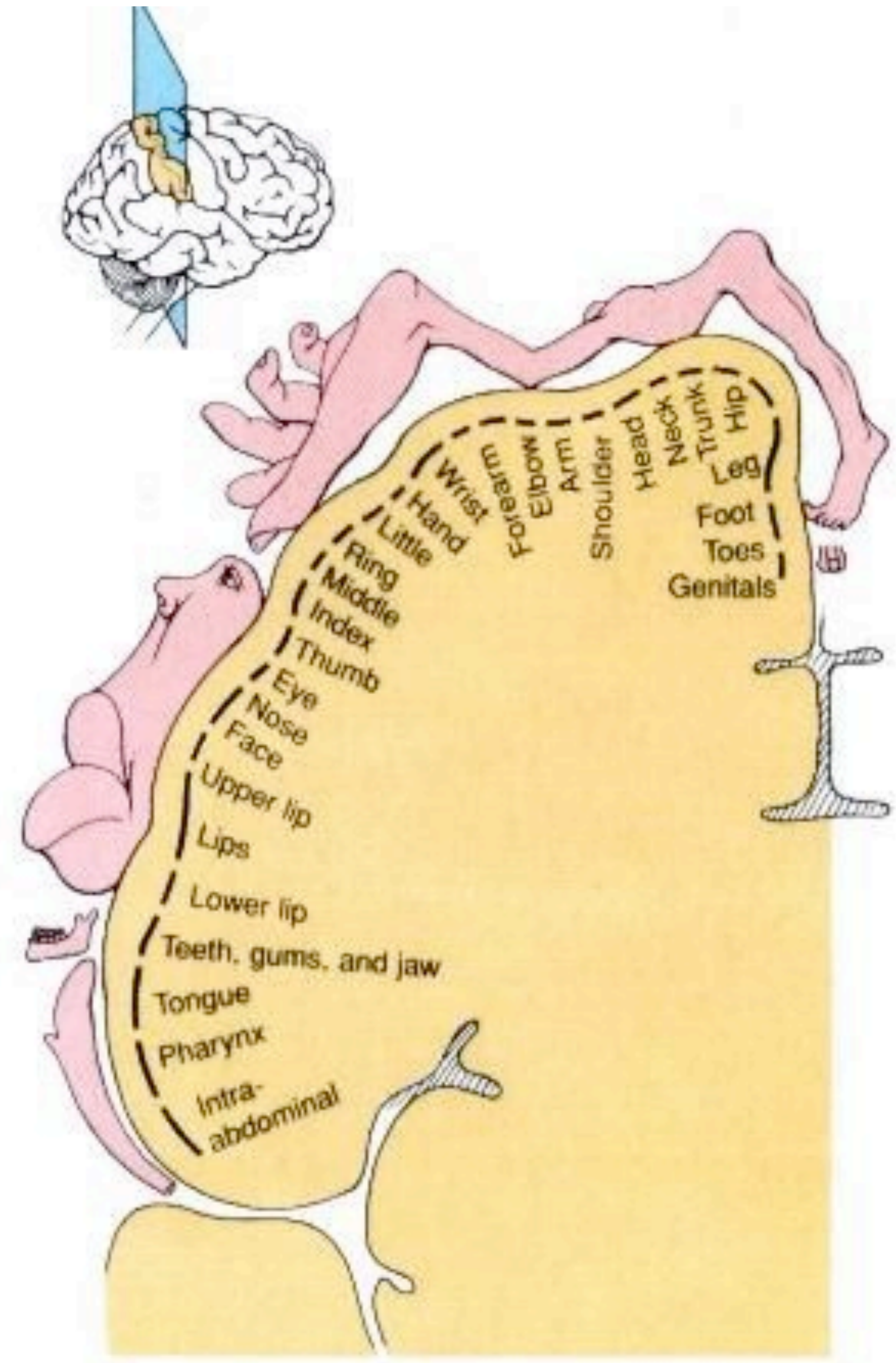
Cutaneous receptors



Receptor	Meissner corpuscles	Merkel discs	Ruffini corpuscles	Pacinian corpuscles
Stimuli	changes in texture, low-frequency vibrations	sustained touch and pressure	sustained pressure, skin stretch, slip	deep pressure, high-frequency vibrations
Frequency response	3/10–50 Hz	0.4–10 Hz	0.4–10/100 Hz	10/100–1000 Hz
Receptive field	small, well defined	small, well defined	large, indistinct	large, indistinct
Rate of adaptation	RA-I	SA-I	SA-II	RA-II
Percentage (hand)	43 %	25 %	19 %	13 %

Human factors

Sensory homunculus

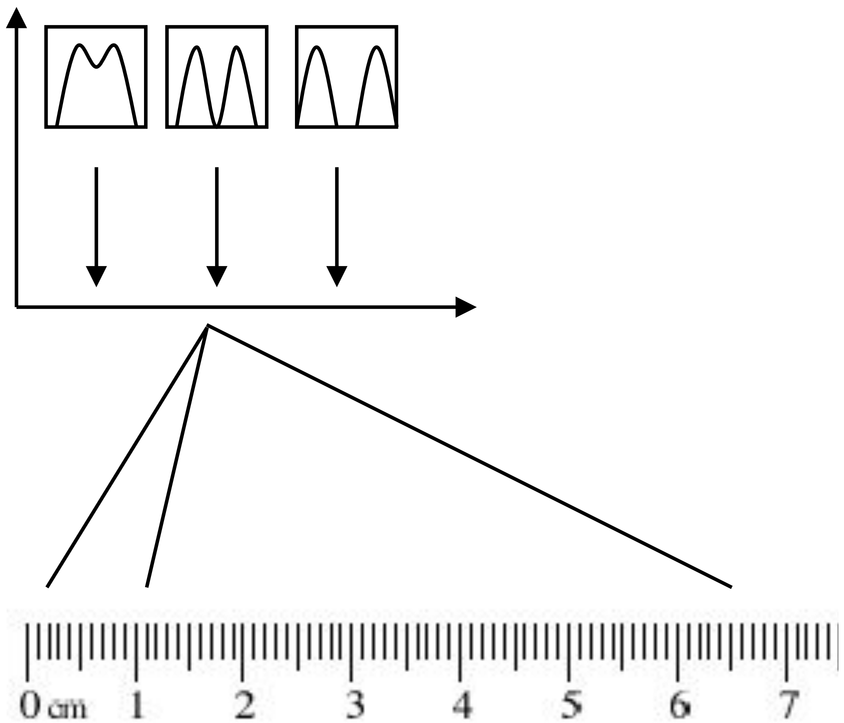


Somatosensory cortex

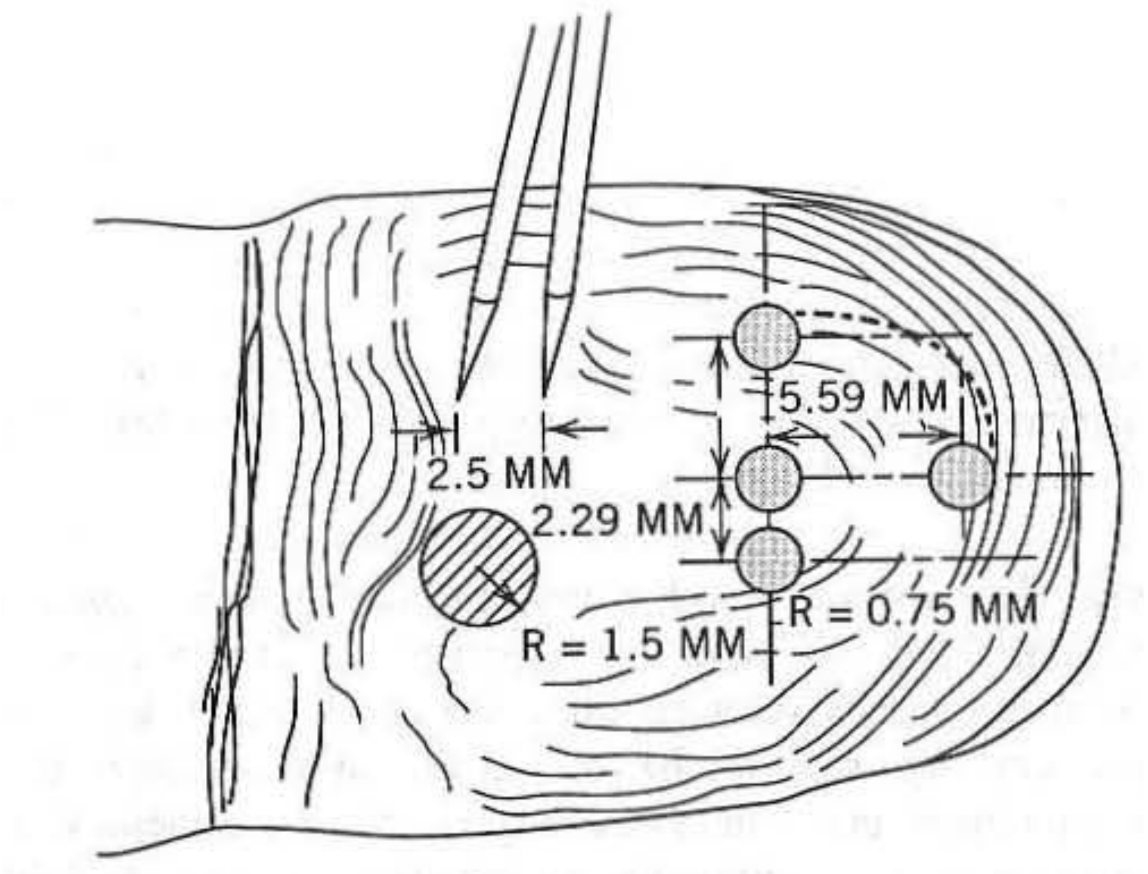
http://harmonicresolution.com/Sensory%20Homunculus.htm

Human factors

Spatial/temporal resolution



Finger tip: 2.5 mm   Palm: 11 mm   Thigh: 67 mm

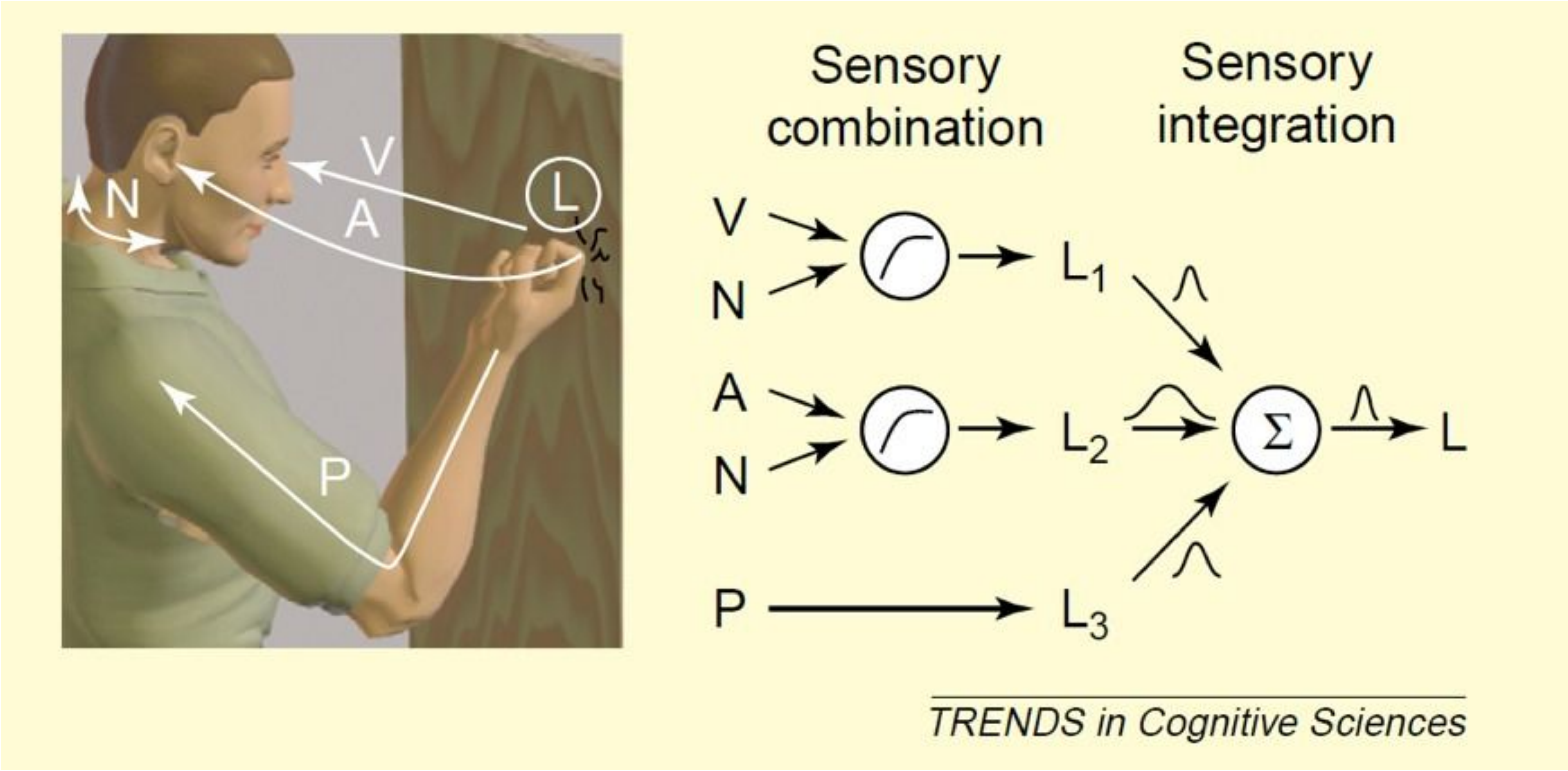


JND – Just Noticeable Difference

Joint	Hip	Shoulder	Elbow	Wrist	Finger	Toe
JND (°)	0.2	0.8	2.0	2.0	2.5	6.1

Force: ~7%

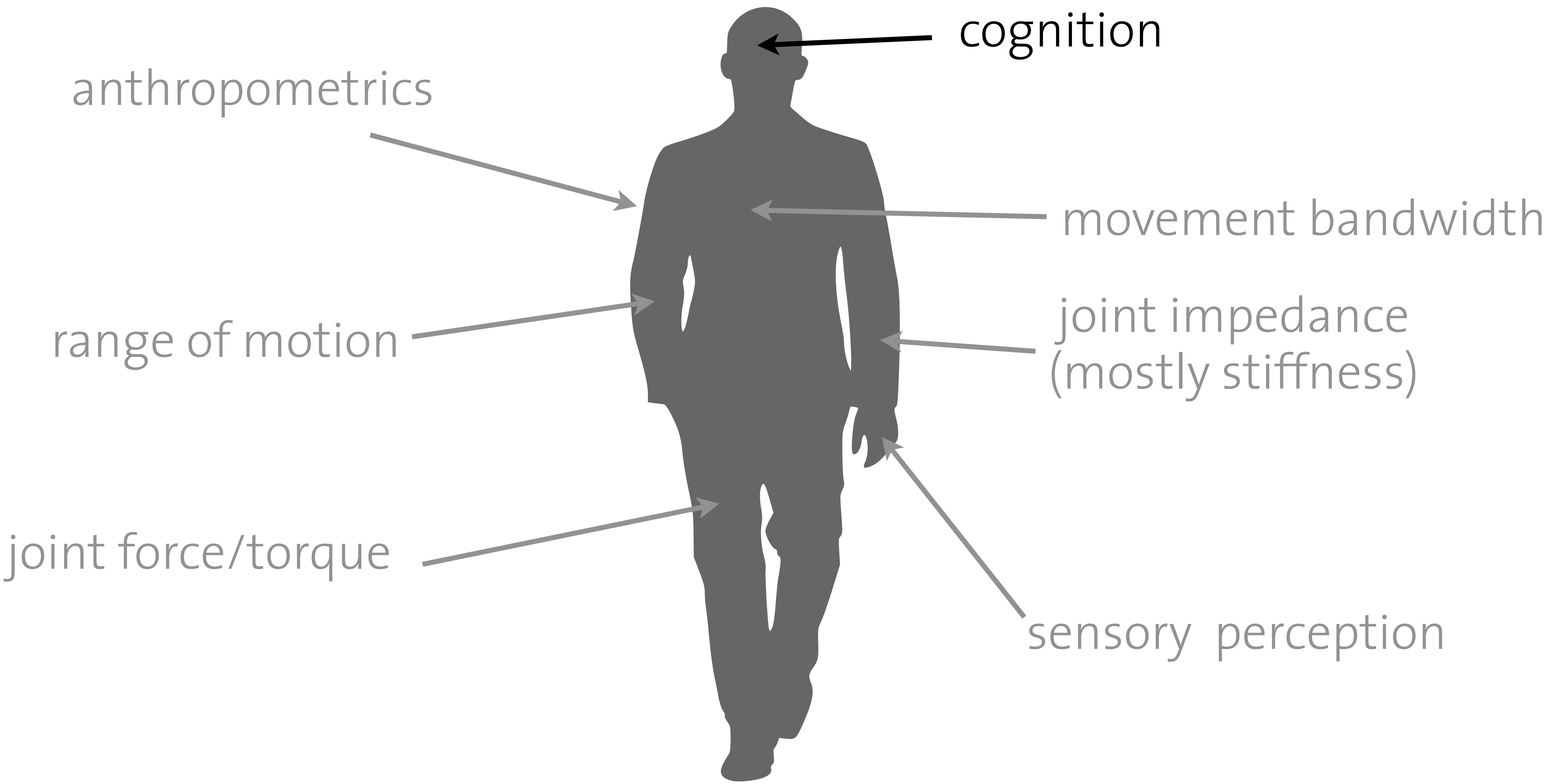
Cue combination



Ernst and Bülthoff, *Trends* (2004)

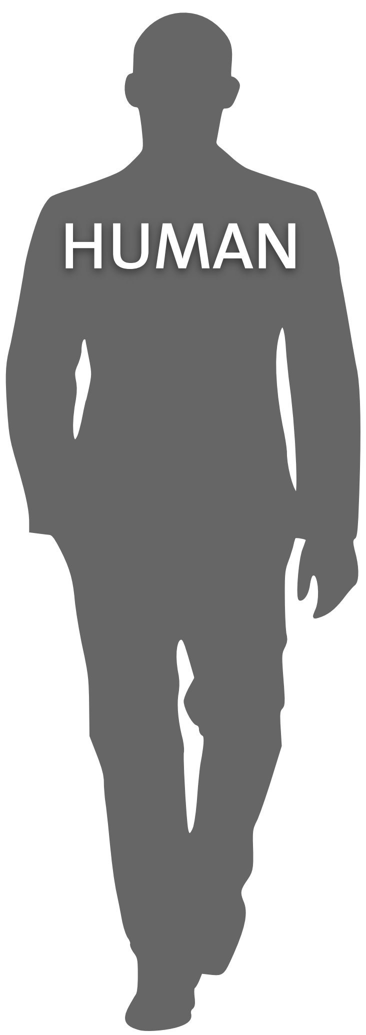
Human factors

Understand the human

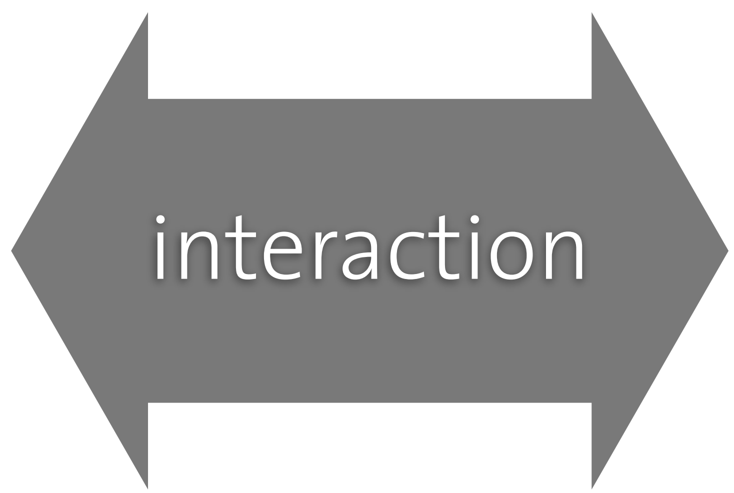


Human-Robot Interaction

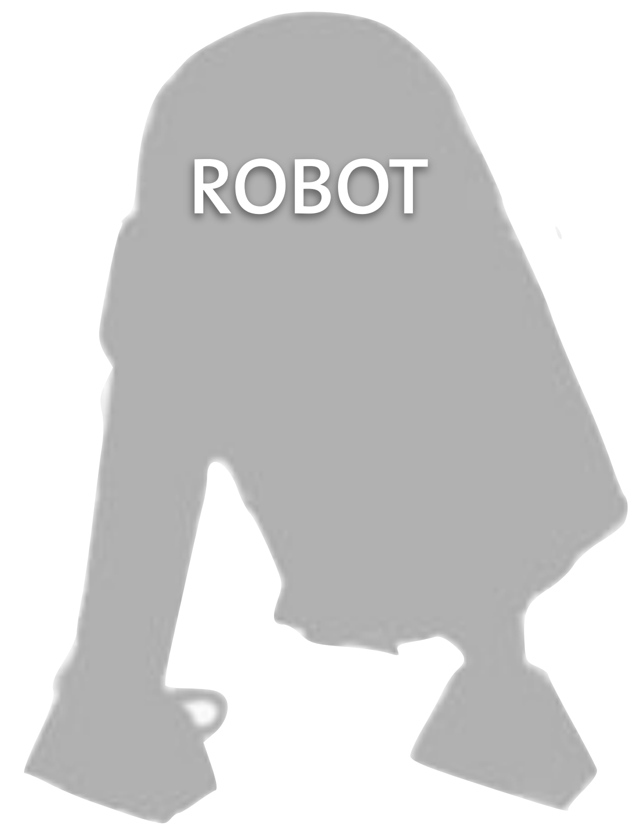
How to design human-robot interaction?



- defined system!
- needs
- limitations

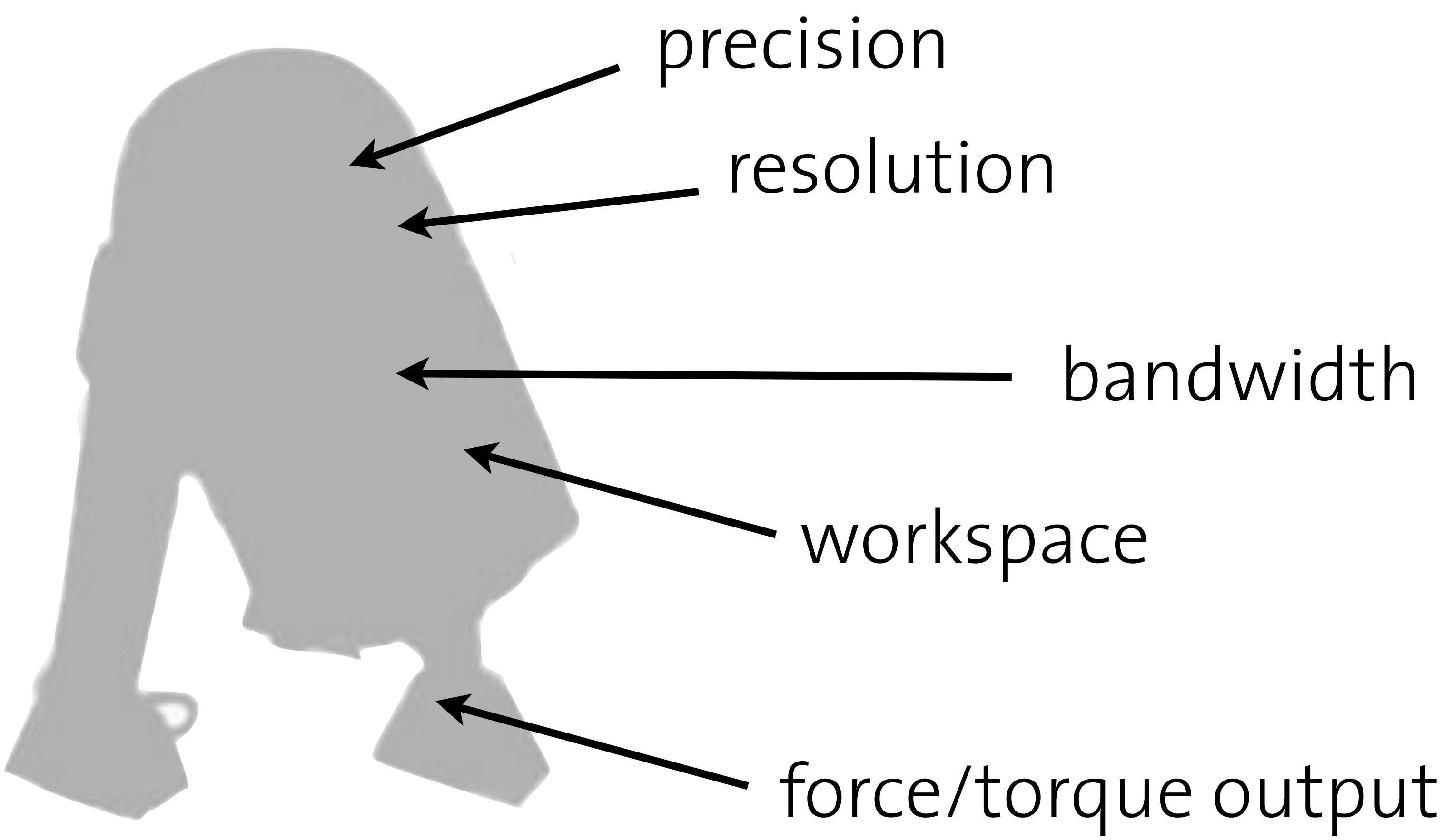


- realistic
- safe
- provide an advantage



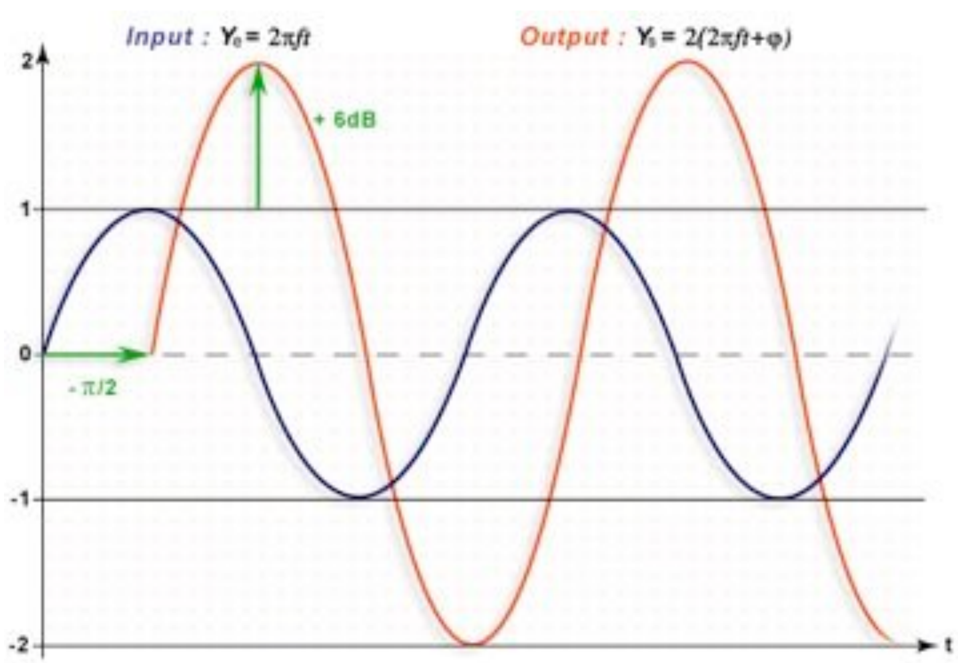
- flexible system
- virtually no limitations...

Conventional metrics



Bandwidth

- interaction of human and machine implies that the bandwidth of the device is of great importance
- position/force frequency response



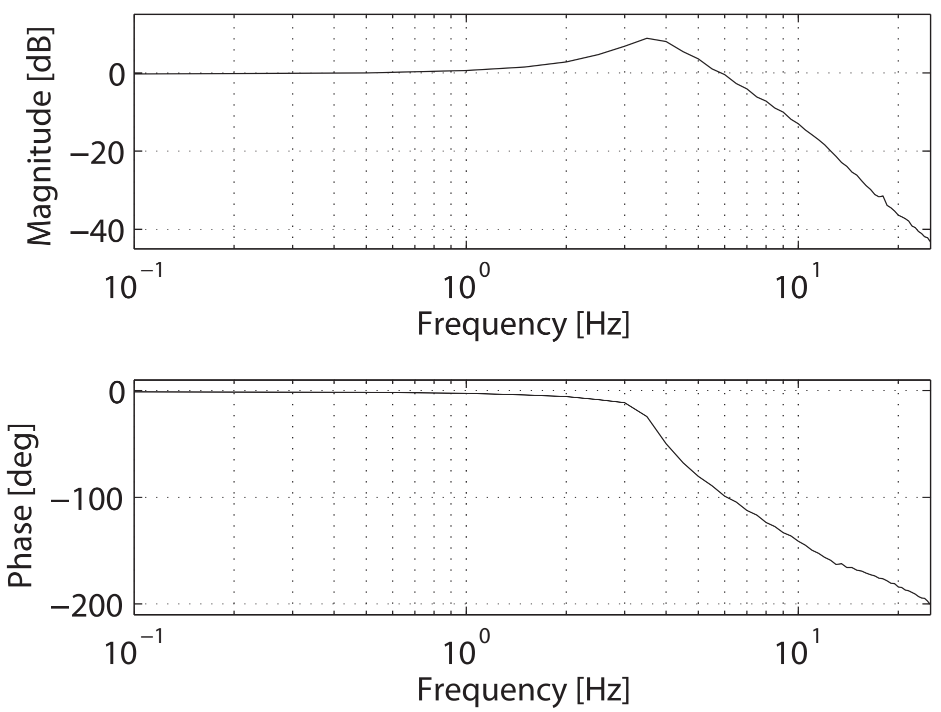
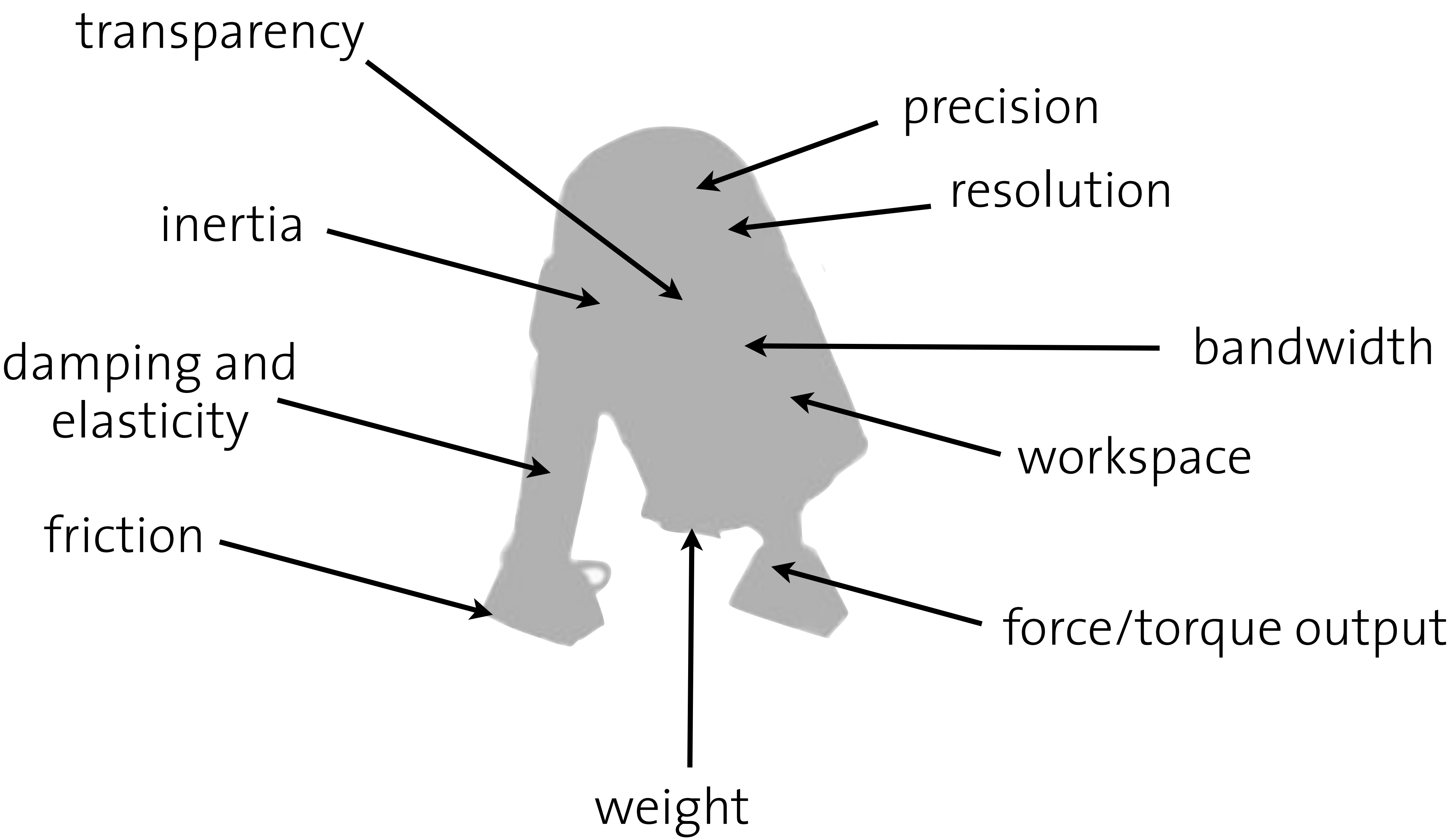


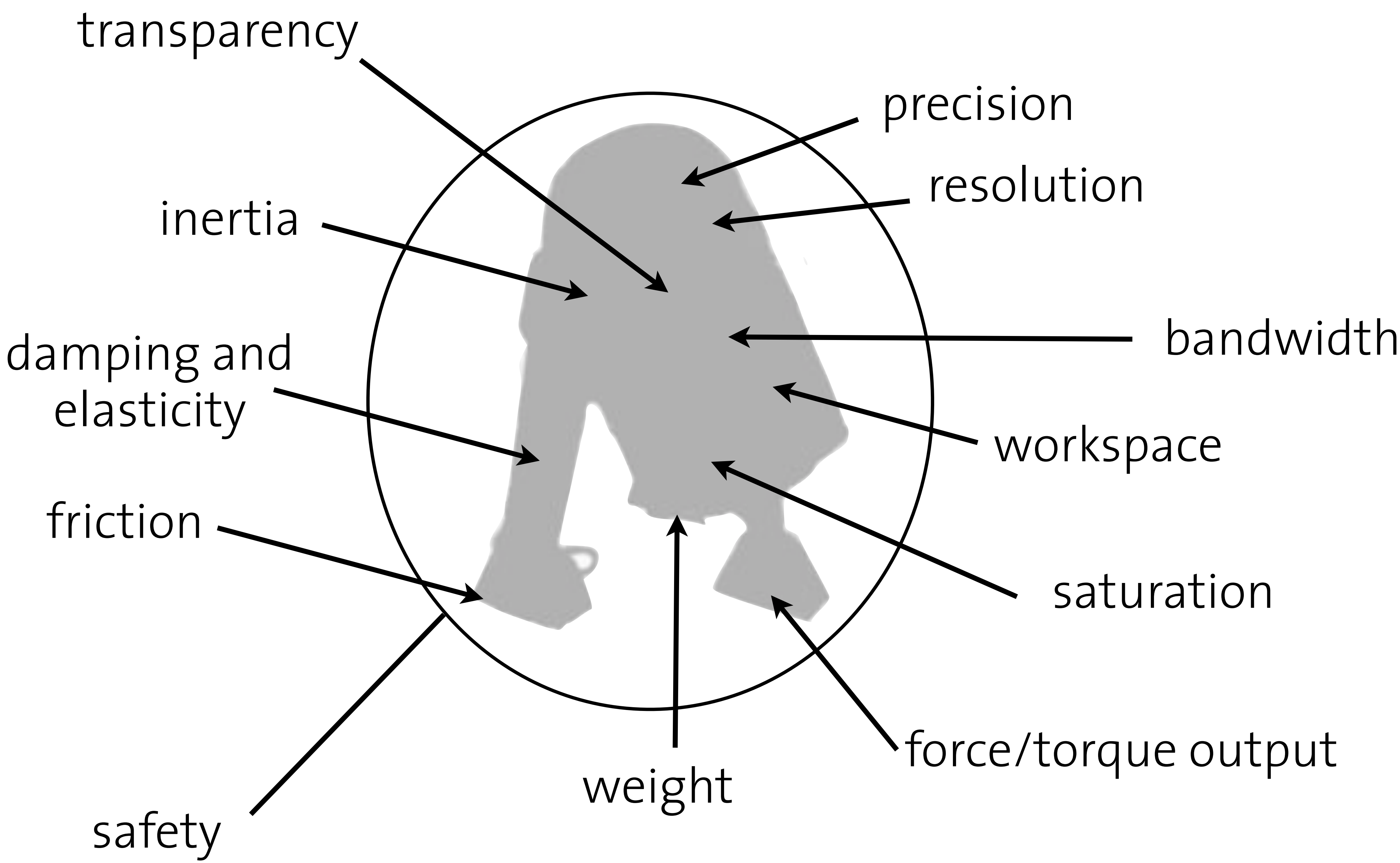
Fig. 6. Bode plot of the translational DOF to determine the PID controlled position bandwidth of 6.6 Hz.

Metzger et al, IROS 2011

Conventional metrics



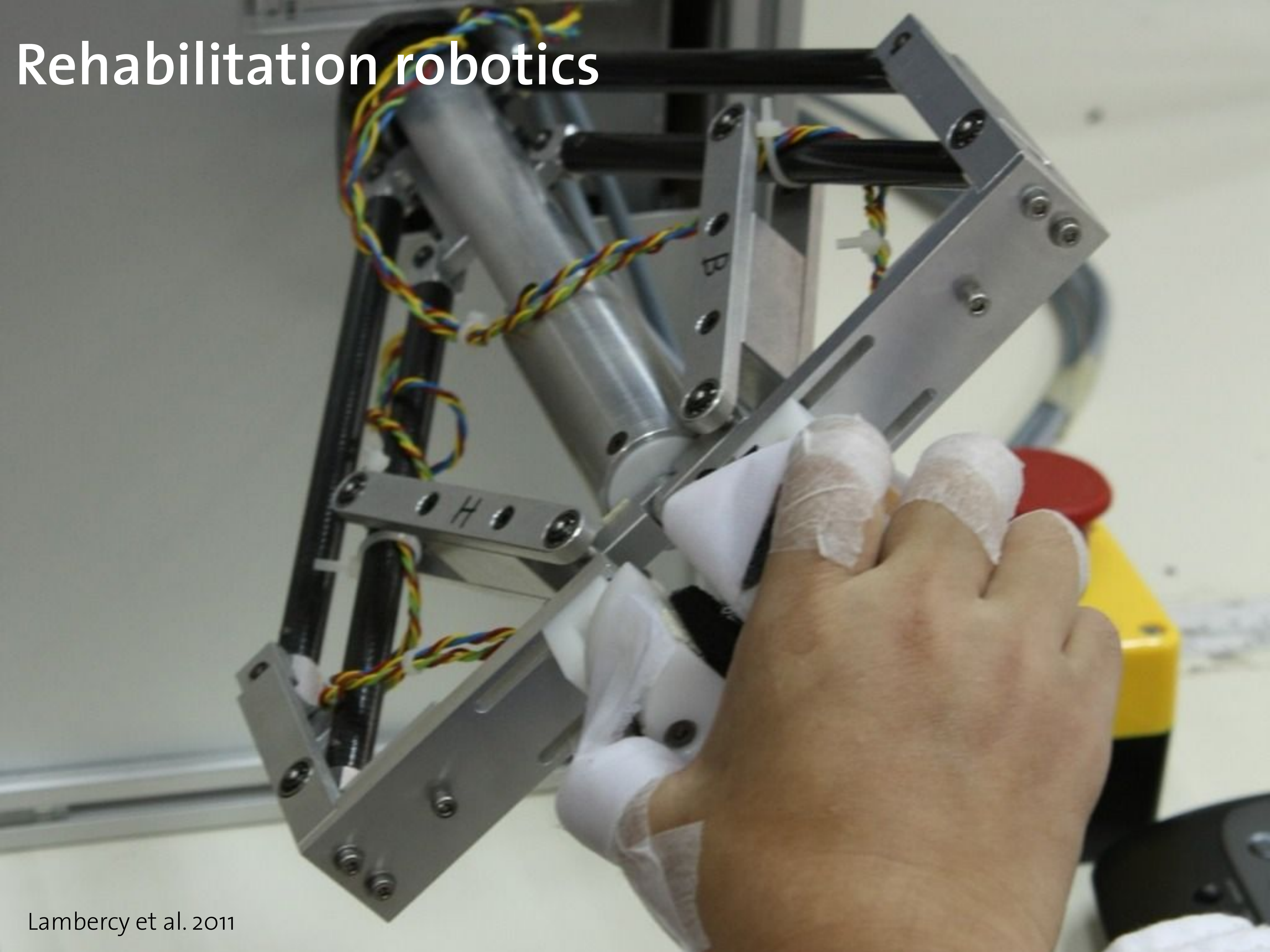
Conventional metrics



Safety

- mechanical stops, torque limiters
- emergency button / dead-man‘s switch
- redundant sensing
- software routines (e.g. position, velocity and torque limits)
- watchdog
- weight compensation (e.g. with springs)
- safe & ergonomic design (no sharp edges)
- …

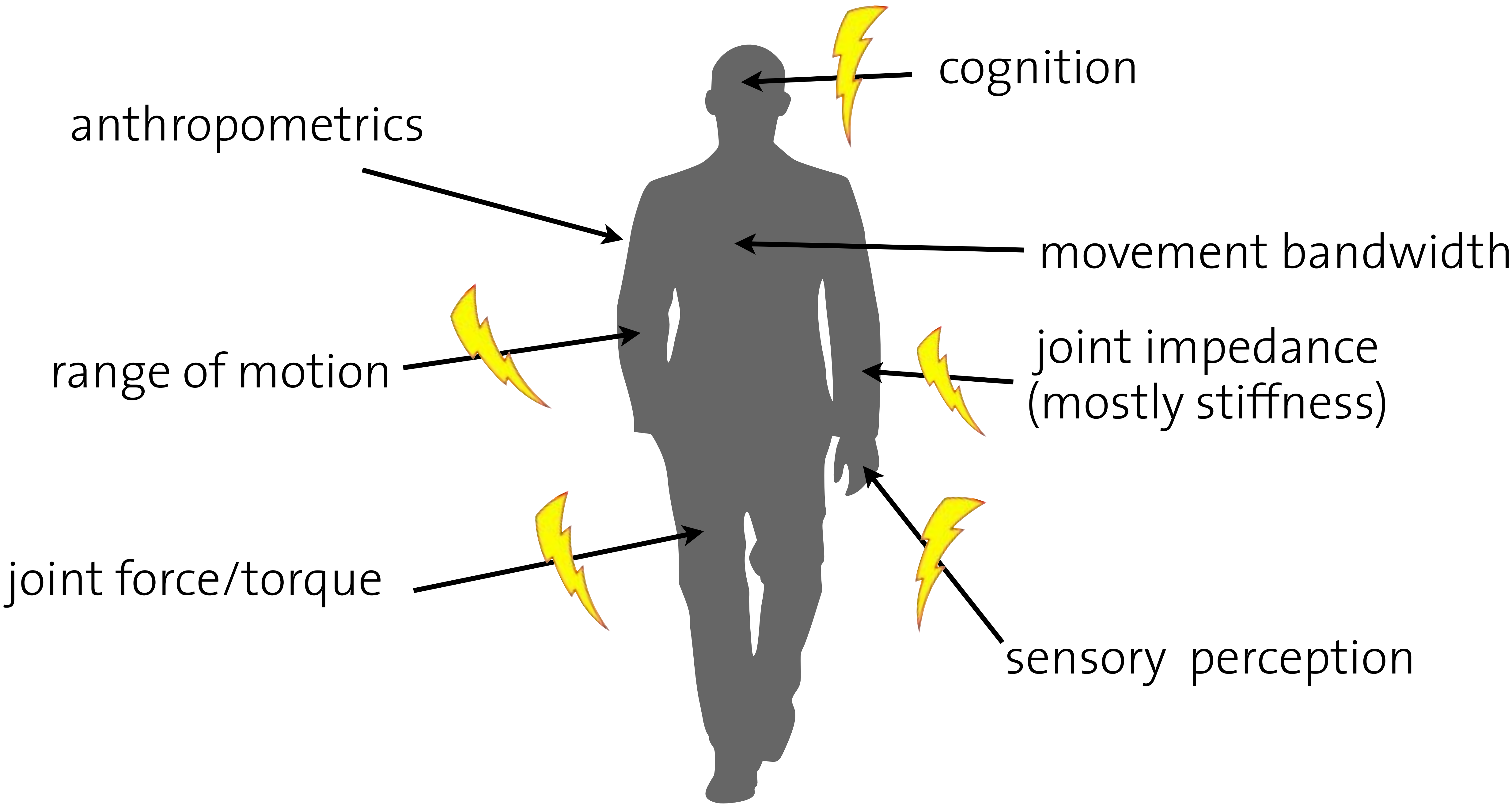
Rehabilitation robotics



Lambercy et al. 2011

The example of rehabilitation robotics

Understand the impaired human



Stroke and disabilities

- first cause of long term adult disability
- ~15 millions strokes per year
- permanent **brain** lesion

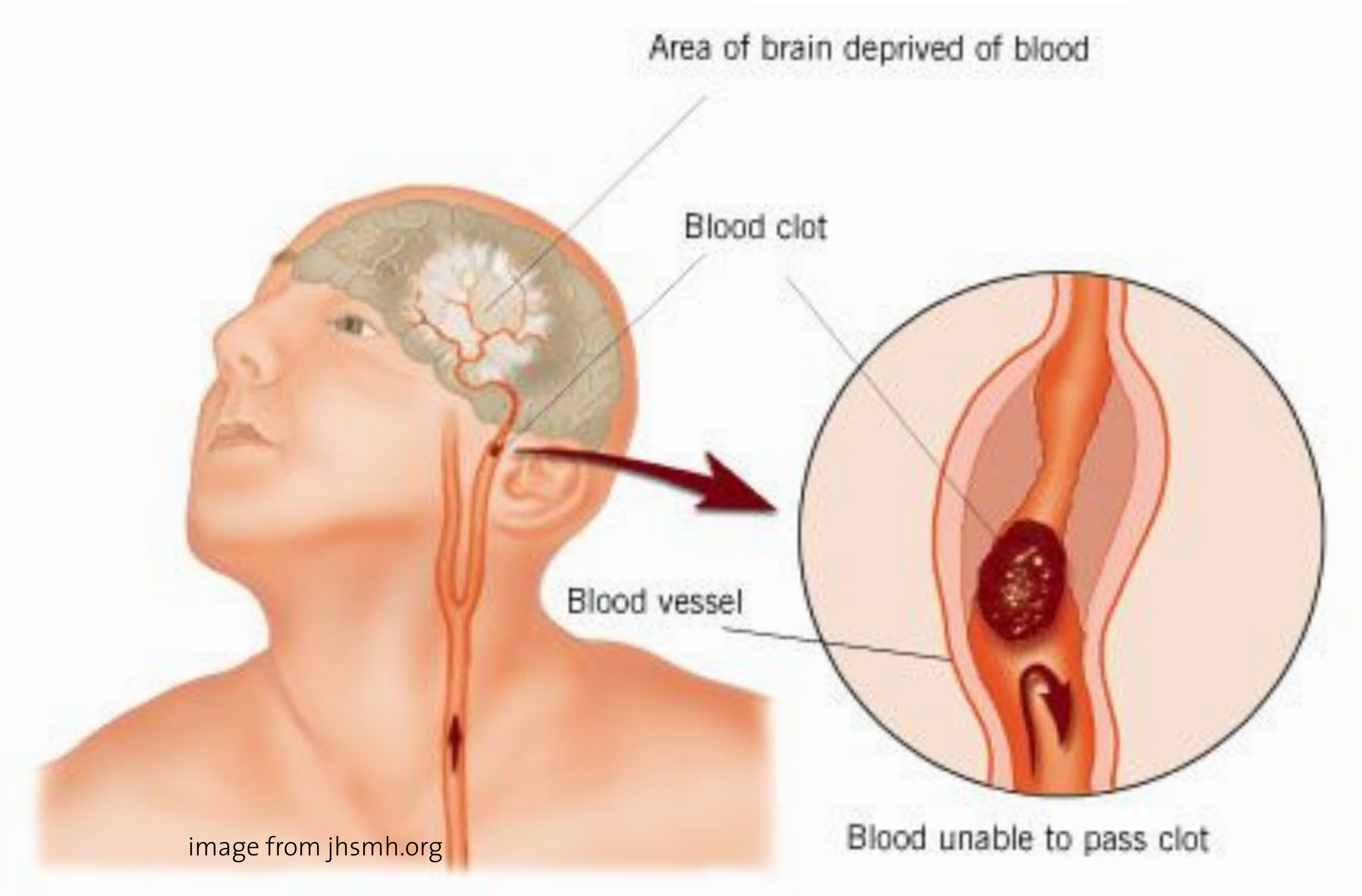
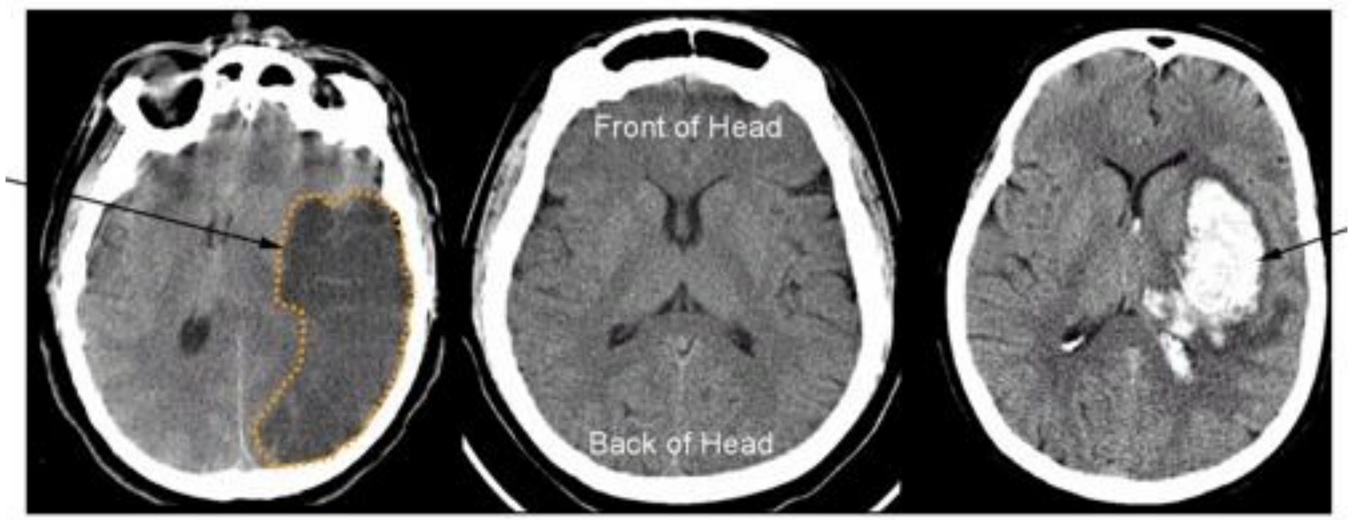
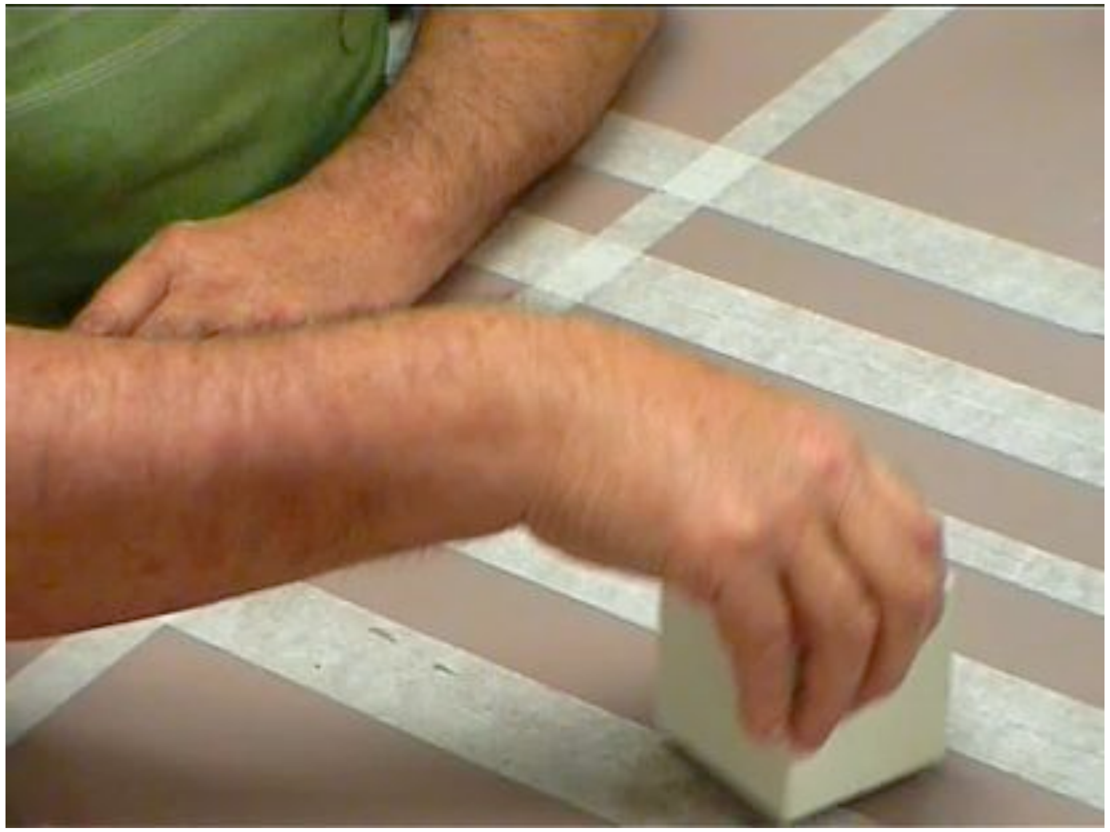


image from jhsmh.org



Stroke and disabilities

- **the hand** is often impaired
- weakness, lack of coordination, abnormal muscle synergies, tone, tremor, sensory loss...

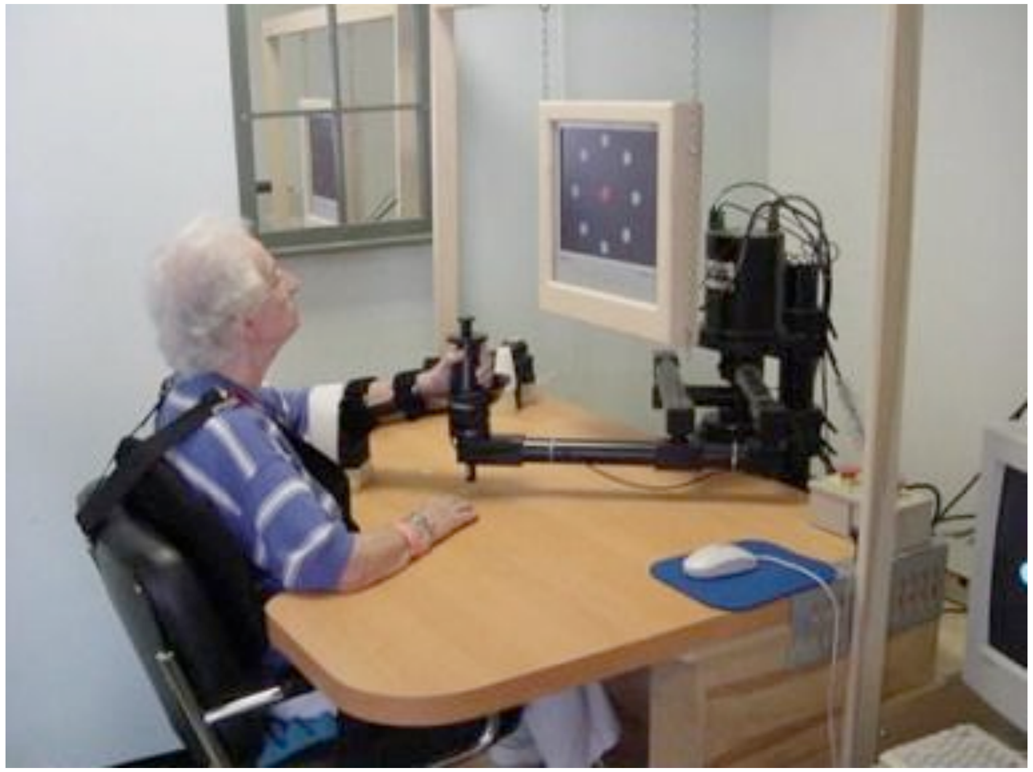


Joe W., 3 years after a stroke

The brain is plastic and functions can be recovered!

Why robots for rehabilitation?

- **augmenting** physical therapy through the use of robotic devices
- providing **objective and precise** assessments
- motivation through the use of virtual reality



MIT Manus

From passive to assist-as-needed

Passive movement

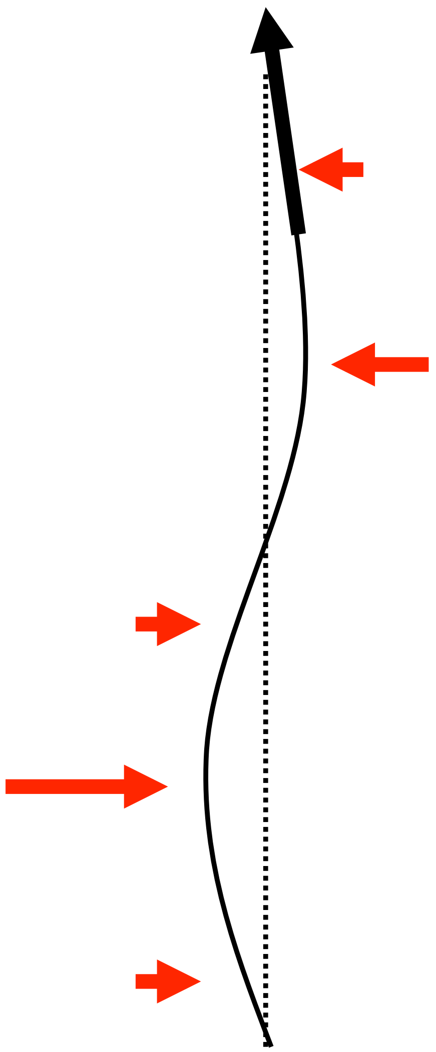
- robot moves patient’s relaxed limb
- provides patient with proprioceptive sensory feedback without active muscle fibers
- can be used to stretch muscles to increase range of motion
- have been shown to have limited efficacy (Hogan et al. 2006)

slide adapted from E. Burdet

From passive to assist-as-needed

Guided movement

- patient moves own limb and robot generates elastic force along desired path
- provides patient with proprioceptive sensory feedback of errors in force direction
- prevents patient from making hand path errors but does not correct muscle activation patterns

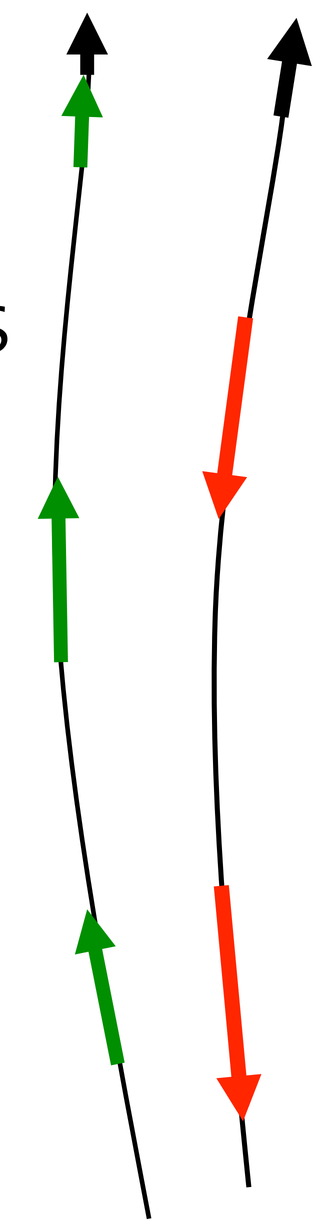


slide adapted from E. Burdet

From passive to assist-as-needed

Active assisted/resisted movement

- patient moves own limb and robot assists/resists to increase speed or range of motion
- resistive training can help patients acquire strength
- level of assistance/resistance can be based on different variables (timing, performance muscle activity, brain activity, etc...)



slide adapted from E. Burdet

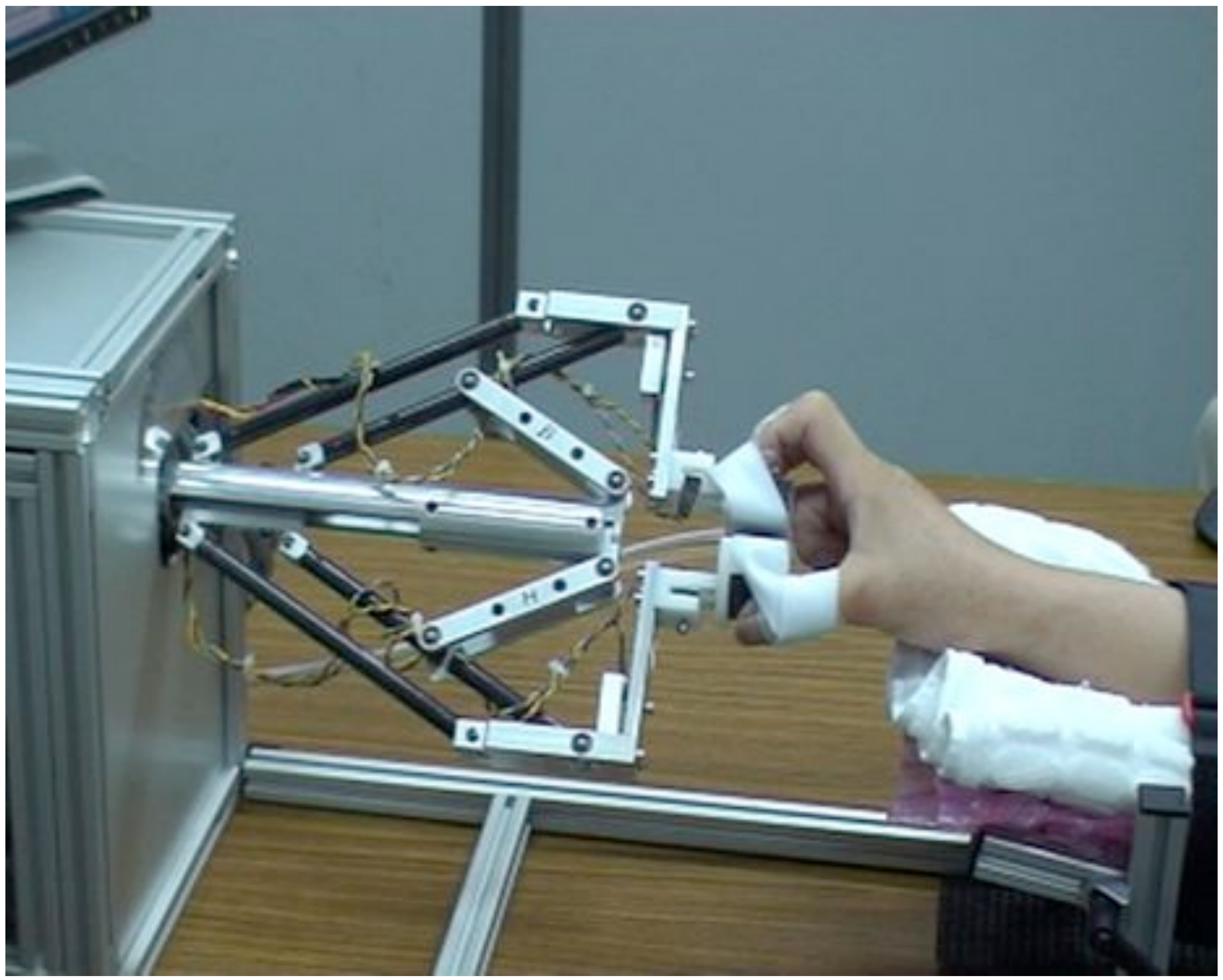
Rehabilitation robotics

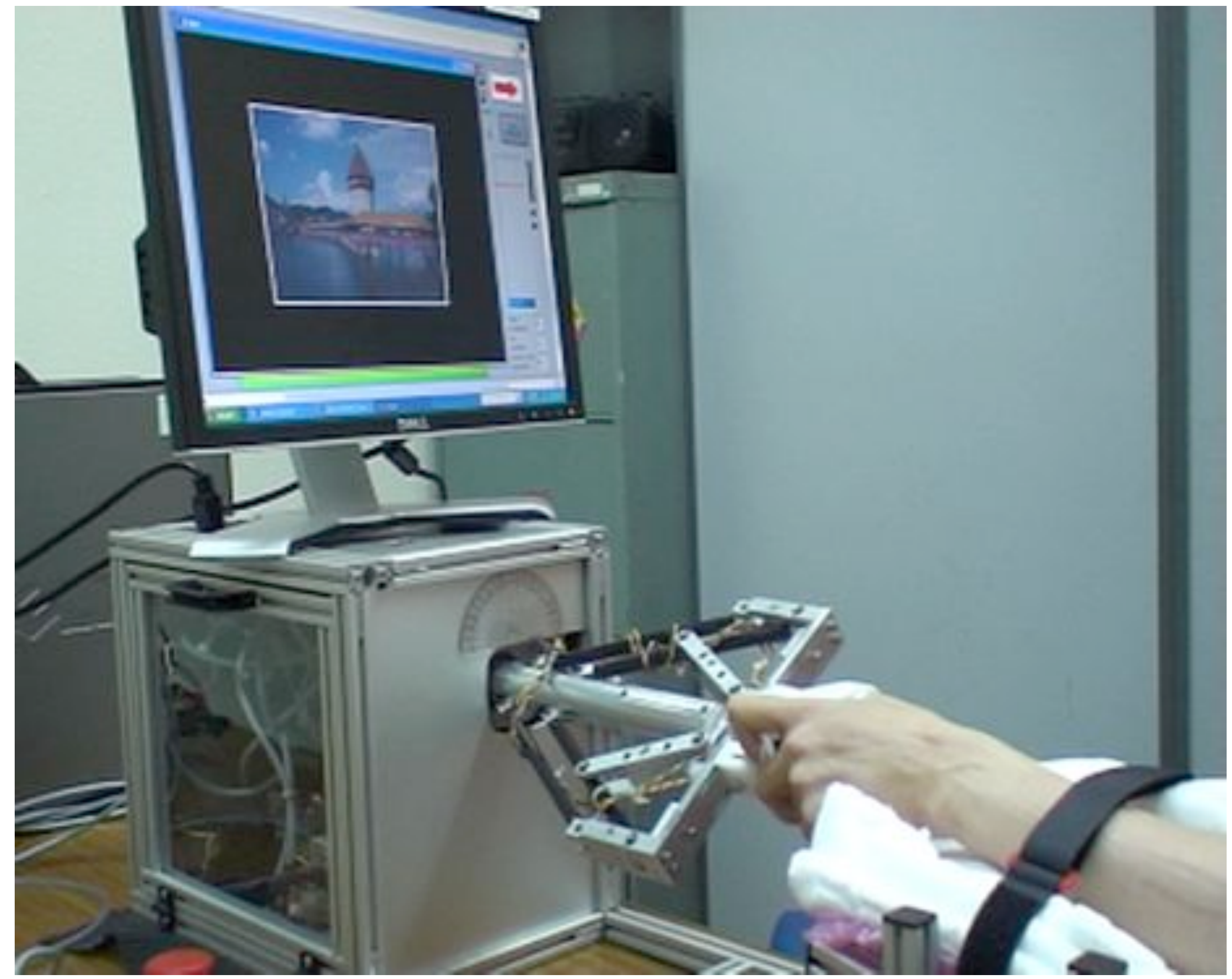
Many developments for the arm and legs...

...little has been done for the hand

Our approach

The HapticKnob

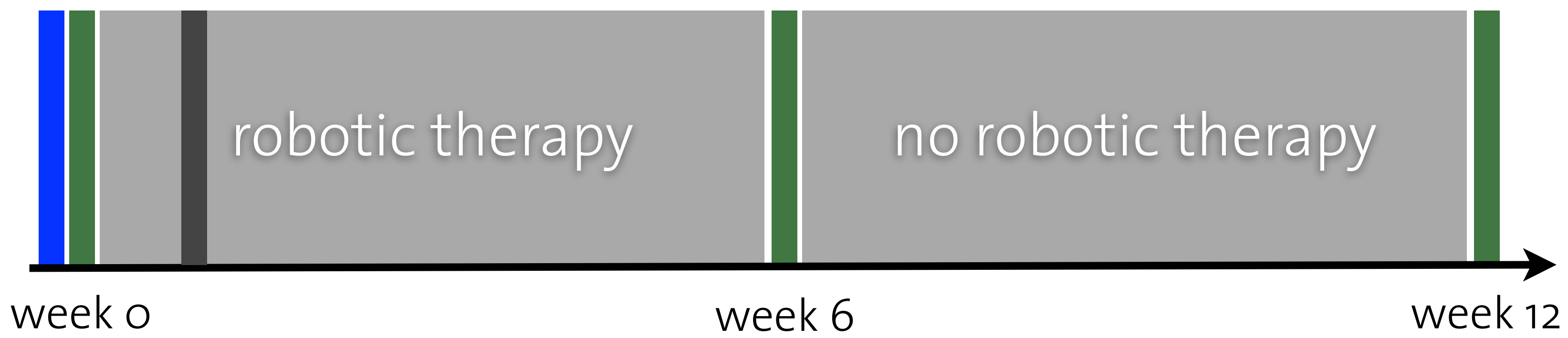


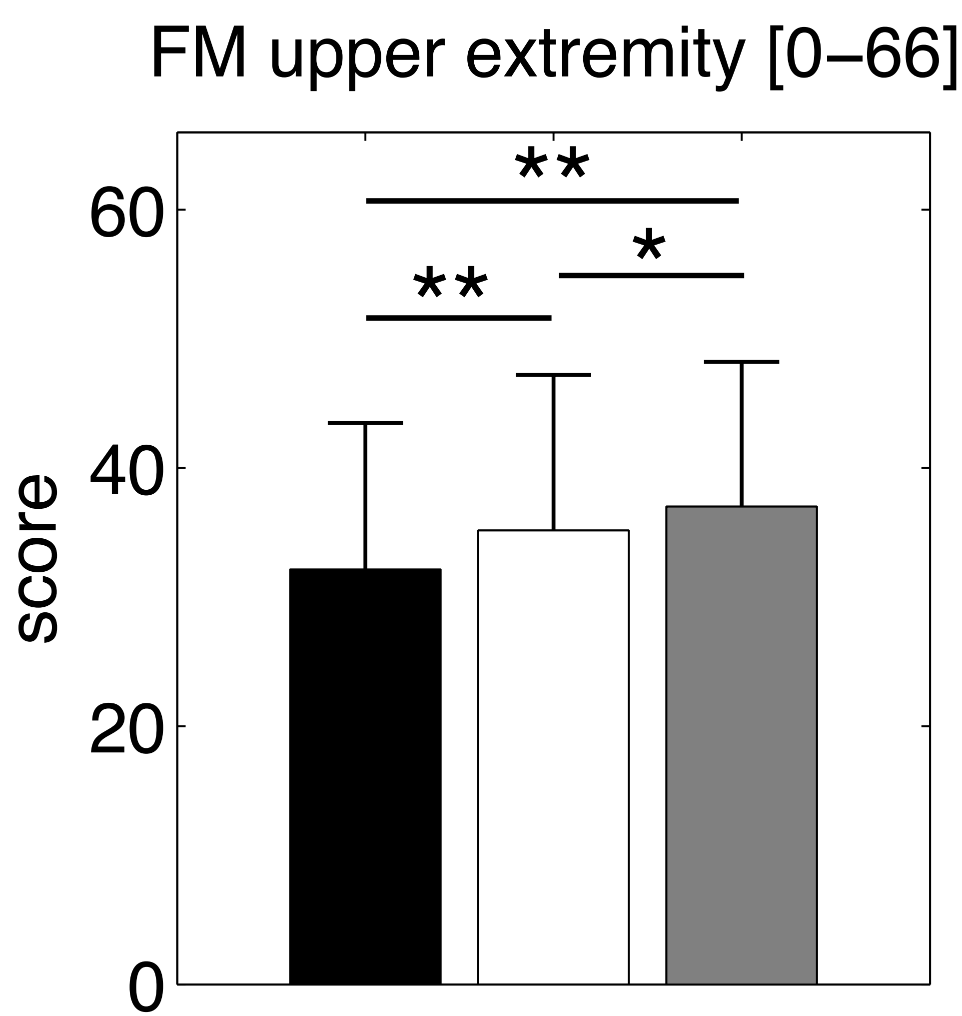


Lambercy et al. 2011

Our approach

The HapticKnob





“Function of my hand increased immensely; more flexibility and wider range of motion.”

Joe W. (54)

Lambercy et al. 2010, Lambercy et al. 2011

Our approach

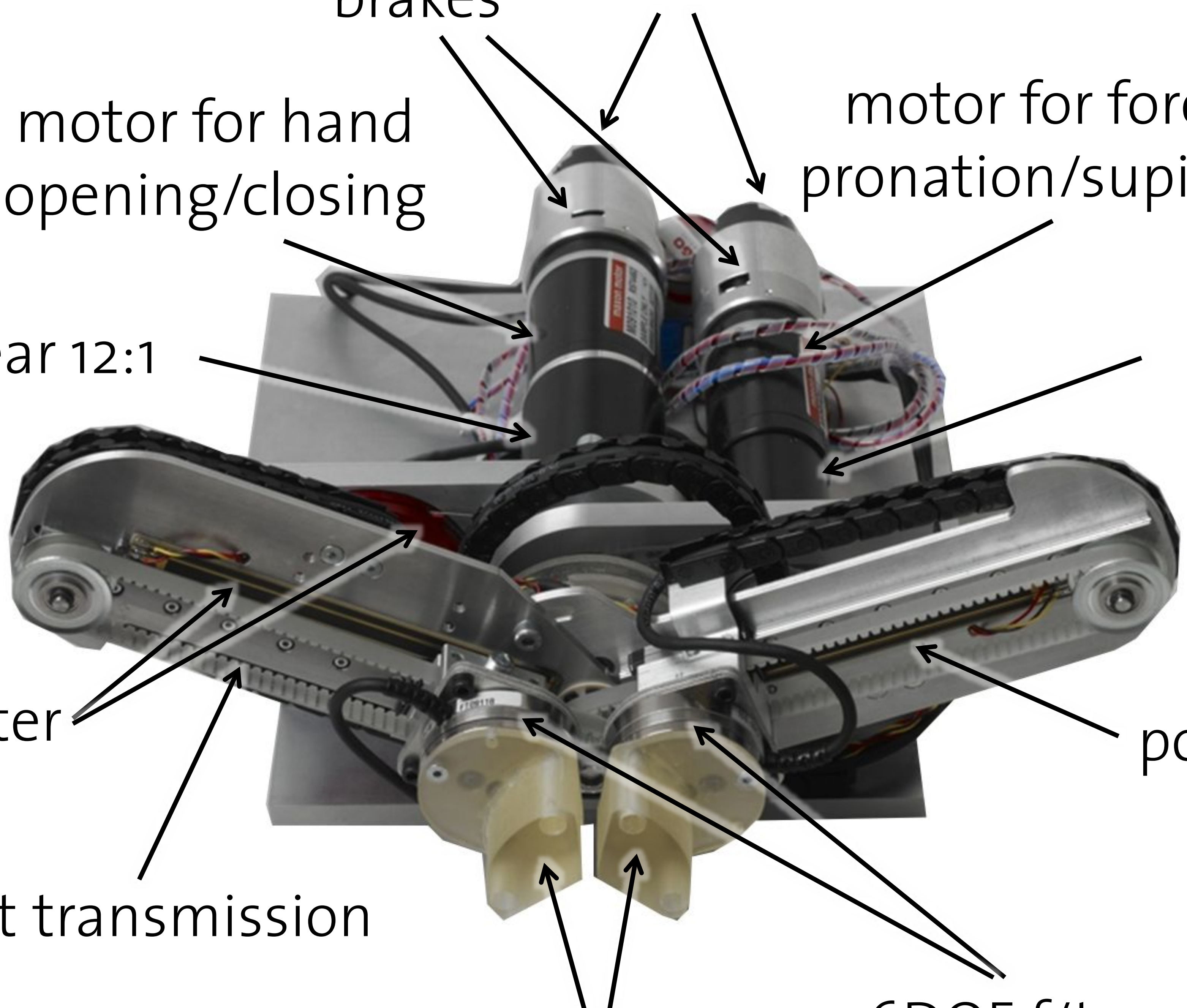
A robot to:
assist severely impaired patients
(unable to move, increased muscle tone)

device with a
large Z-Width

challenge patients with improved dexterity
-> train fine motor function

slide adapted from J.C. Metzger

The ReHapticKnob



Metzger et al. 2011

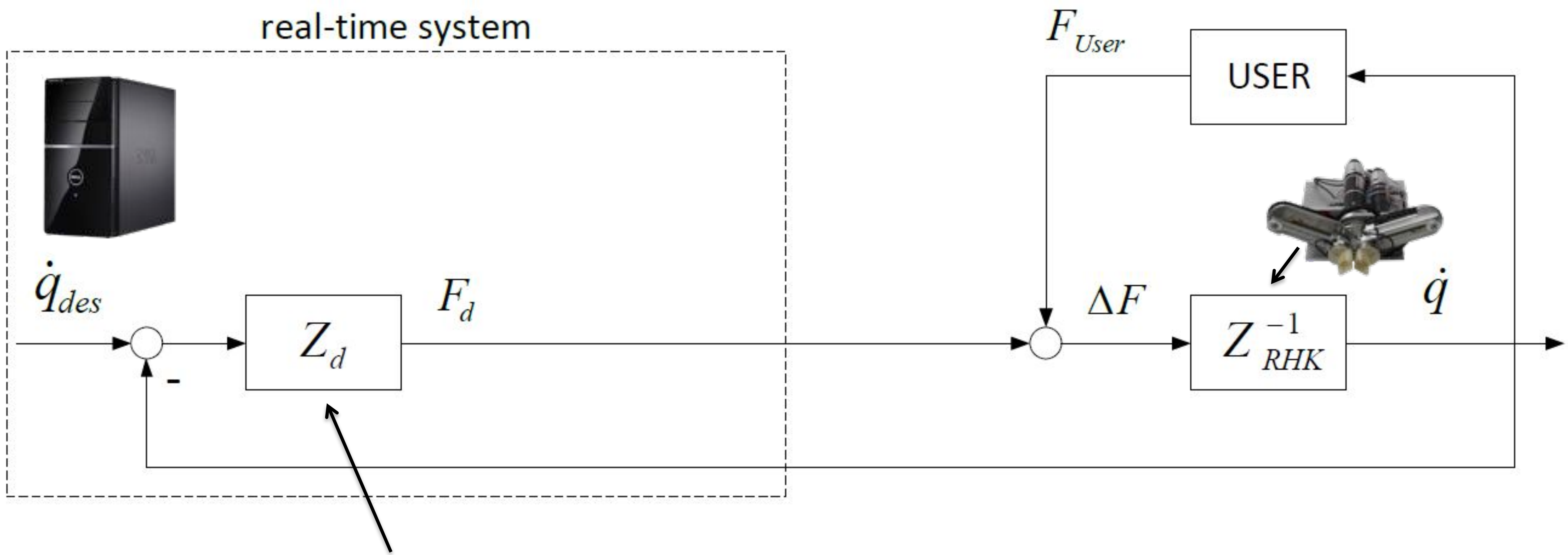
Our approach

Use tools/metrics from haptics to improve robot-assisted rehabilitation:

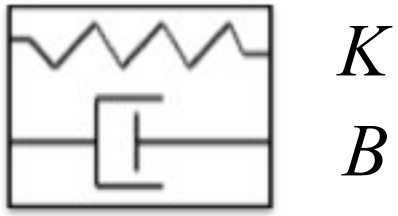
- Large **peak acceleration** to render virtual objects (abrupt changes in velocity) (Stocco 1996, Hayward 1996)
- Force sensor at end-effector: Impedance control with force feedback to reduce apparent impedance (Hogan 1985, Carignan and Cleary 2000)
- **Velocity filtering** to increase renderable impedance (Colgate and Brown 1994, Janabi-Sharifi 2000, Chawda 2010)

slide adapted from J.C. Metzger

Impedance control

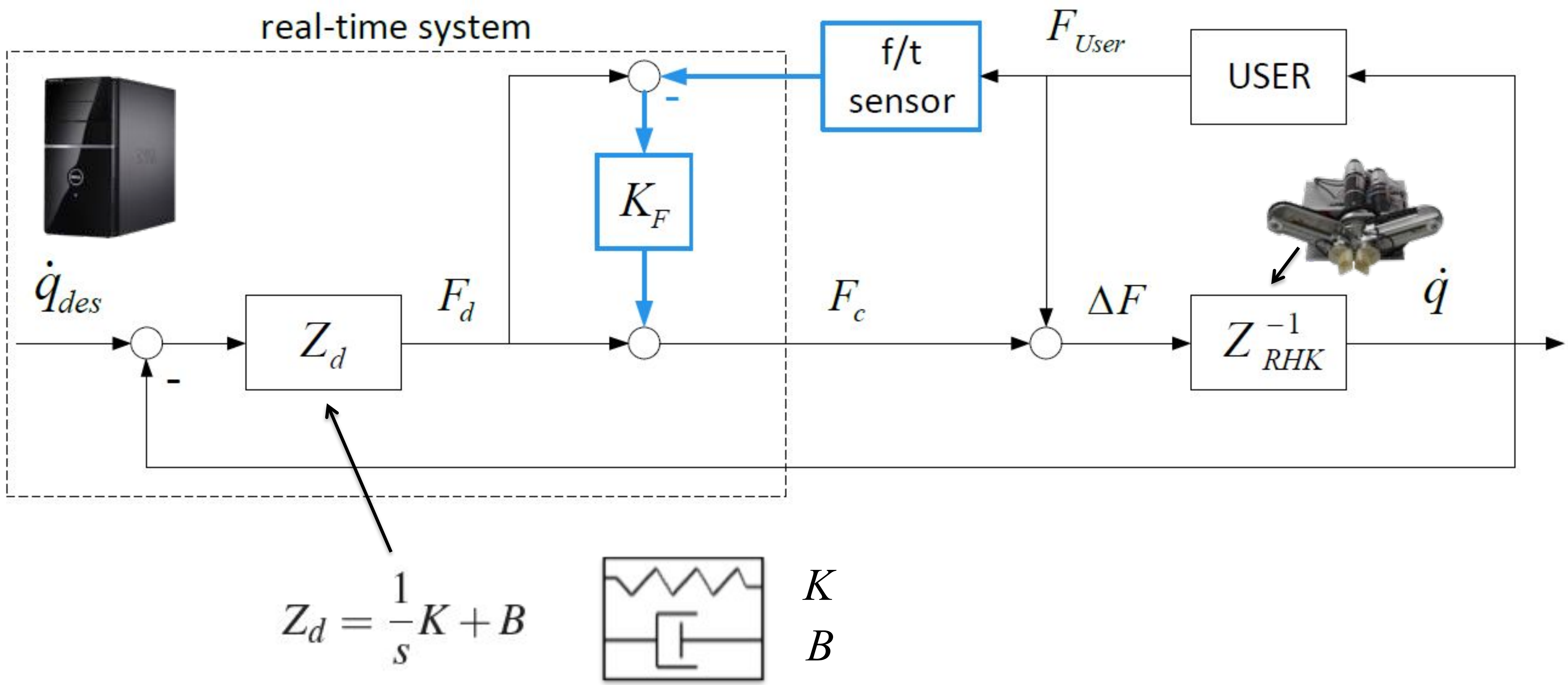


$$Z_d = \frac{1}{s}K + B$$



slide adapted from J.C. Metzger

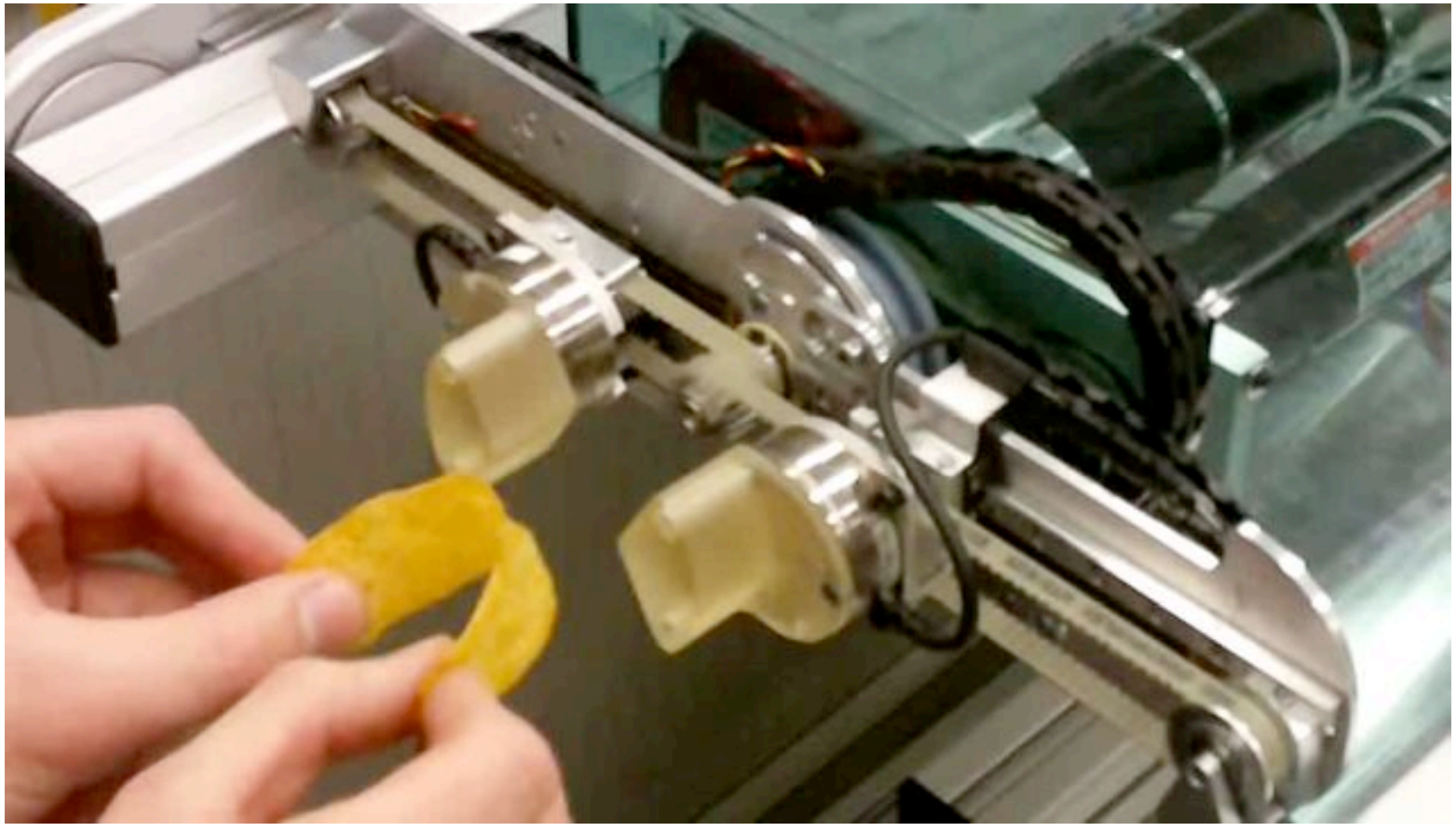
Impedance control with force feedback



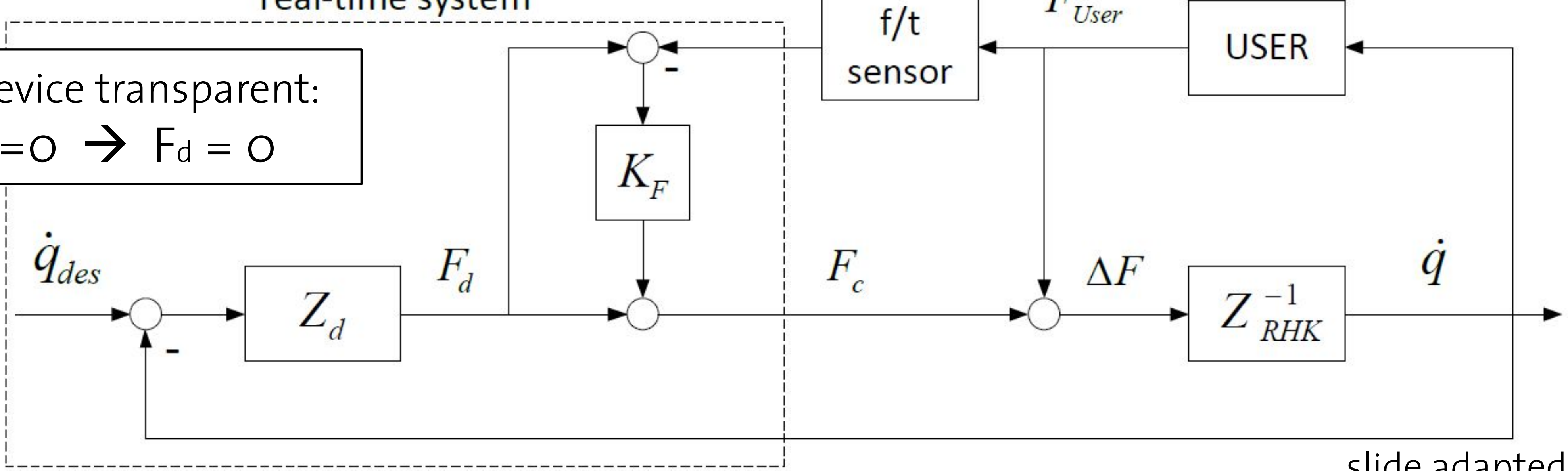
Force feedback reduces the apparent impedance of the device
The desired impedance (Z_d) is perceived at the end-effector

Hogan 1985, Carignan and Cleary 2000

Reduction of the apparent impedance

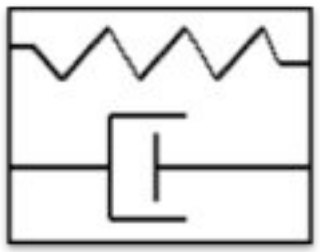


Make device transparent:
K=0, B=0 → F_d = 0



slide adapted from J.C. Metzger

Velocity filtering



K

B

$$F_{desired} = (x - x_d) \cdot K + \dot{x} \cdot B$$

Velocity estimation:

Euler backward approximation +
1st and 2nd order Butterworth (BW)

T

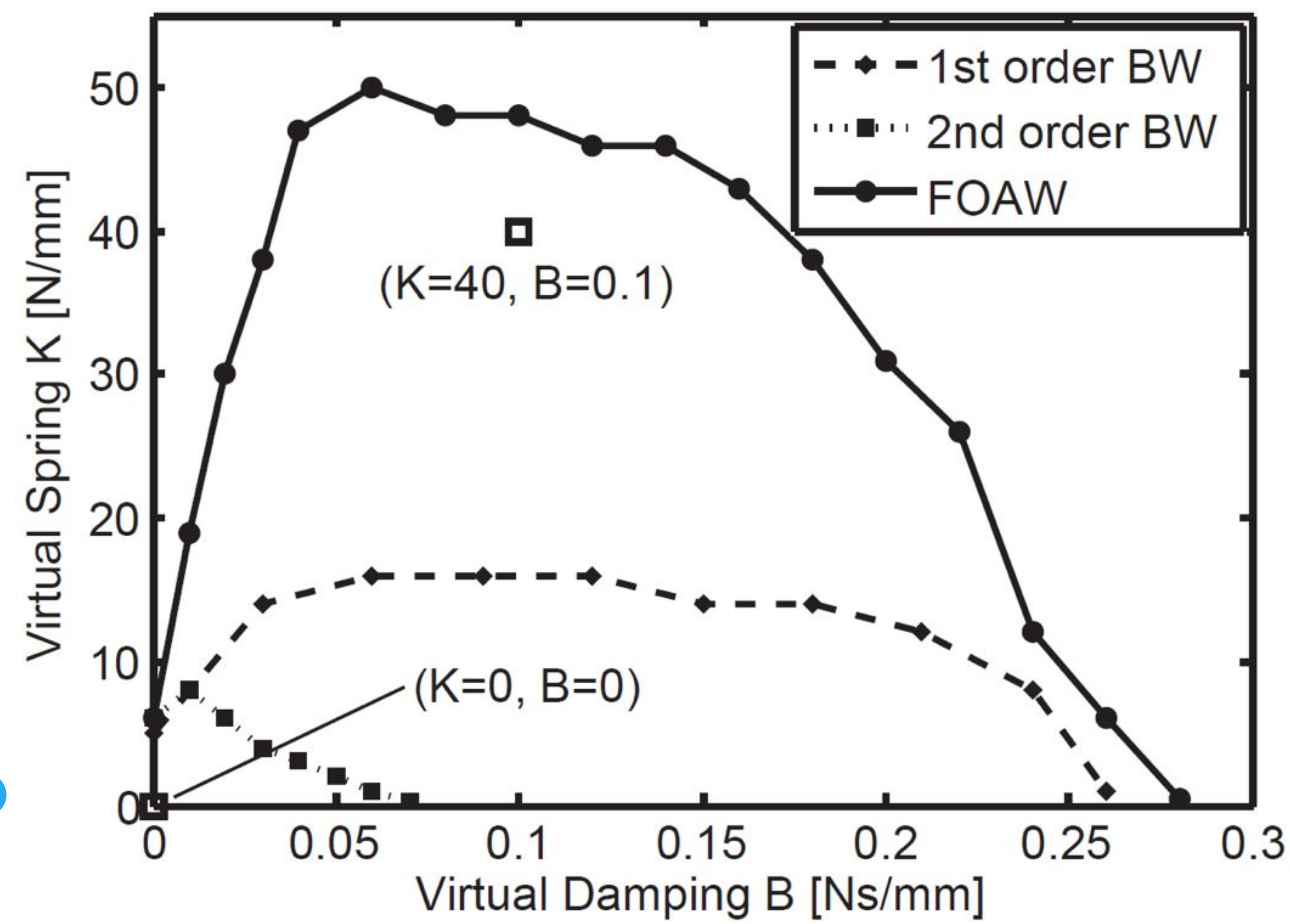
$$\dot{x} = (x_k - x_{k-1})/T$$

First Order Adaptive Window (FOAW)

Adaptive window length *n=f(|x|)*

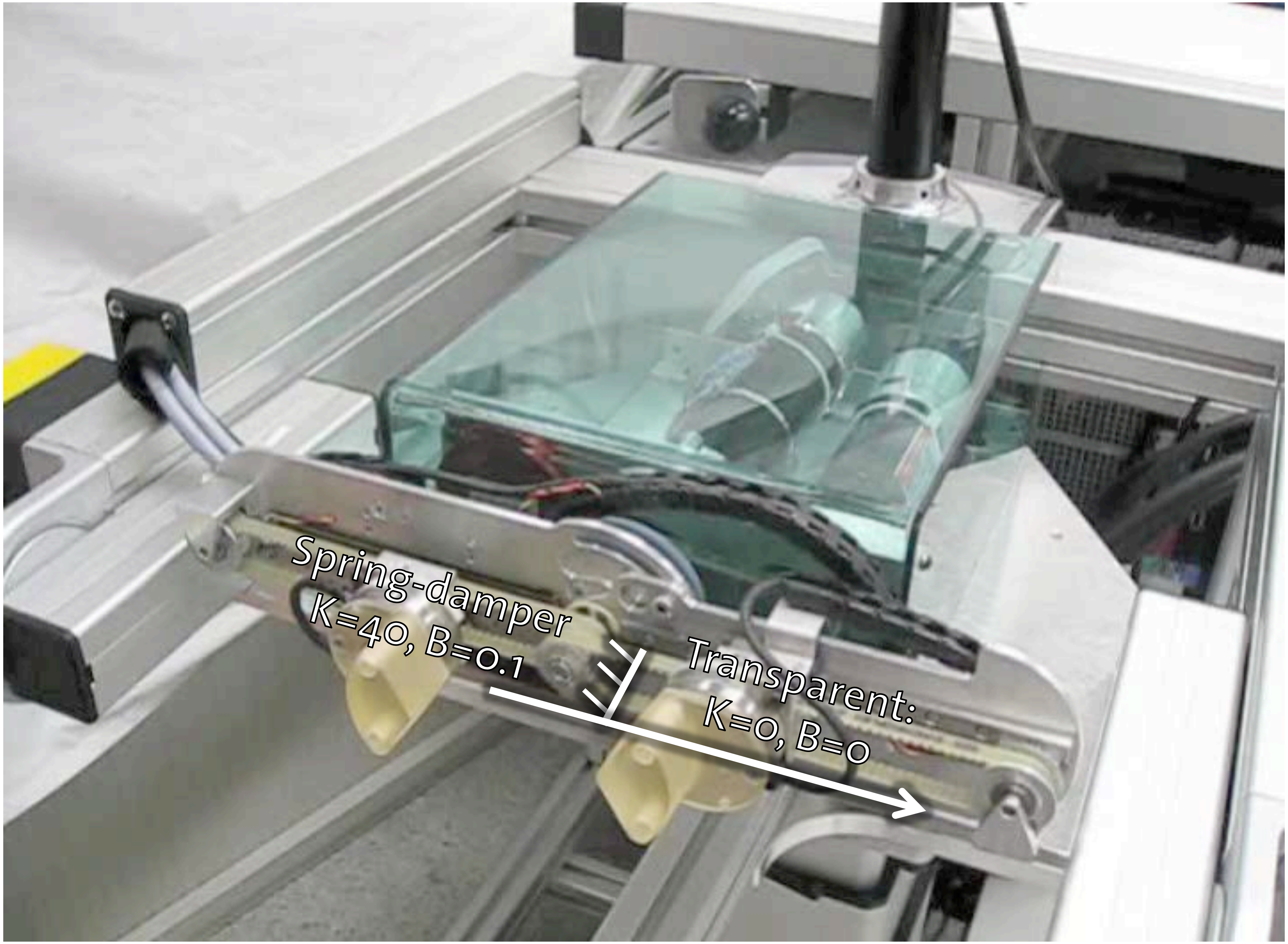
$$\dot{x} = g(x_k, x_{k-1}, \ldots, x_{k-n})$$

(Janabi-Sharifi 2000)

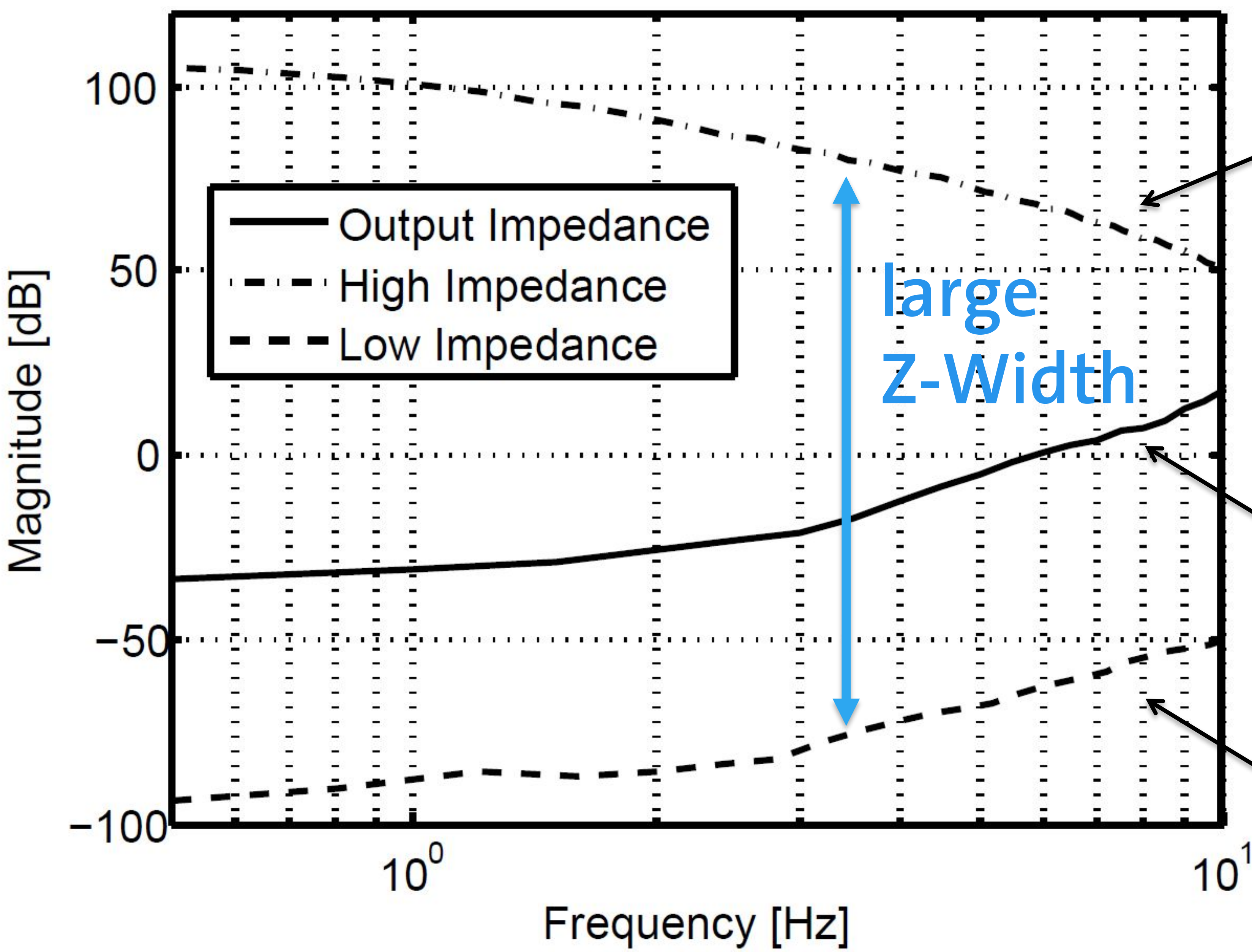


(KB plot, Colgate and Brown 1994)

Human robot interaction



Z-width



High Impedance:
K = 40, B = 0.1
(large forces, small movement)

Output Impedance:
Inherent friction, inertia

Low Impedance:
K = 0, B = 0
(small forces, large movement)

(Weir 2008)

The ReHapticKnob

slide adapted from J.C. Metzger

Take Home Messages

- the human is a “defined” system that determines the requirements for the robot and interaction
- important metrics: friction, bandwidth, z-width, safety...
- softness in rehabilitation: different types of interaction
- interaction with objects of various dynamic properties is a promising approach

Acknowledgments

Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Roger Gassert
Marie-Christine Fluet
Yeongmi Kim
Jean-Claude Metzger

NUS National University of Singapore

Ludovic Dovat
Teo Chee Leong

Imperial College London

Etienne Burdet

McGill

Theodore Milner

Tan Tock Seng Hospital

Seng Kwee Wee
Christopher Kuah
Karen Chua

Arizona State University

Marco Santello

universiteit hasselt

Peter Feys
Ilse Lamers

UniversitätsSpital Zürich

Andreas Luft
Joachim Cerny
Katrin Mengel

KLINIKEN SCHMIEDER
Neurologisches Fach- und Rehabilitationskrankenhaus

Joachim Liepert
Marcus Kaiser

Funding sources:
NCCR Neural Plasticity and Repair, NCCR Robotics, i-SUR EU-FP7 project, ETH CHIRP1, Gottfried and Julia Bangerter-Rhyner-Stiftung

Questions

RELAB

REHABILITATION ENGINEERING LAB

Contact: olambercy@ethz.ch

Contents

- **Part 2 (11h30-12h00)**

  1) The ETHZ haptic paddle

  2) Sensing and calibration

  3) Implementation of virtual wall

Goals

Why the ETH Haptic Paddle?

- hands on experience of Human Robot Interaction
- experience in the use of conventional robotics hardware
- direct application of the proposed evaluation metrics
- introduction to LabView programing environment

Haptic Paddles

Based on open hardware haptic paddle from leading US universities

- Stanford University
- Johns Hopkins University
- Rice University
- University of Michigan
- University of Utah
- Vanderbilt University

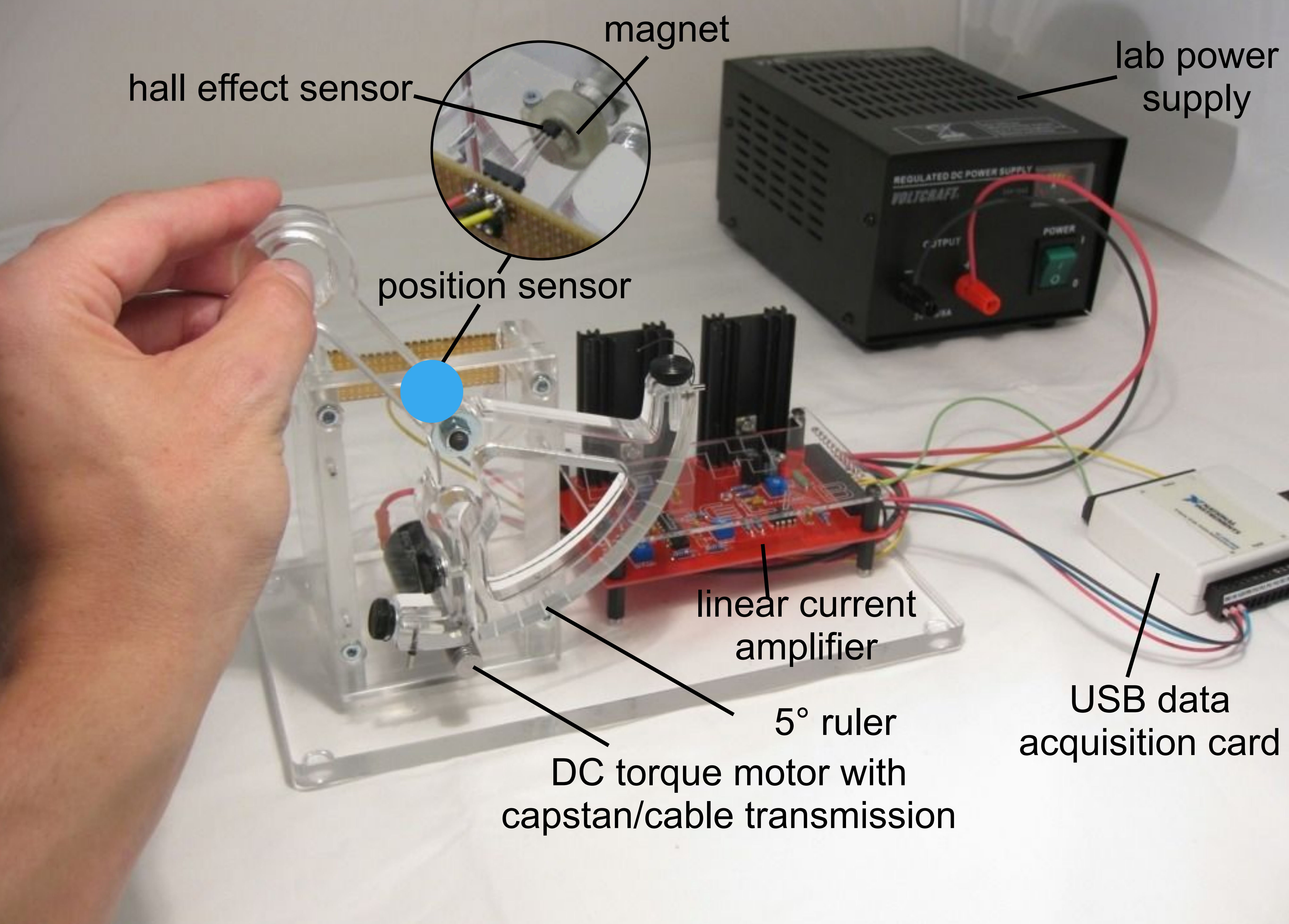
University of Michigan


Stanford University


Rice University

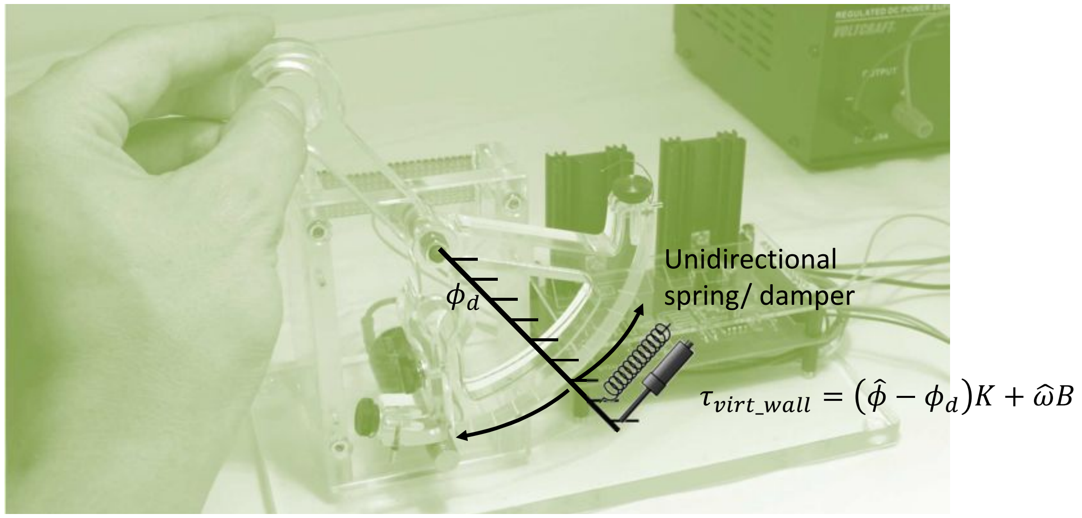

Johns Hopkins University


Vanderbilt University


magnet
hall effect sensor
lab power supply
position sensor
linear current amplifier
USB data acquisition card
5° ruler
DC torque motor with capstan/cable transmission

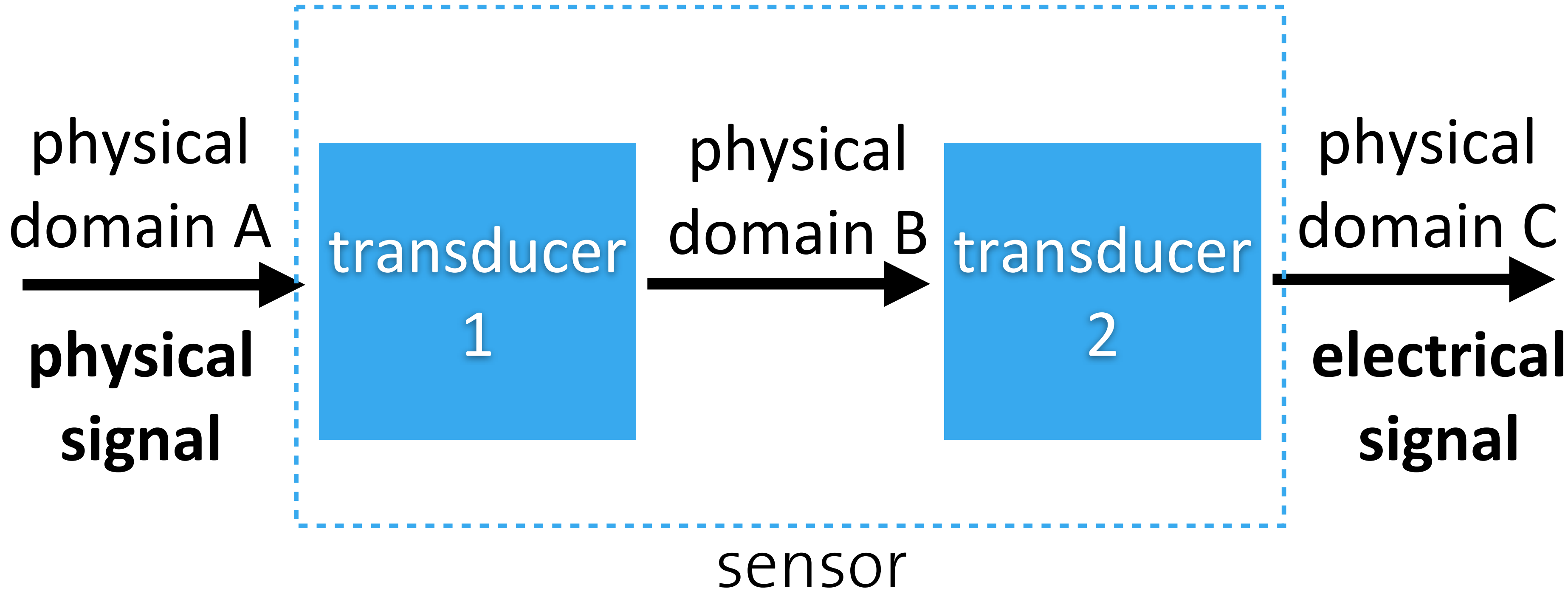
Tutorial Overview

- hall effect position sensor:
  - working principle
  - output linearization
  - transfer function
- position discretization & quantization:
  - sampling
  - sensor noise
  - DAQ resolution
- velocity estimation:
  - Euler method
  - filtering
- implementation (LabView):
  - virtual spring & damper
  - K-B plot

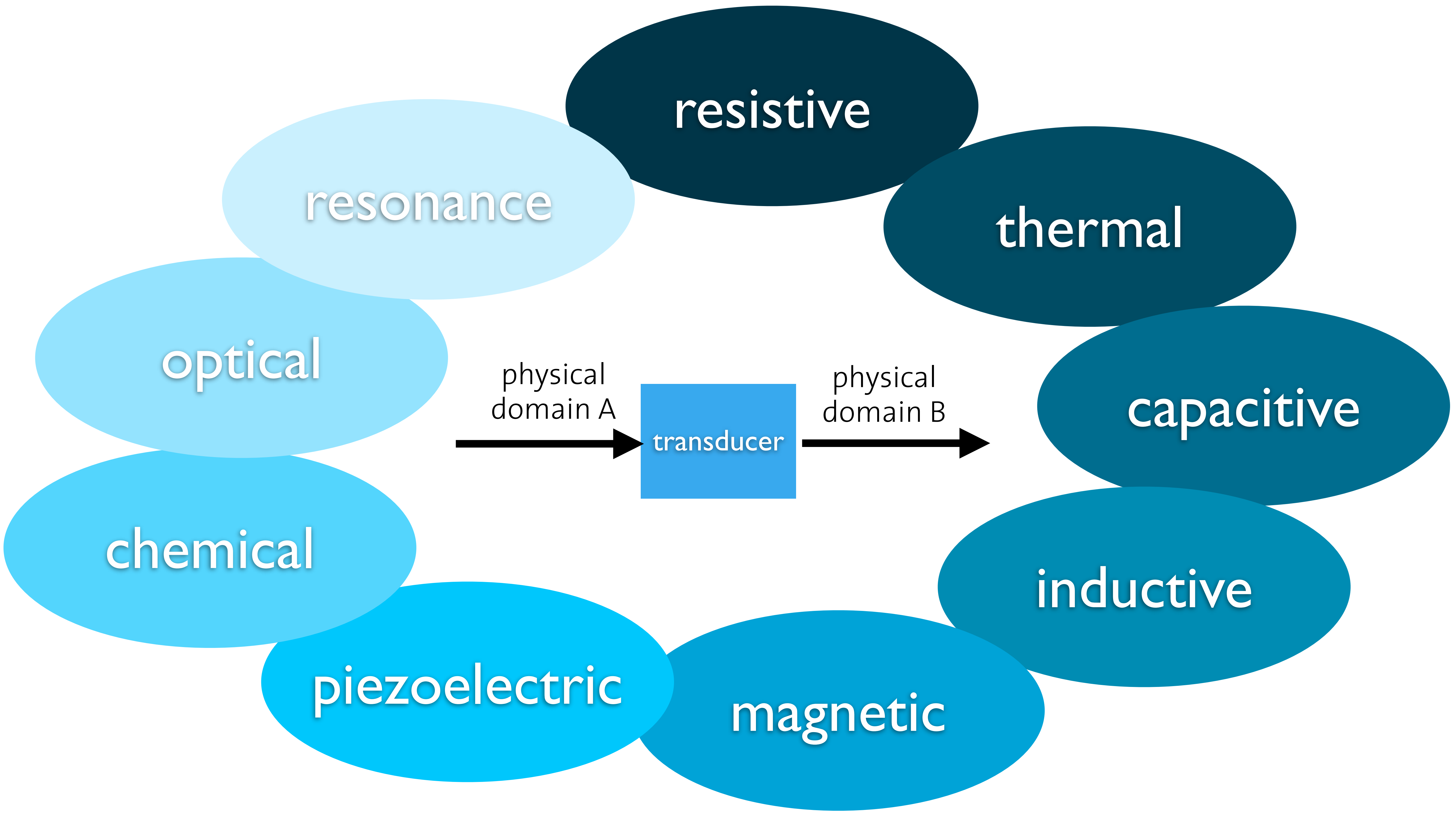


Key definitions

- **Sensor**: an element of a mechatronic or measurement system that produces a measurable change in response to a physical condition
- The **transducer** is the **active element** of a sensor that **transforms** signal from one physical domain to another physical domain



Sensing principles

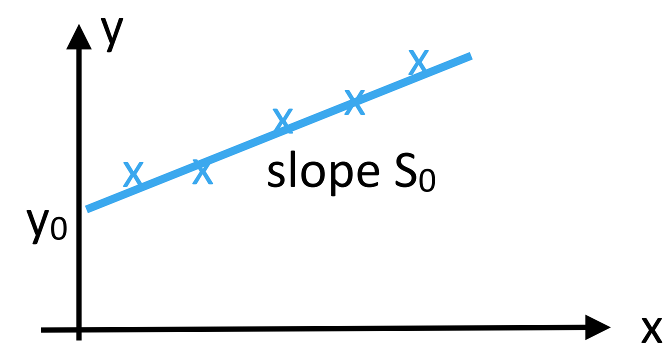


Performance Metrics

- **Transfer function**

  Most transducers assume a **linear relationship** between input and output over the working range

$$y = S_0 * x + y_0$$



- **Sensitivity S_0:** relationship indicating how much the output y varies per unit of the input x

$$S_0 = \frac{dy}{dx}$$

- **Offset y_0**: output value under the null input condition

Performance Metrics

- **Accuracy**

  The extent to which the value indicated by a measurement system **might be wrong**

- **Repeatability (precision)**

  Describes a sensor's ability to give the same output for repeated application of the same input value

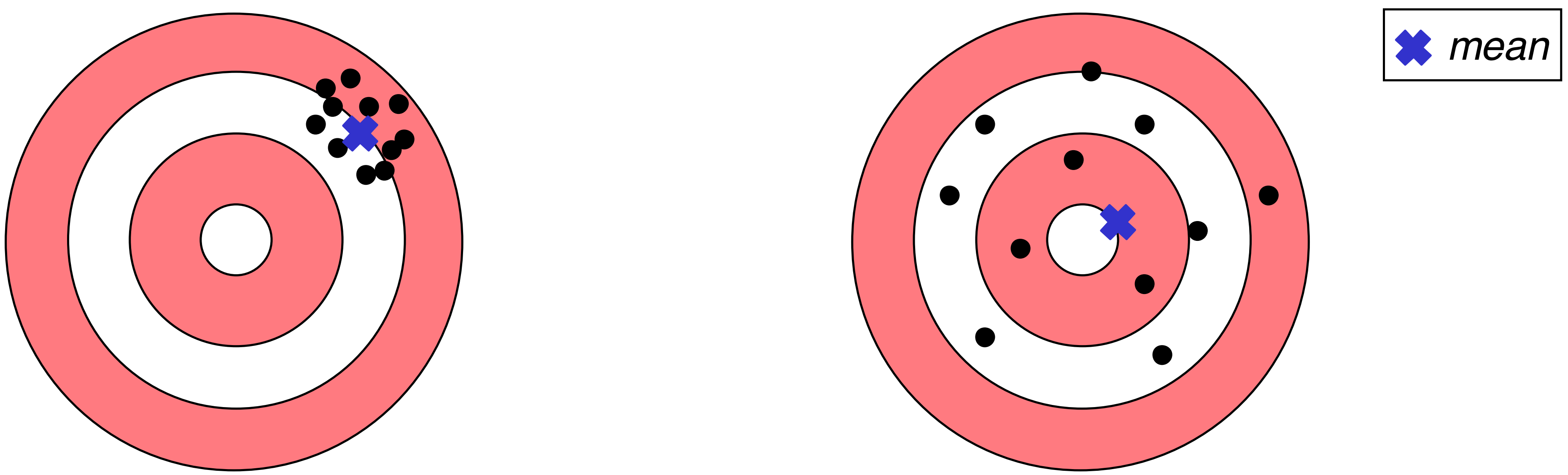
- **Resolution**

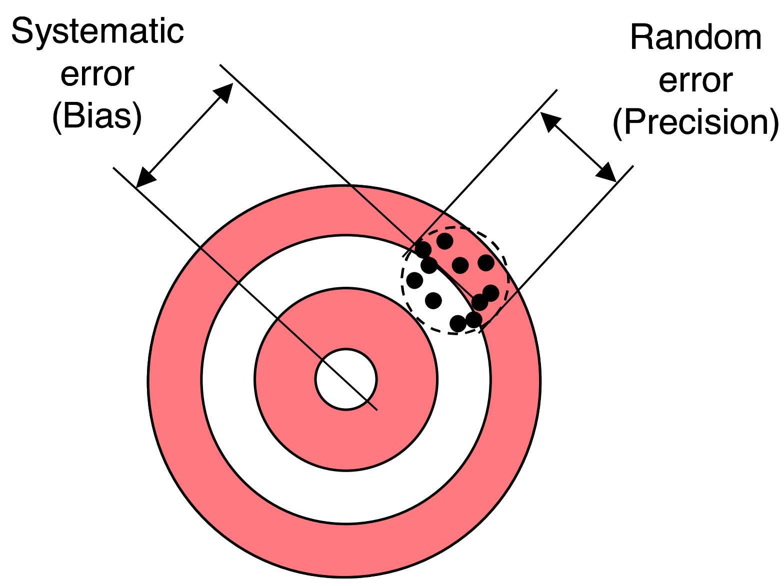
  Smallest change in input value x that will produce an observable change in the output y

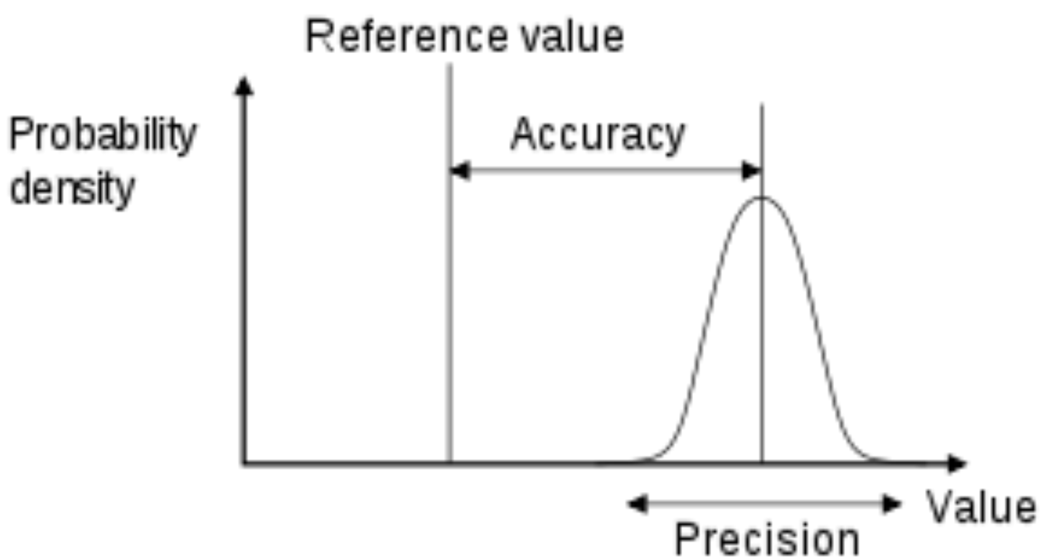
$$Res = \frac{noise\ density}{sensitivity}$$

Performance Metrics

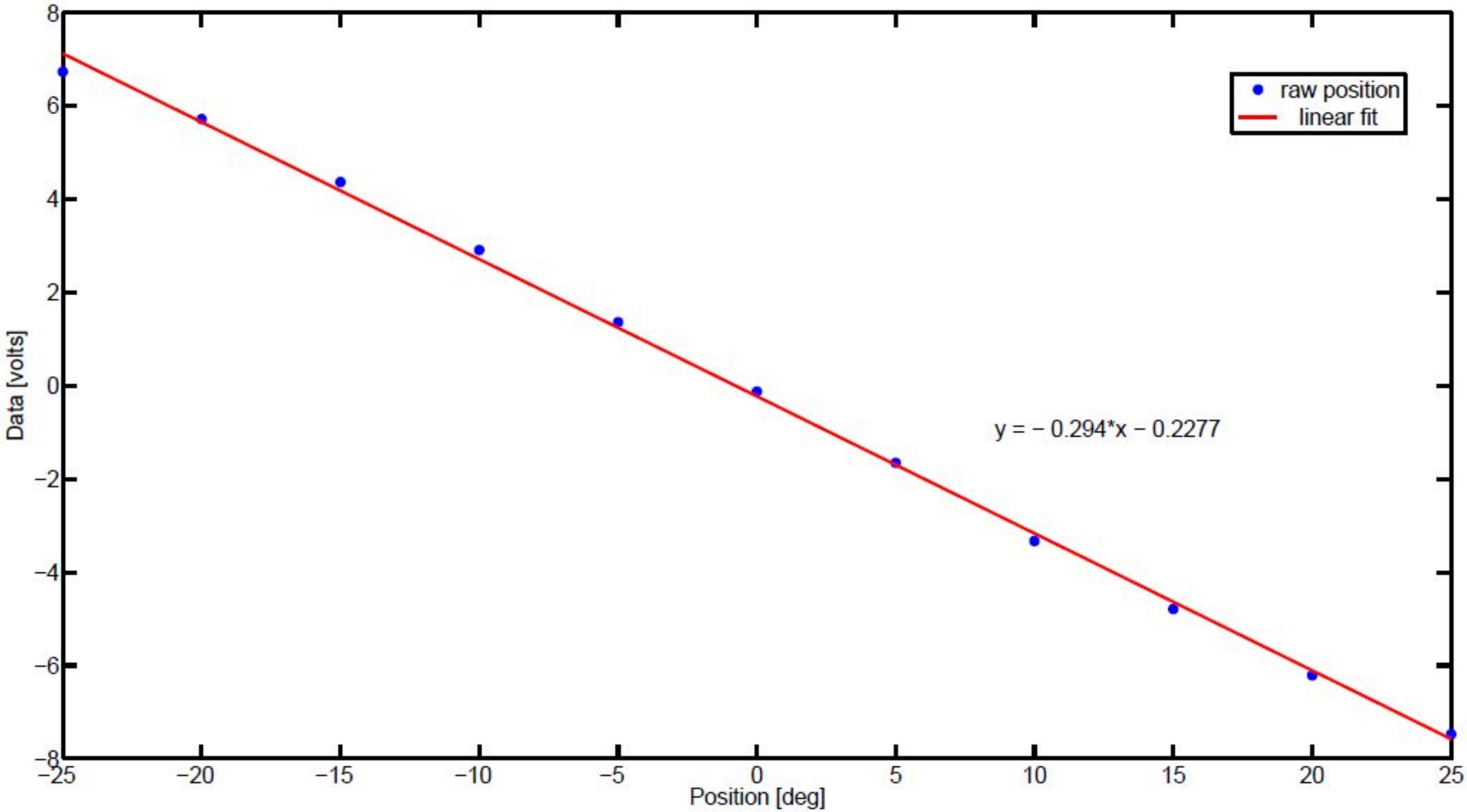
- Which one is more accurate?
- Which one is more precise?







Hall Effect Position Sensor



Velocity and Acceleration

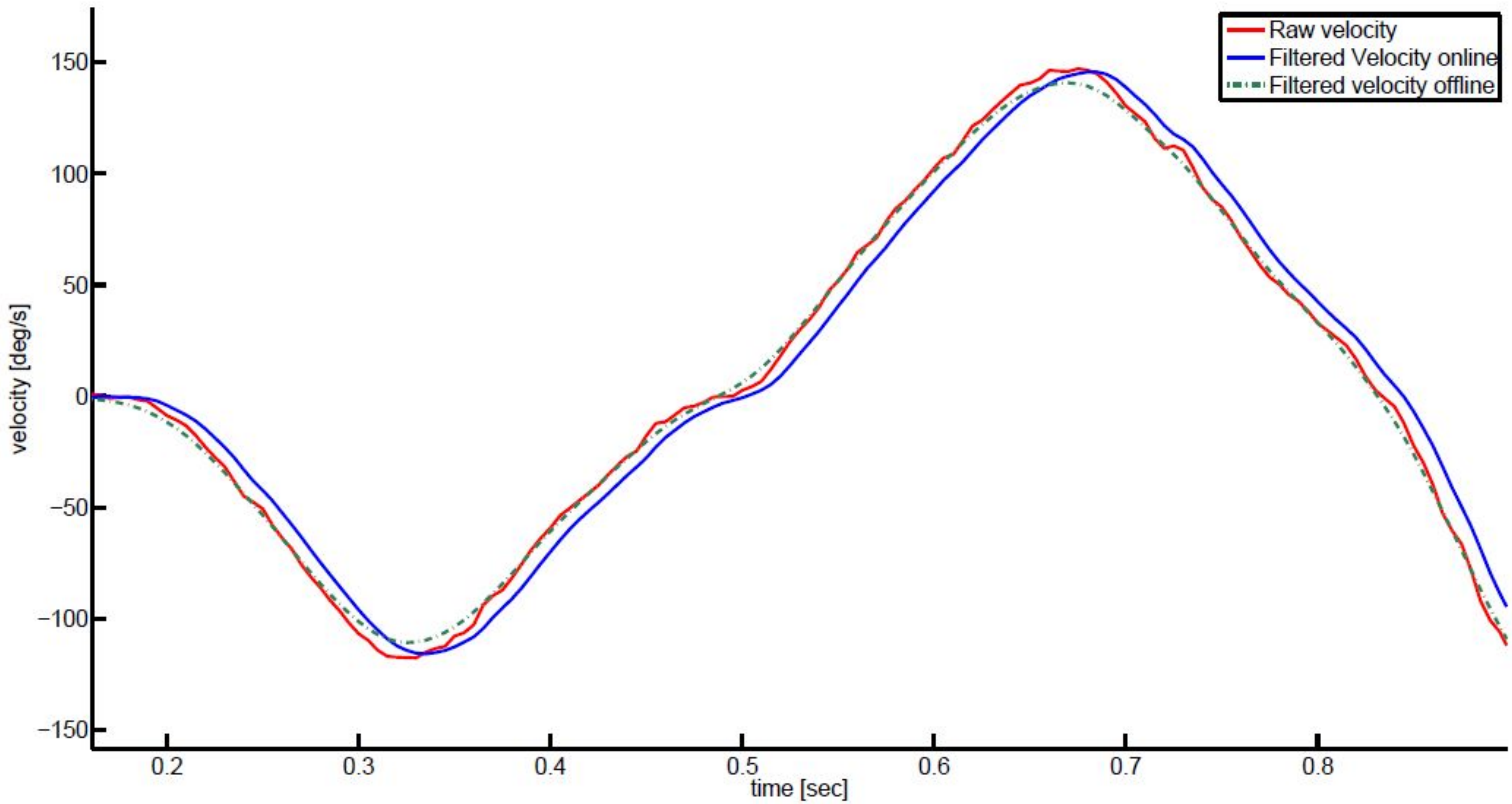
- **velocity and acceleration** can be differentiated from position measurements

$$velocity(k) = \frac{position(k) - position(k-1)}{T}$$

- differentiation acts like a high-pass filter
-> **amplifies noise**
-> filter

- direct measure of velocity (tachometer) or acceleration (accelerometer)

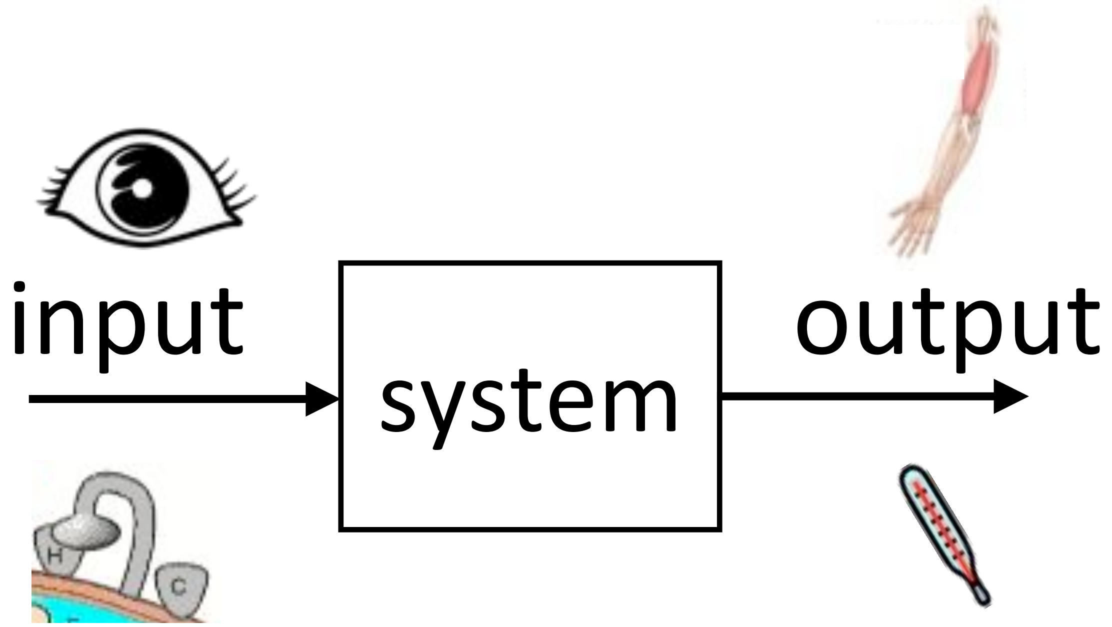
Velocity and Acceleration



Human Motor Control vs Digital Control

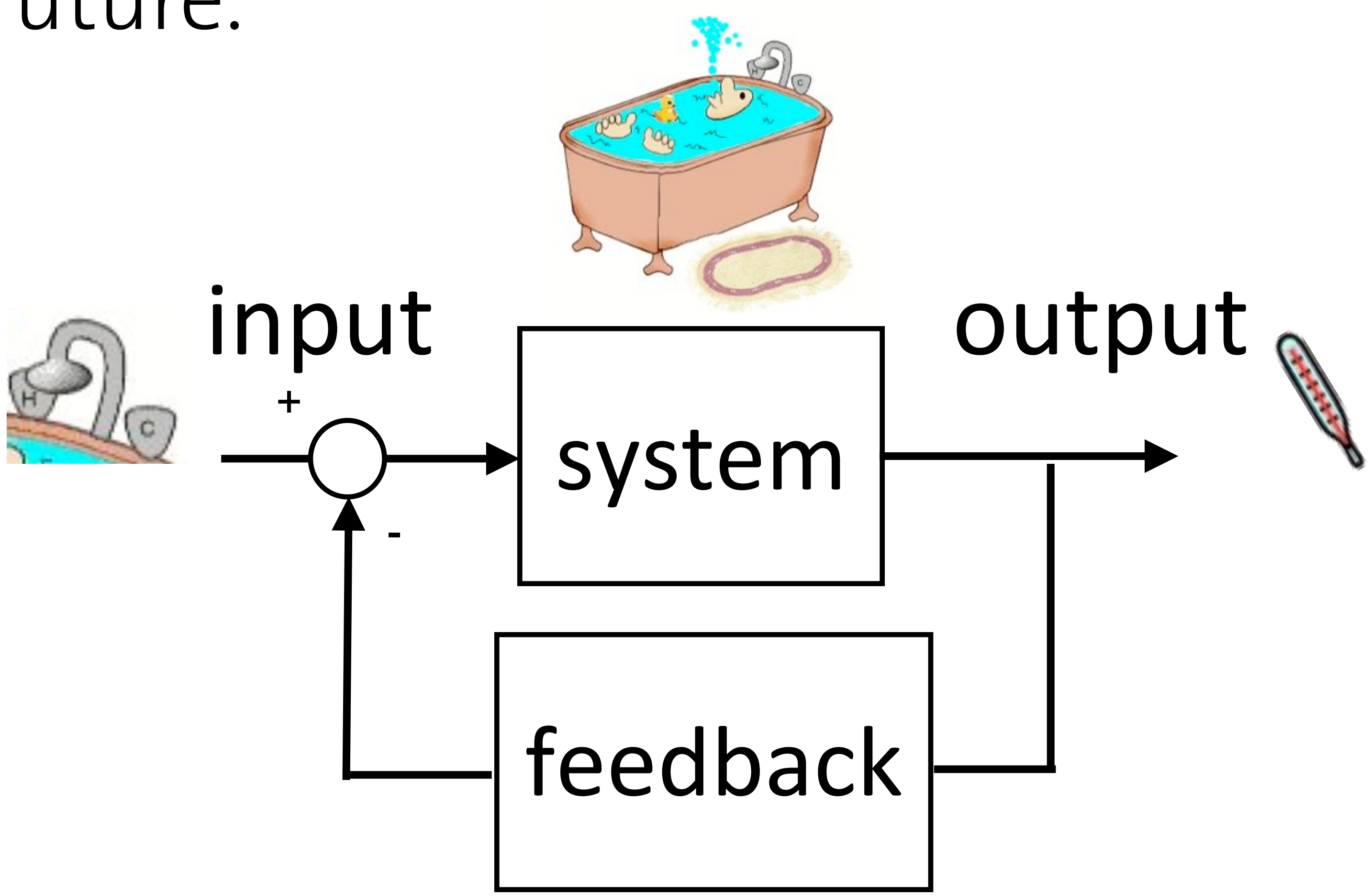
Control theory deals with the behavior of dynamical systems

Problem: sensor noise and large delay in humans (and bathtubs)



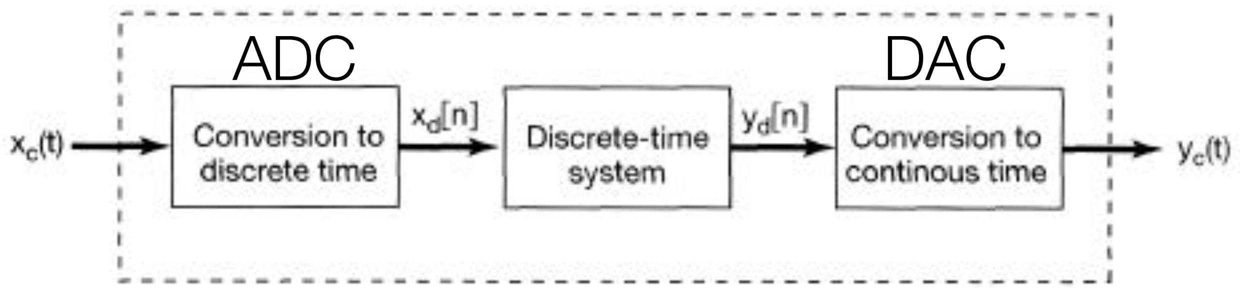
Feedback Control

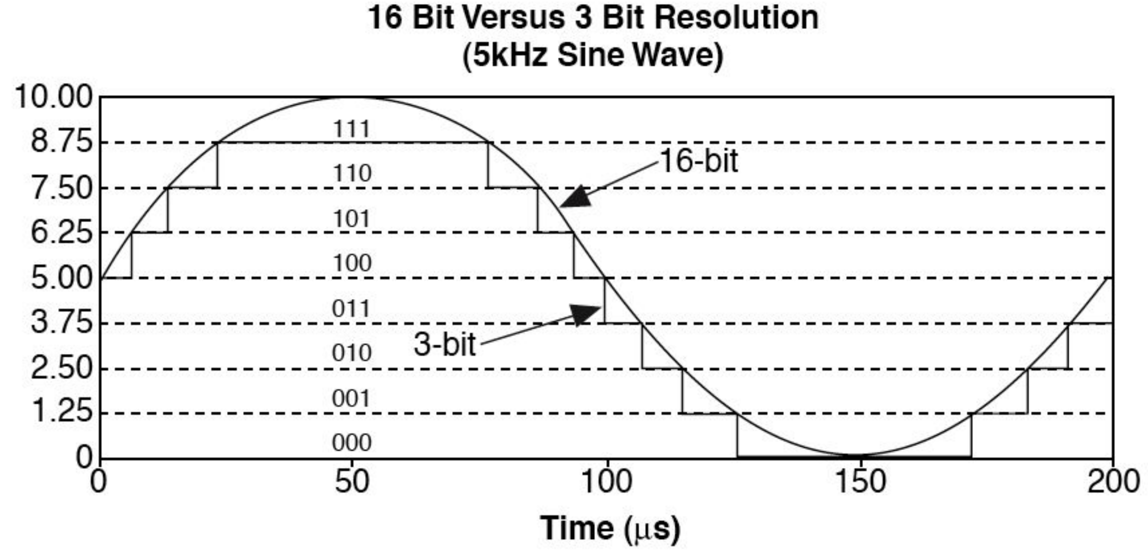
Feedback describes the situation when the output from a system in the past will influence the same system in the present or future.



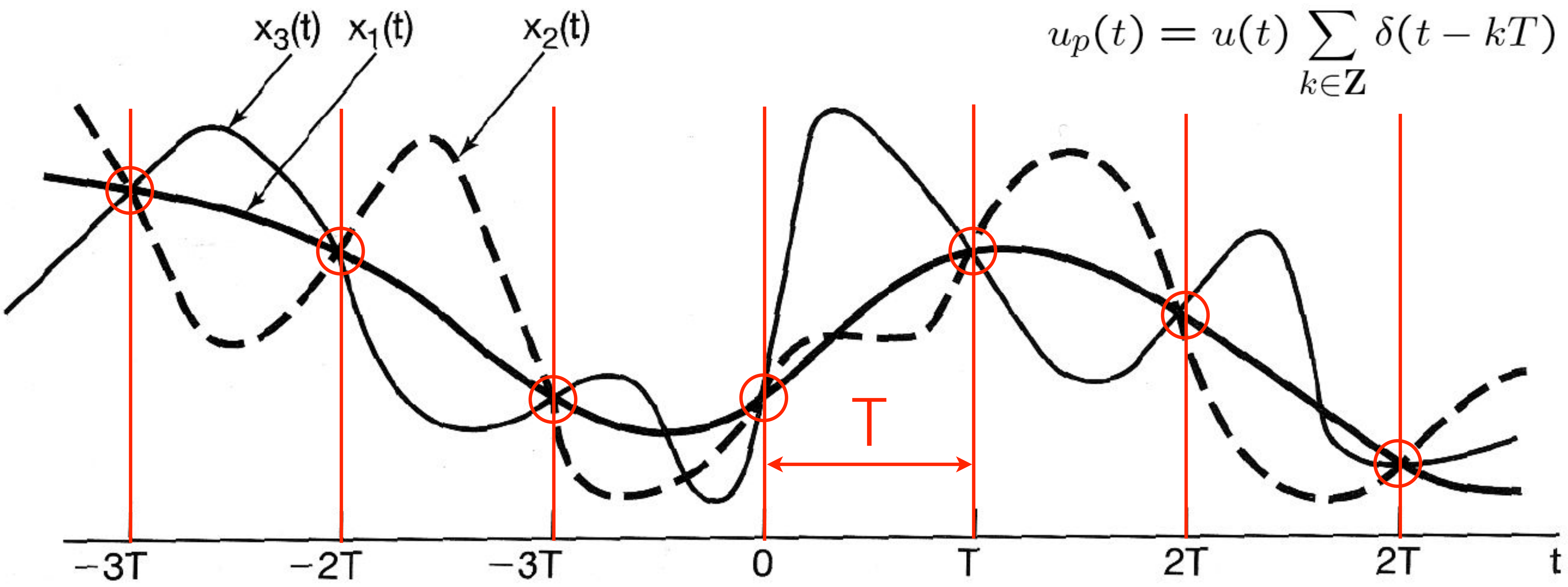
human: ~5 Hz
machine: typically 100Hz–1kHz to over 100 kHz

Sampling of Continuous Signals

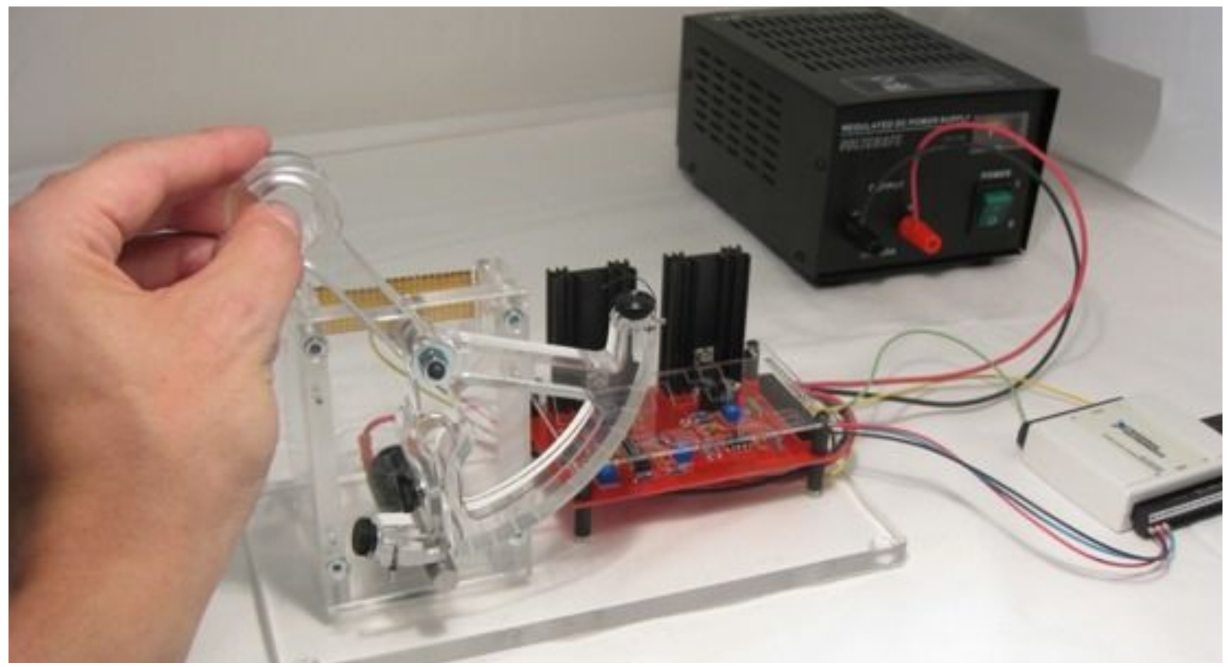


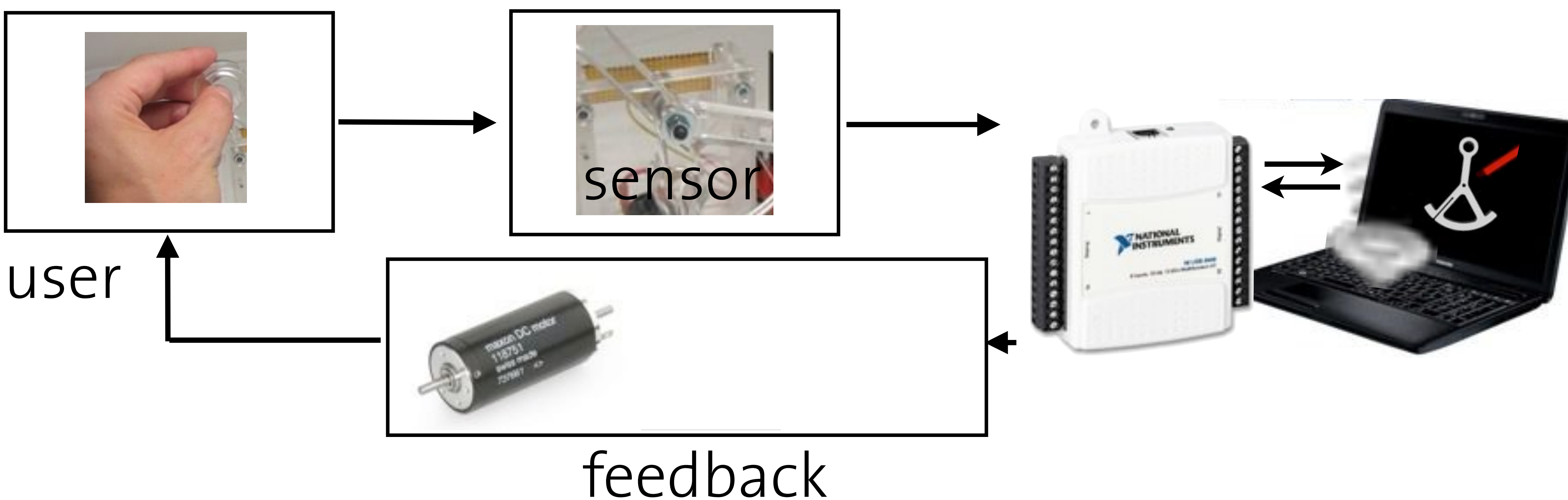


$$u_p(t) = u(t) \sum_{k \in \mathbf{Z}} \delta(t - kT)$$



Haptic Paddle: Control and Feedback

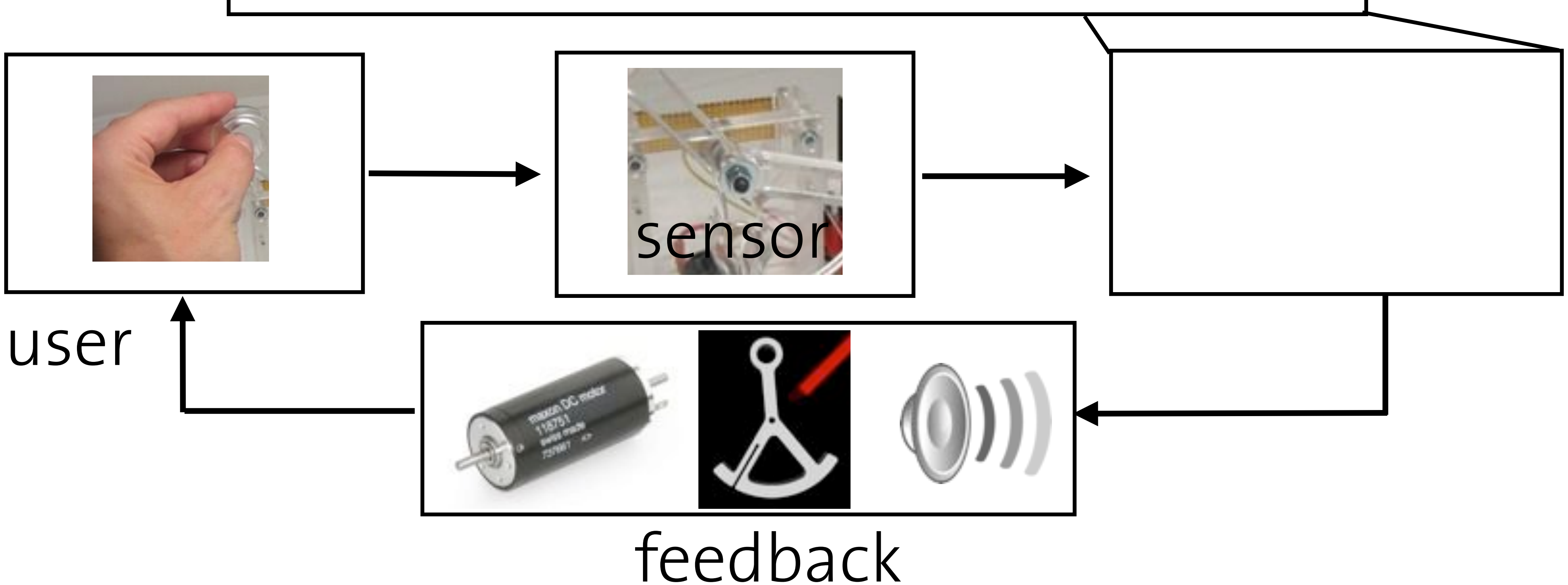




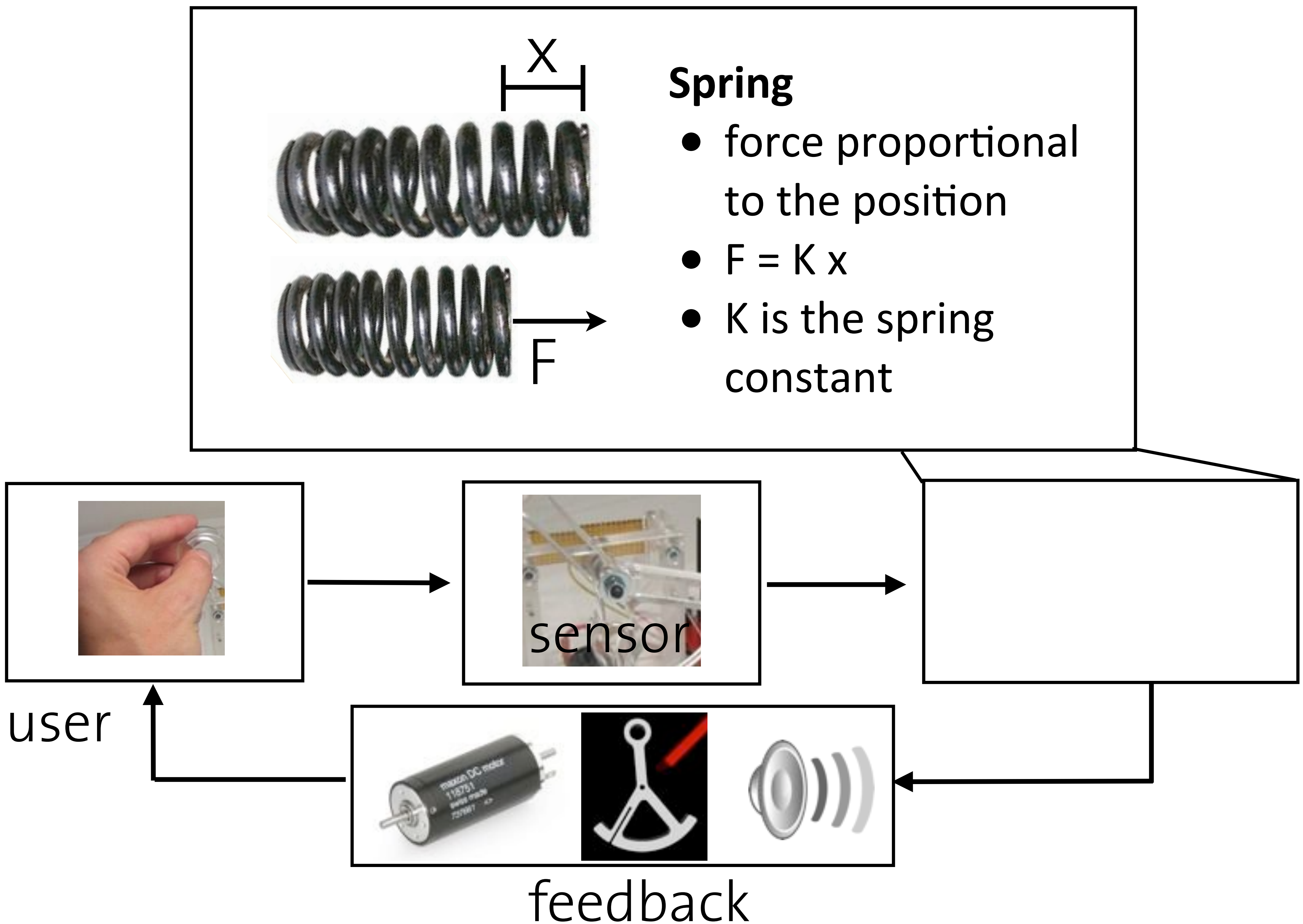
Haptic Paddle: Control and Feedback

Load

- constant force
- F = L or or mgsin(ø)
- no influence of position or projection



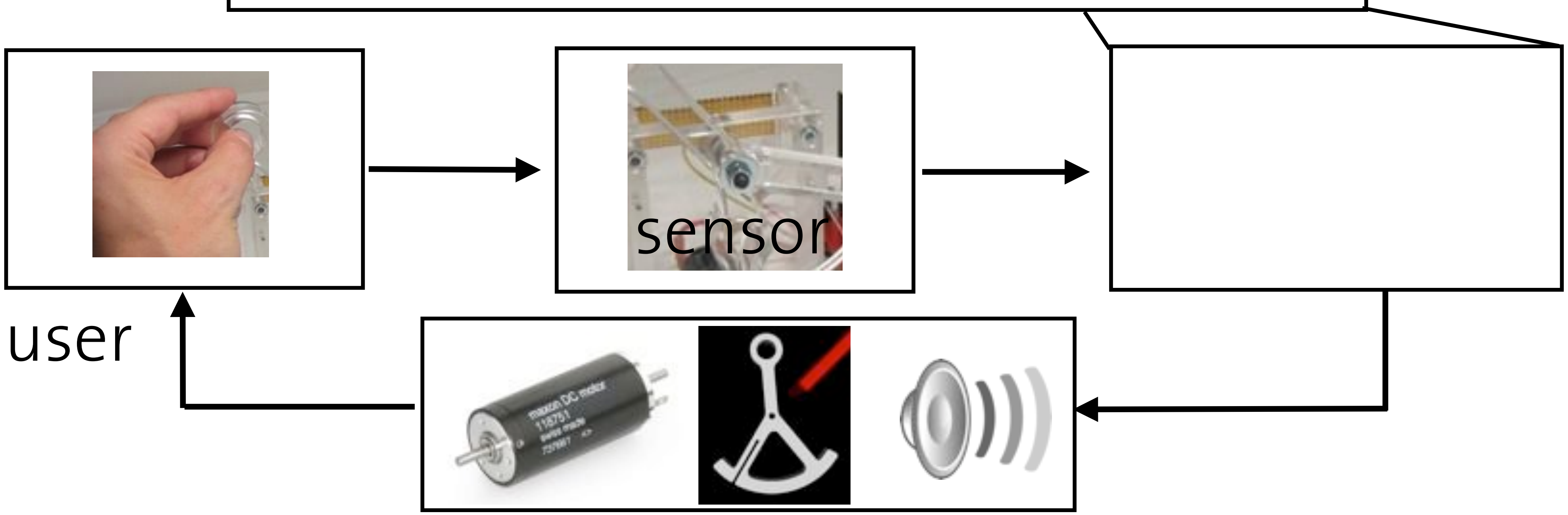
Haptic Paddle: Control and Feedback



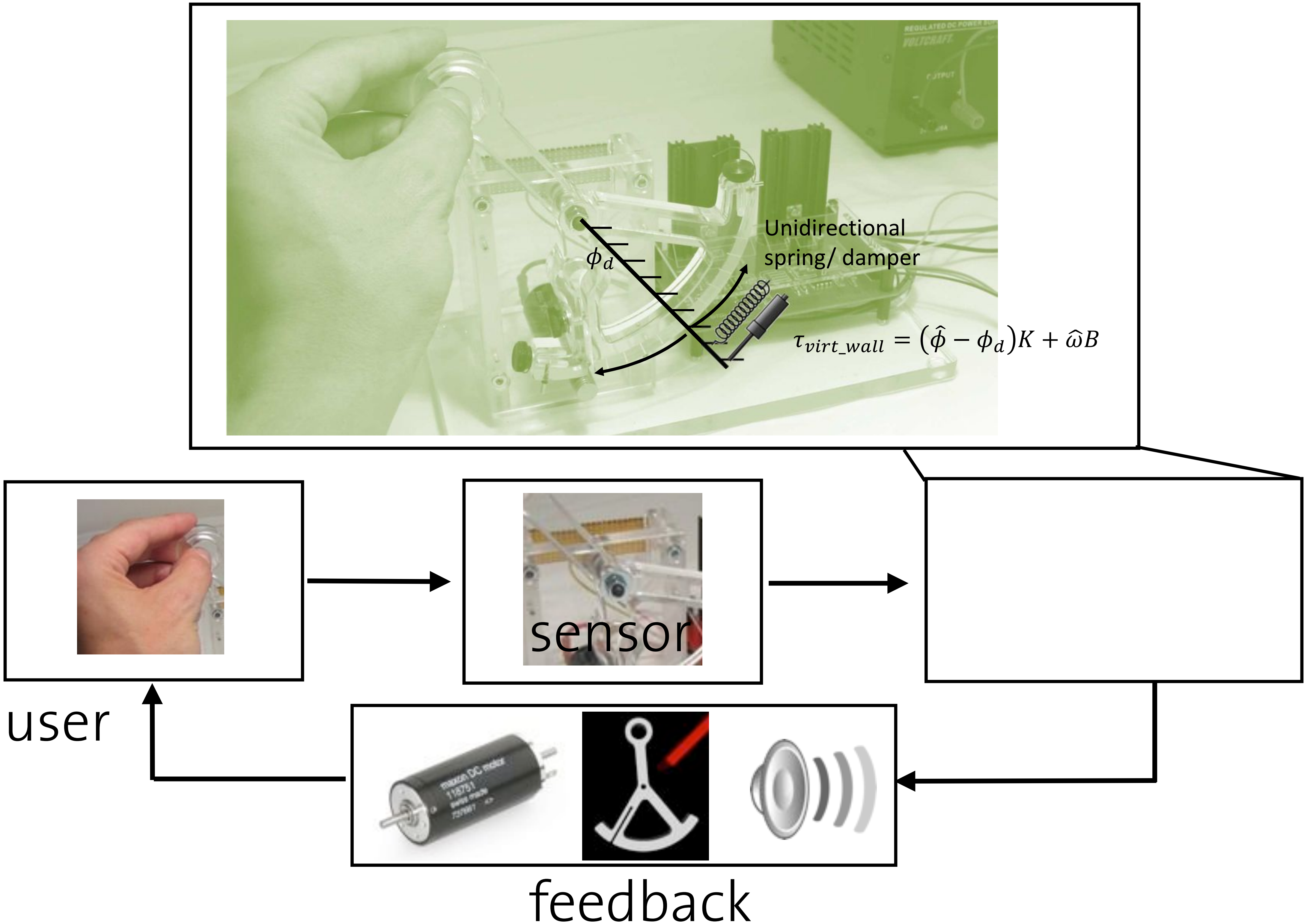
Haptic Paddle: Control and Feedback

Damping

- force proportional to the velocity
- F = D v
- D is the damping constant



Haptic Paddle: Control and Feedback

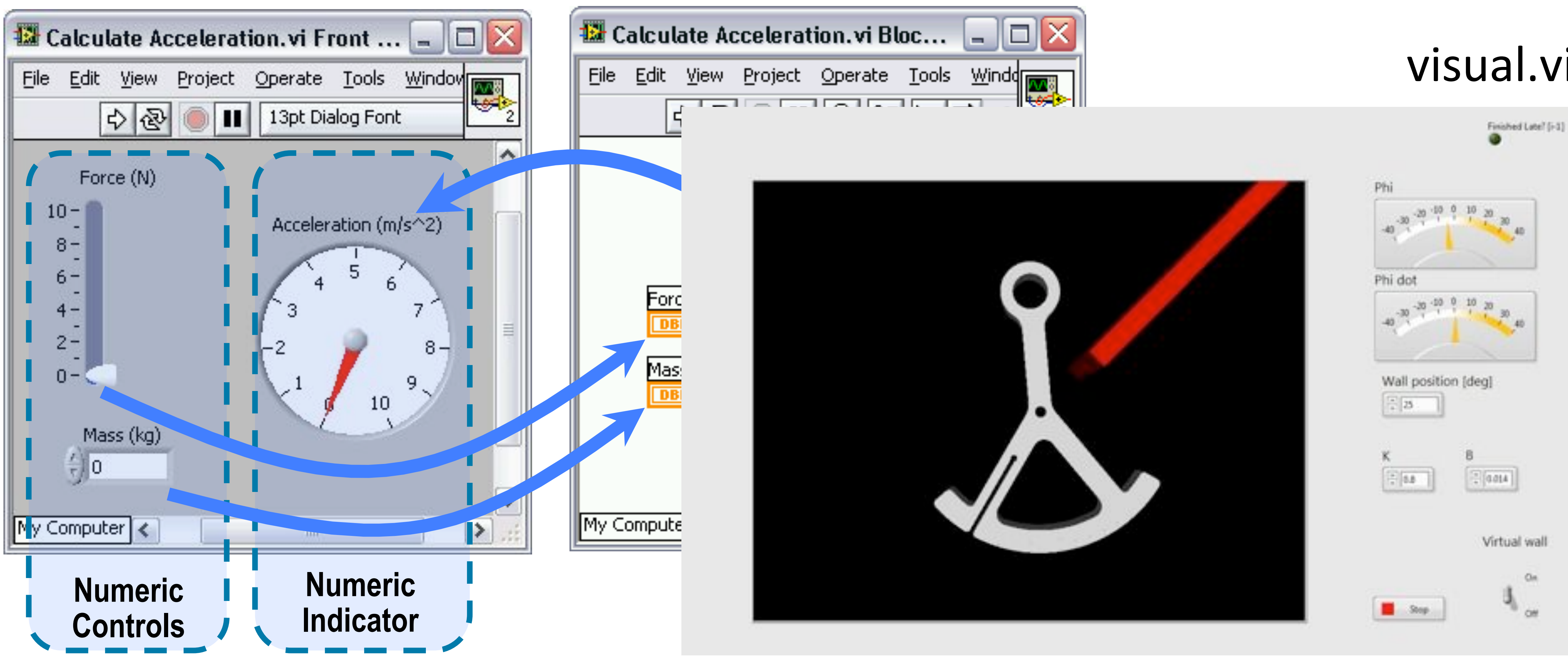


LabVIEW

LabVIEW 2011 from National Instruments

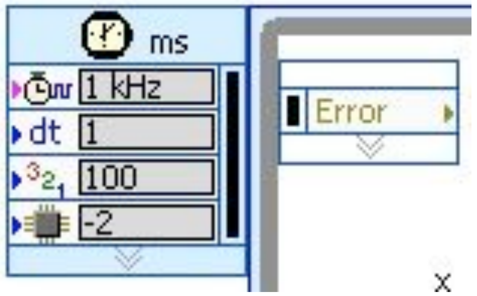
Visual programming language

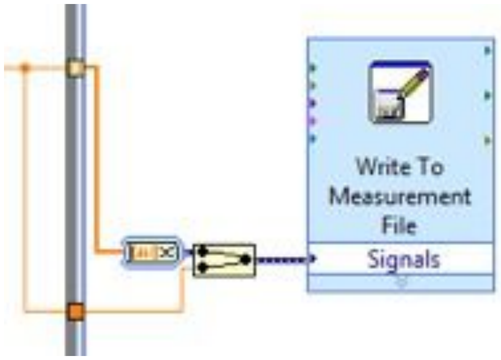
visual.vi



Hands-on Demos

- timed loop with stop button
- change sampling time; iteration duration
- logical test to stop after X increments of the loop
- send in value from outside loop and do simple addition
- shift register and array
- file I/O
- cluster for plot (plot 2 values)
- LabView template for sensor readout and motor write





This afternoon

- **Meeting: ML E floor main hall at 13h10**
- Tutorial room: HG G1
- Groups of 3 people

Questions

RELAB
REHABILITATION ENGINEERING LAB

Contact: olambercy@ethz.ch