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Laboratory Techniques: Computer simulation of human movement

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Multi-Level Modeling in Motor Control and Rehabilitation Robotics

Hertie Institute for Clinical Brain Research

Eberhard-Karls Universität Tübingen



Hertie-Institut
für klinische Hirnforschung

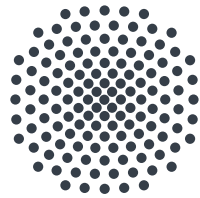
Biomechanics and Biorobotics

Stuttgart Centre for Simulation Sciences

University of Stuttgart



Collaboration



Universität Stuttgart

Syn
Schmitt
2B

SimTech
Cluster of Excellence

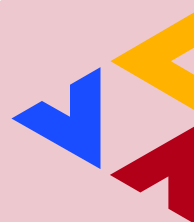
MoCoM

 **CIN**
Werner Reichardt
Centrum für Integrative
Neurowissenschaften

Comp
Sens



Hertie Institute
for Clinical Brain Research



Eberhard-Karls-Universität
UKT
Universitätsklinikum Tübingen

EBERHARD KARLS
**UNIVERSITÄT
TÜBINGEN**



Cases

Implants

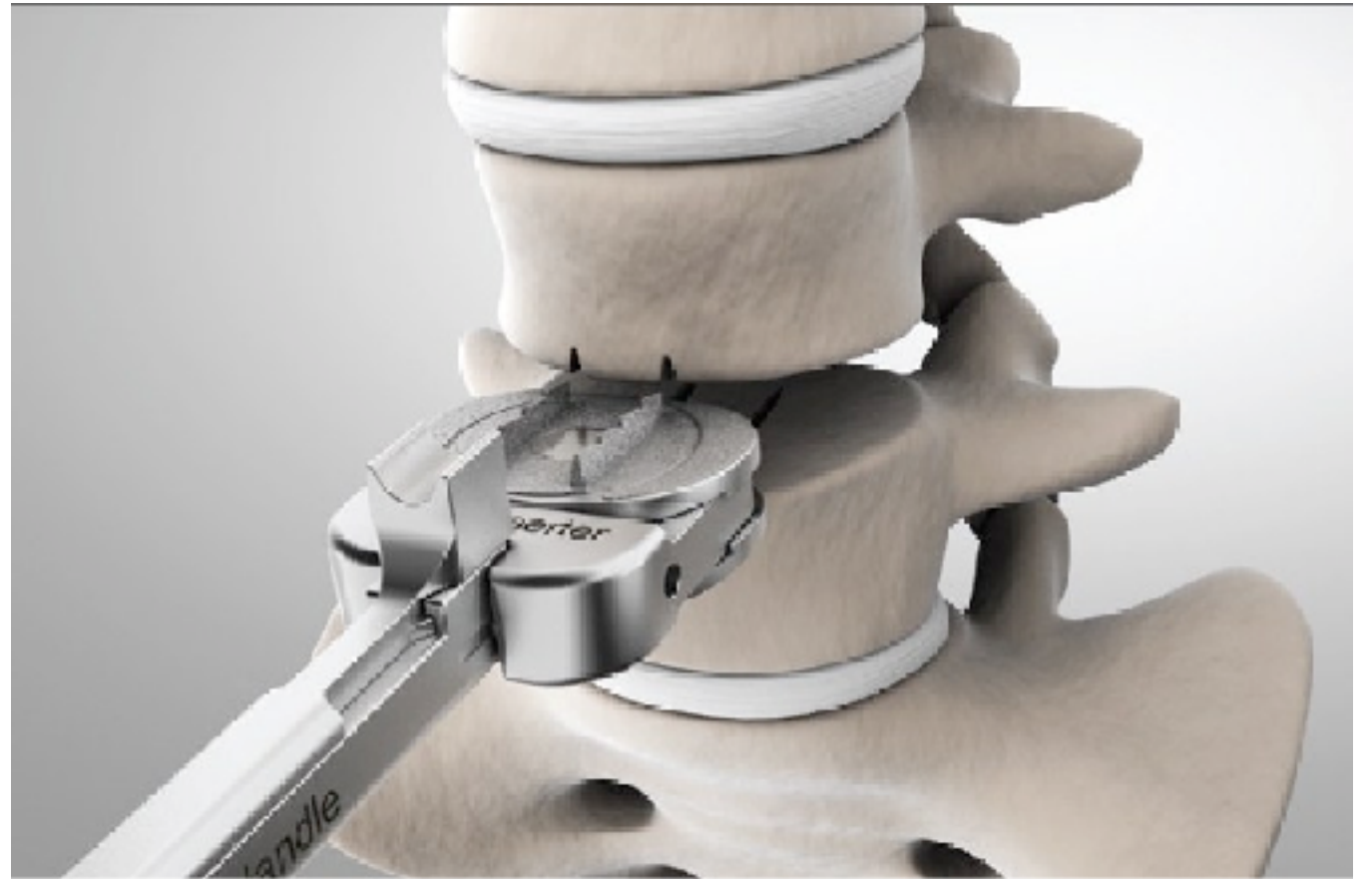


http://www.qmed.com/sites/default/files/ck_images/biomet_hip_implant.jpg

<http://www.osmifw.com/wp-content/uploads/2015/11/knee-replacement-x-ray.jpg>



Intervertebral disks (IVD)



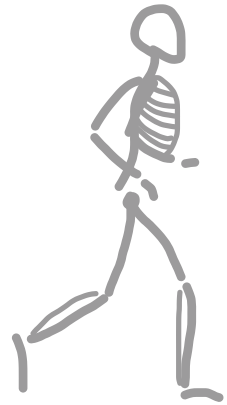
<https://www.joint-surgeon.com/orthopedic-joint-surgeon/artificial-spinal-disc/lumbar-disc-prosthesis-implantation-surgery.jpg>

<http://sherwoodspinalcare.com/wp-content/uploads/2015/09/Spine.jpg>

Problem:
**How to determine
internal forces and
loads?**

logosj

Forces in the human body



Bones



Tissue



Muscle

(shear
Loading forces)

Gravity acting on mass

frictional forces

Contact forces → deformation of soft tissue

internal pressure

Tensile forces (passive)

active muscle forces

Newton's laws

① if $F = 0$ $\frac{dv}{dt} = 0$ (Trägheitsgesetz) inertia

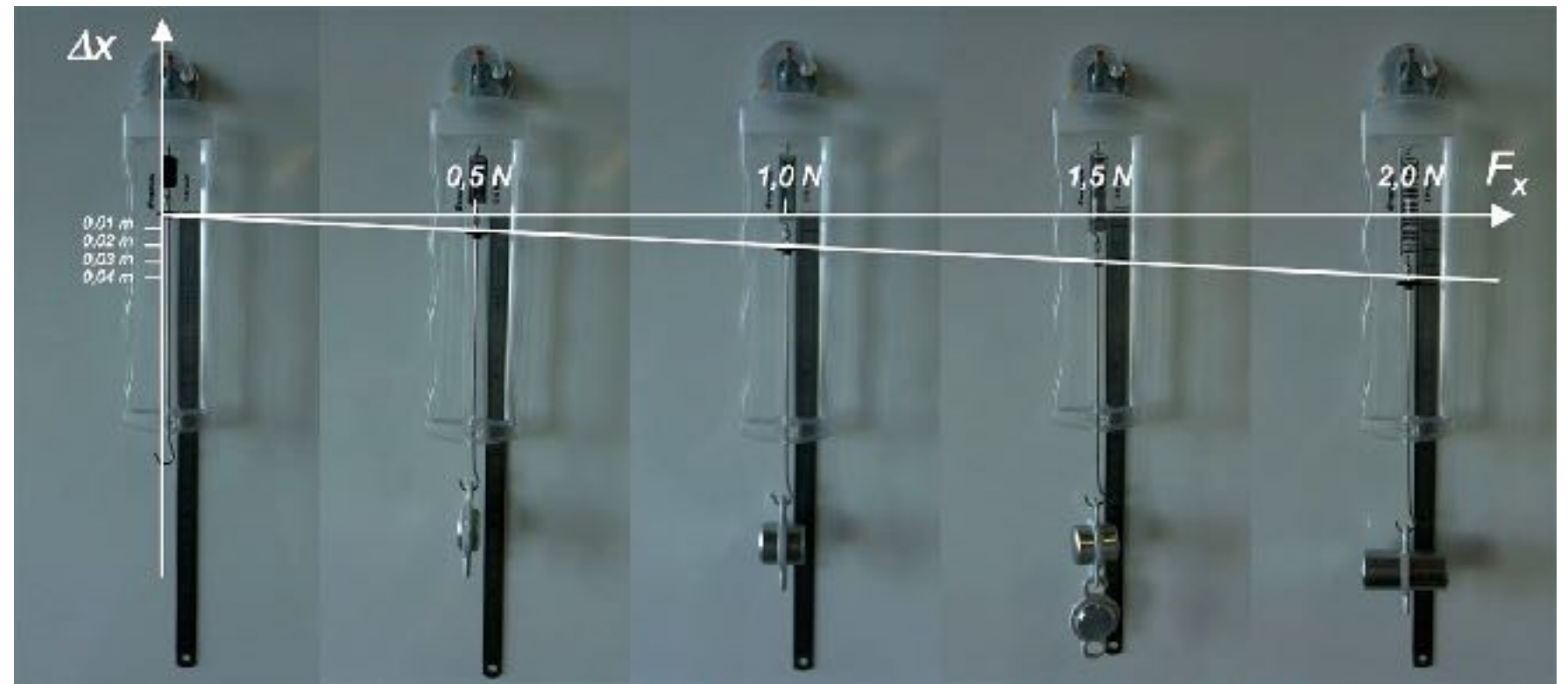
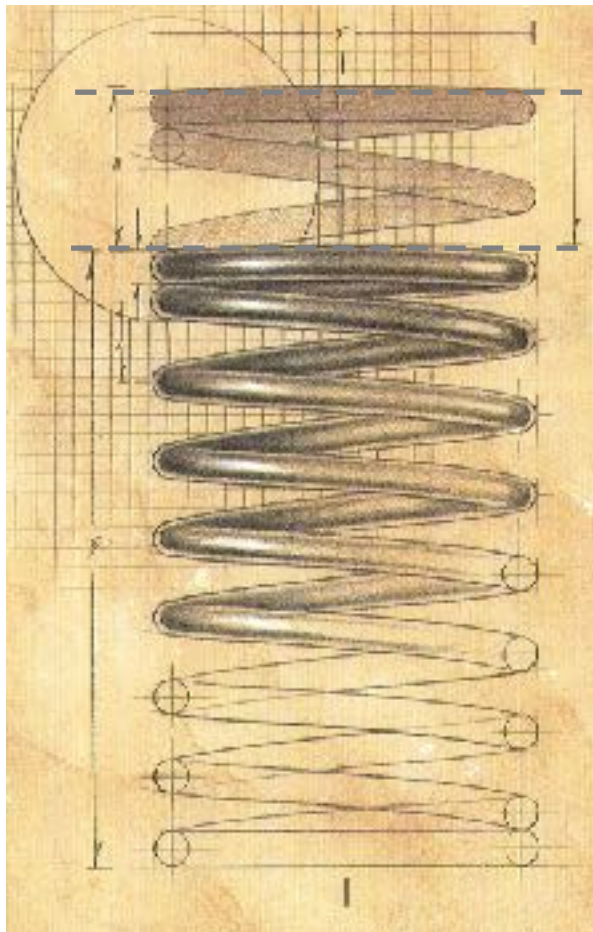
② $F = \frac{dp}{dt} = \frac{d(mv)}{dt}$ $m = \text{const.}$

$$F = ma = m\ddot{x}$$

③ $F_{\text{actv}} = -F_{\text{reactio}}$

How to measure force: first approach

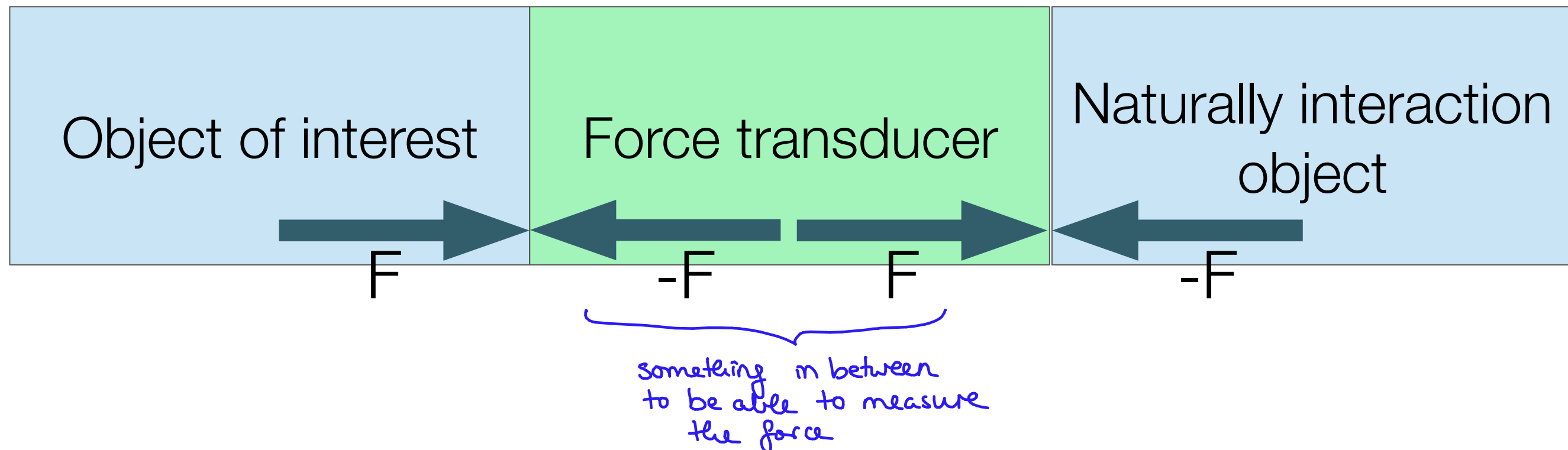
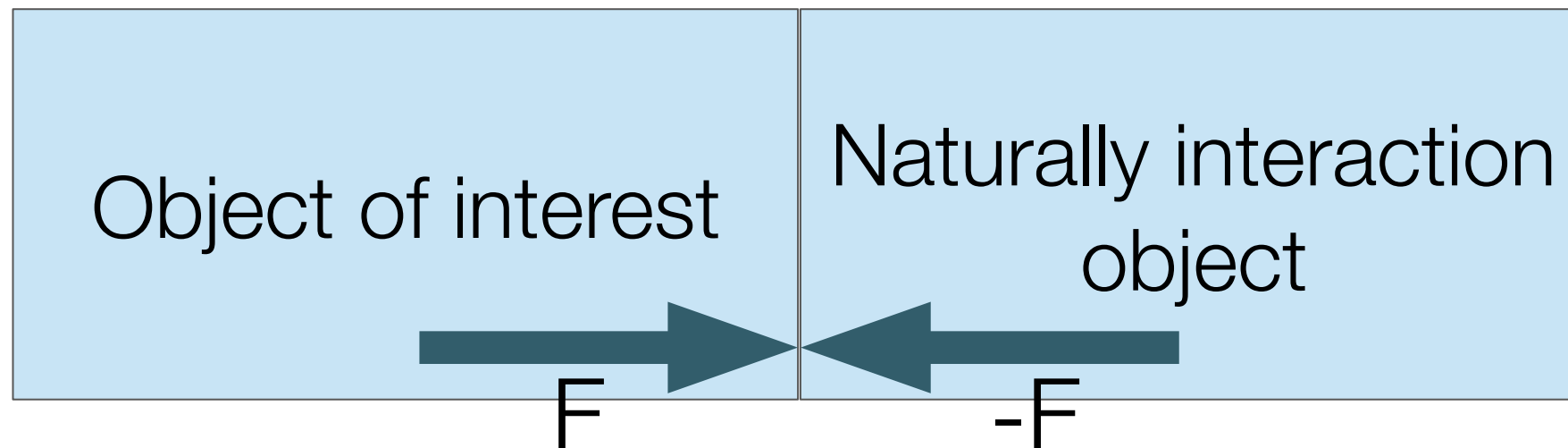
→ Deformation caused by force [deformation to calculate force]



Hooke's law

$$F = -k \Delta L$$

How to measure force



Measure force in a tendon: Buckle force transducer

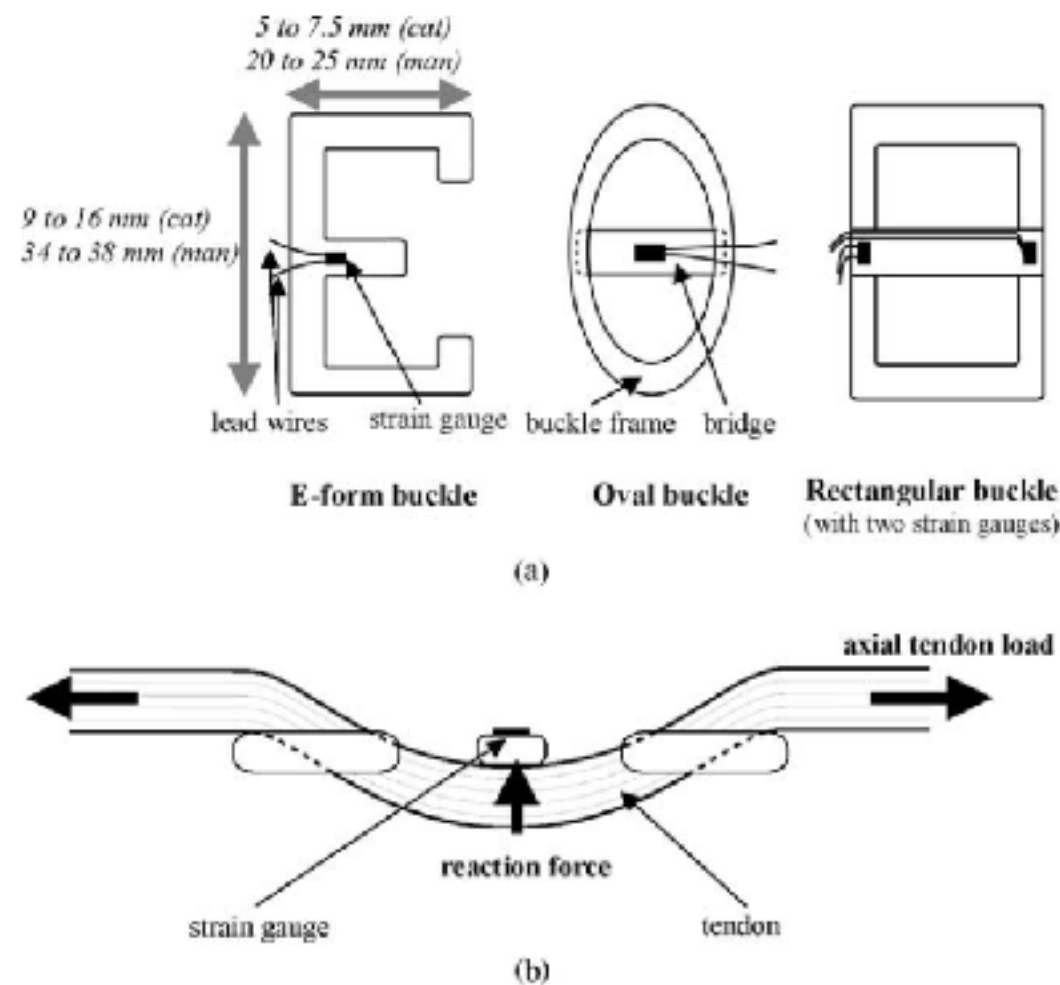
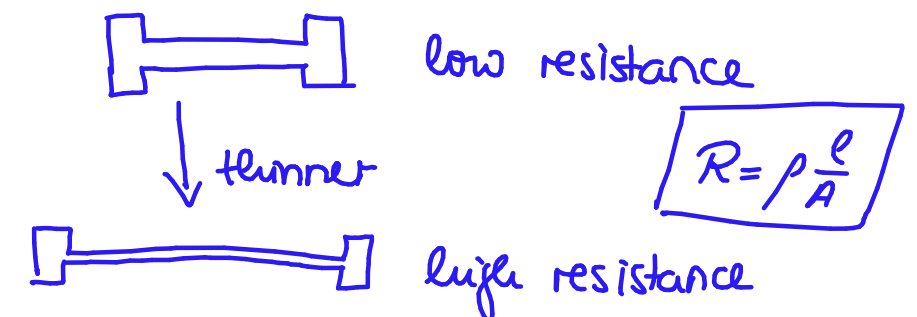
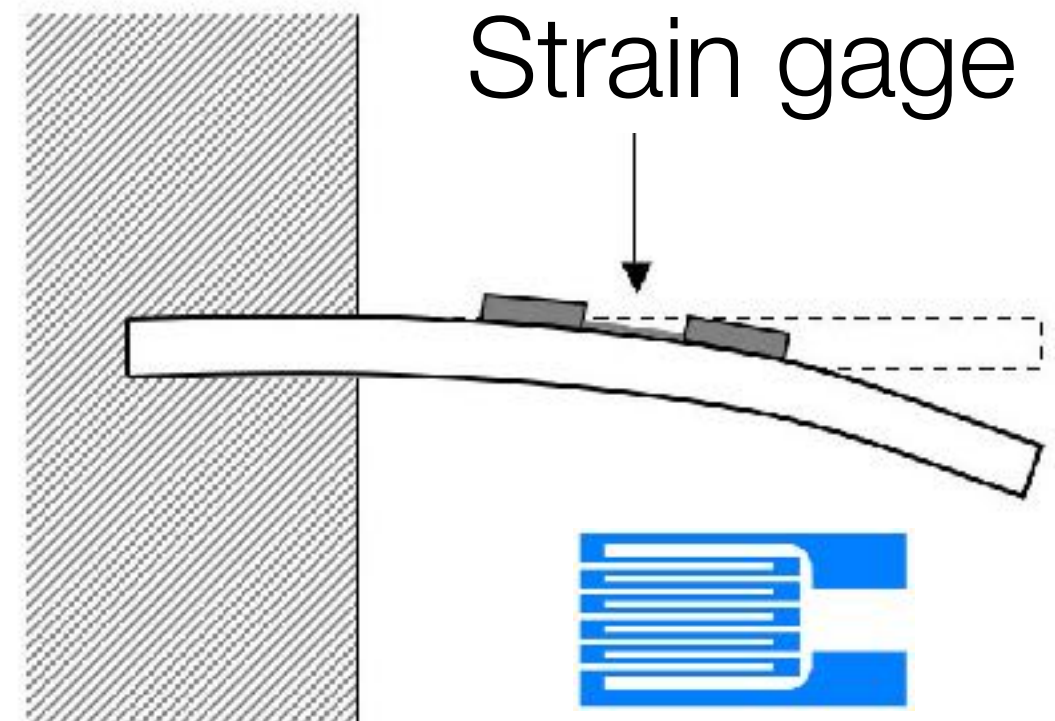
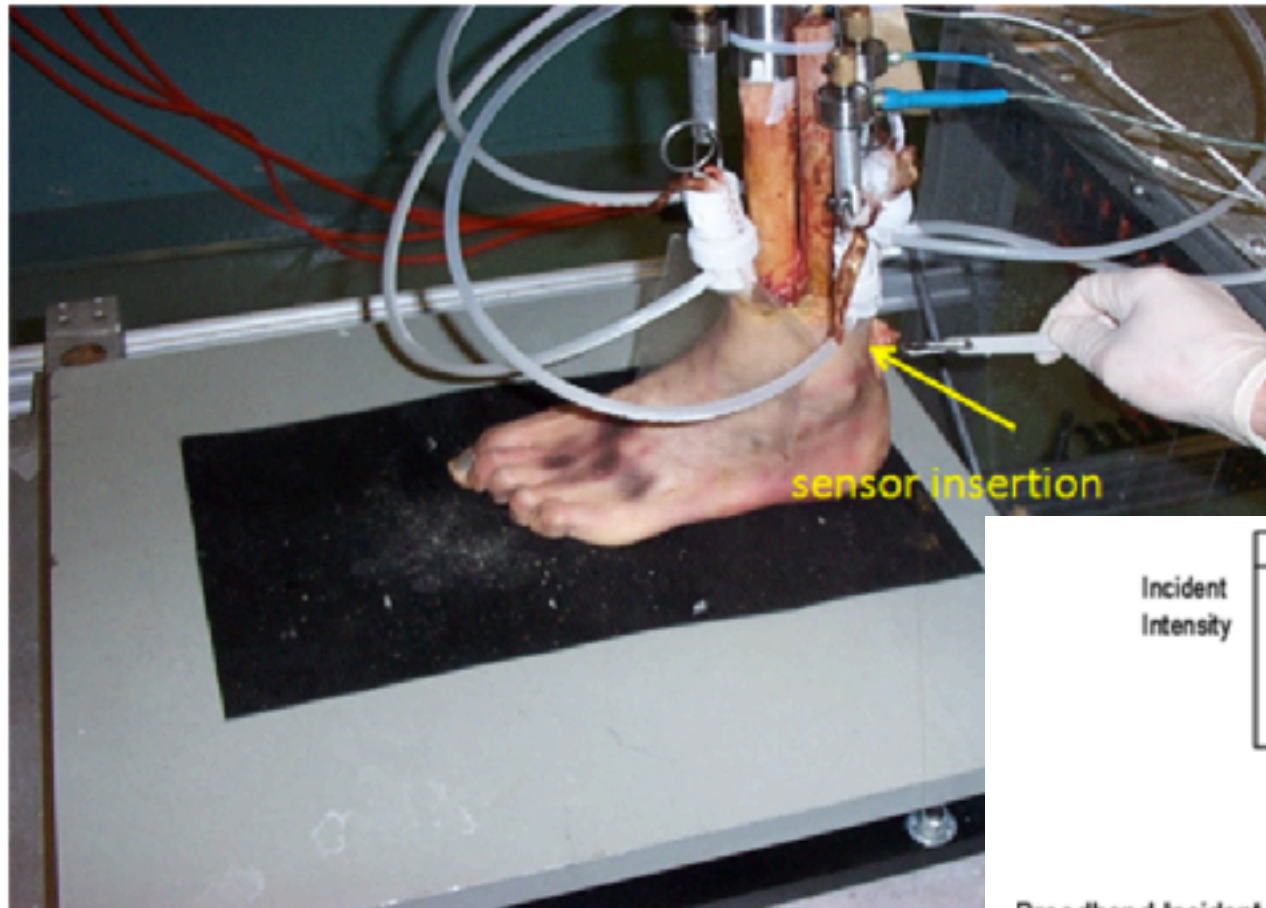


Fig. 2. Schematic diagram of the buckle transducer (Keegan et al., 1991, 1992; Roberts et al., 1994; Stone et al., 1983). (a) Schematic view and dimensions of the buckle transducer (top view of the transducer). (b) Position of the transducer within the tendon or the ligament (side view of the transducer).



Optical fibre in the tendon



Behrmann et al. BioMedical Engineering OnLine 2012, 11:77 <http://www.biomedical-engineering-online.com/content/11/1/77>

16 The Dynamic Gate Simulator, CELOS, Penn State University.

→ Deformation can be detected via wavelength of the reflected and transmitted light

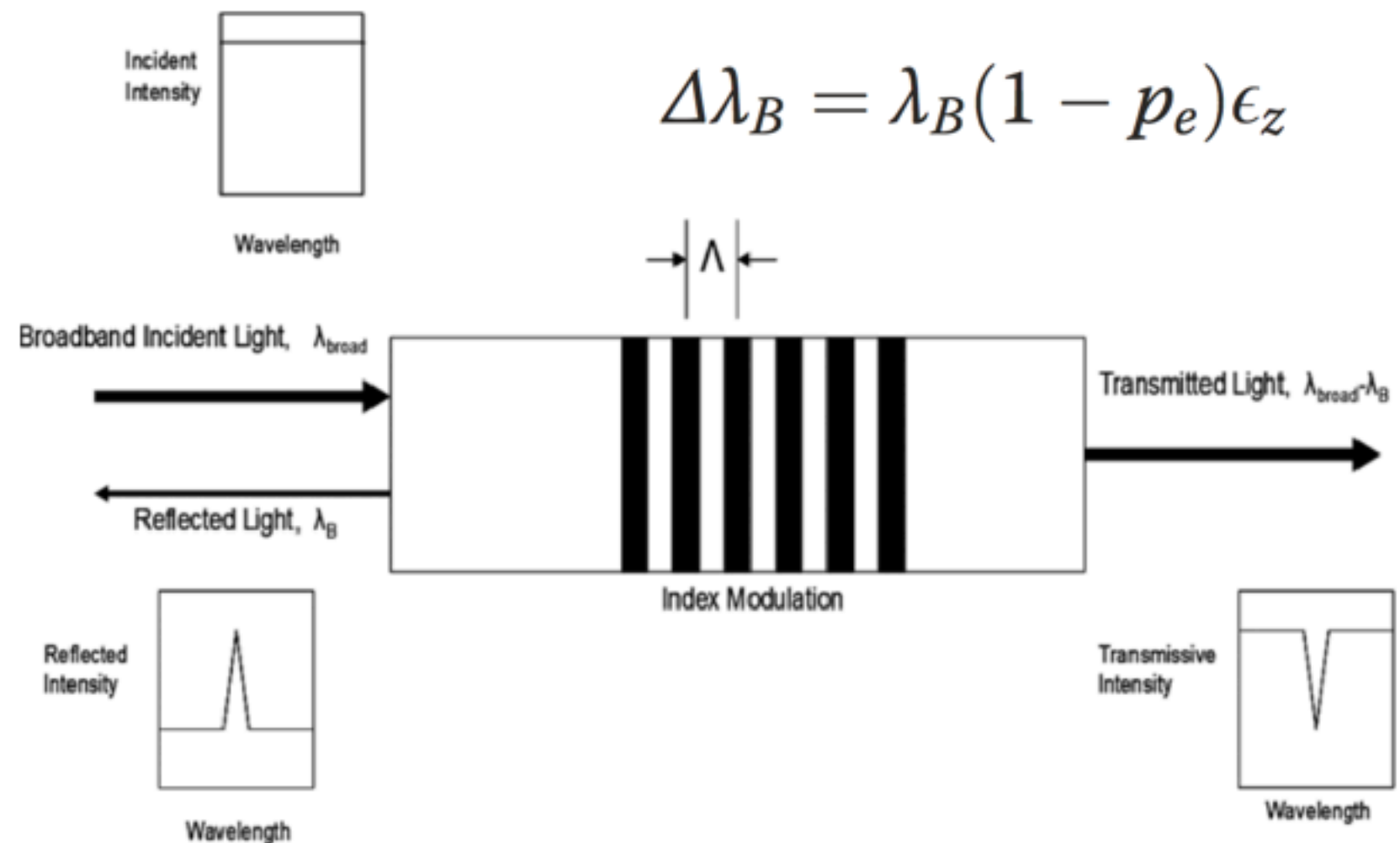


Figure 2 A fiber Bragg grating structure illuminated by broadband light.

Measure pressure in IVD: pressure transducer

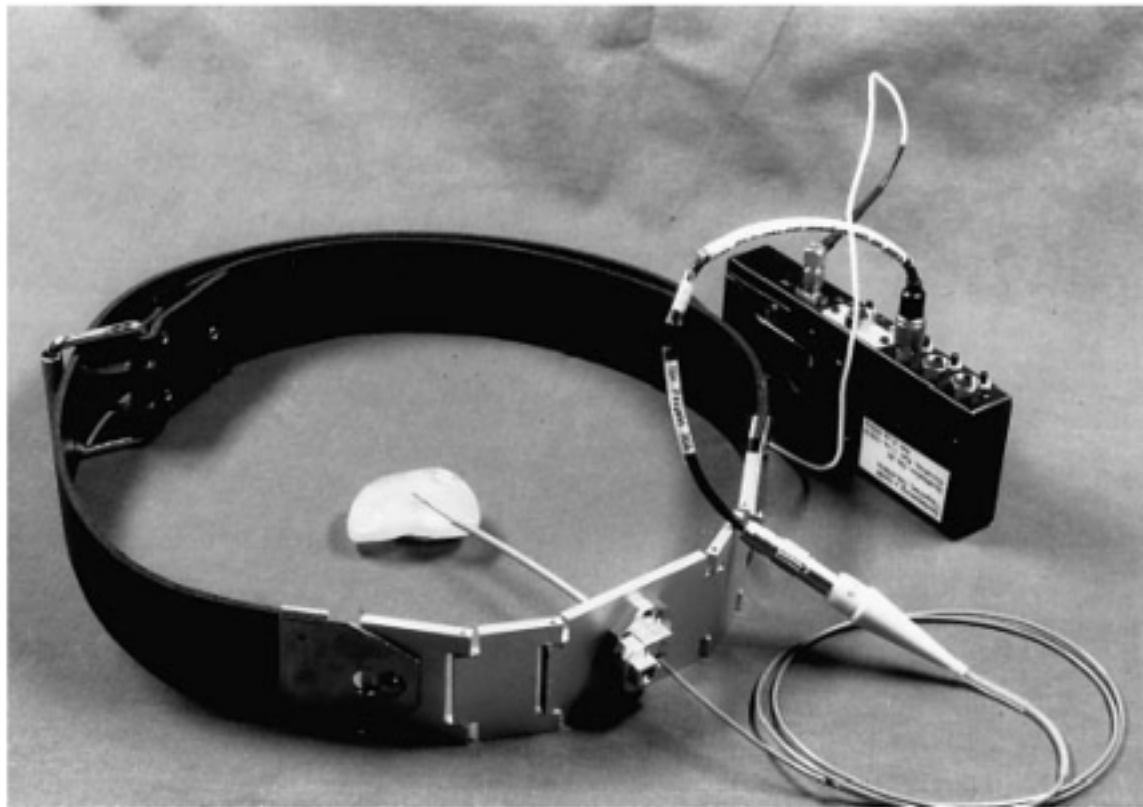


Figure 2. Spatial relation of implanted transducer, intervertebral disc and stabilization, and transmission belt.

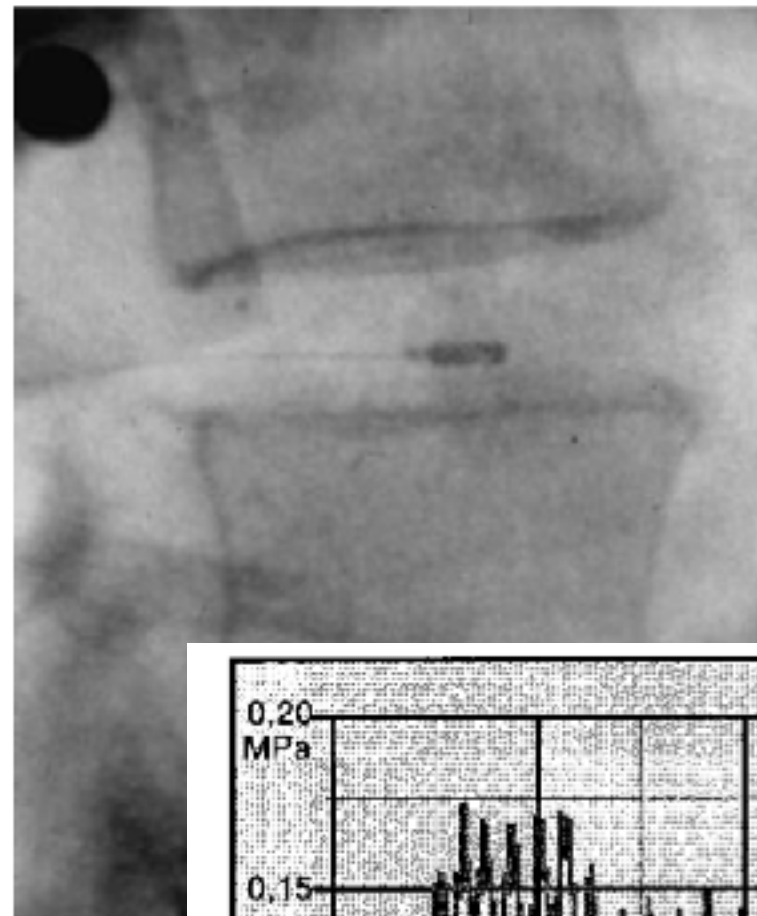
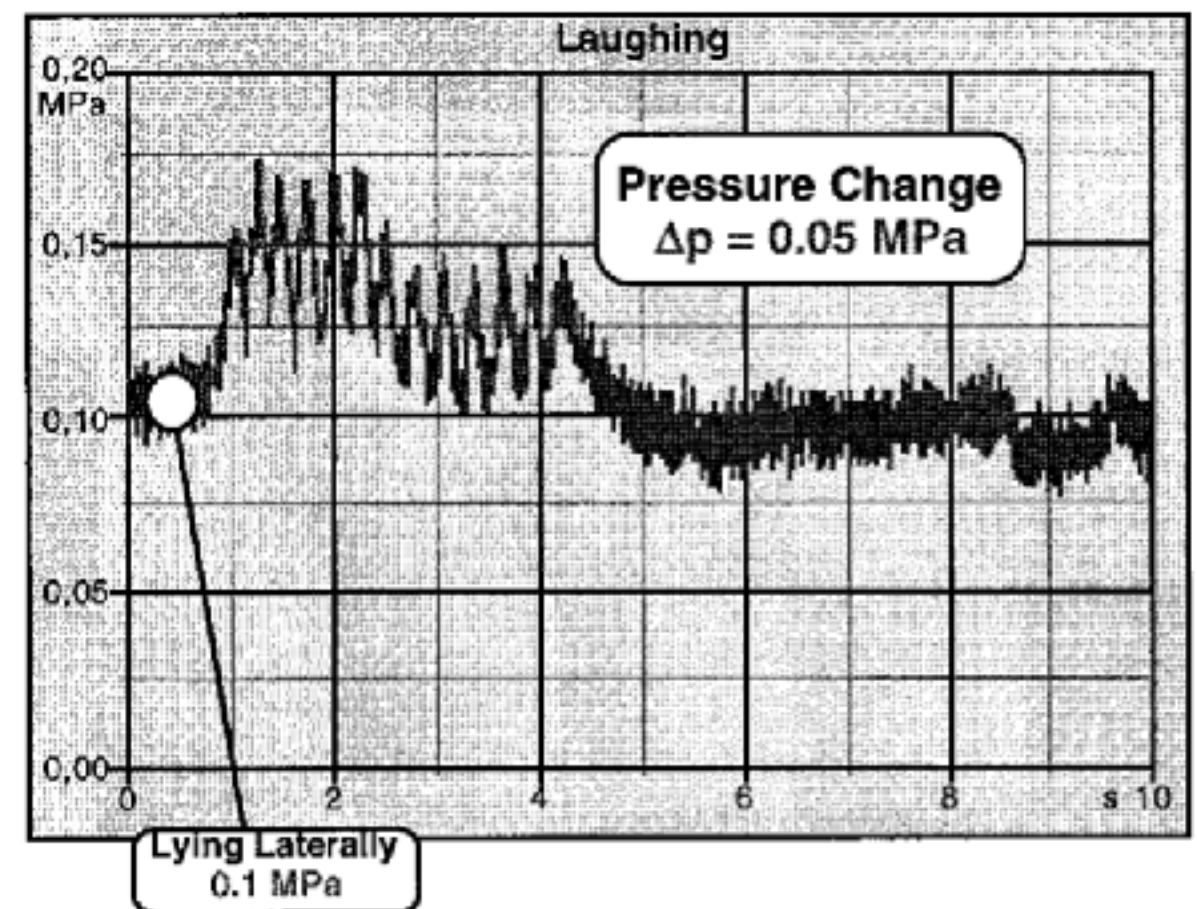


Figure 3. Close-up of the implanted transducer.



Wilke et al. 1999, New In Vivo Measurements of Pressures in the Intervertebral Disc in Daily Life, SPINE Volume 24, Number 8, pp 755–762

Force transducers: advantages and disadvantages

Advantages

- * direct measurement via deformation
- * many options { deformable object
measure deformation

Disadvantages

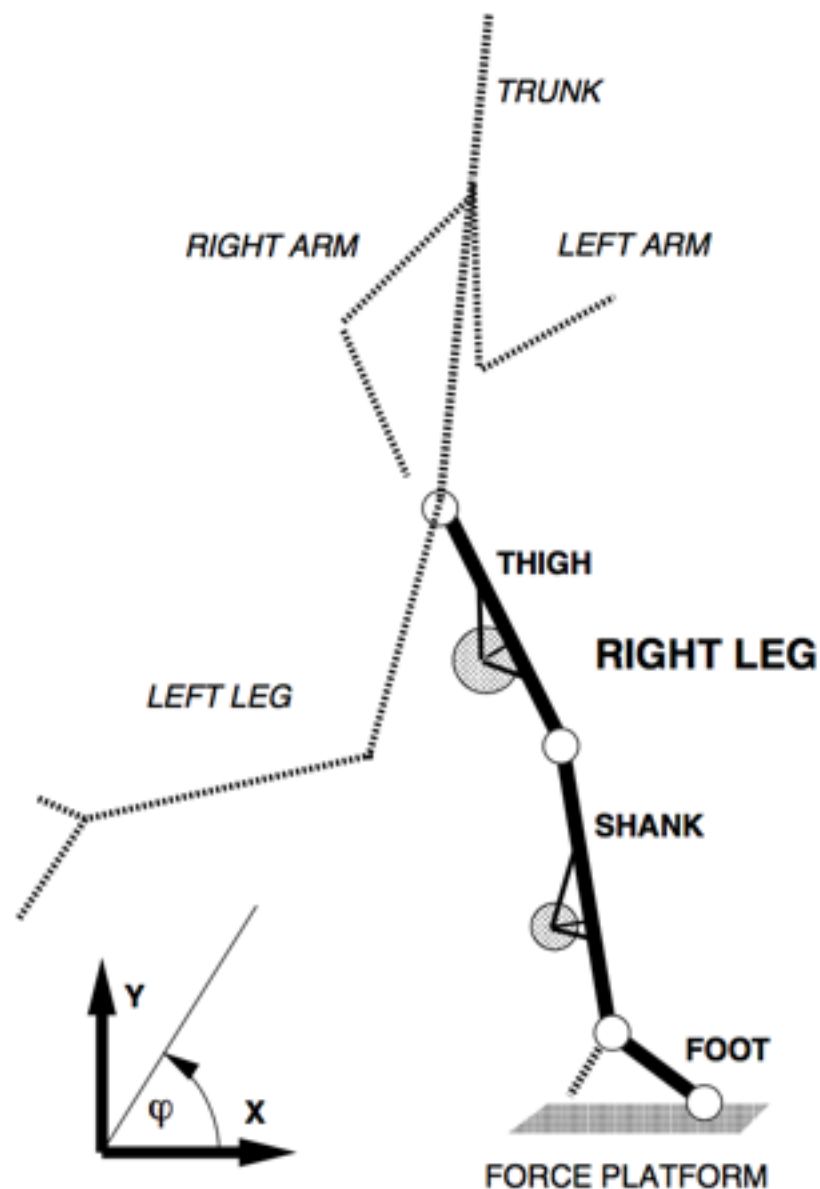
- * always need an additional device to be inserted (invasive)
- * analysis tool

How to measure force: second approach

Inverse dynamics

$$F = m \ddot{x}$$

$$M = J \ddot{\varphi}$$



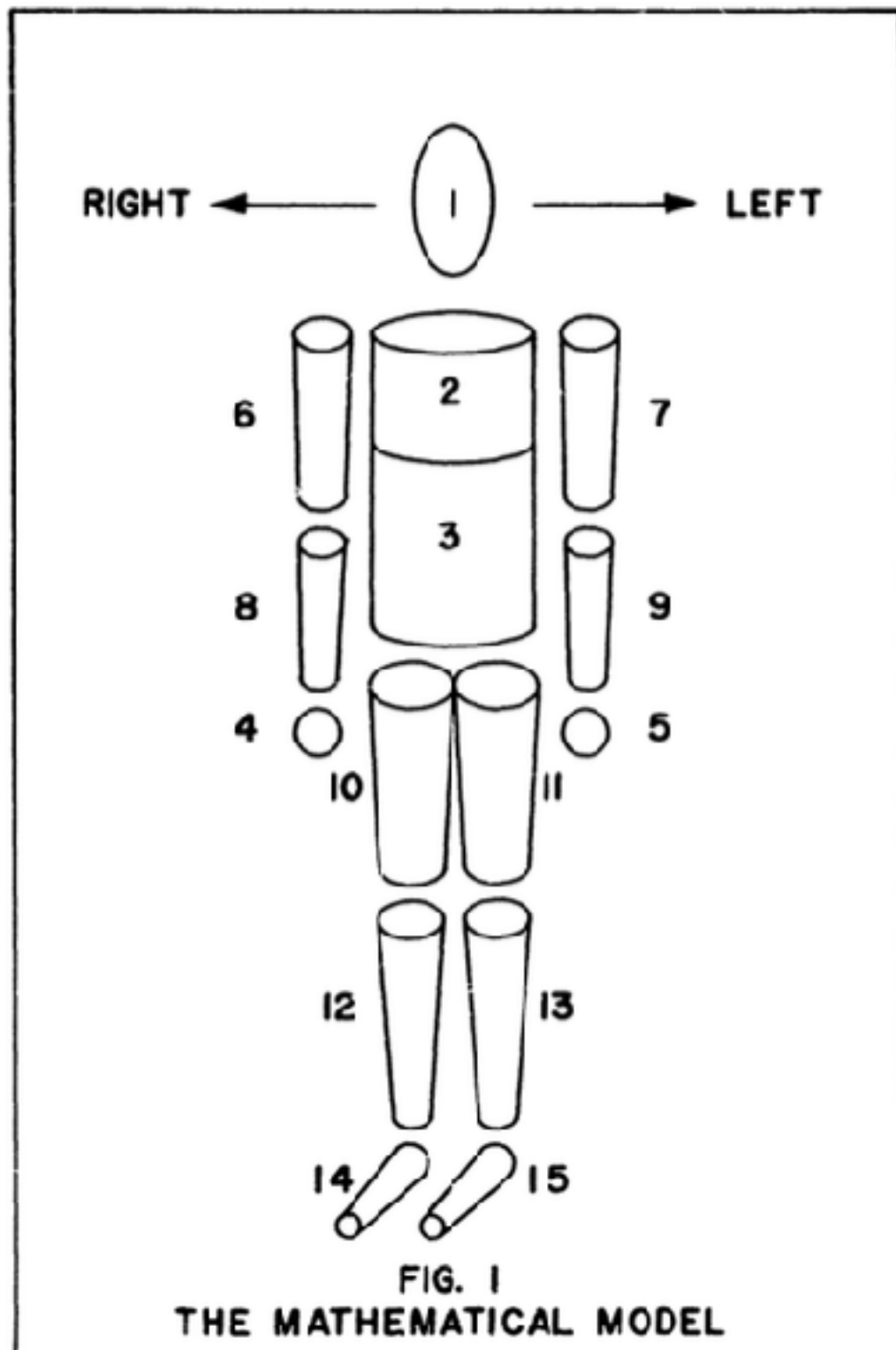
$$M_{i+1,i} = \theta_i \ddot{\varphi}_i - M_{i-1,i} - X_{i,i-1} F_{i-1,i/y} + Y_{i,i-1} F_{i-1,i/x}$$

$$- X_{i,i+1} F_{i+1,i/y} + Y_{i,i+1} F_{i+1,i/x} - \sum_{k=1}^{n_{k(i)}} M_{k,i/coup} (\vec{F}_{k,i/coup}) .$$

Günther, M., Sholukha, V. a., Kessler, D., Wank, V., & Blickhan, R. (2003). Dealing With Skin Motion and Wobbling Masses in Inverse Dynamics. *Journal of Mechanics in Medicine and Biology*, 3(03n04), 309–335. <http://doi.org/10.1142/S0219519403000831>

How to acquire masses?

→ Anthropometric models give mass and inertia of each segment



Weight of head neck and trunk

$$\text{HNT} = .47 W + 12.0$$

Weight of upper arm

$$\text{BUA} = .08 W - 2.9$$

Weight of forearm

$$\text{BFO} = .04 W - 0.5$$

Weight of hand

$$\text{BH} = .01 W + 0.7$$

Hanavan, E. P. (1964). A mathematical model of the human body. Wright-Patterson Air Force Base, OH.

How to acquire accelerations?

also record ground reaction forces



Figure 1. Experimental setup. Four force plates in series were embedded in the indoor track. Force plates were covered with the same material (different color) as the entire indoor track. Twelve Vicon cameras arranged around the force plates captured the athletes' motions.

→ motion capture

→ inertia measurement units (IMUs)

Brüggemann, G.-P., Arampatzis, A., Emrich, F., & Potthast, W. (2009). Biomechanics of double transtibial amputee sprinting using dedicated sprinting prostheses. *Sports Technology*, 1(4–5), 220–227. <http://doi.org/10.1002/jst.63>



Haeufle, D. F. B., Worobets, J., Wright, I., Haeufle, J., & Stefanyshyn, D. (2012). Golfers do not respond to changes in shaft mass properties in a mechanically predictable way. *Sports Engineering*, 15(4), 215–220. <http://doi.org/10.1007/s12283-012-0104-9>

Inverse dynamics: advantages and disadvantages

$$F = m \ddot{x}$$

Advantages

- * non invasive
 - * robust algorithms exist
 - * commercially available
- popular in (sports -)
biomechanics

Disadvantages

- * Analysis method
 - * only net joint torque /
contact forces
- co-contraction is not
resolved

Problem:

**How to predict internal
forces and loads?**

**...predict outcome of
surgery?**

surgery?

What we need:

Forward dynamics

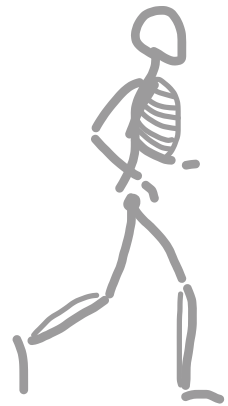
makes use of Newton's law $F = ma = m\ddot{x}$

$$\ddot{x} = \frac{F}{m}$$

predict internal forces and movement by
mathematical models of structures in
the human body

→ computer simulation

Structures



Bones



Tissue



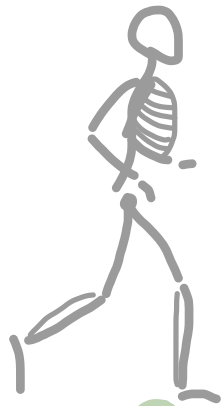
Muscle



Neurons



Our viewpoint on natural systems



Bones
Structure

Rigid
bodies

$$\frac{d}{dt} \frac{\partial L}{\partial \dot{q}_i} - \frac{\partial L}{\partial q_i} = Q_i$$



Ligaments,
cartilage, fat
Springs

Passive
force

depend on mechanical system state

$$F_p = f(z, \dot{z})$$

with $\mathbf{z} = [q_1, \dots, q_n, o_1, \dots, o_m]^T$

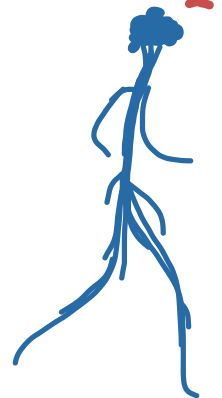


Muscles
Motors

Active
force

$$F_a = f(z, \dot{z}, \mathbf{u})$$

with $\mathbf{u} = [u_1, \dots, u_k]^T$



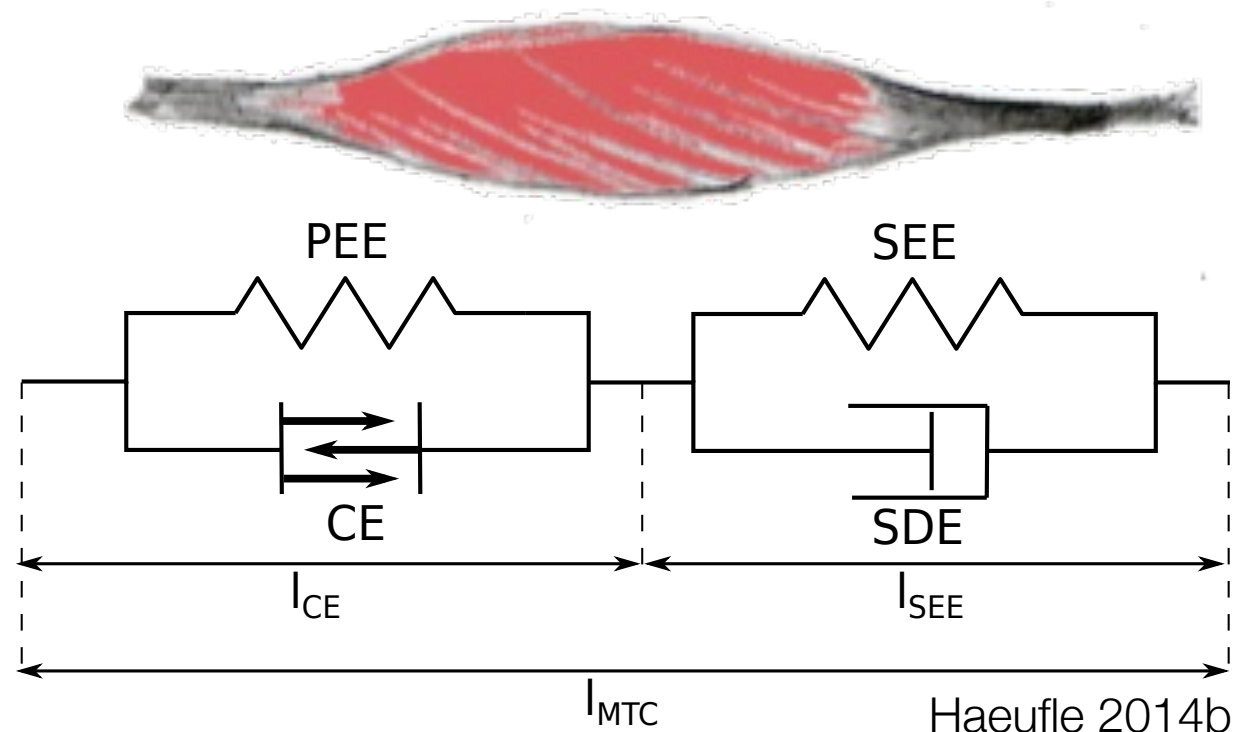
Neurons
Wires, CPU

Reflexes,
commands

$$\mathbf{u} = f(z, \dot{z}, \text{"brain"})$$



Structure: muscle



Biochemistry: activation dynamics

$$\dot{a}_j = f_a(a_j, l_j^{CE}, u_j^{CE})$$

Biophysics: contraction dynamics

$$\dot{l}_j^{CE} = f_v(l_j^{MTU}, v_j^{MTU}, l_j^{CE}, a_j)$$

$$F_j^{MTU} = f_f(l_j^{MTU}, v_j^{MTU}, l_j^{CE}, a_j)$$



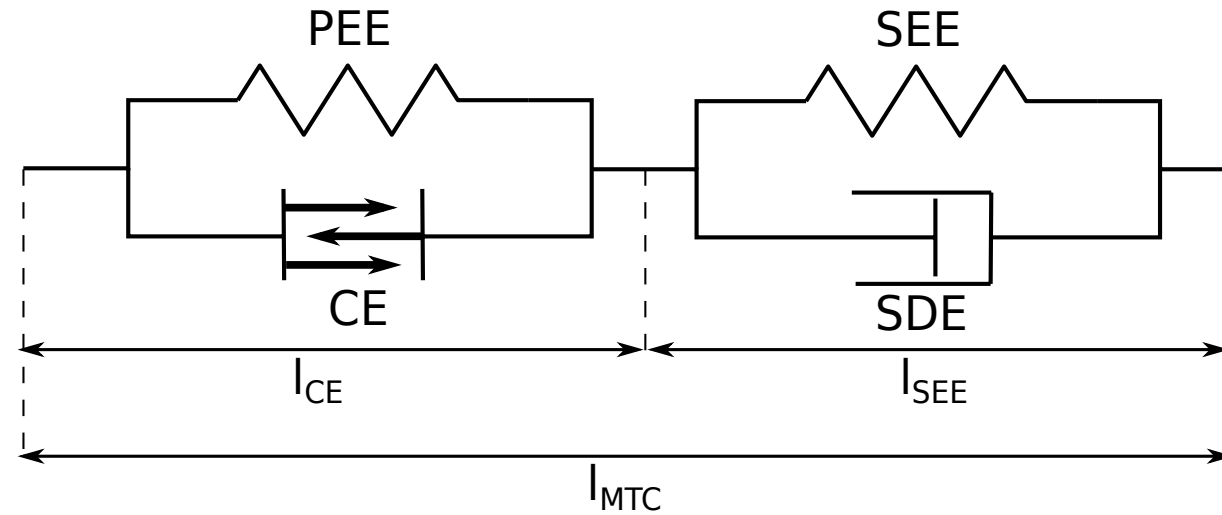
Structure: muscle

$$F_{PEE}(l_{CE}) = \begin{cases} 0, & l_{CE} < l_{PEE,0} \\ K_{PEE}(l_{CE} - l_{PEE,0})^{\nu_{PEE}}, & l_{CE} \geq l_{PEE,0} \end{cases}$$

$$K_{PEE} = \mathcal{F}_{PEE} \frac{F_{max}}{(l_{CE,opt}(\Delta W_{limb=des} + 1 - \mathcal{L}_{PEE,0}))^{\nu_{PEE}}}$$

$$F_{SEE}(l_{SE}) = \begin{cases} 0, & l_{SE} < l_{SEE,0} \\ K_{SEE,nl}(l_{SE} - l_{SEE,0})^{\nu_{SEE}}, & l_{SE} < l_{SEE,nll} \\ \Delta F_{SEE,0} + K_{SEE,l}(l_{SE} - l_{SEE,nll}), & l_{SE} \geq l_{SEE,nll} \end{cases}$$

$$F_{CE}(l_{CE}, \dot{l}_{CE}, q) + F_{PEE}(l_{CE}) = F_{SEE}(l_{CE}, l_{MTC}) + F_{SDE}(l_{CE}, \dot{l}_{CE}, \dot{l}_{MTC}, q).$$



$$F_{CE,c}(\dot{l}_{CE} \leq 0) = F_{max} \left(\frac{qF_{isom} + A_{rel}}{1 - \frac{\dot{l}_{CE}}{B_{rel}l_{CE,opt}}} - A_{rel} \right).$$

$$F_{SDE}(l_{CE}, \dot{l}_{CE}, \dot{l}_{MTC}, q) = D_{SDE,max} \cdot \left((1 - R_{SDE}) \cdot \frac{F_{CE}(l_{CE}, \dot{l}_{CE}, q) + F_{PEE}(l_{CE})}{F_{max}} + R_{SDE} \right) \cdot (\dot{l}_{MTC} - \dot{l}_{CE})$$

$$F_{isom}(l_{CE}) = \exp \left\{ - \left| \frac{l_{CE}/l_{CE,opt} - 1}{\Delta W_{limb}} \right|^{\nu_{CE,limb}} \right\}$$



Structure: muscle

$$\dot{l}_{CE} = \dot{l}_{CE}(l_{CE}, l_{MTC}, \dot{l}_{MTC}, q).$$

$$\dot{l}_{CE} = \begin{cases} \frac{-C_1 - \sqrt{C_1^2 - 4 \cdot C_2 \cdot C_0}}{2 \cdot C_2}, & \dot{l}_{CE} \leq 0 \\ \frac{-C_{1,e} + \sqrt{C_{1,e}^2 - 4 \cdot C_{2,e} \cdot C_{0,e}}}{2 \cdot C_{2,e}}, & \dot{l}_{CE} > 0 \end{cases}$$

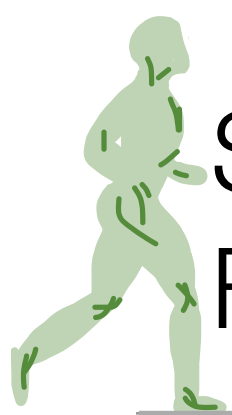
$$C_2 = d_{SE,max}(l_{CE}, q) \cdot \left(R_{SE} - \left(A_{rel}(l_{CE}, q) - \frac{F_{PEE}(l_{CE})}{F_{max}} \right) \cdot (1 - R_{SE}) \right)$$

$$C_1 = -(C_2 \cdot \dot{l}_{MTC} + D_0 + F_{SEE}(l_{MTC}, l_{CE}) - F_{PEE}(l_{CE}) + F_{max} \cdot A_{rel}(l_{CE}, q))$$

$$C_0 = D_0 \cdot \dot{l}_{MTC} + l_{CE,opt} \cdot B_{rel}(l_{CE}, q) \cdot (F_{SEE}(l_{MTC}, l_{CE}) - F_{PEE}(l_{CE}) - F_{max} \cdot q \cdot F_{isom}(l_{CE}))$$

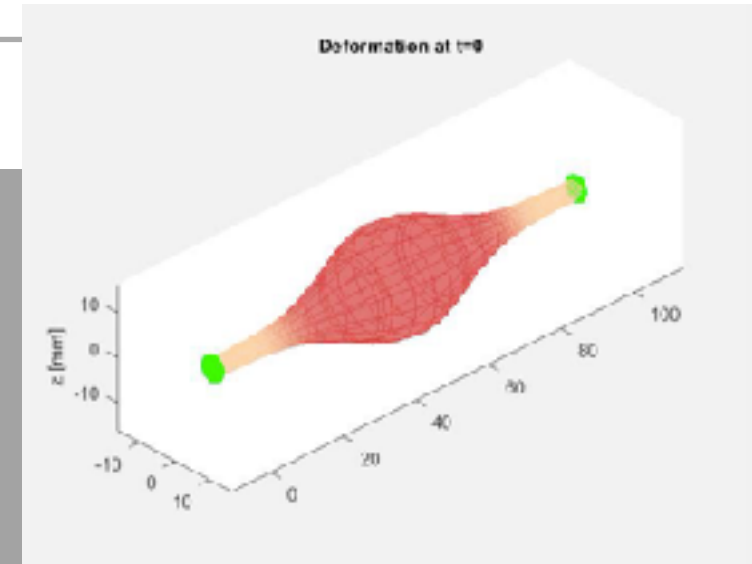
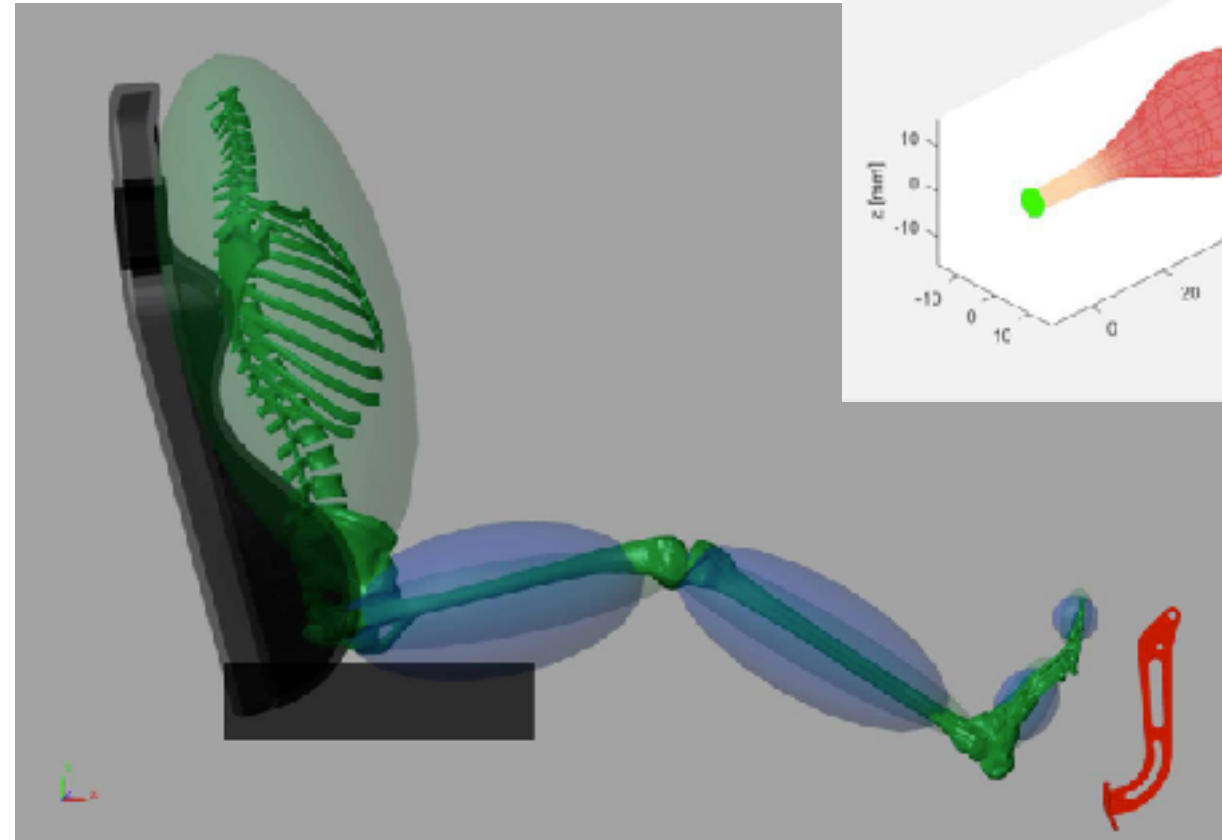
(17)

$$D_0 = l_{CE,opt} \cdot B_{rel}(l_{CE}, q) \cdot d_{SE,max}(l_{CE}, q) \cdot \left(R_{SE} + (1 - R_{SE}) \cdot \left(q \cdot F_{isom}(l_{CE}) + \frac{F_{PEE}(l_{CE})}{F_{max}} \right) \right)$$



Structure: soft tissue

Function: interaction with the environment

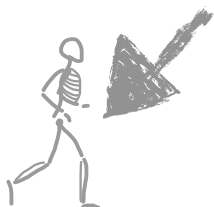


Schmitt 2014

$$\vec{F}_{k,i/coup} = \left(C_{k,i} |\vec{d}|^{eC_{k,i}} + D_{k,i} \frac{\dot{\vec{d}} \vec{e}_d}{|\dot{\vec{d}} \vec{e}_d|^{eD_{k,i}}} \right) \vec{e}_d,$$

Günther et al. 2003

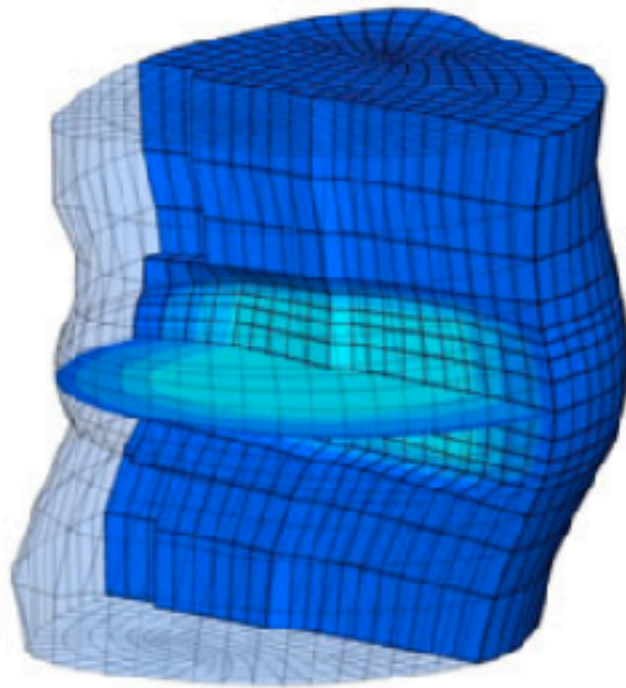
continuum-mechanics
mass distribution



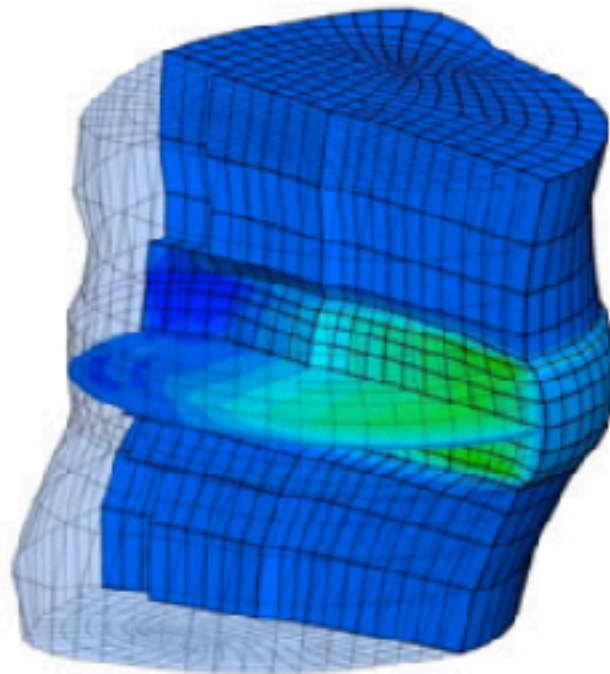


Structure: soft tissue

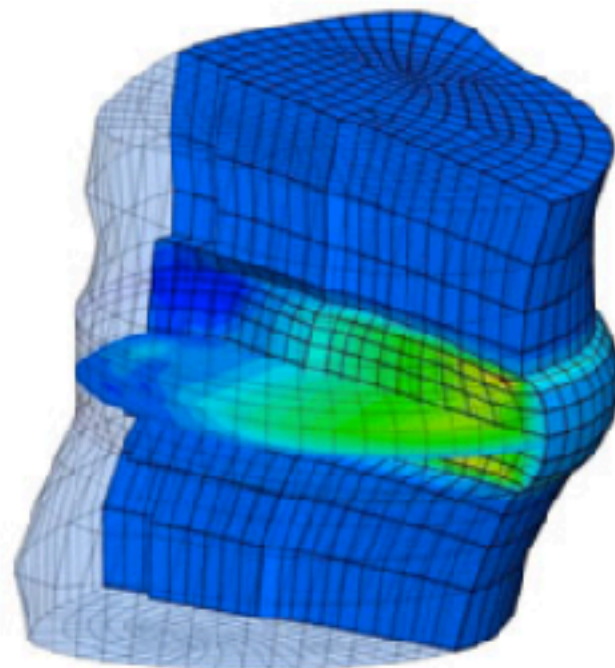
Function: relative movement and absorbing energy



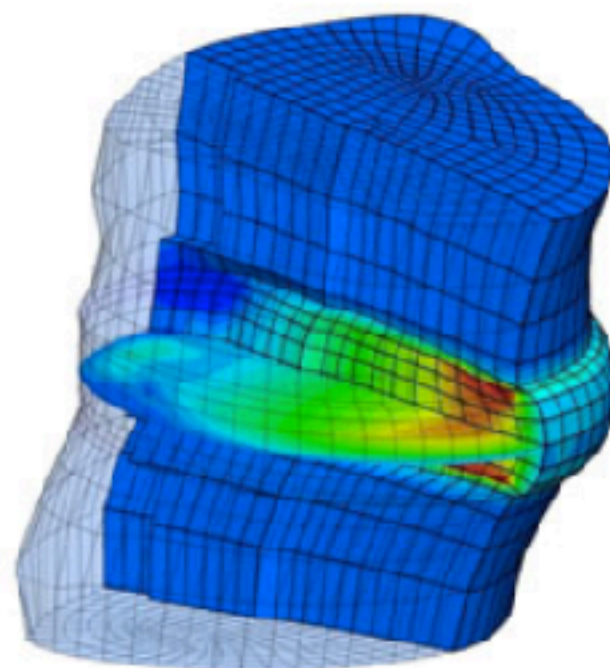
(a) $t = 0$ s



(b) $t = 0.33$ s



(c) $t = 0.66$ s



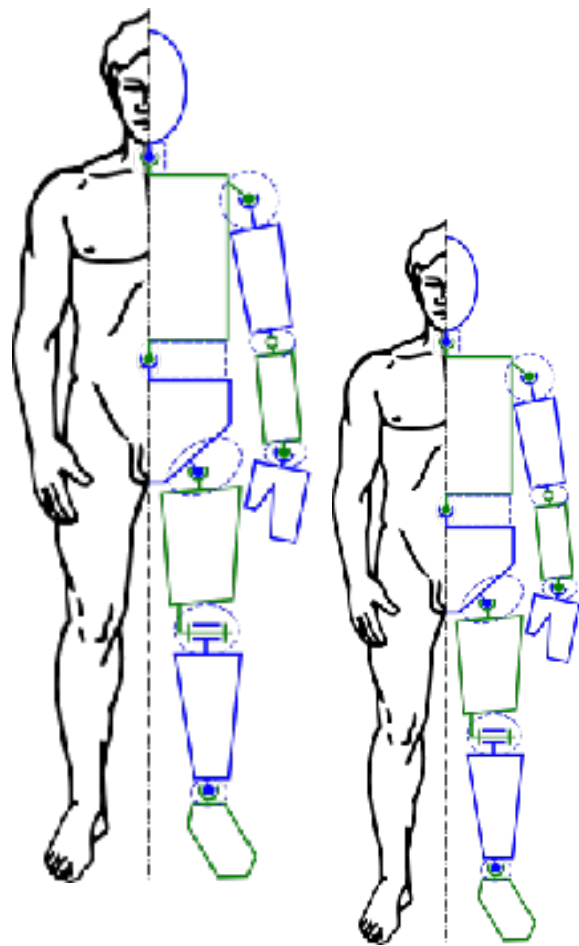
(d) $t = 1.0$ s

Karajan, N. (2012). Multiphasic Intervertebral Disc Mechanics: Theory and Application. Archives of Computational Methods in Engineering, 19(2), 261–339. <http://doi.org/10.1007/s11831-012-9073-1>



Structure: bones and joints

Function: dynamics of the movement





$$\ddot{\underline{q}} = M(\underline{q})^{-1} \left(\underline{f} - C(\underline{q}, \dot{\underline{q}}) - G(\underline{q}) \right)$$

based on Pandy, 2001

$$\begin{aligned} \underline{f} &= \underline{f}^{\text{ext}} + \underline{f}^{\text{active}} + \underline{f}^{\text{passive}} \\ &= \underline{E}(\underline{q}, \dot{\underline{q}}) + R^{\text{act}}(\underline{q}) \underline{F}^{\text{act}}(\underline{q}, \dot{\underline{q}}, u) + R^{\text{pass}}(\underline{q}) \underline{F}^{\text{pass}}(\underline{q}, \dot{\underline{q}}) \end{aligned}$$



Simulation: Demoa
Anthropometry: CalcMan



Structure: neurons

Function: perception and action

low-level control


$$u_i = u_i^{\text{open}} + u_i^{\text{closed}} = u_i^{\text{open}} + \left(k_p \cdot \frac{(\lambda_i - l_i^{\text{CE}})}{l_i^{\text{CE,opt}}} \right)$$

Bayer et al. 2016

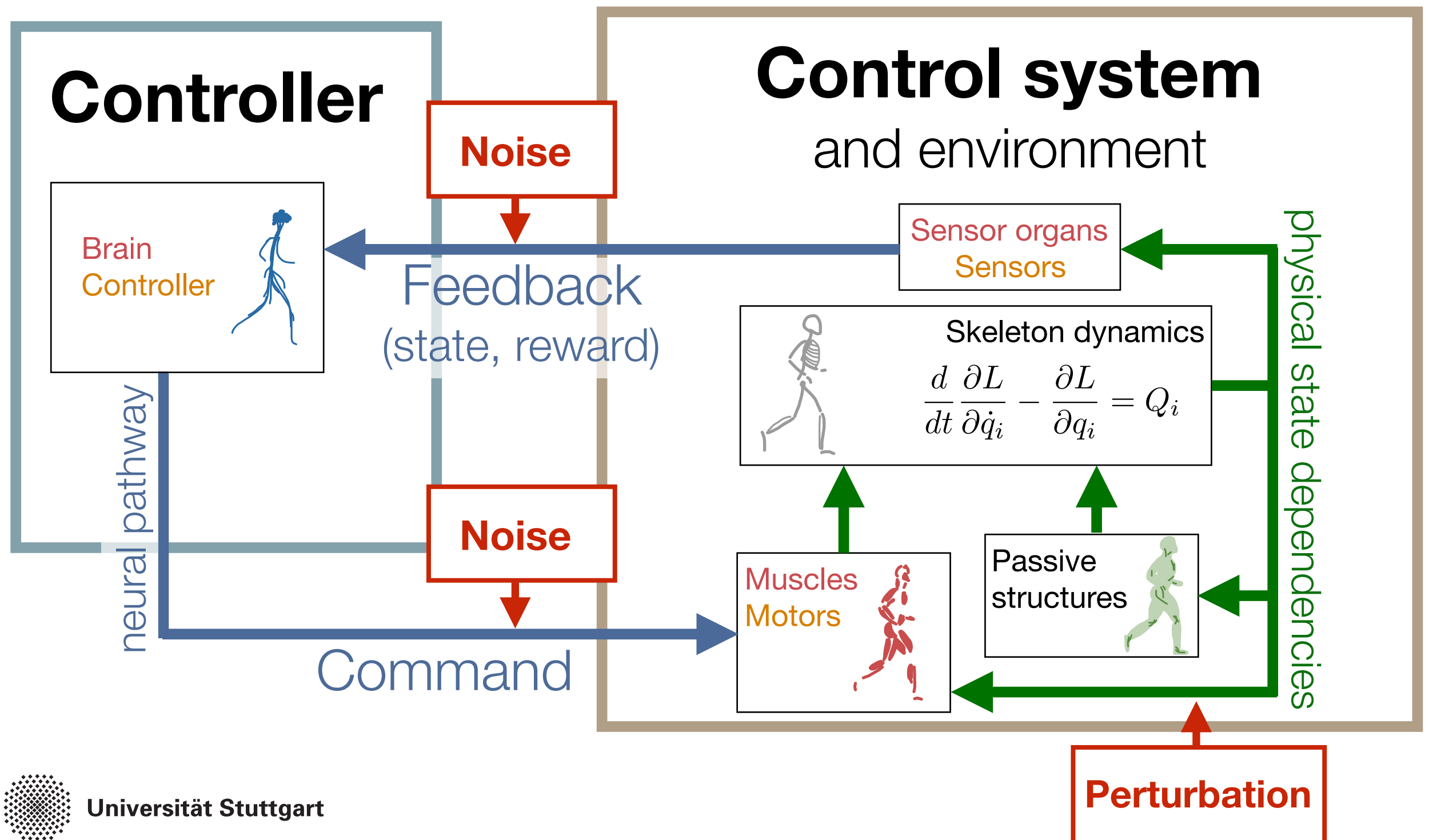
Computational motor control

- mono-synaptic reflexes
- proprioceptive feedback
- central pattern generators

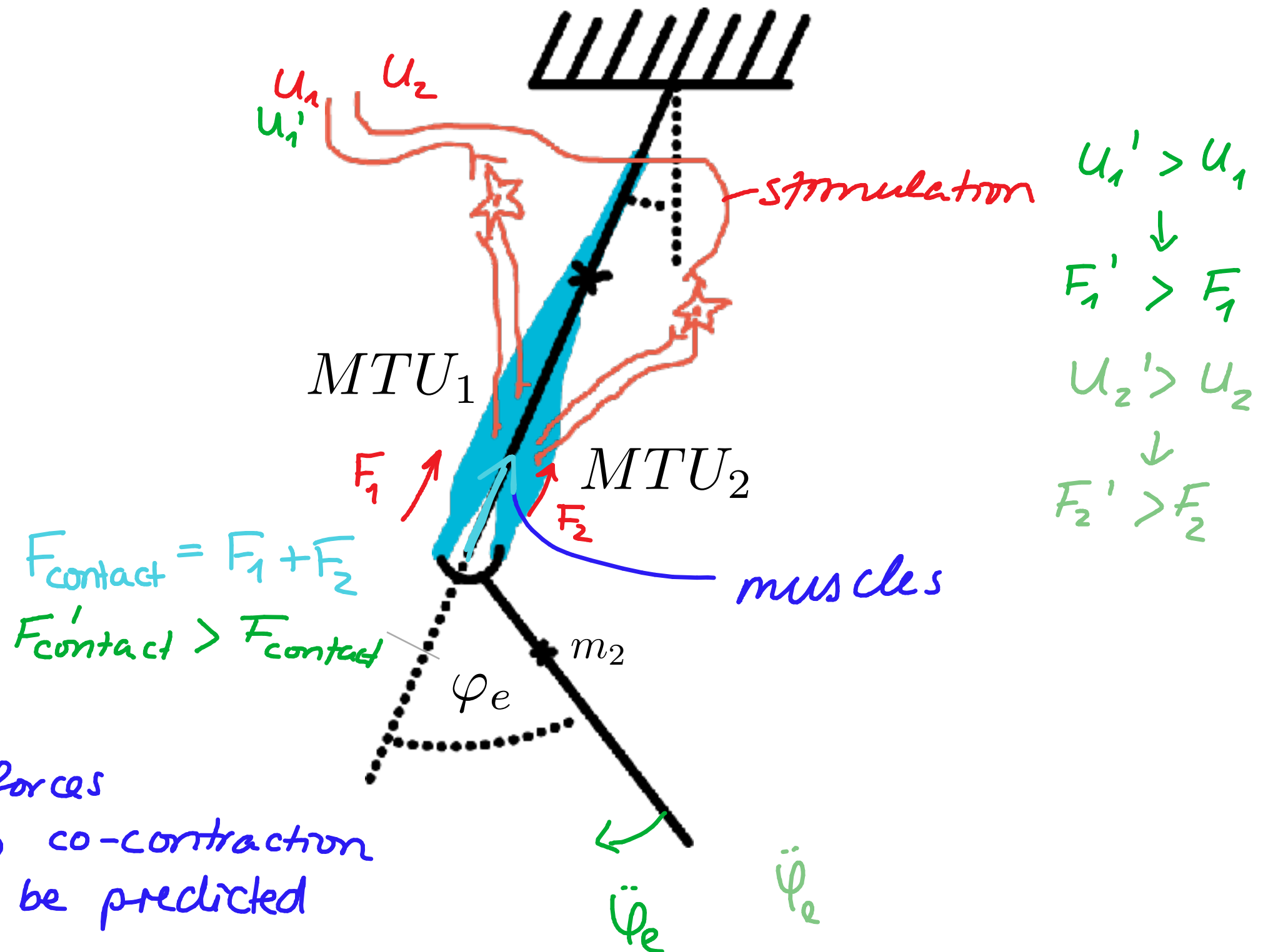

$$u_i = (w - 1)GF^M(t - \delta) + w \cdot u^{CPG}(t)$$

Haeufle et al. 2012b, 2016

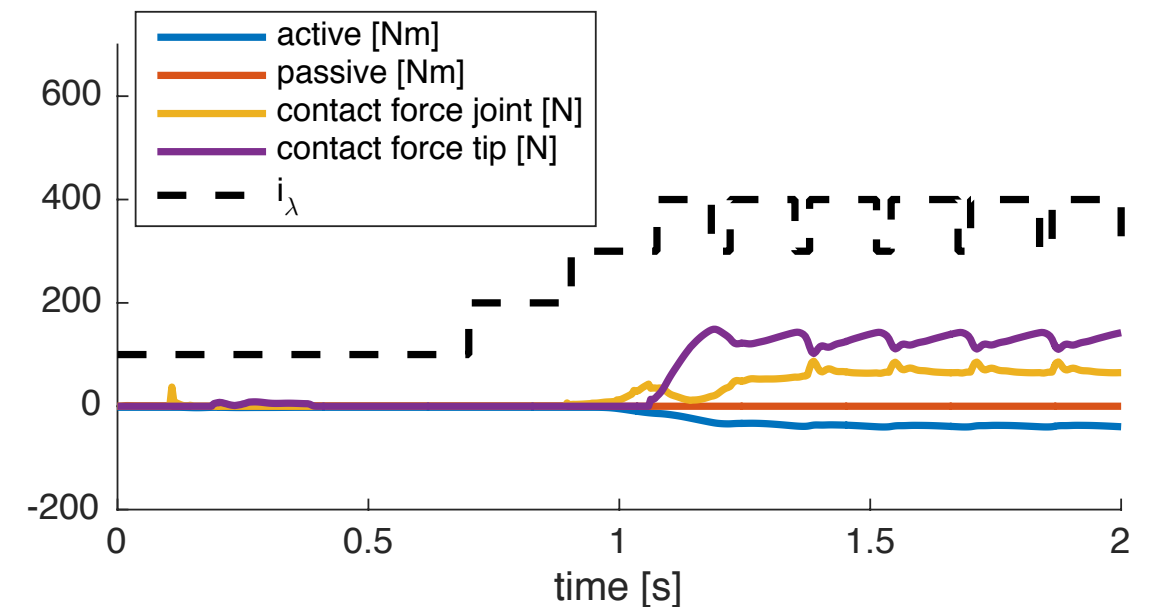
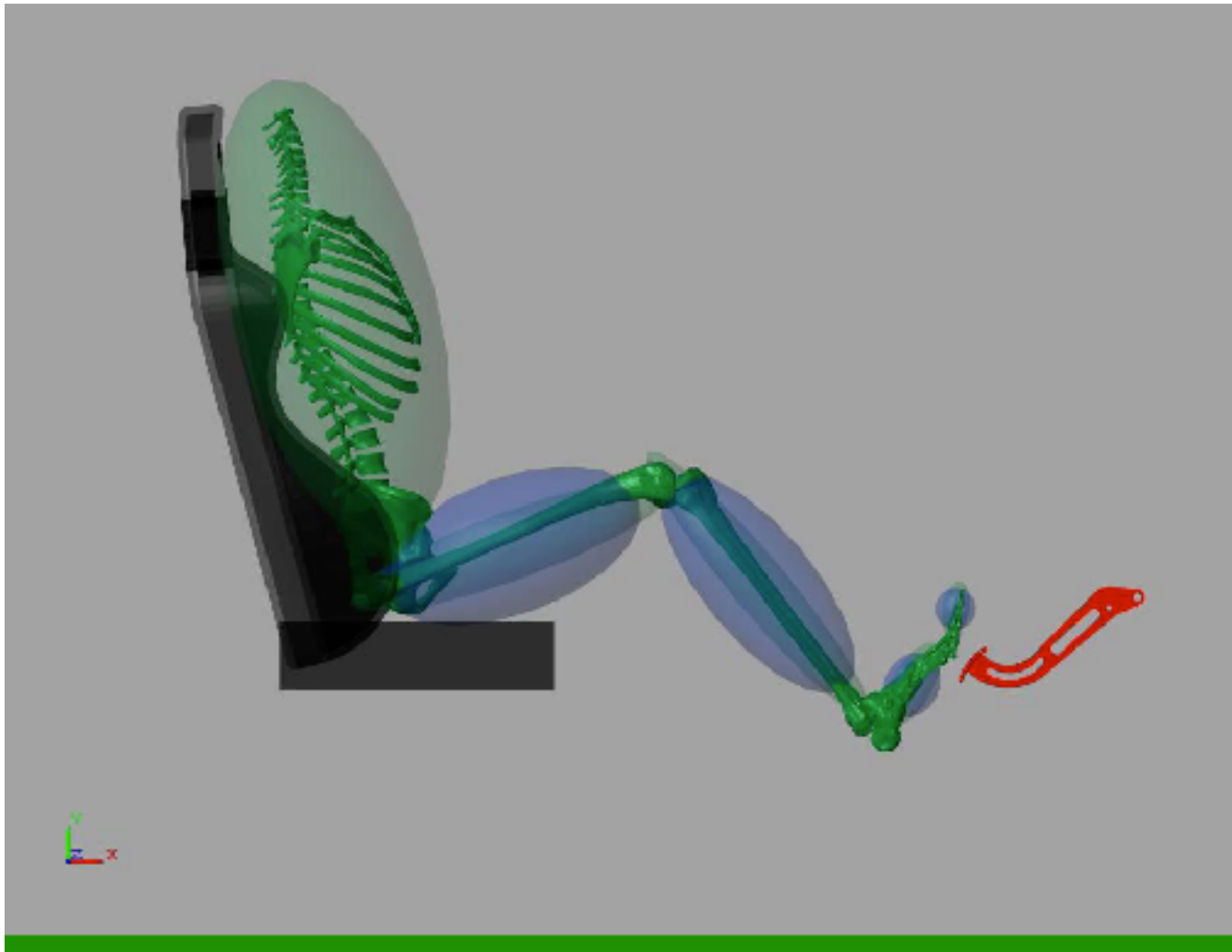
Interaction of the structures



Predicting muscle forces and joint loading



Predict internal and external forces in a car, which has not been built yet



Cannot be measured with force transducers,
cannot be analysed with inverse dynamics.

Forward dynamics computer simulation: advantages and disadvantages

Advantages

- * consider detailed forces and loads
- * predict an outcome (not analysis)
- * may be used to plan surgery

Disadvantages

- * computationally expensive
- * difficult to model forces of all structures

⇒ Synthesis (Prediction)



Stelian Coros

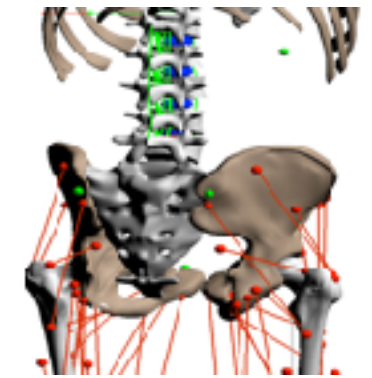
<https://www.youtube.com/watch?v=3K0gmSgOJiw>

Our most advanced human body model

Human model - lower extremity and spine



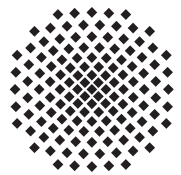
13	body segments
452	degrees of freedom (DOFs)
48	mechanical DOFs
202	muscle-tendon-complexes
58	non-linear ligaments
5	IVDs (non-linear, coupled)



skeletal anatomy	male, 68kg, 1,78m (NASA, 1978)
ligaments	anatomy (Panjabi, 1982), physiology (Chazal, 1985)
muscles	anatomy and physiology (Bogduk, 1992a,b, 1998; Hansen, 2006; Christophy, 2012)
IVDs	multi-scale model (Karajan, Röhrle, Ehlers & Schmitt, 2012)



***Vibration analysis of lumbar spine loading -
influence of two different muscle activity levels***



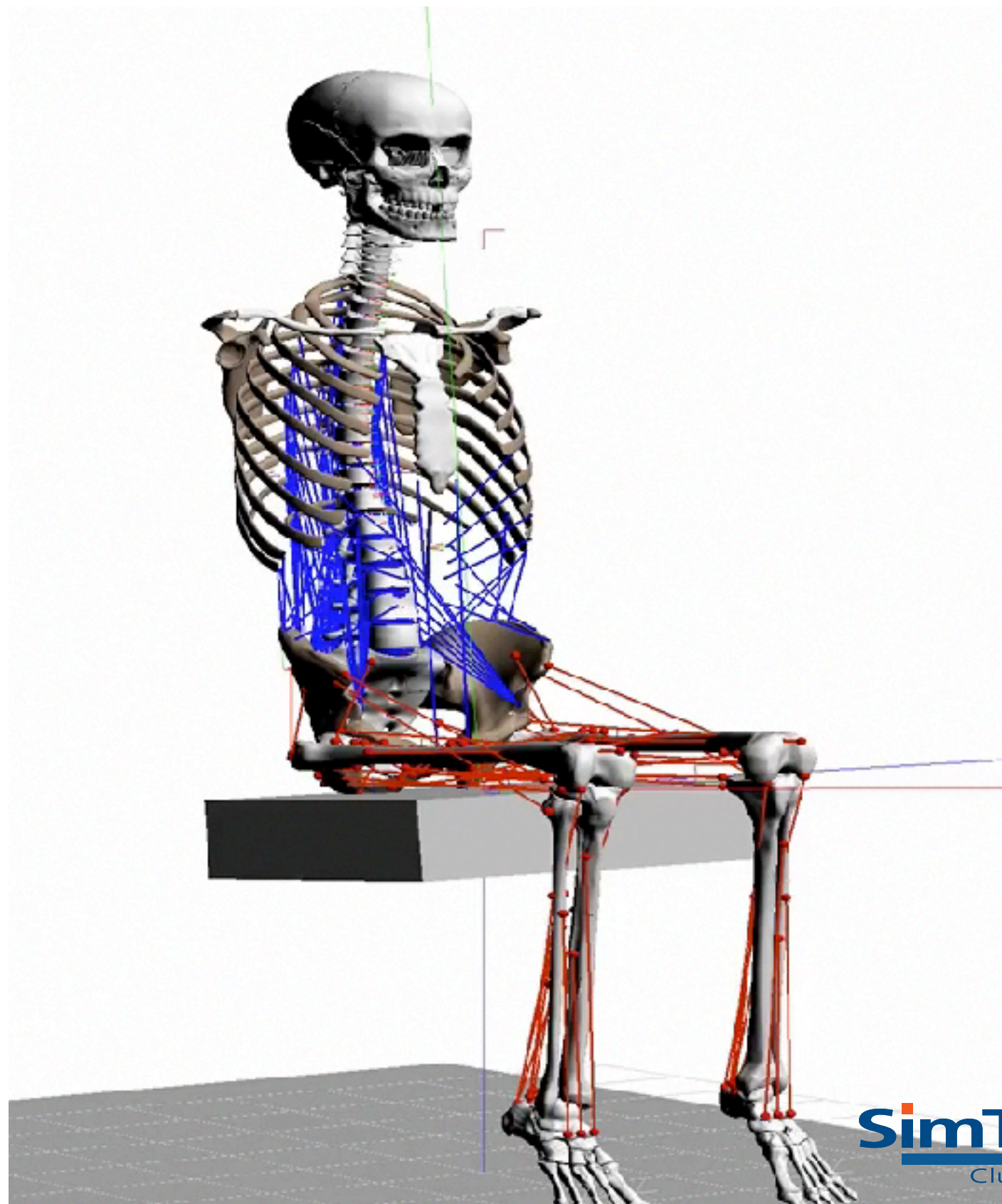
Universität Stuttgart

seated vibration
at 15Hz, 5mm

two models

(1) passive trunk
muscles,
(2) active trunk
muscles

**dynamic peak
loads** on ivds
are reduced
up to 30%



SimTech
Cluster of Excellence

Bayer et al. (2016) submitted

A numerical application in spinal fusion surgery

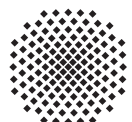
Spinal fusion surgery

... number of spinal-fusion surgery... is rapidly increasing.
(Deyo et al., 2004)

Adjacent segment degeneration and adjacent segment disease: the consequences of spinal fusion?
(Hilibrand & Robbins, 2004)

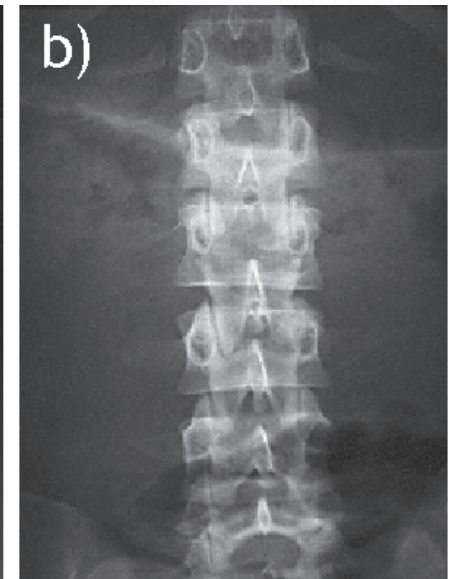
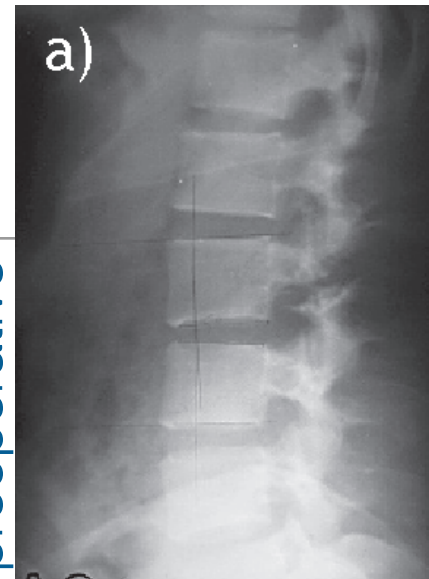


**Change of ...
...displacement, internal
forces and moments?**

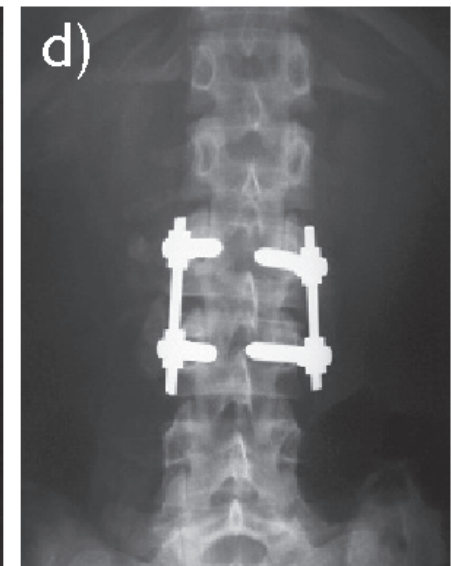
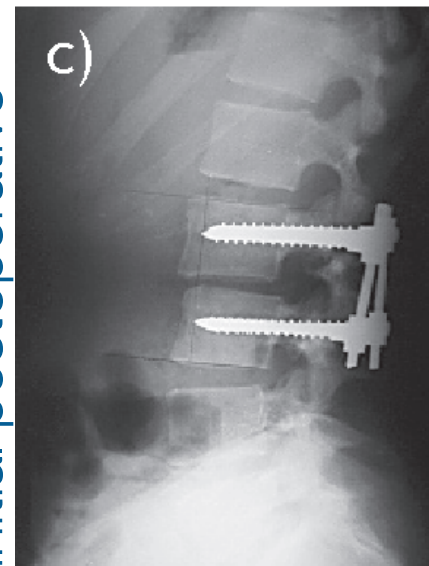


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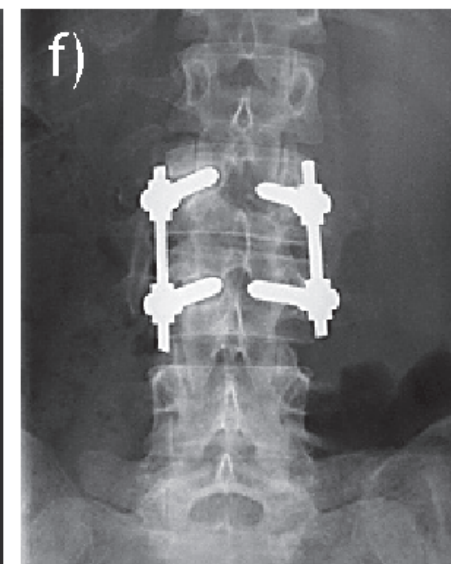
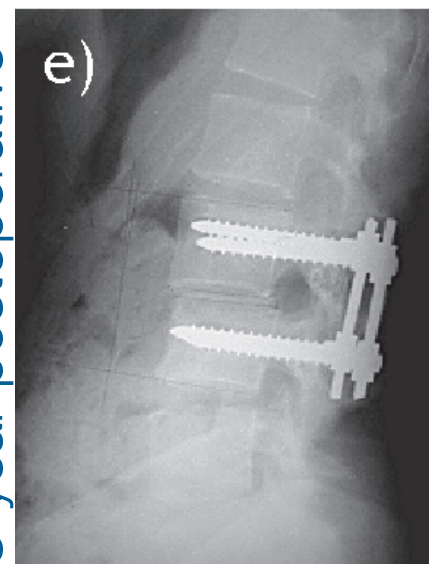
preoperative



initial postoperative



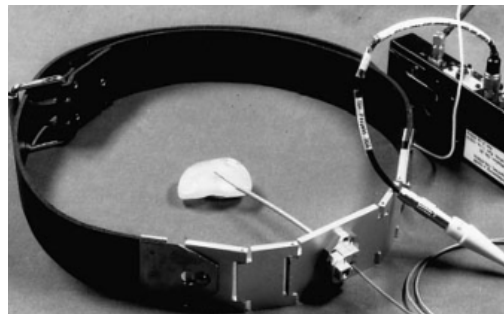
8-year postoperative



(Defino & Scarparo, 2005)

Take home:

- Knowing about internal dynamics, loads and forces is important

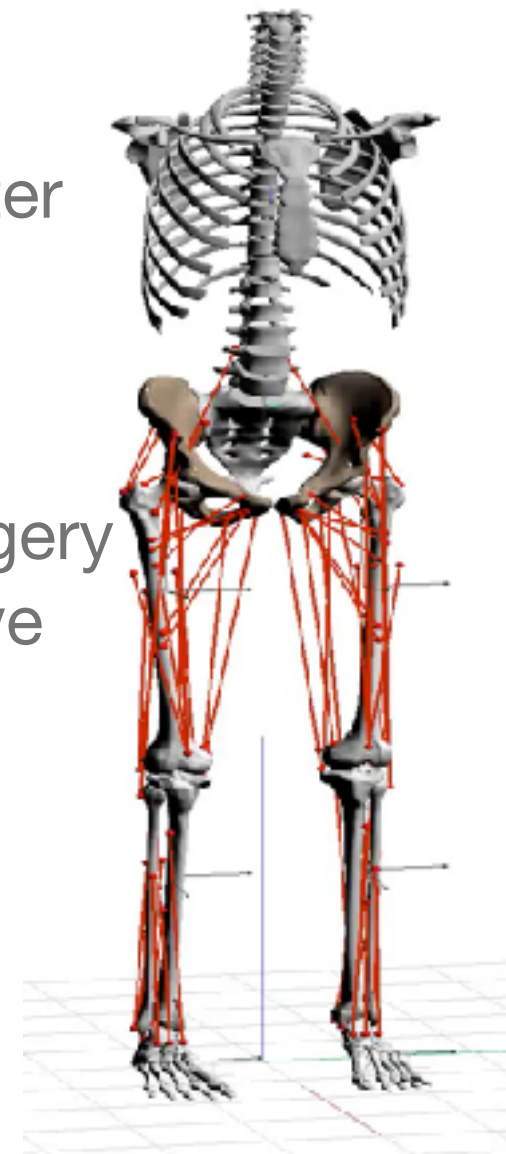


- Measure forces:
 - + direct results
 - invasive
 - analysis tool

- Inverse dynamics
 - + robust
 - + clinical acceptance
 - only net joint torques
 - analysis tool



- Forward dynamics computer simulation
 - + synthesis tool
 - + predicts outcome
 - + may be used to plan surgery
 - computationally expensive
 - difficult to model



Homework

Spine Exoskeleton

Weston, E. B., Alizadeh, M., Knapik, G. G., Wang, X., and Marras, W. S. (2018). Biomechanical evaluation of exoskeleton use on loading of the lumbar spine. *Appl. Ergon.* 68, 101–108. doi:10.1016/j.apergo.2017.11.006.

Knee prosthesis

Pauline Gerus, Massimo Sartori, Thor F. Besier, Benjamin J. Fregly, Scott L. Delp, Scott A. Banks, Marcus G. Pandy, Darryl D. D'Lima, David G. Lloyd, (2013) Subject-specific knee joint geometry improves predictions of medial tibiofemoral contact forces, *Journal of Biomechanics*, 46(16), 2778-2786, doi:10.1016/j.jbiomech.2013.09.005.

Install Matlab Simulink from ZDV

Try command: smnew (if it does not work install required toolboxes)

Download test model (will be uploaded in time)