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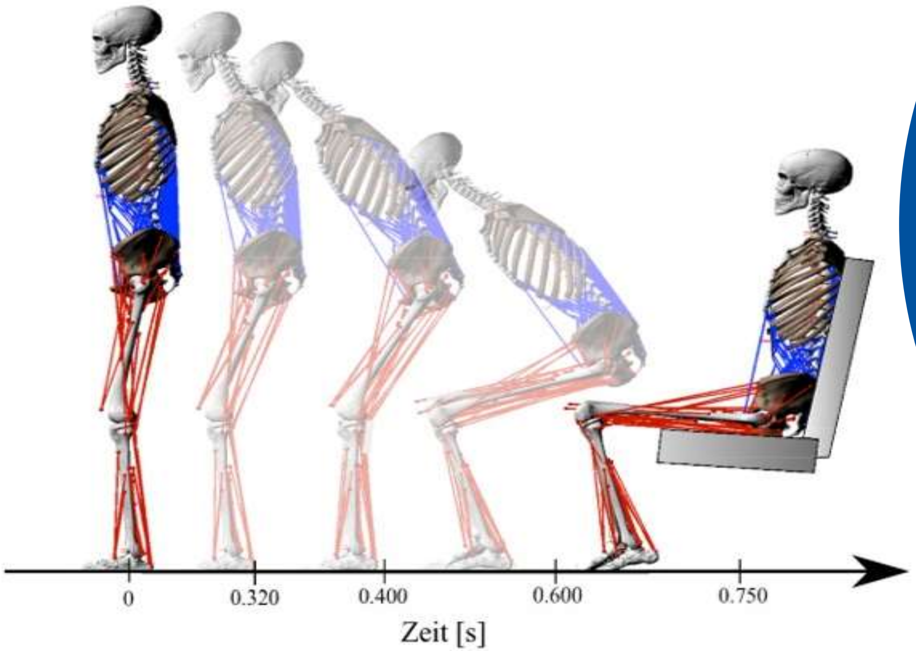
SimTech
Cluster of Excellence

Stuttgart Research Centre for Simulation Technology
S. Schmitt, M. Günther, A. Bayer, D. Häufle, O. Martynenko



Computersimulation mit einem digitalen Menschmodell:
zur Prognose von Produkt- und Produktionsergonomie

Prof. Dr. Syn Schmitt

Infoday Human Models, DYNAmore GmbH, 02.06.2016

Human movement taken to the extreme – Dean Potter†

Slack line: 30m long, 1000m above ground, Taft Point, Yosemite Valley, USA

neurons
100 millions – 1 billion

brain
clock speed ~100Hz

nerves
wire speed 0.5-120m/s

information processing and storing

sensors
X millions
delay ~10ms

visual
tactile
auditory
vestibular
proprio-
ceptive

actuators
>600

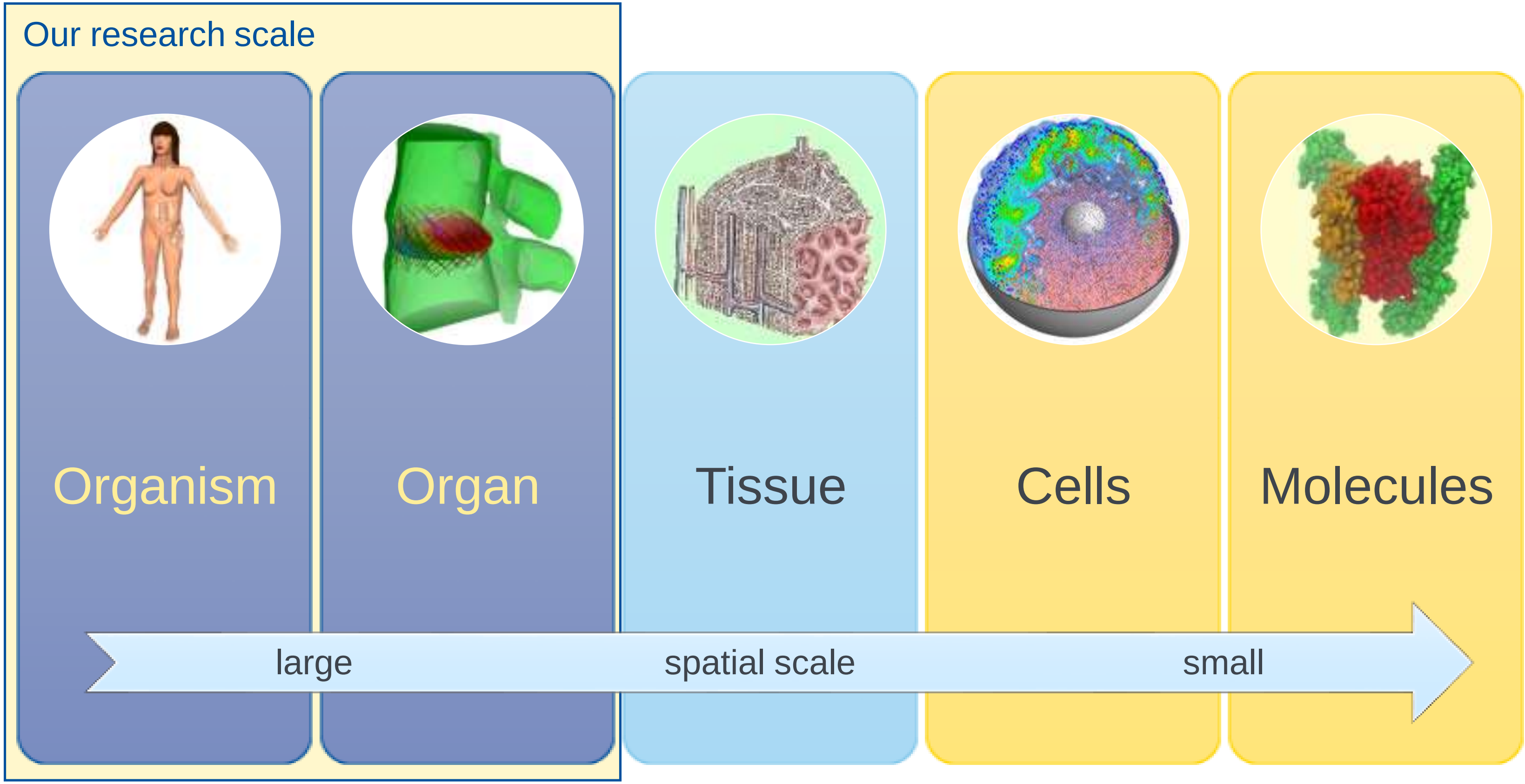
muscles
(skeletal,
smooth,
cardiac)
tendons,
ligaments

actions resulting on different parameters

Video source radX YouTube channel : https://youtu.be/KVaTsulE5Z0

Multi-scale nature of a biological system

From a millimetres to angstroms



Our research scale

Organism

Organ

Tissue

Cells

Molecules

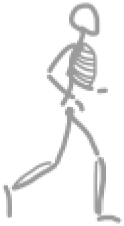
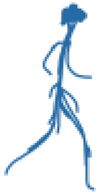
large

spatial scale

small

Our viewpoint on natural systems

From single joint to complex movement generation: numerical models

	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 forces	$F_p = f(z, \dot{z})$ with $\mathbf{z} = [q_1, \ldots, q_n, o_1, \ldots, o_m]^T$
	Muscles Motors	Active forces	$F_a = f(z, \dot{z}, u)$ with $\mathbf{u} = [u_1, \ldots, u_k]^T$
	Neurons Wires, CPU	Reflexes, commands	$u = f(z, \dot{z}, \text{"brain"})$

Multibody Dynamics of the skeletal system

Bones as linked rigid bodies

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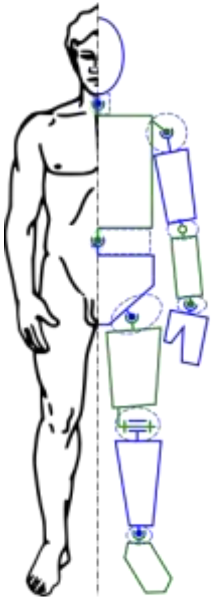
Forward dynamics equation of motion



Skeletal system
as kinematic
rigid body chain

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

after Pandy, 2001

where

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

$\underline{q}$ - generalized coordinate

$C(\underline{q},\dot{\underline{q}})$ - Coriolis and centrifugal forces

$G(\underline{q})$ - Gravitation

$M(\underline{q})$ - System matrix

M. G. Pandy. Computer modeling and simulation of human movement. Annual Review of Biomedical Engineering, 3:245-273, 2001.

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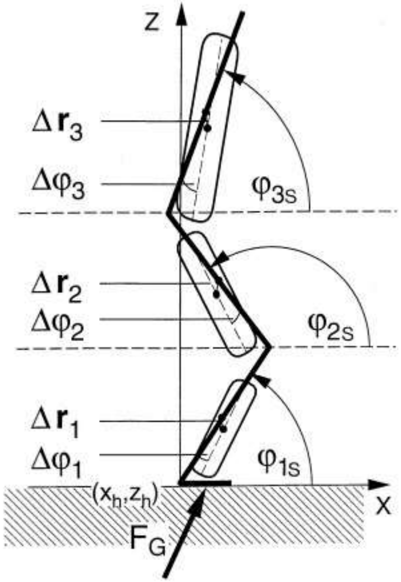
Soft tissue relative to bone movement

Muscle tissue and traveling shock waves

Keppler V, Günther M (2006) Visualization and quantification of wobbling mass motion — a direct non-invasive method. Journal of Biomechanics 39:S53.
http://dx.doi.org/10.1016/s0021-9290(06)83091-5

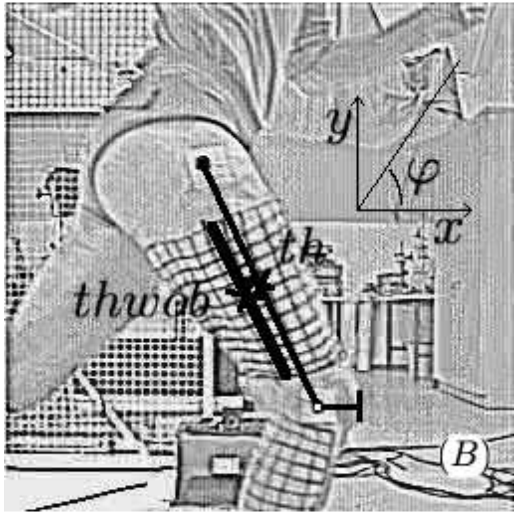
Soft tissue relative to bone movement

Wobbling masses



$$P_{k/x,\mathrm{wob}}(t) = F_{k/x,\mathrm{coup}}(t) \cdot \dot{X}_{k,\mathrm{wob}}(t)$$
$$P_{k/y,\mathrm{wob}}(t) = F_{k/y,\mathrm{coup}}(t) \cdot \dot{Y}_{k,\mathrm{wob}}(t)$$
$$P_{k/\varphi,\mathrm{wob}}(t) = M_{k/z,\mathrm{coup}}(t) \cdot \dot{\varphi}_{k,\mathrm{wob}}(t)$$

$$\Delta E_{k/j,\mathrm{wob}} = \int_{t=0}^{t=90\,\mathrm{ms}} P_{k/j,\mathrm{wob}}\mathrm{d}t$$



Wobbling masses:

- … facilitate short ground contact time
- … allow for fast signal travelling along the body
- … represent well adjusted inertia properties of the distal segments

Schmitt S, Günther M (2010) Human leg impact: energy dissipation of wobbling masses. Arch Appl Mech 81:887–897. http://dx.doi.org/10.1007/s00419-010-0458-z

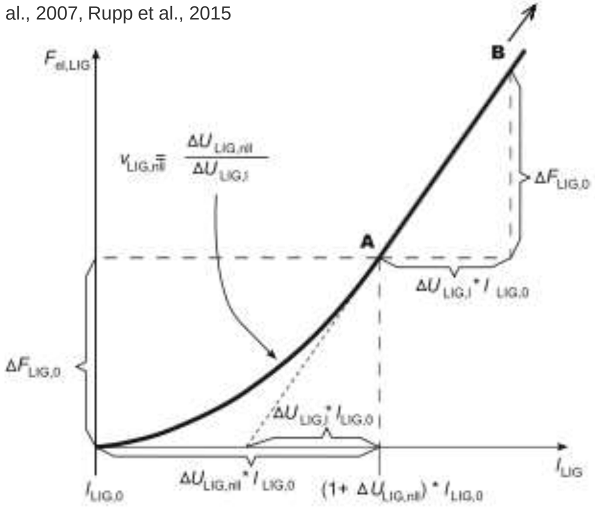
Passive structures

Ligaments, cartilage, fat

Non-linear ligaments

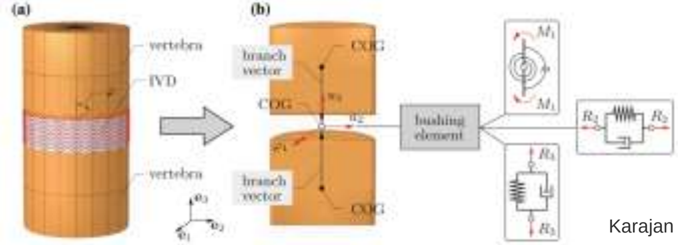
$$F_{\mathrm{el,LIG}}(l_{\mathrm{LIG}}) = \begin{cases} 0 & l_{\mathrm{LIG}} < l_{\mathrm{LIG,0}} \\ K_{\mathrm{LIG,nl}}\,(l_{\mathrm{LIG}} - l_{\mathrm{LIG,0}})^{\nu_{\mathrm{LIG,nll}}} & l_{\mathrm{LIG}} < l_{\mathrm{LIG,nll}} \\ \Delta F_{\mathrm{LIG,0}} + K_{\mathrm{LIG,l}}\,(l_{\mathrm{LIG}} - l_{\mathrm{LIG,nll}})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

Guenther et al., 2007, Rupp et al., 2015



Non-linear intervertebral discs

$$\begin{aligned}
F_{\text{IVD-nl,x}} &= 14.548\,\mathrm{Nm}^{-3} \times r_x^3 + 0.4186\,\mathrm{Nm}^{-2} \times r_x^2 \\
&\quad + 43.764\,\mathrm{Nm}^{-1} \times r_x, \\
F_{\text{IVD-nl,y}} &= 14.548\,\mathrm{Nm}^{-3} \times r_y^3 - 0.4186\,\mathrm{Nm}^{-2} \times r_y^2 \\
&\quad + 43.764\,\mathrm{Nm}^{-1} \times r_y, \\
F_{\text{IVD-nl,z}} &= 32.432\,\mathrm{Nm}^{-3} \times r_z^3 - 65.925\,\mathrm{Nm}^{-2} \times r_z^2 \\
&\quad + 380.96\,\mathrm{Nm}^{-1} \times r_z, \\
M_{\text{IVD-nl,x}} &= 1.6\,\mathrm{Nm/deg} \times \varphi_x, \\
M_{\text{IVD-nl,y}} &= 0.0046\,\mathrm{Nm/deg}^3 \times \varphi_y^3 - 0.0001\,\mathrm{Nm/deg}^{-2} \\
&\quad \times \varphi_y^2 + 1.0158\,\mathrm{Nm/deg}^{-1} \times \varphi_y, \\
M_{\text{IVD-nl,z}} &= 6.9\,\mathrm{Nm/deg} \times \varphi_z,
\end{aligned}$$



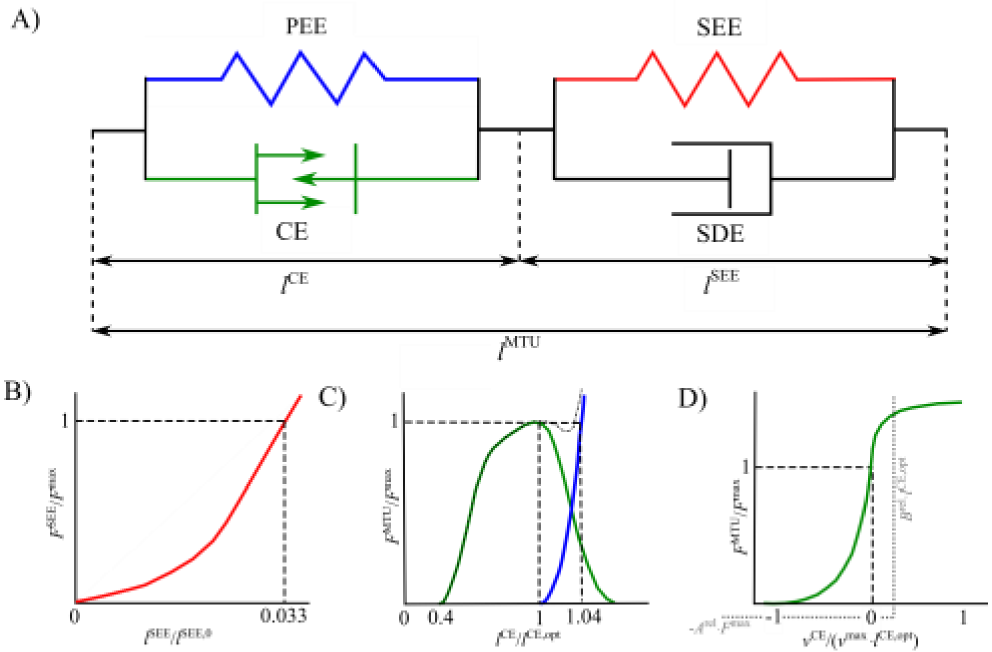
Karajan et al., 2012

Rupp TK, Ehlers W, Karajan N, Guenther M, Schmitt S (2015) A forward dynamics simulation of human lumbar spine flexion predicting the load sharing of intervertebral discs, ligaments, and muscles. Biomechanics and Modeling in Mechanobiology, 14(5):1081-1105. http://dx.doi.org/10.1007/s10237-015-0656-2
Günther M, Schmitt S, Wank V (2007) High-frequency oscillations as a consequence of neglected serial damping in Hill-type muscle models. Biol Cybern 97:63–79. http://dx.doi.org/10.1007/s00422-007-0160-6

Active structures

Modified Hill-Type Muscle Model

Muscle-tendon unit with serial damping and eccentric force–velocity relation



Force equilibrium: F^{MTU}

$$= F^{\mathrm{CE}}(l^{\mathrm{CE}}, \dot{l}^{\mathrm{CE}}, \mathrm{a}) + F^{\mathrm{PEE}}(l^{\mathrm{CE}})$$

$$= F^{\mathrm{SEE}}(l^{\mathrm{CE}}, l^{\mathrm{MTU}}) + F^{\mathrm{SDE}}(l^{\mathrm{CE}}, \dot{l}^{\mathrm{CE}}, \dot{l}^{\mathrm{MTU}}, \mathrm{a})$$

Activation dynamics:

$$\dot{a}_i = f_a(a_i, l_i^{CE}, u_i)$$

Contraction dynamics:

$$\dot{l}_i^{CE} = f_v(l_i^{MTU}, v_i^{MTU}, l_i^{CE}, a_i)$$

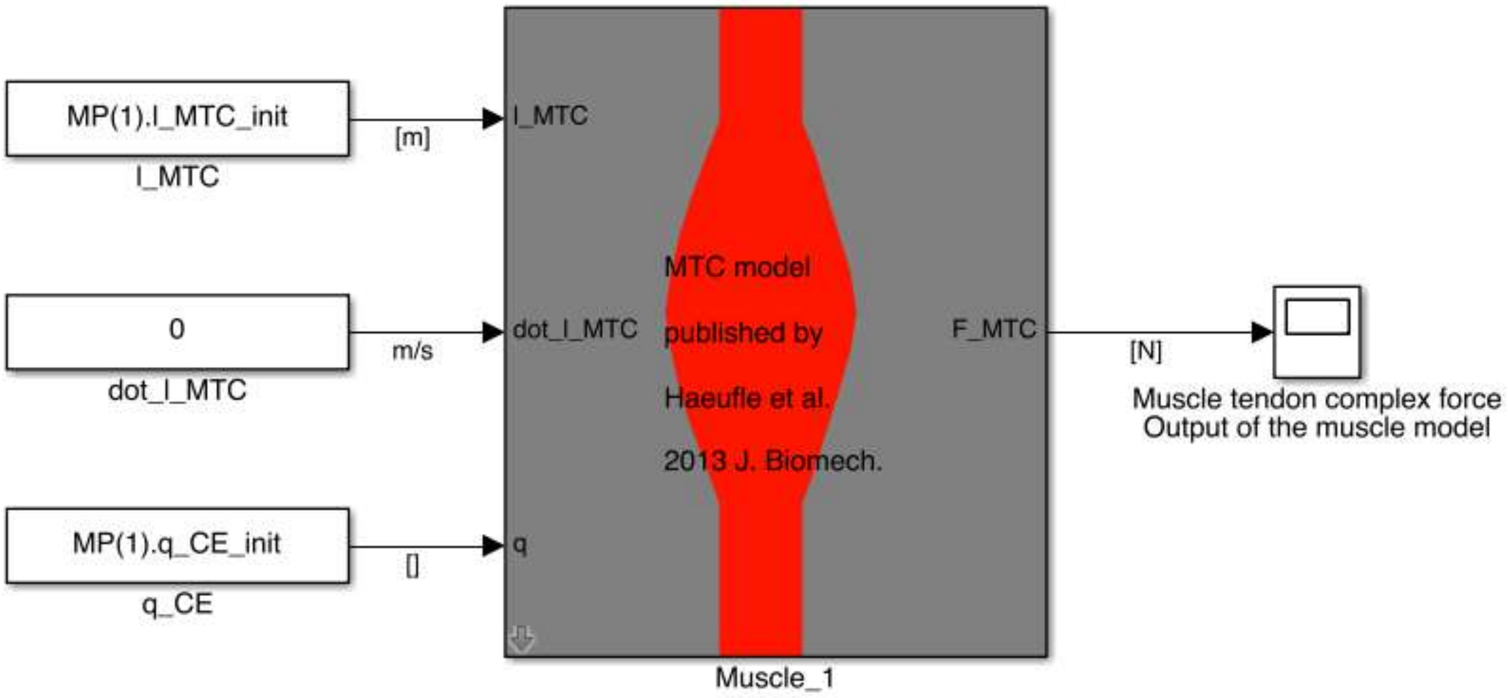
Häufle et al., 2014

Häufle DFB, Günther M, Bayer A, Schmitt S (2014) Hill-type muscle model with serial damping and eccentric force-velocity relation. Journal of Biomechanics 25;47(6):1531–6. http://dx.doi.org/10.1016/j.jbiomech.2014.02.009

Modified Hill-Type Muscle model

Available as open source code

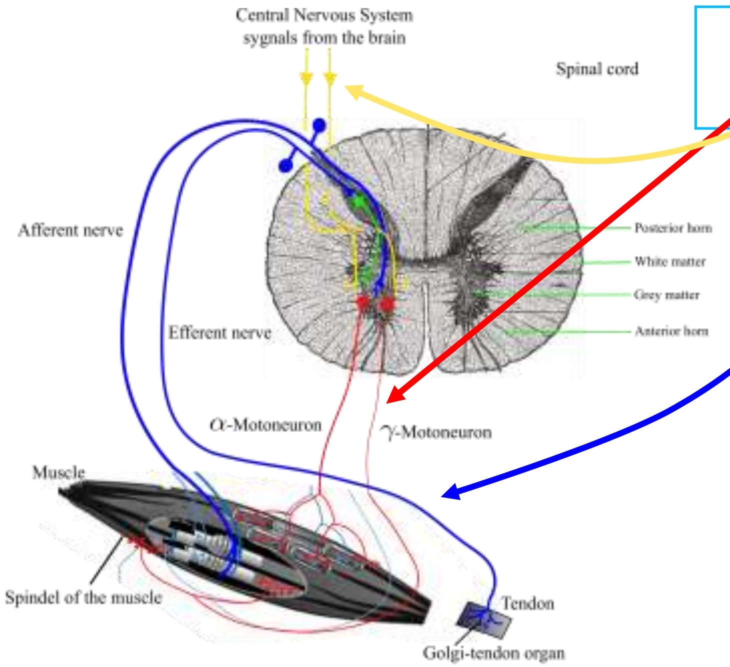
Can be found online at http://dx.doi.org/10.1016/j.jbiomech.2014.02.009



Häufle DFB, Günther M, Bayer A, Schmitt S (2014) Hill-type muscle model with serial damping and eccentric force-velocity relation. Journal of Biomechanics 25;47(6):1531–6. http://dx.doi.org/10.1016/j.jbiomech.2014.02.009

Biological control of the muscle model

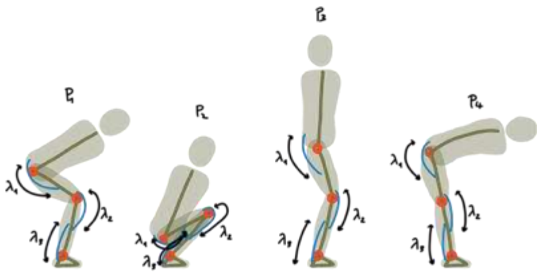
Neural control algorithm



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

Bayer et al., 2016 (submitted); Feldman et al., 1986; Kistemaker et al., 2006

Learning of target muscle lengths



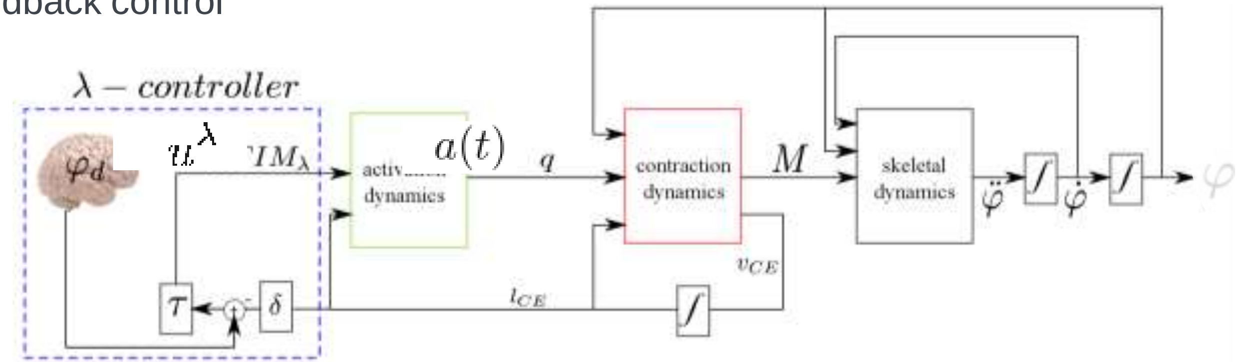
P_1	P_2	P	P_3	P_4
λ_1	λ_1	λ_1	λ_1	λ_1
λ_2	λ_2	λ_2	λ_2	λ_2
λ_3	λ_3	λ_3	λ_3	λ_3

A. G. Feldman. Once more on the equilibrium-point hypothesis (lambda model) for motor control. Journal of Motor Behavior, 18(1):17-54, 1986.
D. A. Kistemaker, A. J. Van Soest & M. F. Bobbert. Is equilibrium point control feasible for fast goal-directed single-joint movements? Journal of Neurophysiology, 95(5):2898-2912, 2006. http://dx.doi.org/10.1152/jn.00983.2005

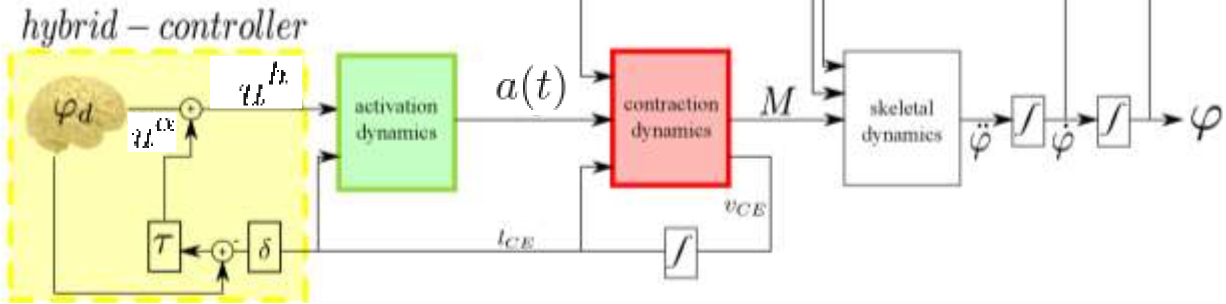
Biological control of the muscle model

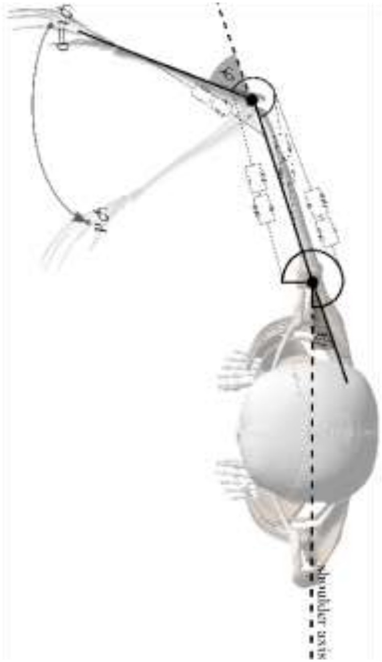
Lambda and hybrid controllers

feedback control



feedforward and feedback control

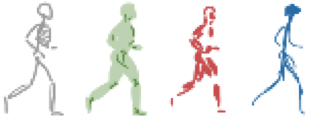




Bayer et al. (2016) submitted

System dynamics perspective

Modular chart of the human motion modelling



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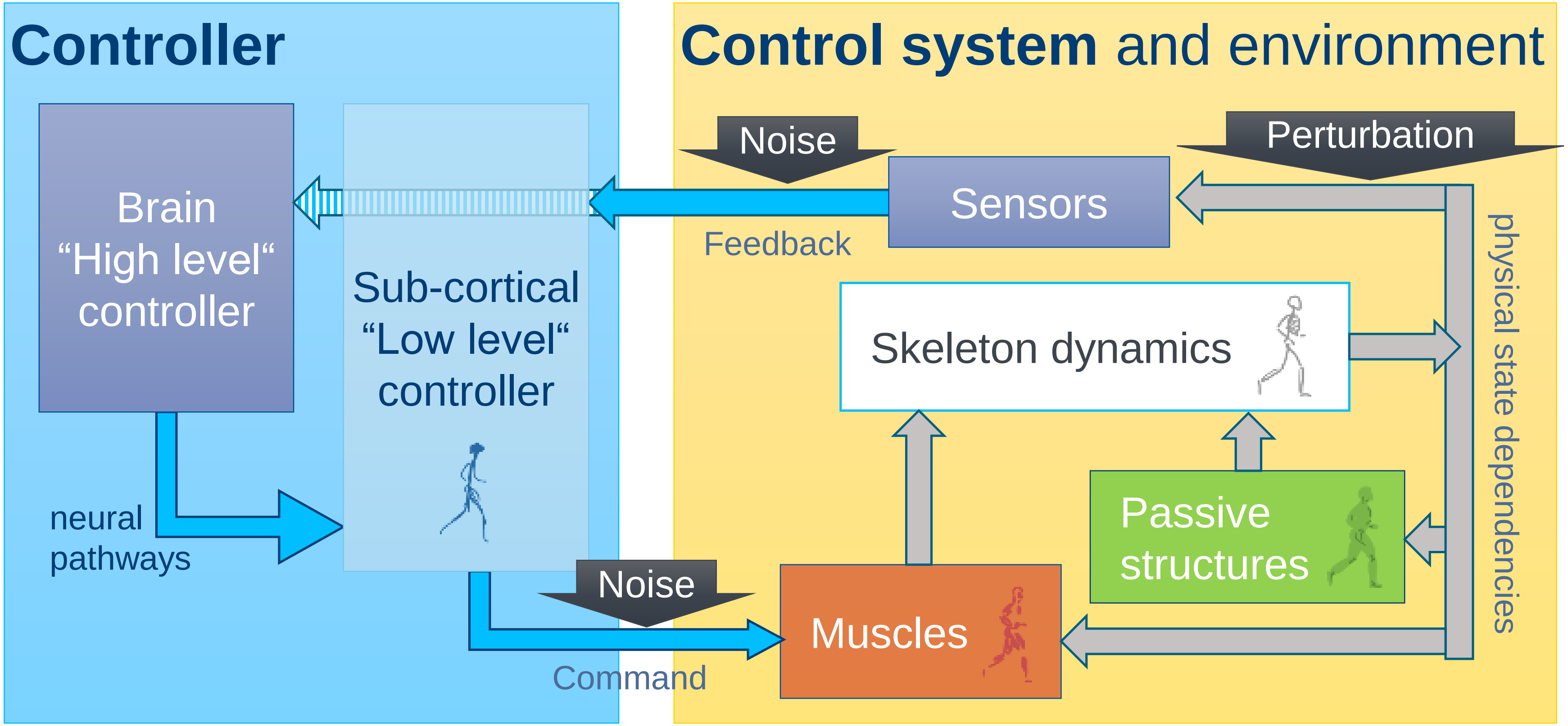

Controller

Brain
“High level“
controller

Sub-cortical
“Low level“
controller

neural
pathways

Control system and environment

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Biomechanical response of the human body to vibrational loads

Simulation studies

Seated vibrations as typical nowadays load

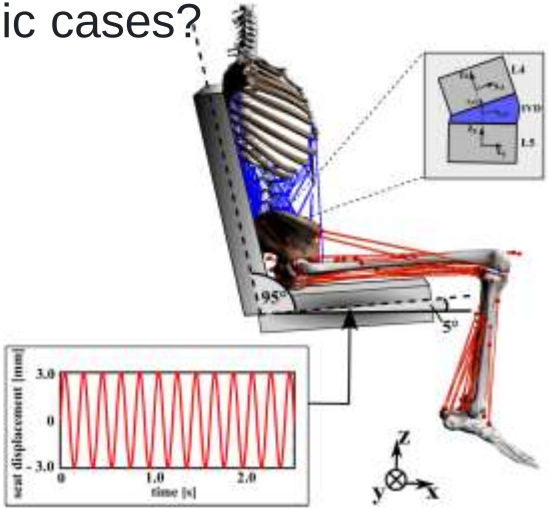
What we **don't** know…

Questions:

1. Is muscular activity at spine level able to reduce internal loads in the intervertebral disc?
2. Is there any difference between static and dynamic cases?
3. Role other biological parts of the spine play?

Hypotheses

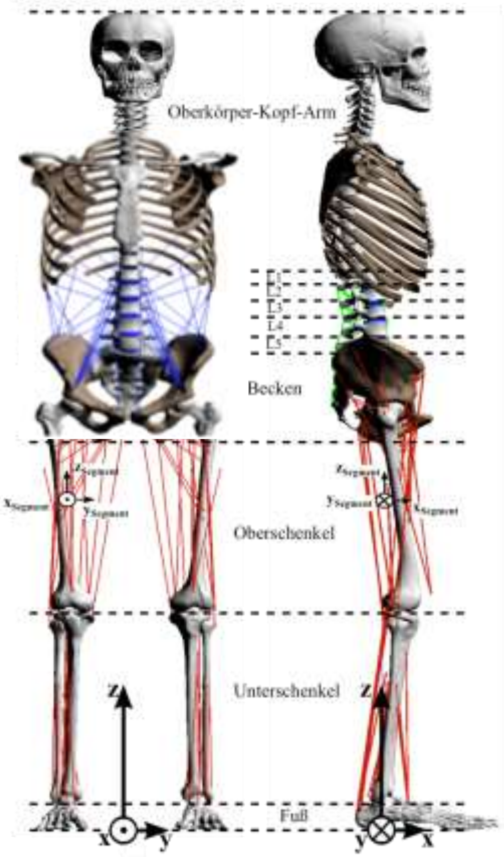
1. Static loads on the intervertebral disc increase
   with increased muscular activity
   of the trunk muscles.
2. Muscular activity is able to shift loads between biological parts in the spine in the dynamic load case.



Bayer et al. (2016) submitted

Biomechanical response of the human body

Full human multibody model description



13 Rigid Bodies (1,78 m, 68 kg)

Feet, Shanks,
Thighs, Pelvis
Waist, Head, Arm

Rupp et al., 2015

58 nonlinear ligaments in the lumbar spine

ALL, PLL, LF, ISL, SSL

Panjabi et al., 1982
Pintar et al., 1992
Rupp et al., 2015

5 nonlinear, coupled IVDs

Properties taken from homogenized FE model

Karajan et al., 2013

252 Muscle-Tendon Units

CE, SEE, PEE, SDE

Häufle et al., 2014

1 Neuronal controller

Combination of
Open-loop control and
Closed-loop control

Bayer et al., 2016
Kistemaker et al., 2016

Passive and active muscles influence comparison

2 models in a sitting posture, exposed to whole-body vibrations

Modell M^{aktiv}

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

Modell M^{passiv}

Muscle-tendon units:

actively driven

Muscle control parameters:

u^{open} – 2% … 6%

u^{closed} – $k_p = 2$

Resulting stimulation

up to 13.5%

Muscle-tendon units:

passively driven

Muscle control parameters:

u^{open} – up to 0.001%

u^{closed} – $k_p = 0$ result

Resulting stimulation

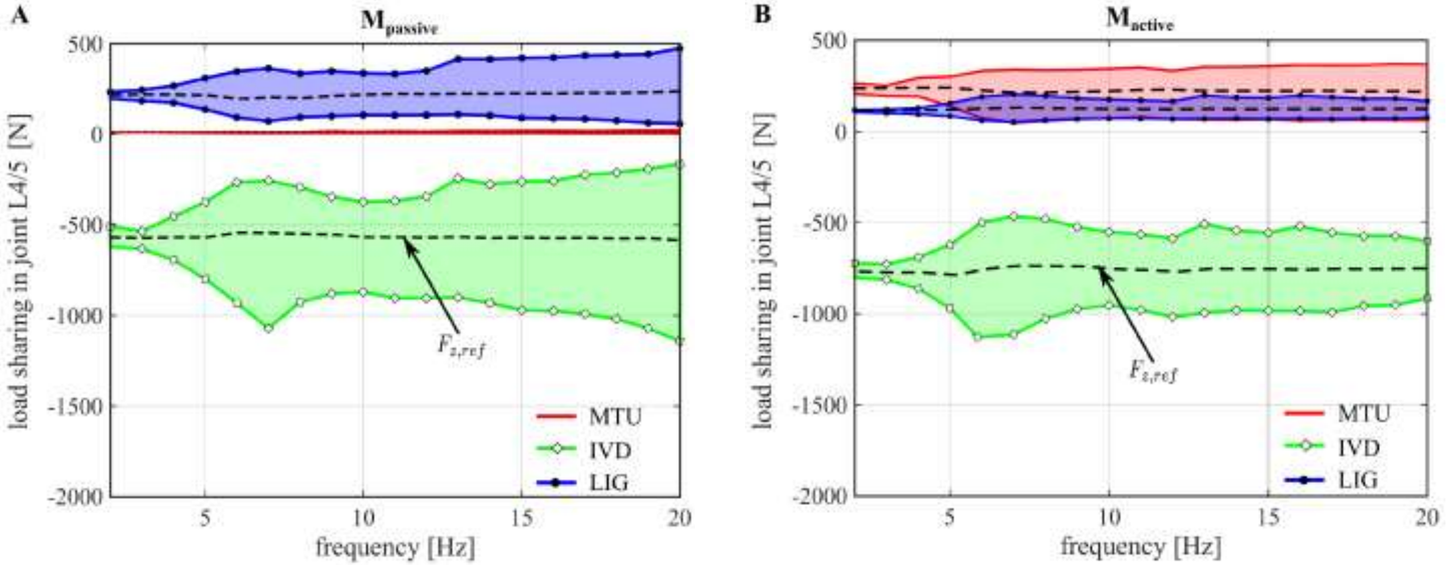
up to 0.001%

Muscular activity reduces peak loads on the IVD

Internal load components in joint L4/5

Model with passive muscles

Model with active muscles



Bayer et al. (2016) submitted

- **Muscle forces** are **lower** for passive model: 30N max vs 380N max
- **Ligament forces** are **higher** for passive model: 473N max vs 210N max

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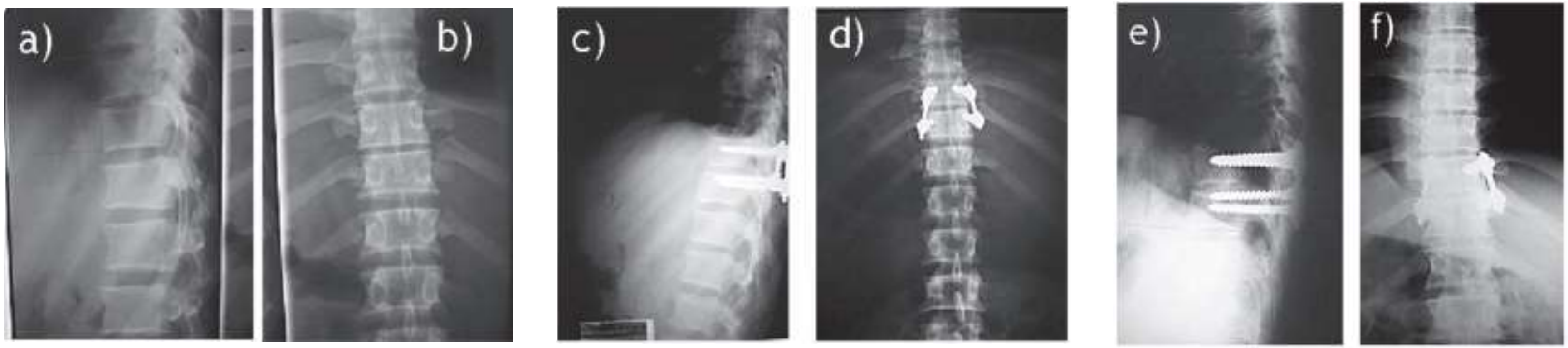
Spine surgery
and
Personalized medicine

Simulation studies

Spinal fusion surgery and Personalised medicine

How to perform proper implantation?


preoperative

initial postoperative

8-year postoperative

(Defino & Scarparo, 2005)

?

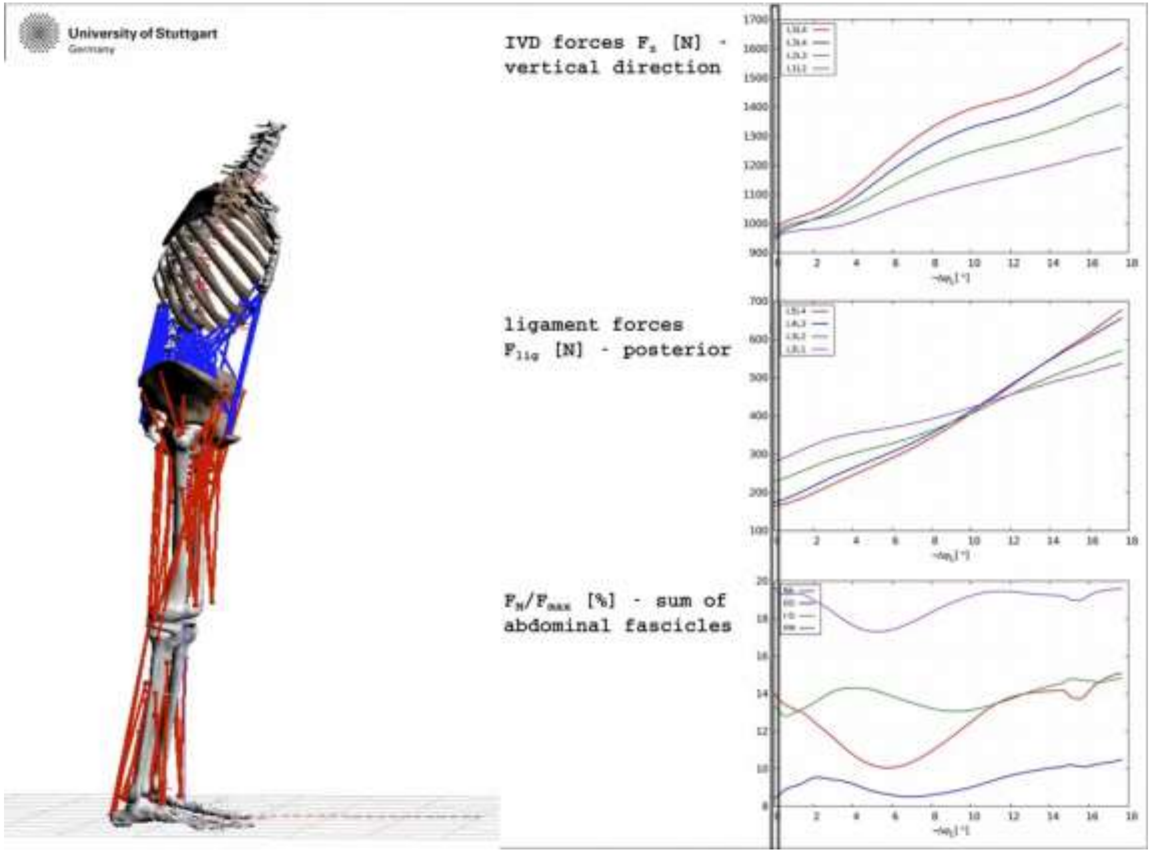
Change of ...
…displacement, internal forces and moments?

?

Defino HL, Scarparo P (2005) Fractures of thoracolumbar spine: monosegmental fixation. Injury 36:S90–S97. http://dx.doi.org/10.1016/j.injury.2005.06.019

Human model - lower extremity and spine

Same full human multibody model as above



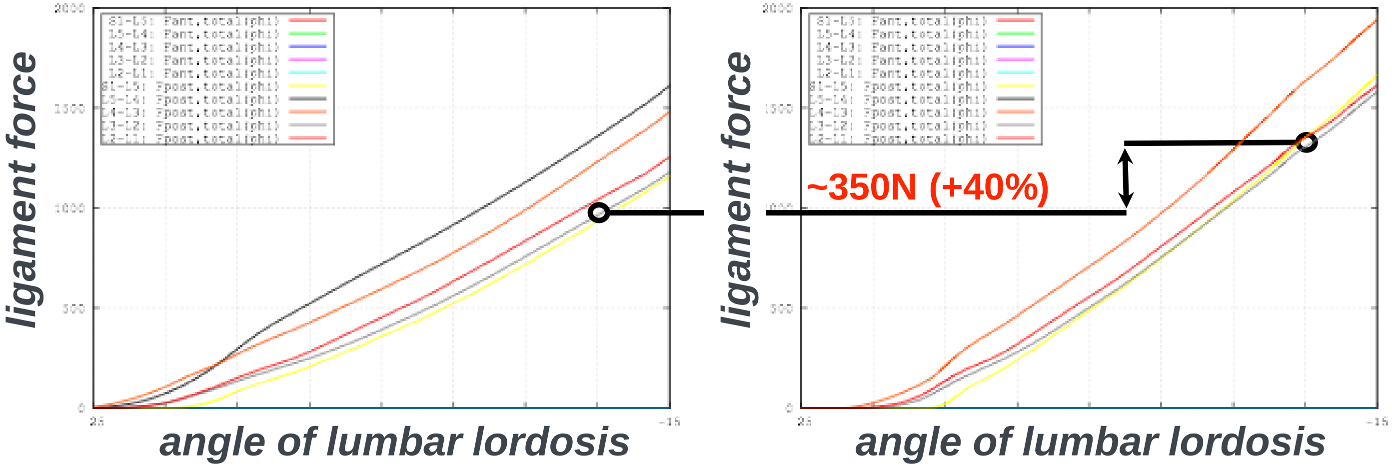
Video source HMSL YouTube channel: https://youtu.be/EanNZJPVwD0

Human model - lower extremity and spine

Loading of posterior ligaments: F_{total}

Unfused IVDs

Fused L4/5



Schmitt, S., Günther, M., Rupp, T., Mörl, F., Bradl, I. (2013).
Mehrkörpersimulation einer detaillierten Lendenwirbelsäule - ein Werkzeug für die Präventionsforschung? In 19. Erfurter Tage, pages 55–62.

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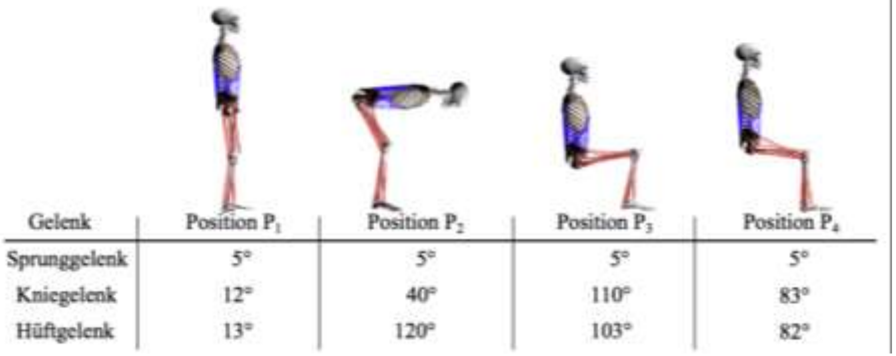
Controlled human movements

Simulation studies

Controlled human movements simulation

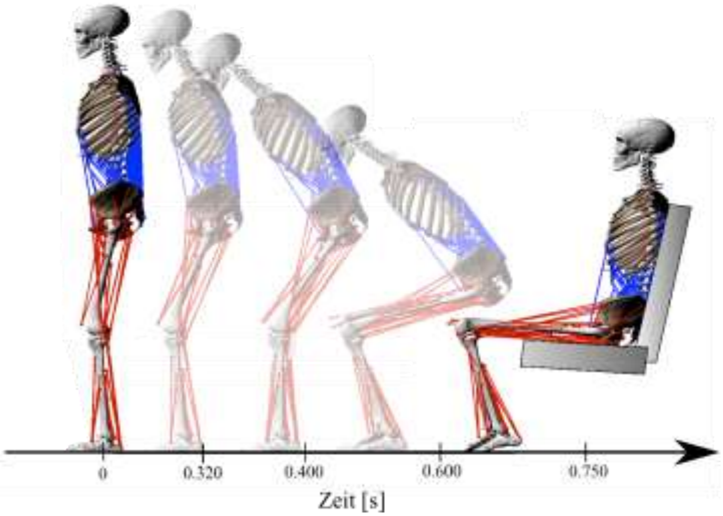
Active sitting down on a seat – full forward-dynamic motion simulation

Motion control with four supporting equilibrium points



Gelenk	Position P_1	Position P_2	Position P_3	Position P_4
Sprunggelenk	5°	5°	5°	5°
Kniegelenk	12°	40°	110°	83°
Hüftgelenk	13°	120°	103°	82°

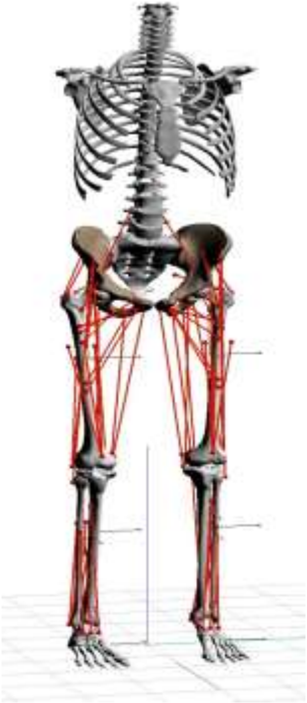
#	Position	Time
P_1	Upright standing	0.00 s <= t < 0.10 s
P_2	Hip flexion	0.10 s <= t < 0.15 s
P_3	Knee flection	0.15 s <= t < 0.55 s
P_4	Upright sitting	0.55 s <= t



Bayer et al. (2016) submitted

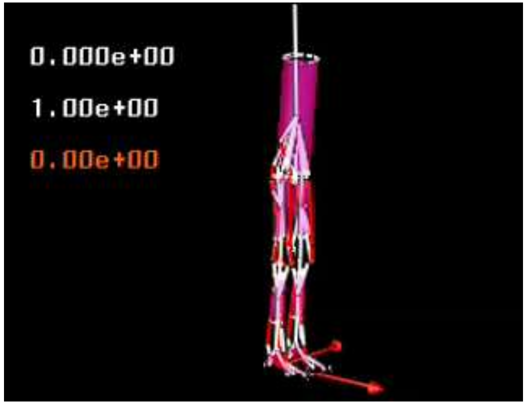
Controlled human movements simulation

Quiet stance and walking in different conditions



… on earth.

… on the moon.



Günther, M., Ruder, H. (2003): Synthesis of two-dimensional human walking: a test of the λ-model. Biological Cybernetics 8(2), 89-106 http://dx.doi.org/10.1007/s00422-003-0414-x
Günther, M., Wagner, H. (2015): Dynamics of quiet human stance: computer simulations of a triple inverted pendulum model. Computer Methods in Biomechanics and Biomedical Engineering 19(8), 819-834 http://dx.doi.org/10.1080/10255842.2015.1067306

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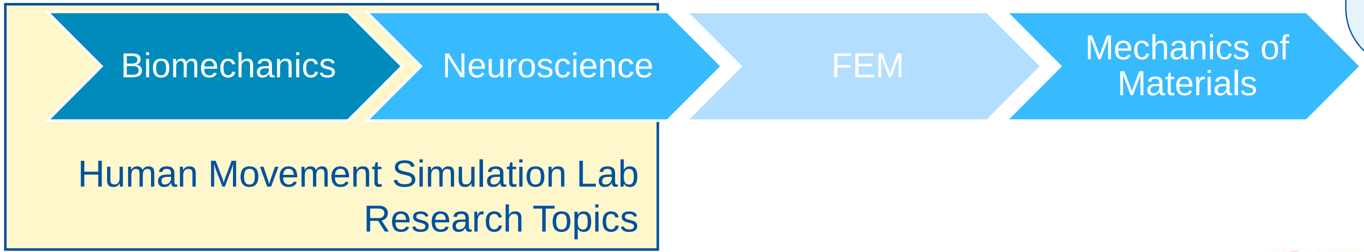
Automotive engineering and Ergonomics

Simulation studies

Automotive engineering and Ergonomics

Active Human Body Model is needed

Active
Human
Body
Model


Biomechanics
Neuroscience
FEM
Mechanics of Materials

Human Movement Simulation Lab
Research Topics

Infoday Human Models, DYNAmore GmbH, 02.06.2016 Video source AUTO BILD YouTube channel: https://youtu.be/DHSeuaoZ-ml

Future concept cars – new way of driving

Autonomous stress free driving, Entertainment and Interaction, Time saving

Safety

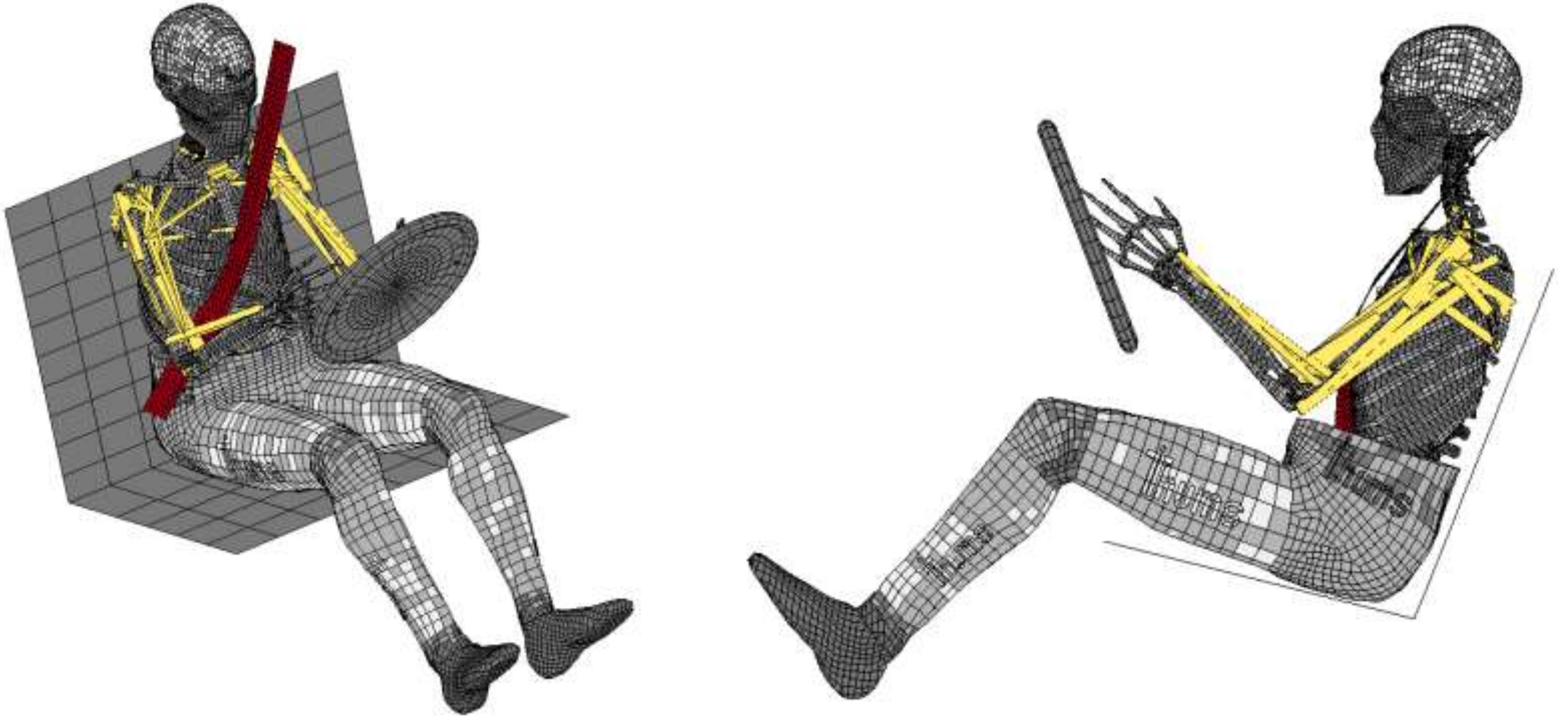
Comfort

Images courtesy of Daimler AG, Rinspeed Inc., Toyota Central R&D Labs. Inc.

Automotive engineering and Ergonomics

University of Stuttgart

THUMS v3 with active muscle elements – steering maneuver simulation



THUMS AM50 Occupant Model Version 3.0

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Interdisciplinary coupling of different numerical methods

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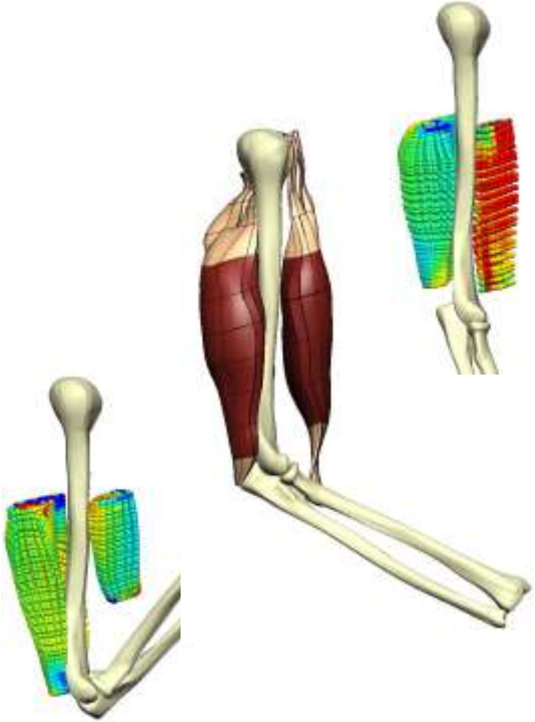
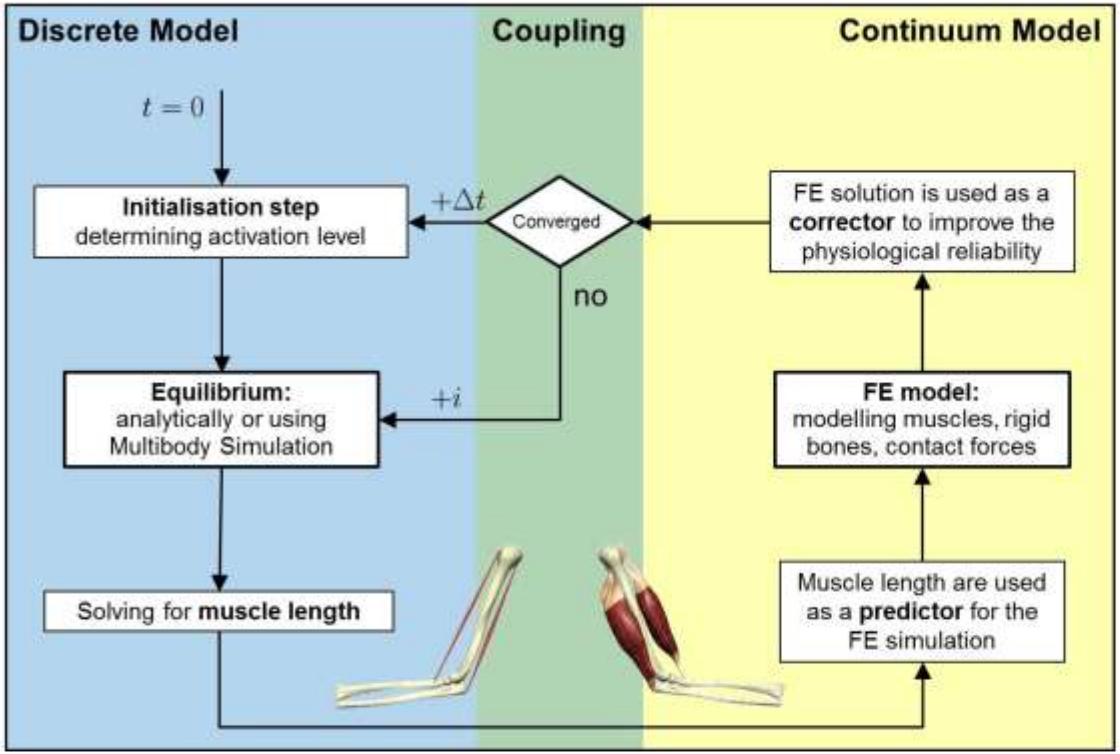
3D Continuum-Mechanical Model for Forward-Dynamics Simulations





Discrete Model

Coupling

Continuum Model

$t = 0$

Initialisation step
determining activation level

$+\Delta t$

Converged

no

Equilibrium:
analytically or using
Multibody Simulation

$+i$

Solving for **muscle length**

FE solution is used as a
corrector to improve the
physiological reliability

FE model:
modelling muscles, rigid
bones, contact forces

Muscle length are used
as a **predictor** for the
FE simulation

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Thank you for your attention!

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