SimTech – The Overall Human Model

Aktive Muskelmodellierung an der Schnittstelle von Mehrkörper- und Kontinuumsmechanik

Jun.-Prof. Dr. Syn Schmitt [1,2]

schmitt@inspo.uni-stuttgart.de

Jun.-Prof. Oliver Röhrle, PhD [1,3]

roehrle@simtech.uni-stuttgart.de

1) Cluster of Excellence for Simulation Technology, Universität Stuttgart

2) Institut für Sport- und Bewegungswissenschaft, Universität Stuttgart

3) Virtual Orthopedic Lab, Biomechatronische Systeme, Fraunhofer IPA

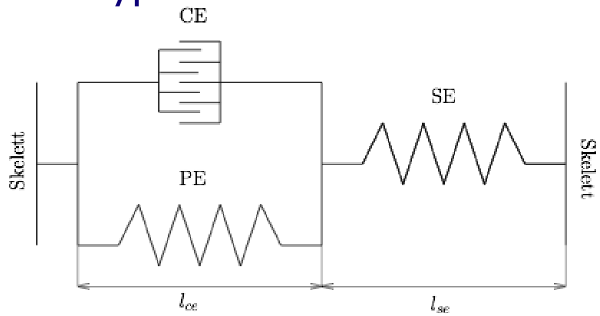
PART I

MULTI-BODY SIMULATIONS

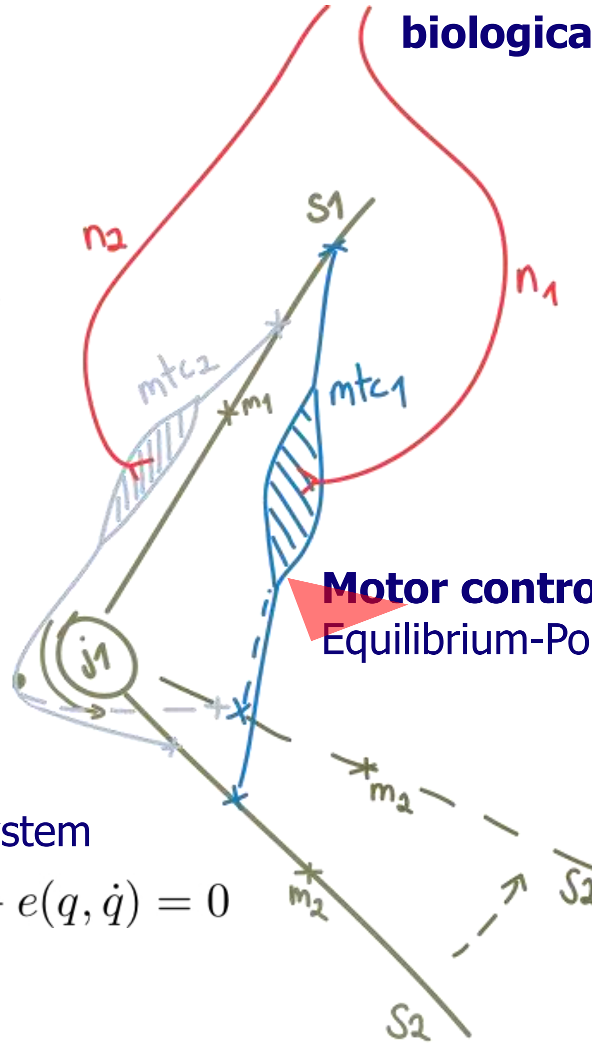
Our View on the Biological Motor

Part I Multi-Body Model
Part II Continuum Model
Part III Coupled Model
Part IV Future Potential

Muscle
Hill-type muscle model



Elementary biological drive



Motor control
Equilibrium-Point-Theory (EPT)

Skeletal apparatus
ODE model of the mechanical system

$$M(q)\ddot{q} + C(q)\dot{q}^2 + g(q) + R(q)f^{mtc} + e(q,\dot{q}) = 0$$

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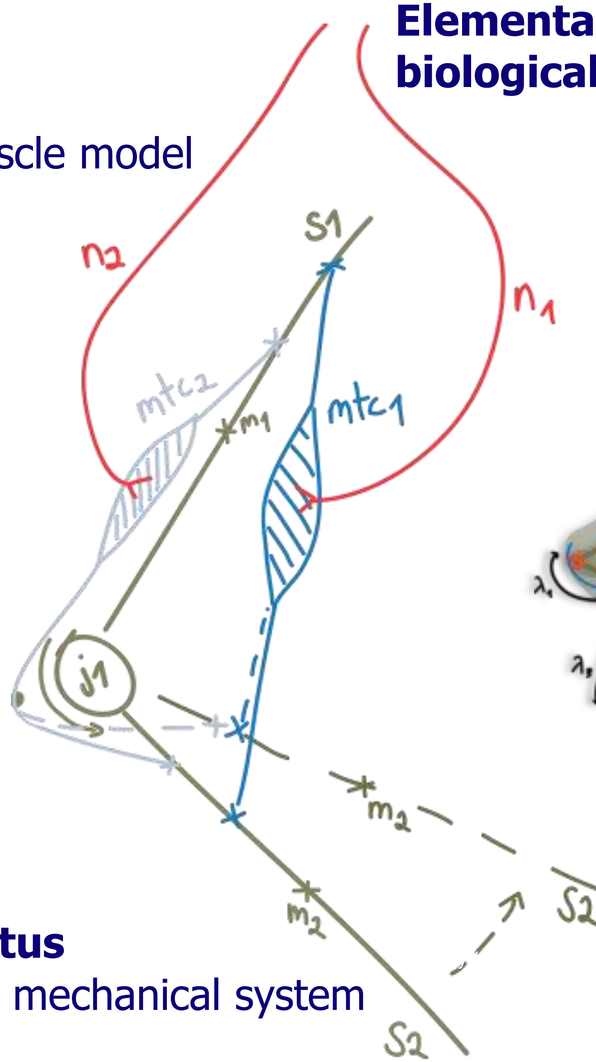
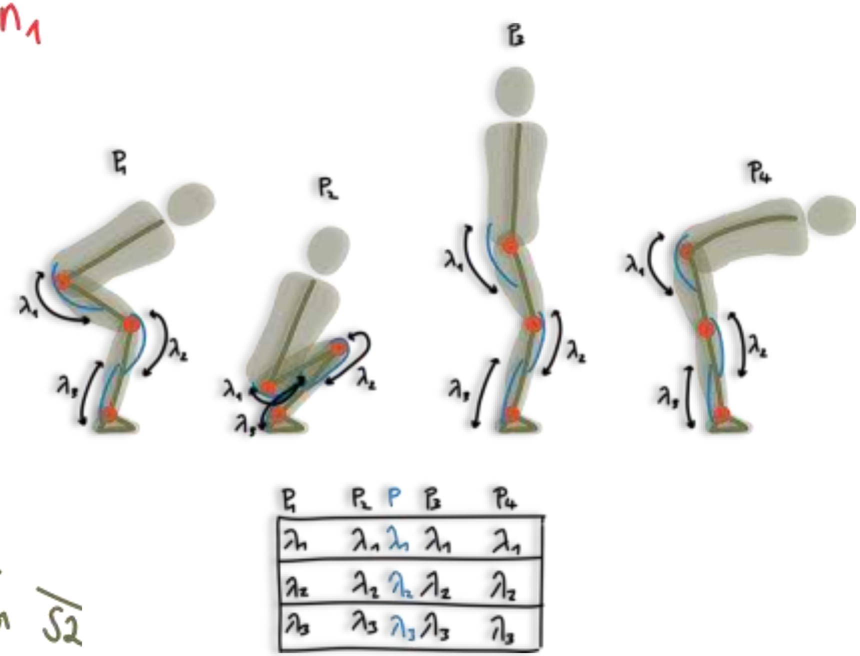




Skeletal apparatus
ODE model of the mechanical system

Computational Motor Control

=

multiple EBDs
(single joint drives)

+

more complex drives
(multi joint drives)

+

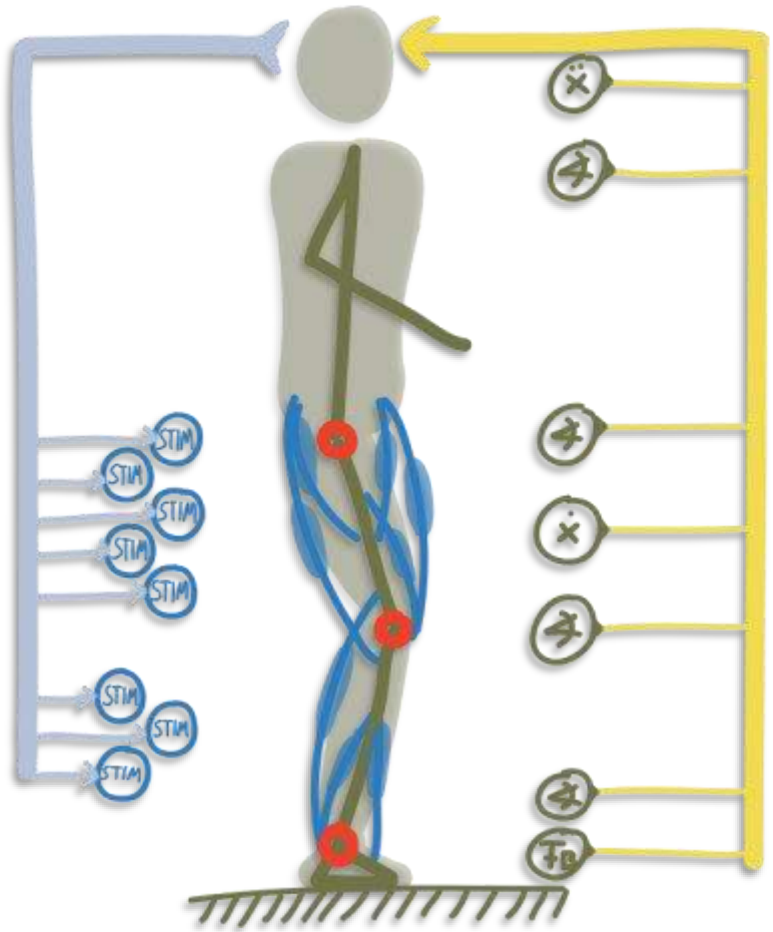
well tuned control
(all drives)

+

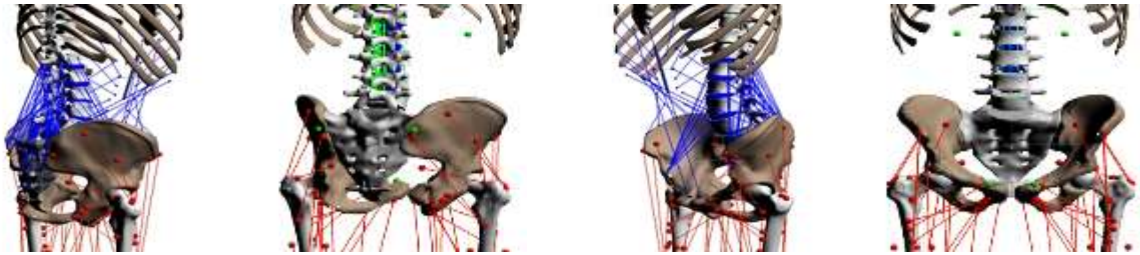
movement tasks
(daily living, ...)

+

account for disturbances
(uneven ground, impact forces, ...)

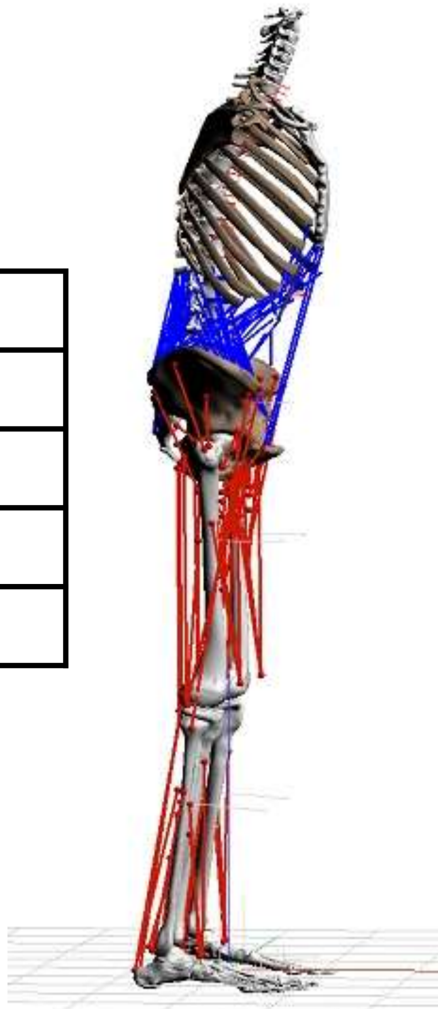


Detailed Lumbar Spine Model



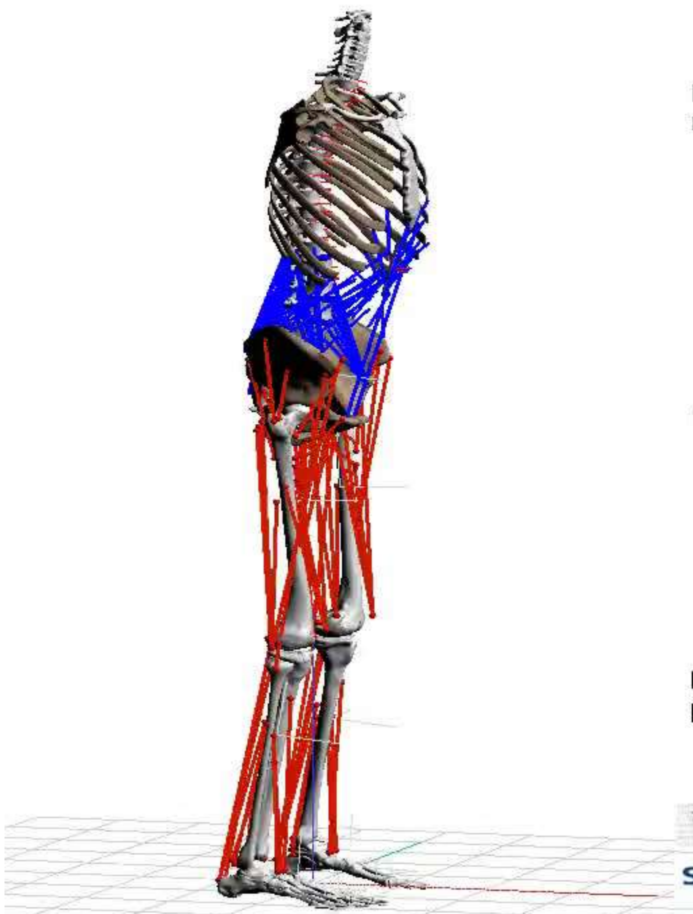
452	degrees of freedom
48	mechanical dofs
202	Muscle-tendon complex (active, Hill-type)
58	non-linear ligaments
5	intervertebral discs (non-linear, coupled)

Anatomy of skeleton: m, 68kg, 1,78m (NASA, 1978)
Ligaments:
Anatomy (Panjabi, 1982), physiology (Chazal, 1985)
Muscles:
Anatomy and physiology (Bogduk, 1992a,b, 1998; Hansen, 2006; Christophy, 2012)



DETAILED LUMBAR SPINE MODEL

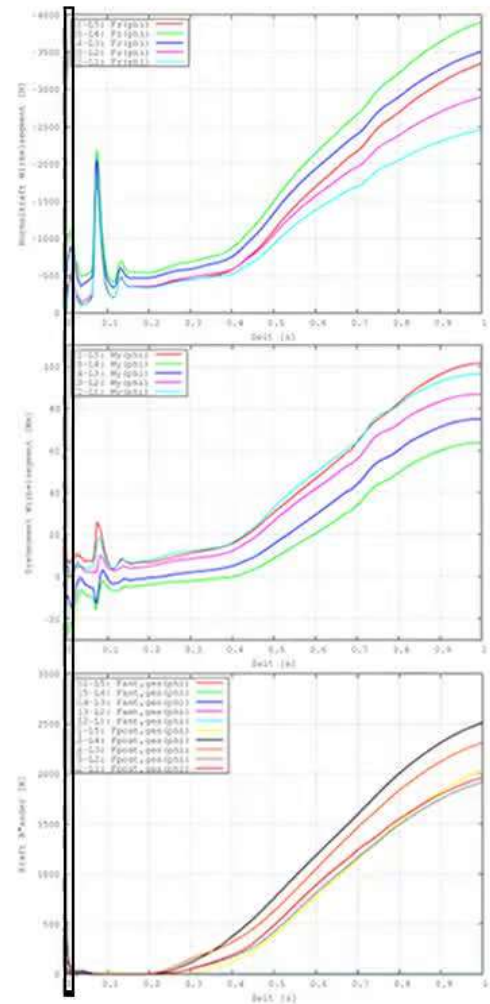
University of Stuttgart Germany



IVD Force normal dir.

IVD Torque

LIG Force posterior



The Human Movement Simulation Lab

SimTech Cluster of Excellence

FUTURE DEVELOPMENT OF MULTI-BODY SIM

Biomechanics

- **Computational motor control should incorporate and evaluate muscle characteristics on control theories.**
- **The muscle model itselfs should account for transverse contraction and act on realistic muscle paths** (via-points)**.**
- **The skeletal apparatus should consider realistic joint kinematics, soft tissue movement, and account for flexible bones** (flexible rgb systems)**.**

Methods

- **Model reduction techniques should be applied to enhance multi-scale approach.**
- **Parallelisation of code should improve simulation time.**
- **User-friendly movement generation algorithms would open direct dynamics approach to engineers.**

PART II

CONTINUUM-MECHANICAL MODELLING

Advantages of Continuum-Mechanical Models

Lumped-parameter models of skeletal muscles crudely represent structural properties of skeletal muscle mechanics, e.g. it is not possible

- **to include complex muscle fibre distributions,**
- **to represent the interaction with surrounding tissue, e.g. inter-muscular force transmission,**
- **to include local muscle activity as obtained by multi-channel EMG measurements.**

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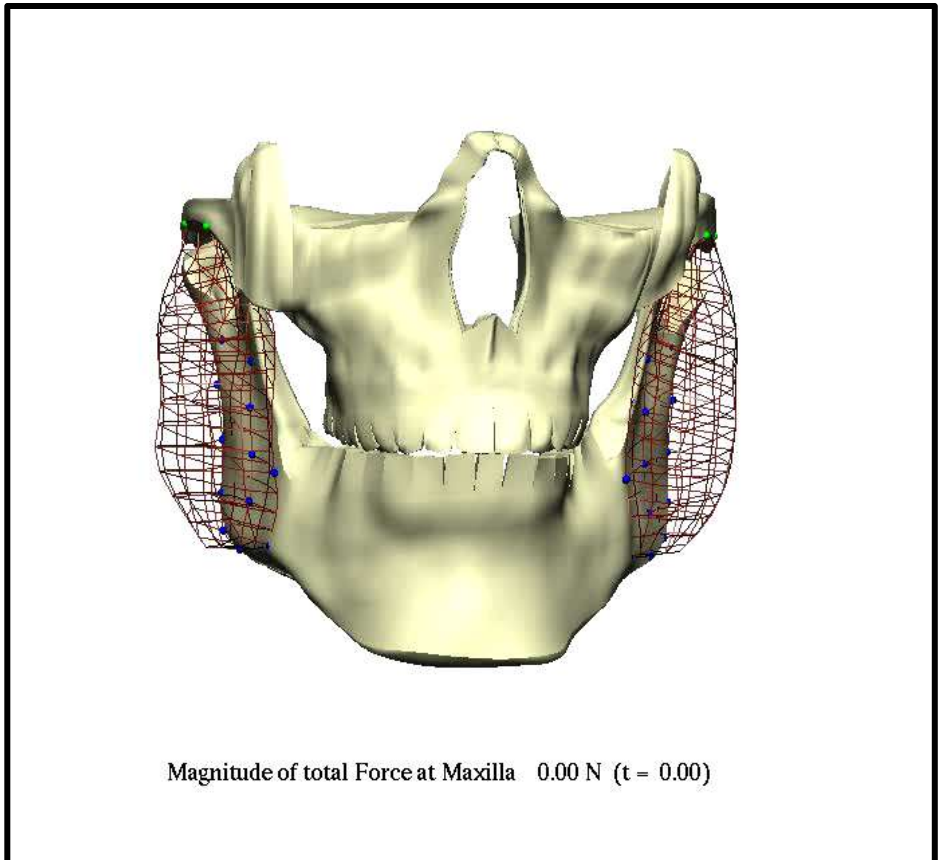
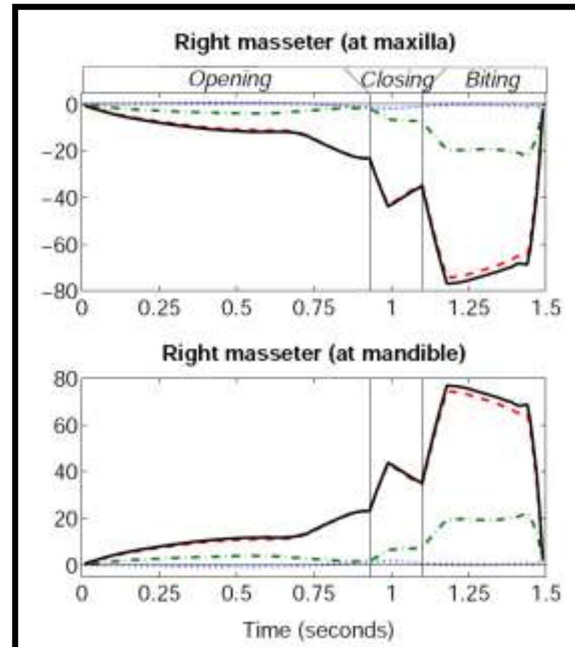
Continuum-Mechanical Skeletal Muscle Model

COMPLEX MUSCLE FIRBE ARCHITECTURE



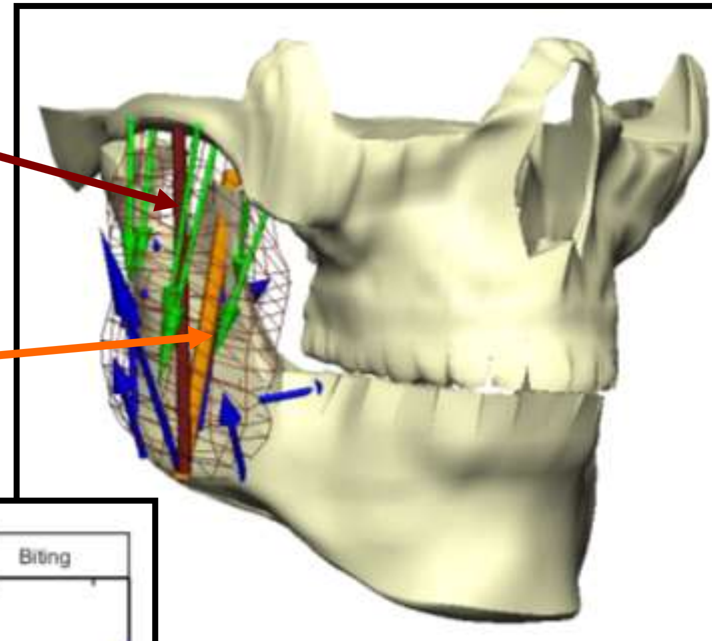
Inverse Dynamics

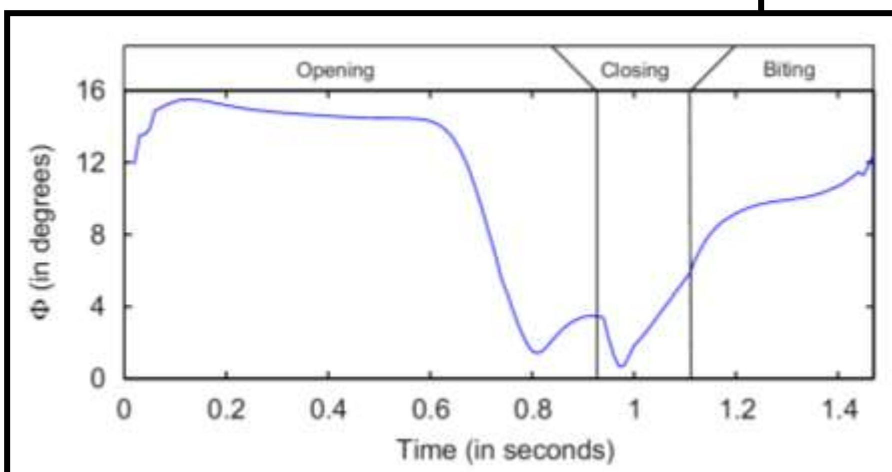


New/Old Muscle Force Directions

1D line of action (centreline approach)

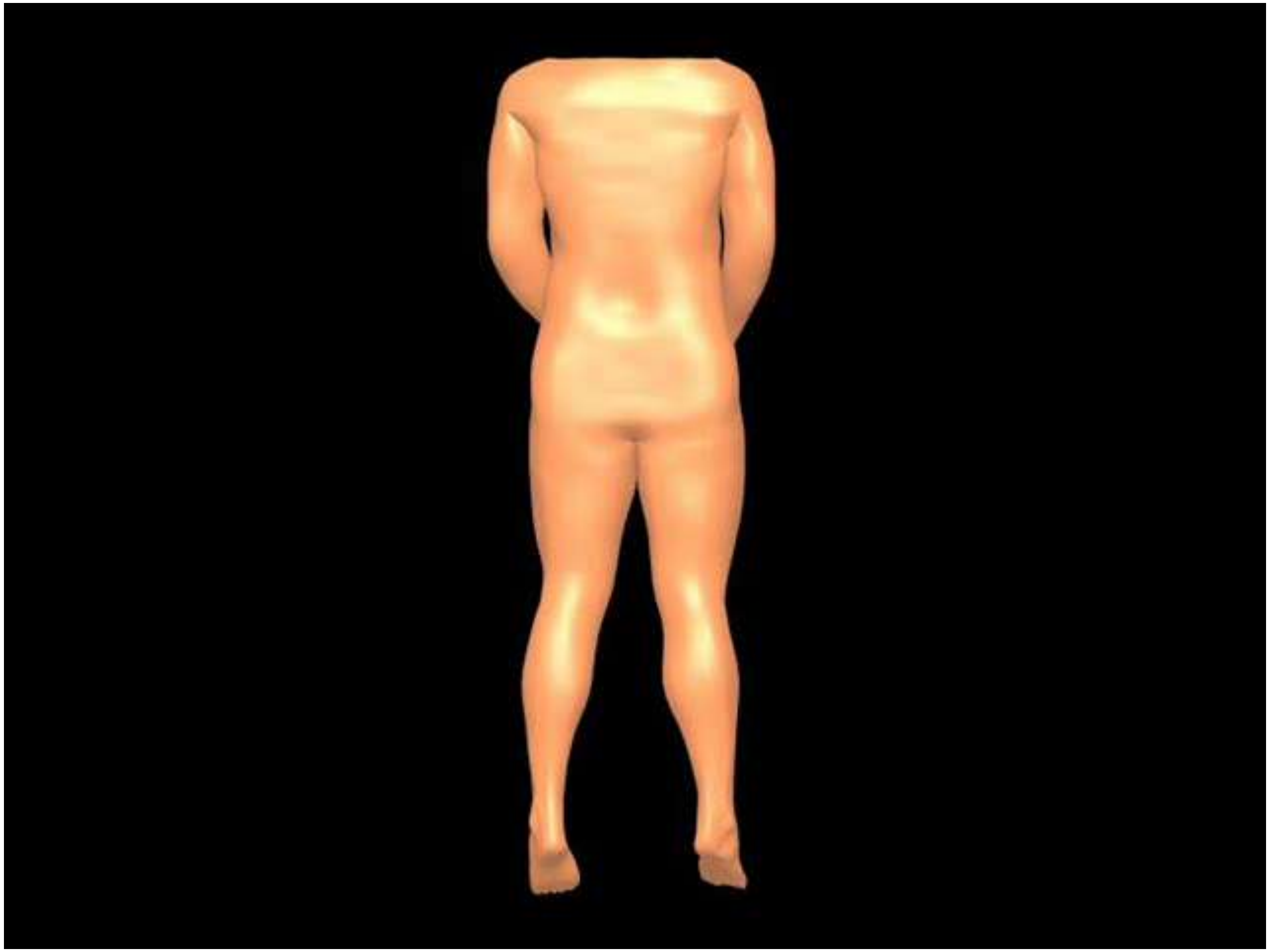
Overall force derived from the 3D model





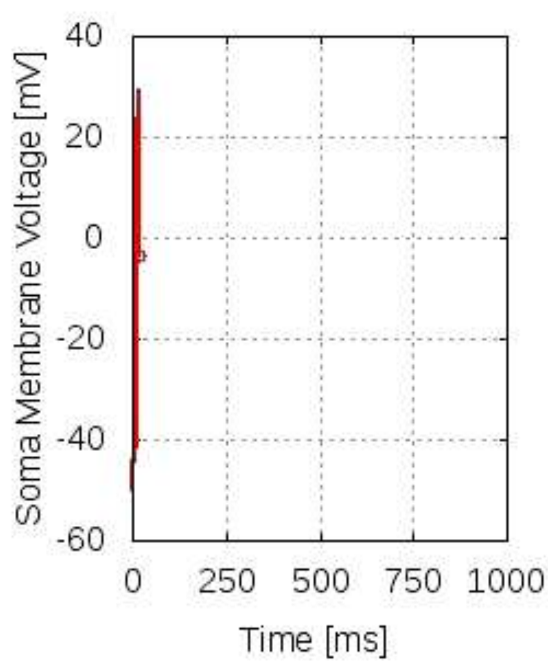
Röhrle, O. and Pullan, A.J., *"Three-dimensional finite element analysis of muscle forces during mastication"*, Journal of Biomechanics, 40 (2007), pp 3363 – 3372

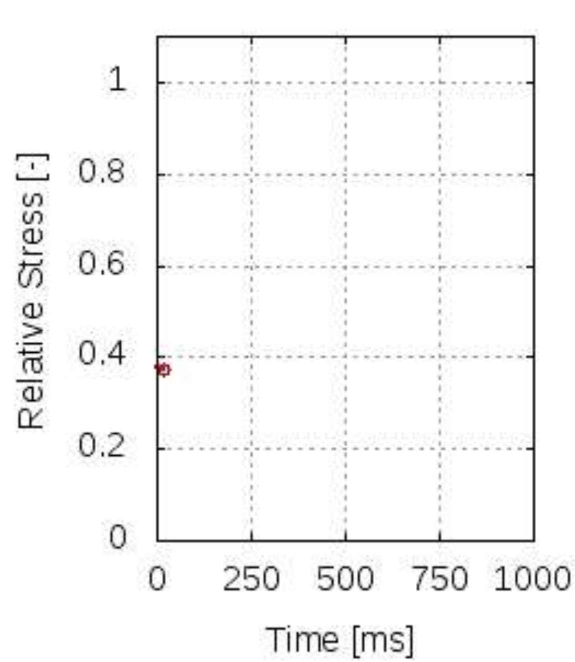
MULTI-SCALE MUSCLE MODELLING



Numerical Example: Combined Model

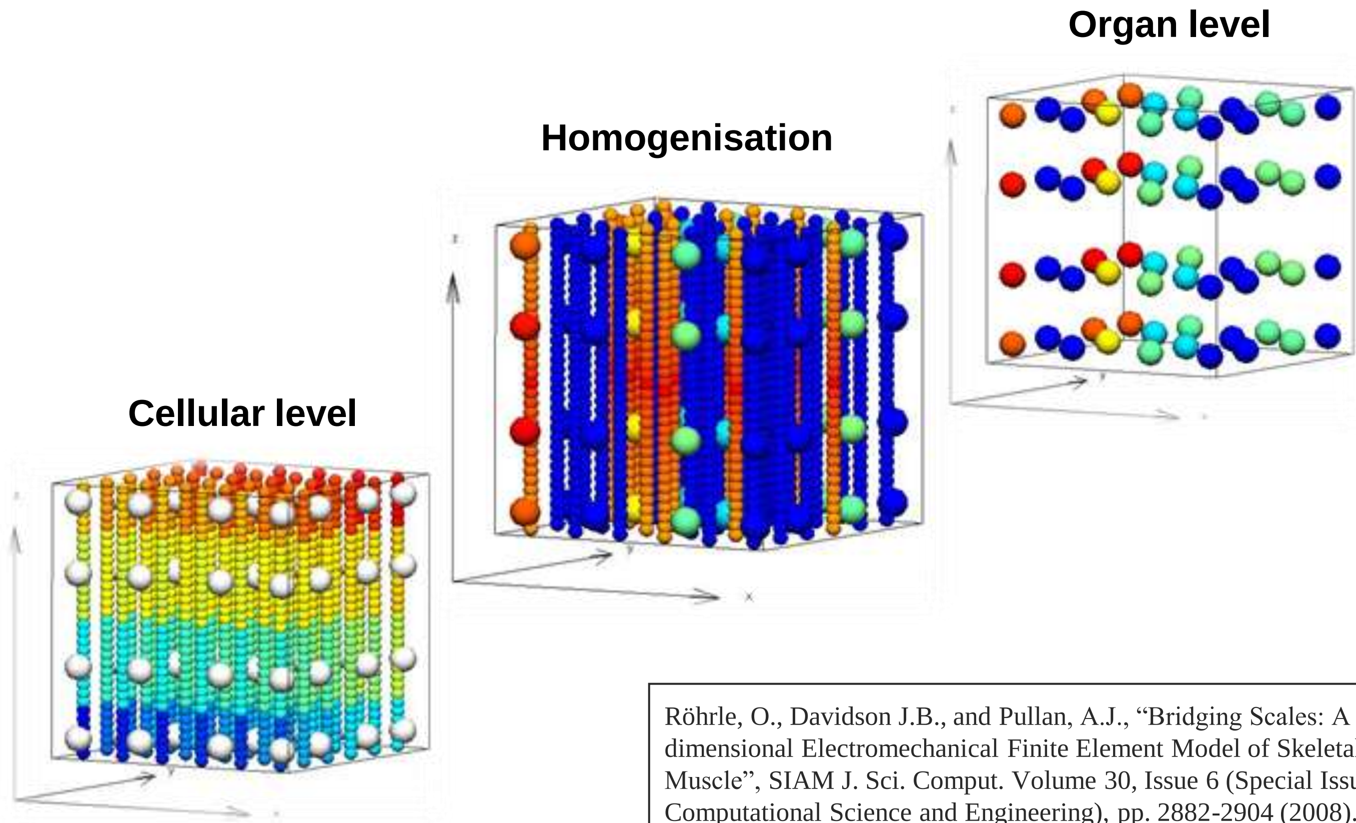
- **First approach towards an integrated model** (Farina, Negro)
  - Electrophysiological model of the motoneurons
  - Biophysical model of the half-sarcomere - active stress
- **Mathematical model:** nonlinear ordinary differential equations
- **Stimulation:** noise-superimposed constant excitation





UPSCALING / HOMOGENISATION

Cellular variables at the Gauss points are computed by averaging the cellular variables of the closest grid points



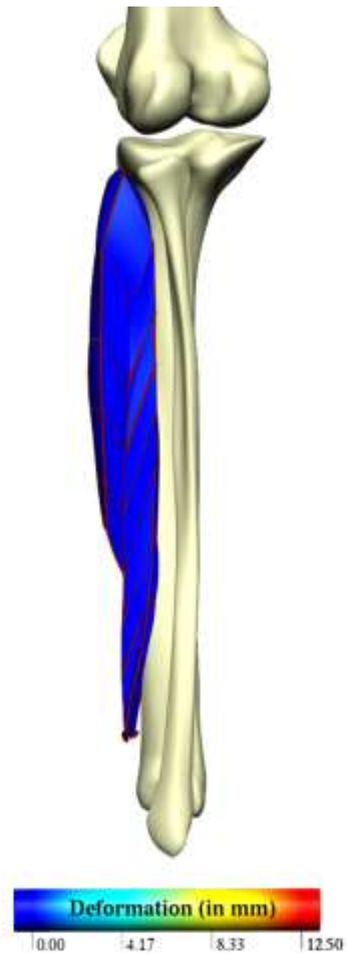
Röhrle, O., Davidson J.B., and Pullan, A.J., "Bridging Scales: A Three-dimensional Electromechanical Finite Element Model of Skeletal Muscle", SIAM J. Sci. Comput. Volume 30, Issue 6 (Special Issue: Computational Science and Engineering), pp. 2882-2904 (2008)..

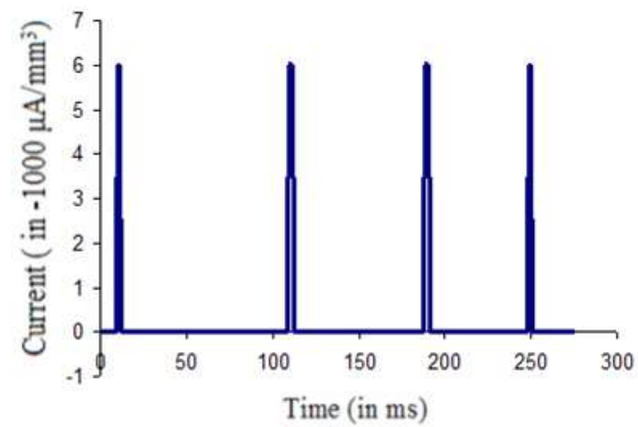
Stimulation of Tibialis Anterior

- **The mechanical finite element mesh consists of 16 quadratic Lagrange elements.**
- **A single muscle fibre is made up of 90 grid points.**
- **A total of 1024 "fibres" are embedded within the tibialis muscle.**
- **70/30 distribution of muscle fibre Type I/II (slow/fast).**
- **The simulation captures 275ms. The cellular variables and the resulting deformations are calculated in 1ms increments.**

Figure: Superficial (red), deep (gold) tibialis anterior and skin and fat (grey)

"EXTERNAL" STIMULATION





Stimulation protocol defining $I_{stim}(t)$ at the nodal locations of the neuromuscular junctions.

O. Röhrle, *"Simulating the Electro-Mechanical Behavior of Skeletal Muscles"*, IEEE Computing in Science and Engineering, DOI 10.1109/MCSE.2010.30

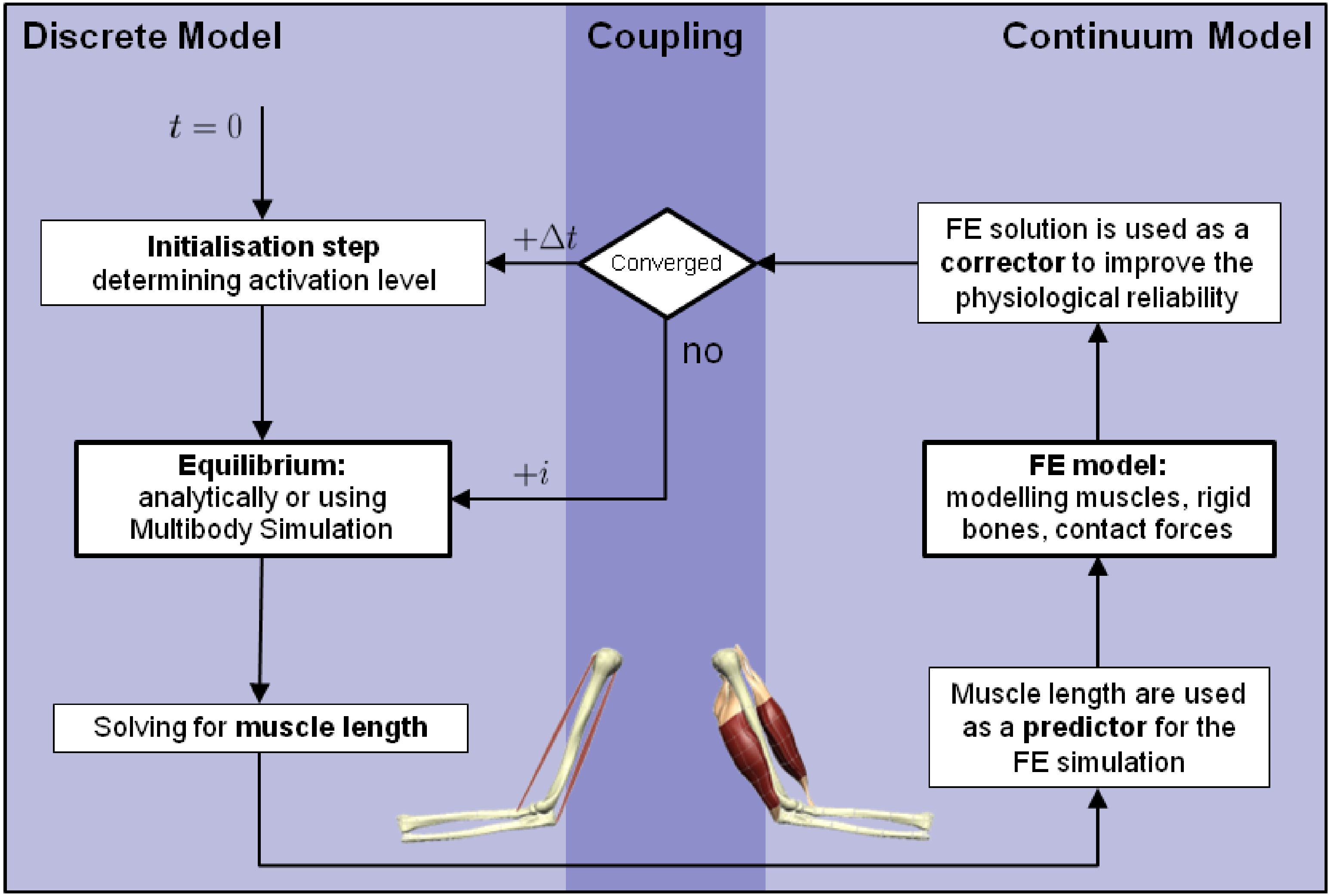
Work In Progress

- Compute virtual EMG signals (for validation and testing).
- Include a mechanical-based spindle model within the electro-mechanical framework.
- Include a biophysical motoneuron model including the feedback from the spindle model.
- DT-MRI for complex muscle fibre distributions.
- Extend framework to simulate the dynamics of a multi-muscle systems during gait (-> residual limb as FP7 ERC Starting Grant).

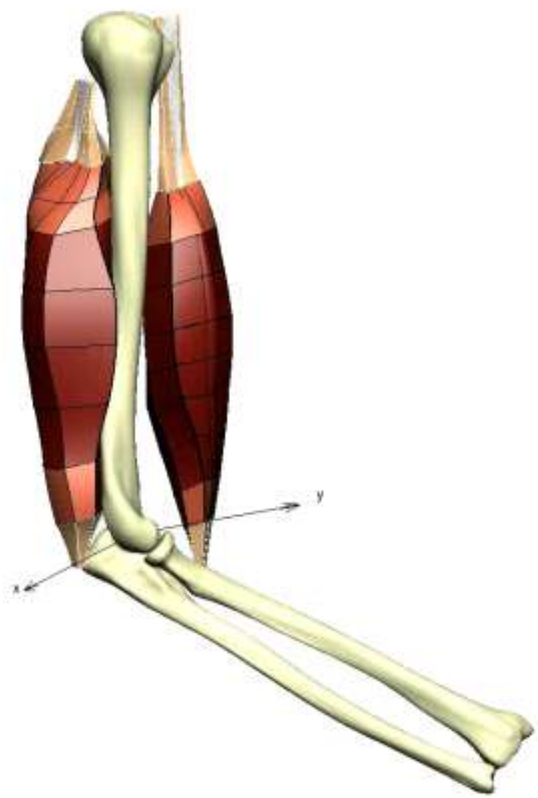
PART III

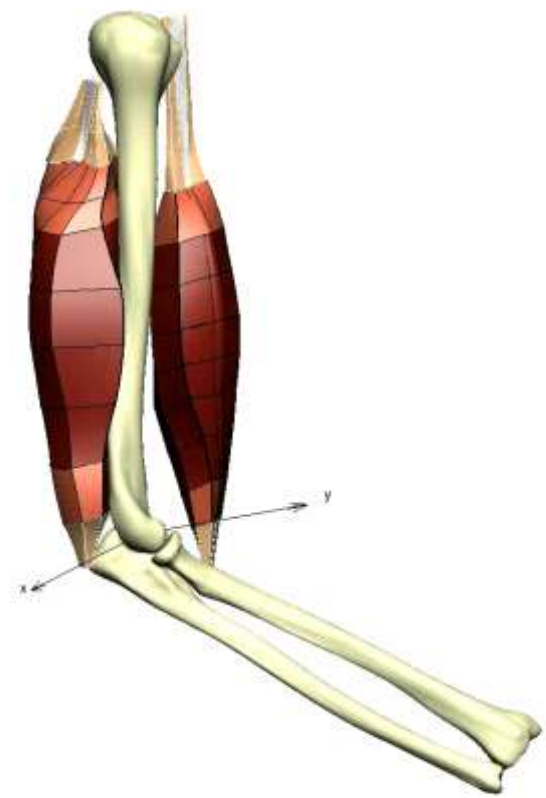
COUPLING MULTI-BODY SIMULATIONS WITH CONTINUUM MECHANICAL MODELS

Forward Dynamics FE Modelling



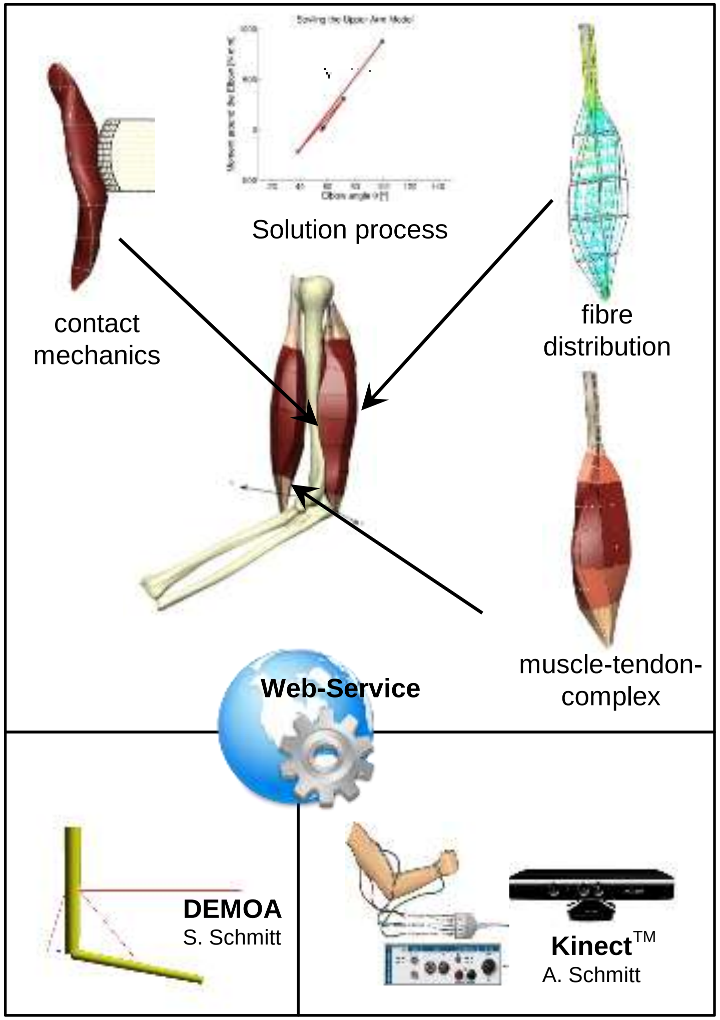
Activation Driven Movement



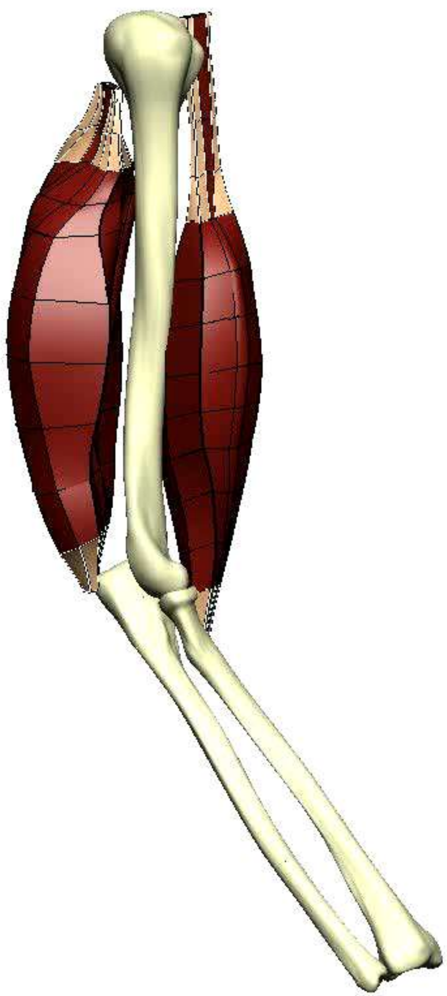


In both cases, the activation of the biceps and triceps are simultaneously and linearly increased from 0..1. Left without contact, right with bone-muscle contact.

Coupling Different Frameworks



First Results



- Activation-driven musculo-skeletal movement
- Activation of the triceps is maintained, while the activation for the biceps is linearly increased.
- Multi-body pre-calculation and corrections from a continuum-mechanical problem that accounts for complex structural arrangements, e.g. fibre distribution, muscle-bone contact.

PART IV

POTENTIALS FOR ADVANCED MUSCULOSKELETAL MODELS

FUTURE POTENTIALS

- **More realistic (crash) simulations due to activation driven musculoskeletal models:**
  - **Mechanical properties of joints**
  - **Force/Stress distribution due to full contact**

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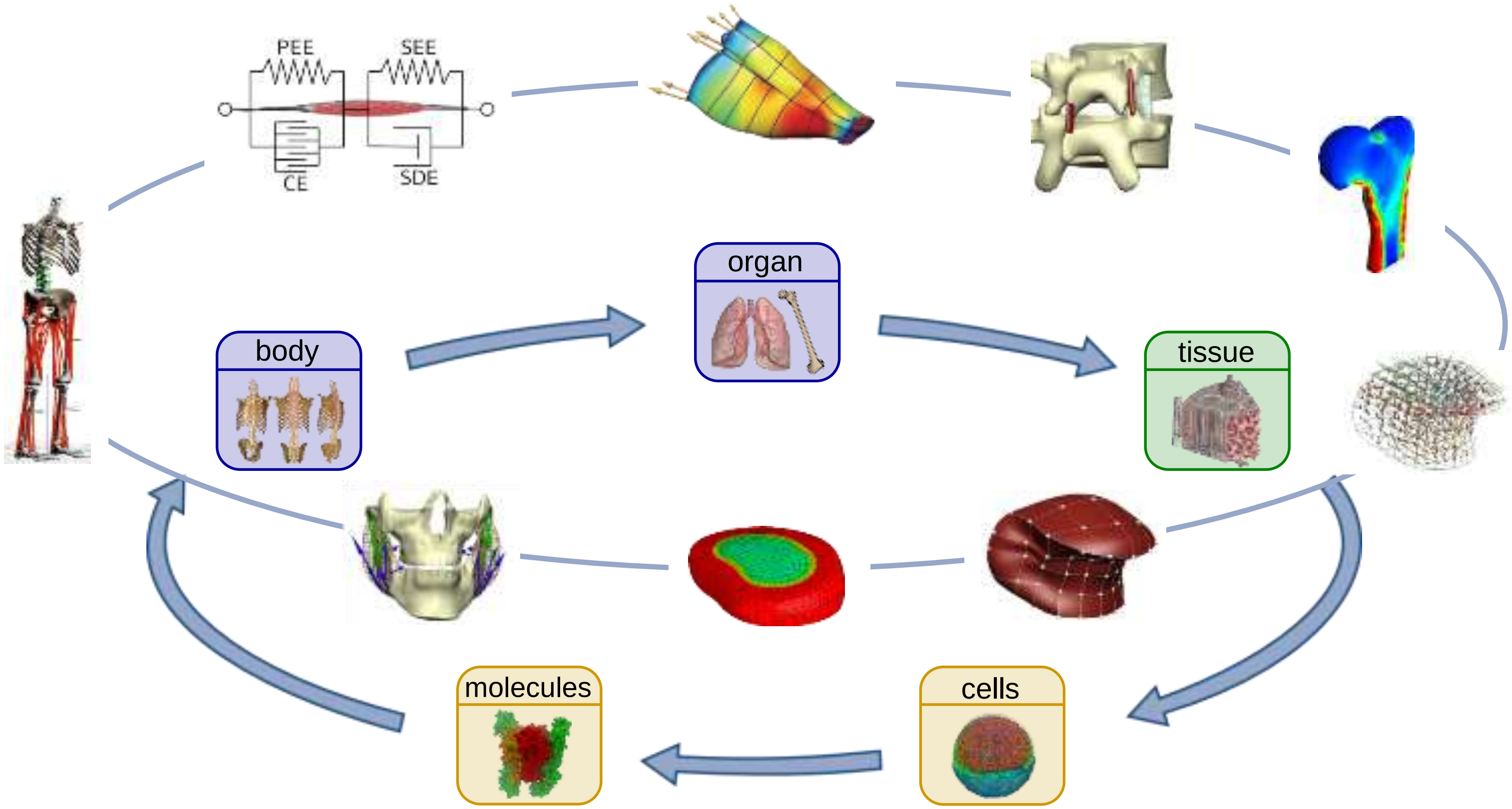
Human factor in pedestrian-car safety

Human factor in passenger safety

Human factor in comfort/car ergonomics

- **Ultimate goal: A realistic biomechanical-based avatar**



THANK YOU!