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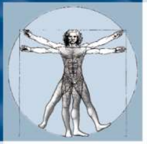

SimTech Research Group on Continuum Biomechanics and Mechanobiology

DREIDIMENSIONALE, KONTINUUMSMECHANISCHE MODELLIERUNG DES MUSKULOSKELETALEN APPARATES

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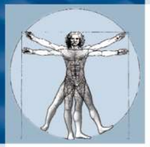
OVERVIEW

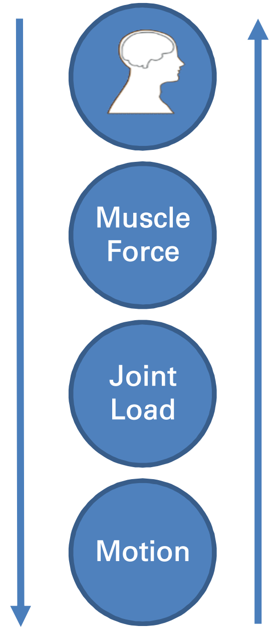
- Motivation
  - Different skeletal muscle modelling approaches
  - Overview on forward-dynamics and inverse-dynamics musculoskeletal modelling approaches
  - Short comings
- Modelling framework of a two-muscle model upper limb model
  - Geometrical Model
  - Continuum-mechanical skeletal muscle model
  - Solving the musculoskeletal system
- Simulation results
  - Convergence studies
  - Contact forces acting within the system
- Outlook



BASIC PRINCIPLES OF FORWARD / INVERSE DYNAMICS

- Forward / inverse dynamics musculoskeletal modelling

Muscle recruitment



Movement

Forward dynamics

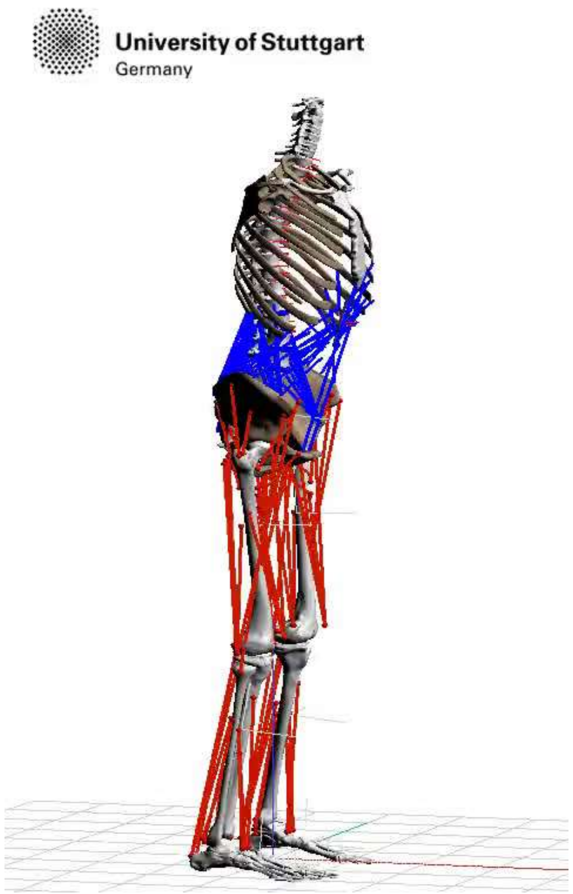
- Control mechanisms / EMG (experimental data driven)
- Optimisation of cost functions associated with the control or muscle length targets

Inverse dynamics

- Cost functions
- Muscle grouping
- Experimental Data (EMG) / assumptions on muscle activities

THE MUSCULOSKELETAL SYSTEM

- There exist many different approaches to model the mechanical behavior of skeletal muscle:
  - Biophysical Huxley-type models (including the neuromuscular system)
  - (Chemo-)Electro-mechanical skeletal muscle models
  - Continuum-mechanical skeletal muscle models
  - Hill-type skeletal muscle models
- Modelling the musculoskeletal system:
  - Inverse dynamics models
  - Forward dynamics models
- State-of-the-art musculoskeletal system models:
  - Inverse dynamics models using Hill-type skeletal muscle models



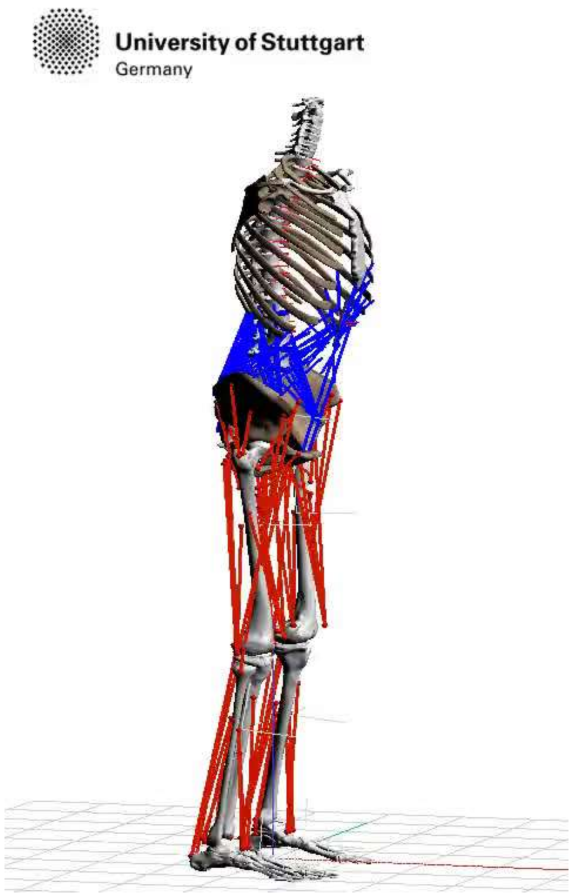
Forward dynamics simulations courtesy of JP Syn Schmitt,
Institut für Sport- und Bewegungswissenschaft, Universität Stuttgart

LIMITATIONS OF EXISTING MUSCULOSKELETAL MODELS

- Limitations of the state-of-the-art models:
  - Hill-type skeletal muscle models are lumped-parameter discrete models that have difficulties to take into account any spatial characteristics of skeletal muscles.
  - They cannot take into account any contact between skeletal muscles and surrounding structures.

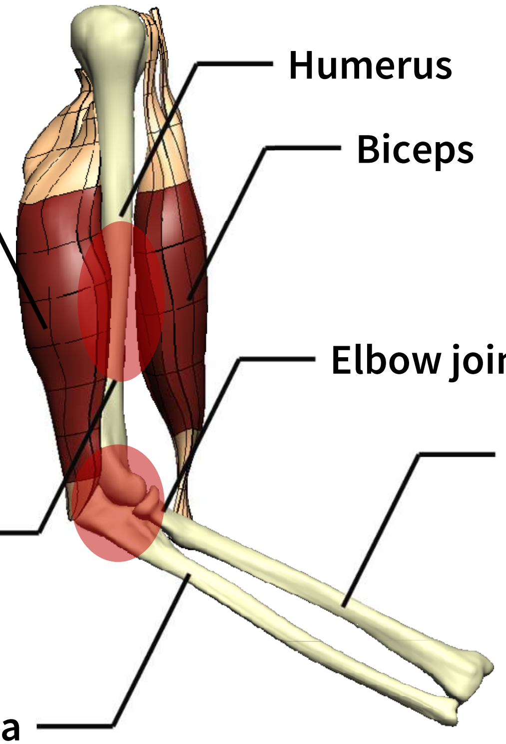
⇨ **Three-dimensional, continuum-mechanical skeletal muscle models**

- Challenges of continuum-mechanical models:
  - Continuum-mechanical models of musculoskeletal systems are rare:
    - → Only a few inverse-dynamics approaches exist
    - → Forward-dynamics frameworks do not exist
  - Computational expensive
  - Convergence due to the force-length relationship

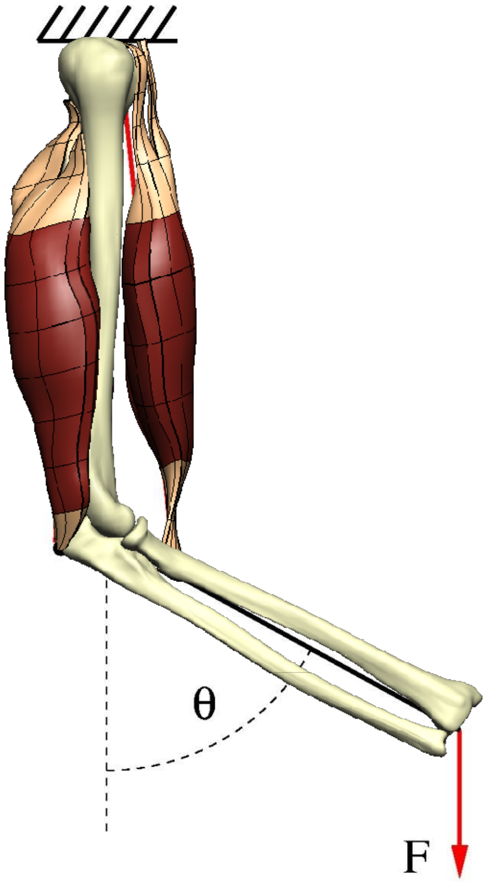


The Upper Limb Model

- Model components from Visible Human Project



THE UPPER LIMB MODEL



Introducing the equivalent static system

→ Muscle length is modelled as the distance between muscle origin and insertion

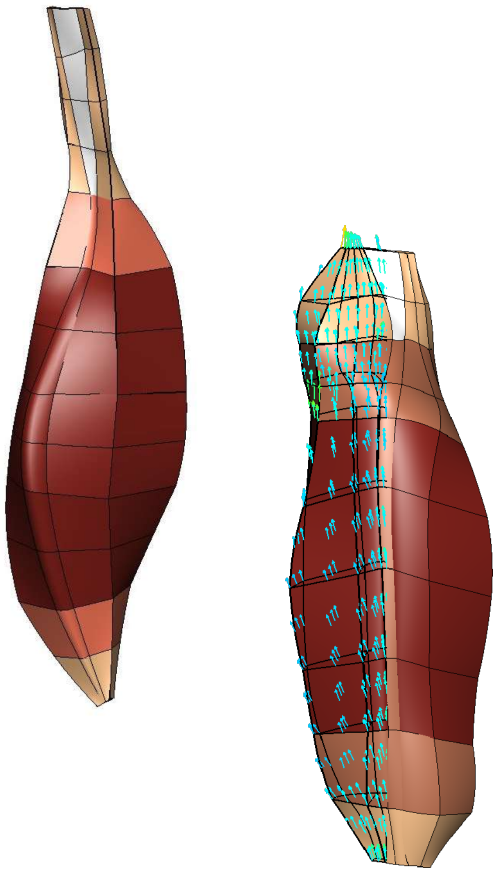
→ Formulating the momentum balance in the elbow joint:

$$T(\theta,\, \alpha_T)\, l_T(\theta) + F\, l_F(\theta) - B(\theta,\, \alpha_B)\, l_B(\theta) = 0$$

→ Initially, the lever arms are be determined using the tendon displacement method or using the actual geometry of the system

→ Muscle forces are determined by FEM simulations using the continuum mechanical muscle approach

Continuum-Mechnical Constitutive Equations

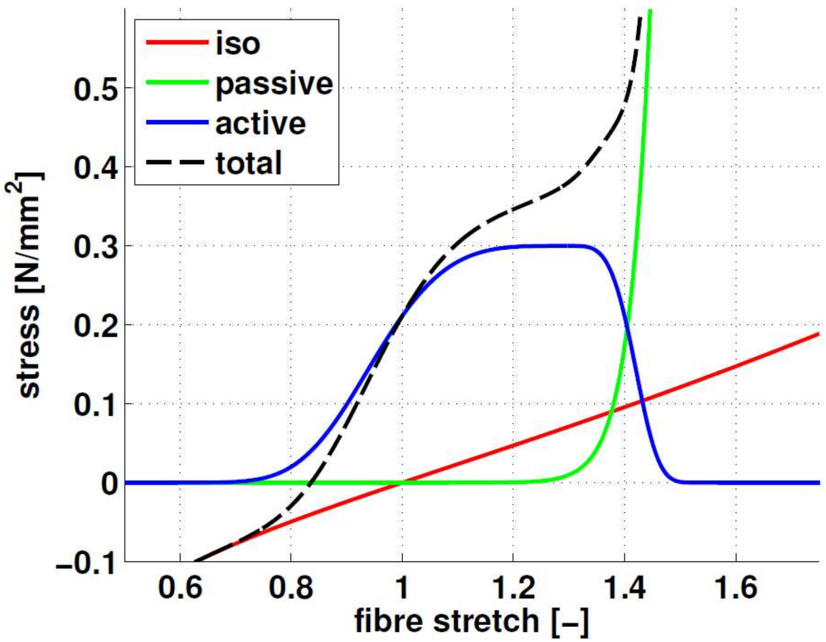


- Continuum-mechanical models describe the mechanics of the muscle and surrounding tissue.
- Assumptions on skeletal muscles model:
  - Hyperelastic, incompressible, transversely isotropic
  - Stress-strain relation (constitutive equation)

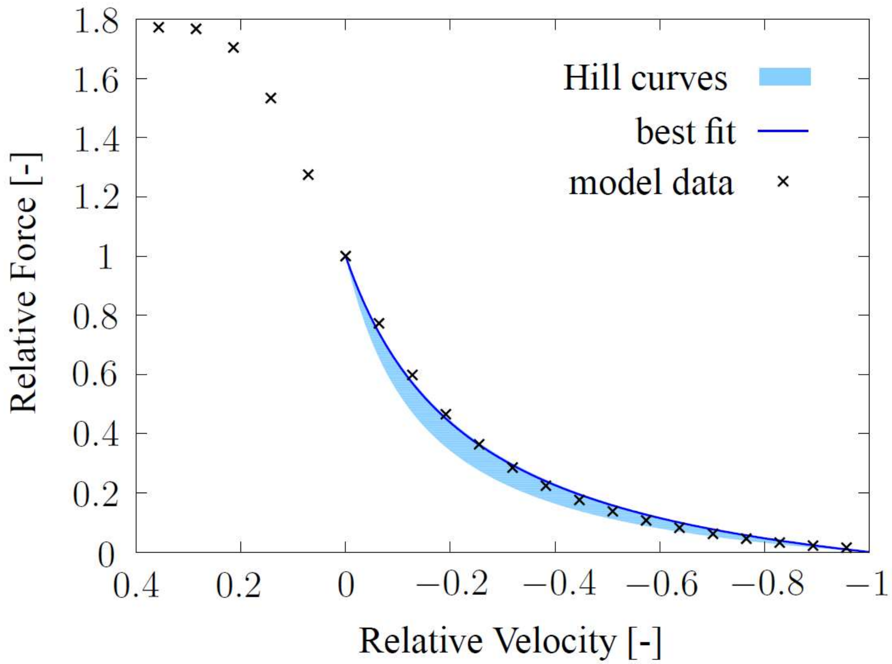
$$\mathbf{S}_{\mathrm{MTC}} = \mathbf{S}_{\mathrm{iso}} + \mathbf{S}_{\mathrm{aniso}} = \mathbf{S}_{\mathrm{iso}} + \left(\mathbf{S}_{\mathrm{passive}} + \alpha\, \gamma_{\mathrm{M}}\, \mathbf{S}_{\mathrm{active}}\right)\left(1 - \gamma_{\mathrm{ST}}\right)$$

tissue	contribution	parameter	triceps	biceps	source
muscle	isotropic	c_{1M}	$3.56 \cdot 10^{-2}$ MPa	$3.56 \cdot 10^{-2}$ MPa	[HaBe1994]
		c_{2M}	$3.86 \cdot 10^{-3}$ MPa	$3.86 \cdot 10^{-3}$ MPa	
	passive	c_{3M}	$4.02 \cdot 10^{-7}$ MPa	$3.57 \cdot 10^{-8}$ MPa	[Zhen1999]
		c_{4M}	38.5 [-]	42.6 [-]	
	active	ΔW_{asc}	0.30 [-]	0.25 [-]	adapted from [Gunt2007]
		ΔW_{desc}	0.10 [-]	0.15 [-]	
		ν_{asc}	4.00 [-]	3.00 [-]	
		ν_{desc}	4.00 [-]	4.00 [-]	
		λ_f^{opt}	1.3 [-]	1.35 [-]	-
		σ_{max}	0.30 MPa	0.30 MPa	-
tendon	isotropic	c_{1T}	2.31 MPa	2.31 MPa	WeGa2001]
		c_{2T}	$1.15 \cdot 10^{-6}$ MPa	$1.15 \cdot 10^{-6}$ MPa	
	passive	c_{3T}	7.99 MPa	7.99 MPa	[WeGa2001]
		c_{4T}	16.6 [-]	16.6 [-]	

CONTINUUM-MECHNICAL CONSTITUTIVE LAW



Force-length relationship



Force-velocity relationship

SOLVING THE EQUILIBRIUM EQUATIONS

Challenge: Solve the equilibrium equations using the muscle forces stemming from the 3D, continuum-mechanical tissue models:

$$T(\theta,\, \alpha_T)\, l_T(\theta) + F\, l_F(\theta) - B(\theta,\, \alpha_B)\, l_B(\theta) = 0$$

- **Position-driven scenario** (activation for a particular elbow position / "inverse model")

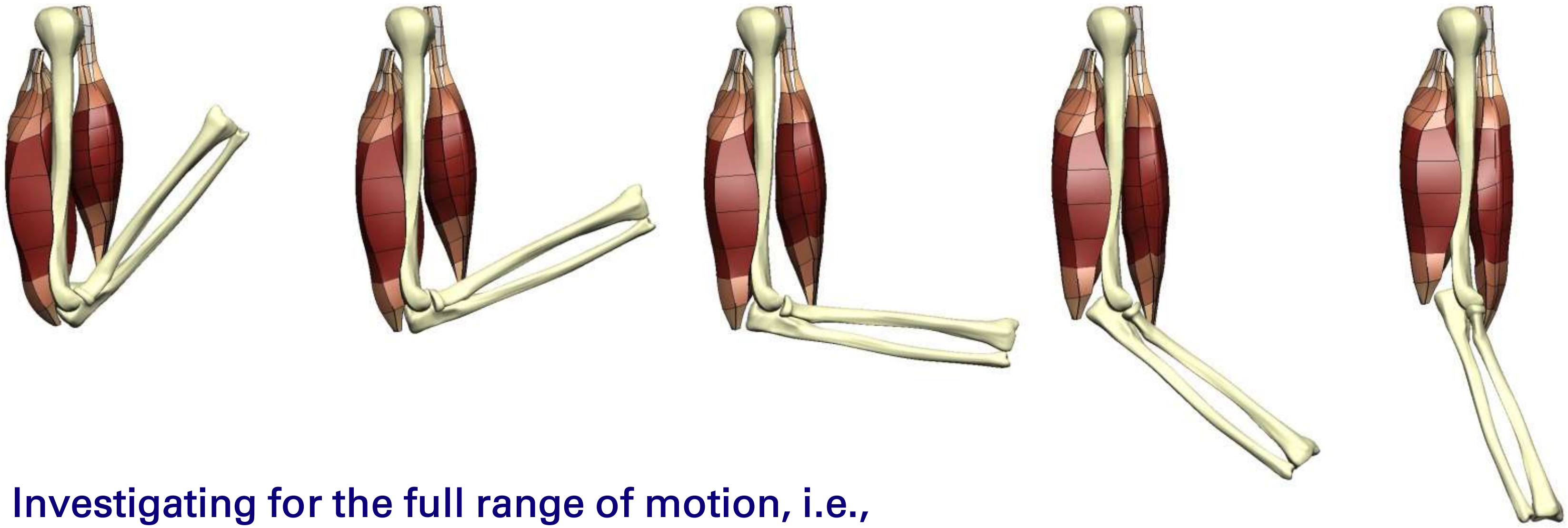
$$\alpha_T^{(i+1)} = \alpha_T^{(i)} - \frac{M^{(i)}}{\dfrac{\partial M^{(i)}}{\partial \alpha_T}}\,, \quad \text{i=1,...,n}\,, \quad \text{with} \quad \frac{\partial M^{(i)}}{\partial \alpha_T} \approx \frac{\Delta M^{(i)}}{\Delta \alpha_T^{(i)}} = \frac{M^{(i)} - M^{(i-1)}}{\alpha_T^{(i)} - \alpha_T^{(i-1)}} = \frac{T^{(i)} - T^{(i-1)}}{\alpha_T^{(i)} - \alpha_T^{(i-1)}}$$

- **Activation-driven scenario** (elbow angle for a prescribed activation / "forward model"):

$$\theta^{(i+1)} = \theta^{(i)} - \frac{M^{(i)}}{\dfrac{\partial M^{(i)}}{\partial \theta}}\,, \quad \text{i=1,...n}\,, \quad \text{with} \quad \frac{\partial M^{(i)}}{\partial \theta} \approx \frac{\Delta M^{(i)}}{\Delta \theta^{(i)}} = \frac{M^{(i)} - M^{(i-1)}}{\theta^{(i)} - \theta^{(i-1)}}$$

- **Force-driven scenario can be described in a similar way.**

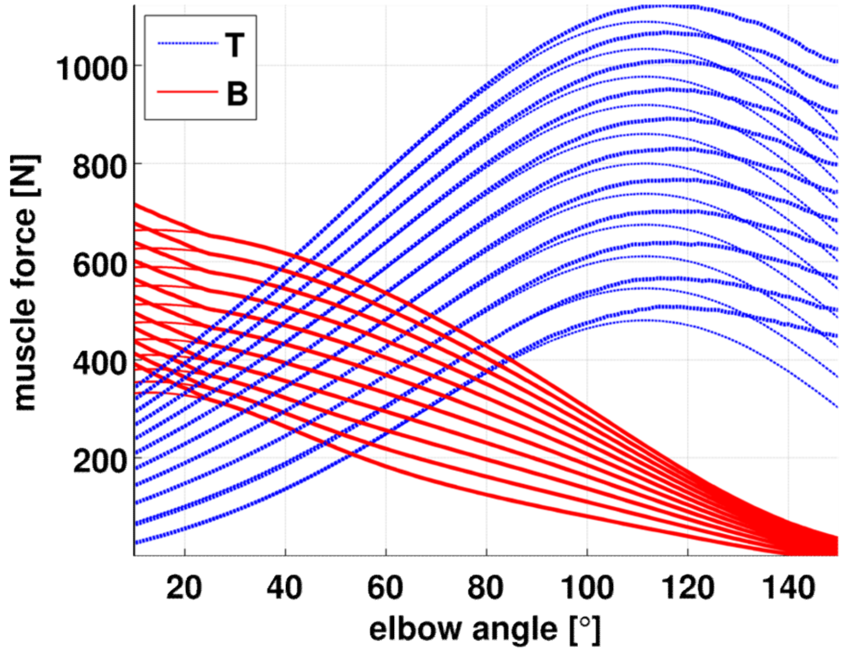
SKELETAL MUSCLES AS ISOLATED SIMULATIONS

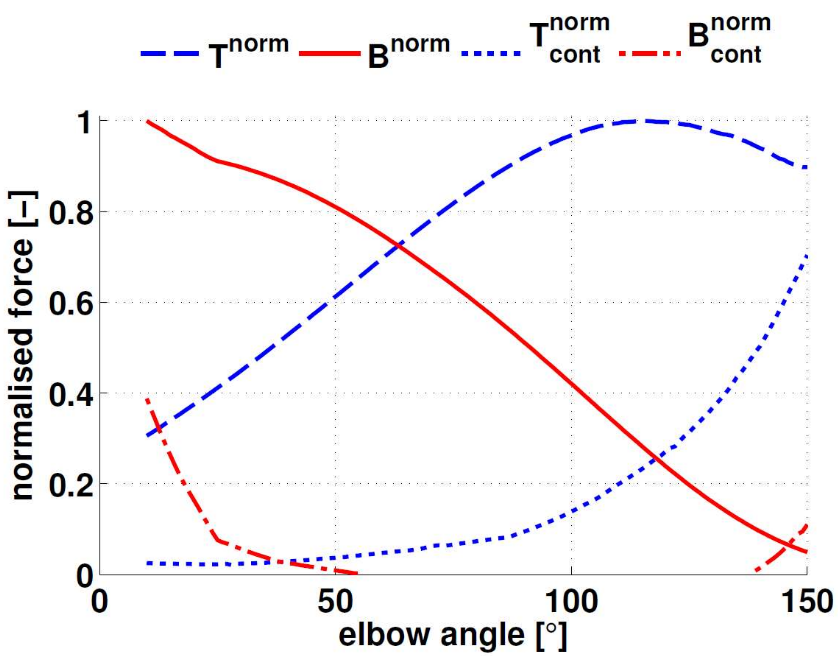


- Investigating for the full range of motion, i.e.,
  - Motion [10 ≤ θ ≤ 150], activation [0 ≤ α ≤ 1], with/ without contact
- The impact on:
  - Reaction forces’ magnitude and orientation
  - Fibre stretch and resulting muscle shapes
  - Impact of muscle-bone interaction

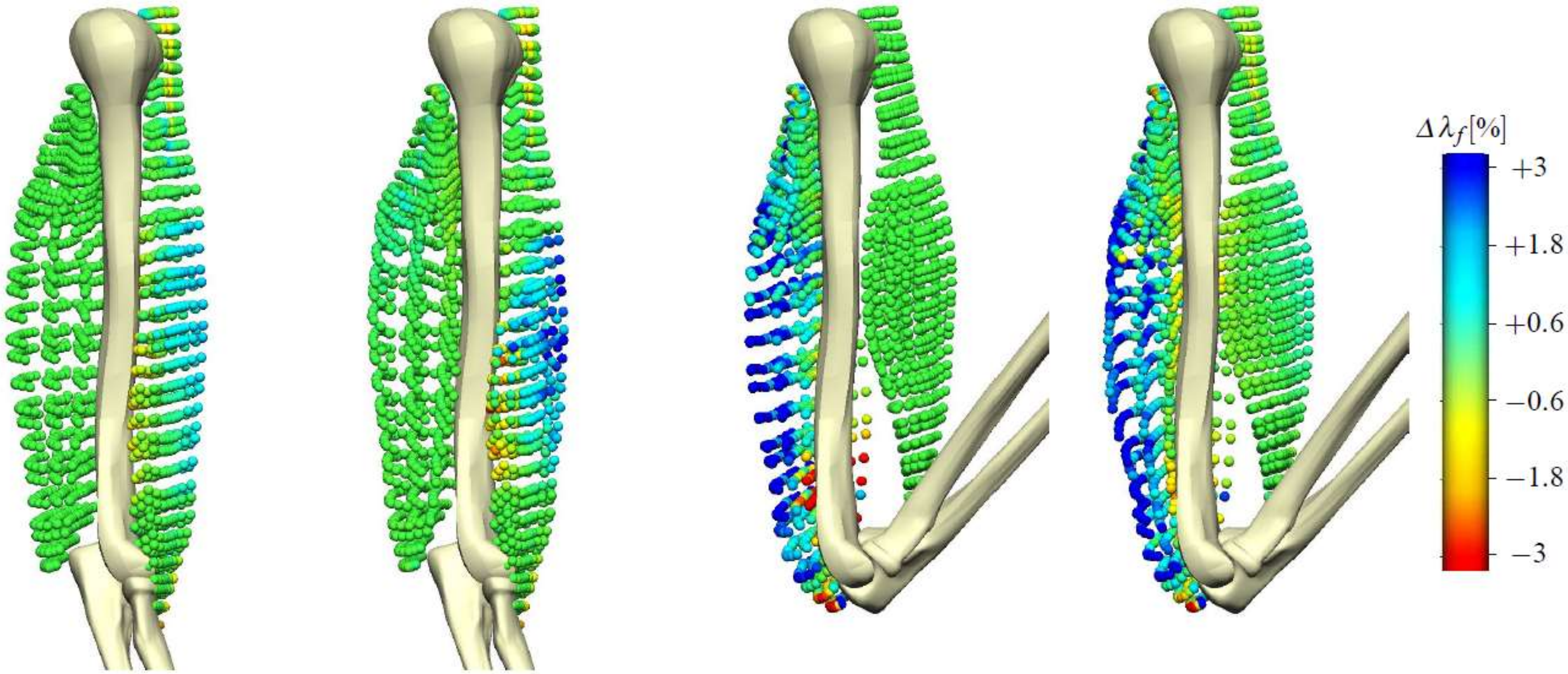
Muscle and Contact Forces

- Muscle forces for the full range of motion and different levels of activation (left) and the contact reaction forces (right) for full activation of the biceps and the triceps muscle.





Impact of Contact on Muscle Fibre Distribution



(a) fully extended, $\theta = 10°$, and $\alpha = 0$

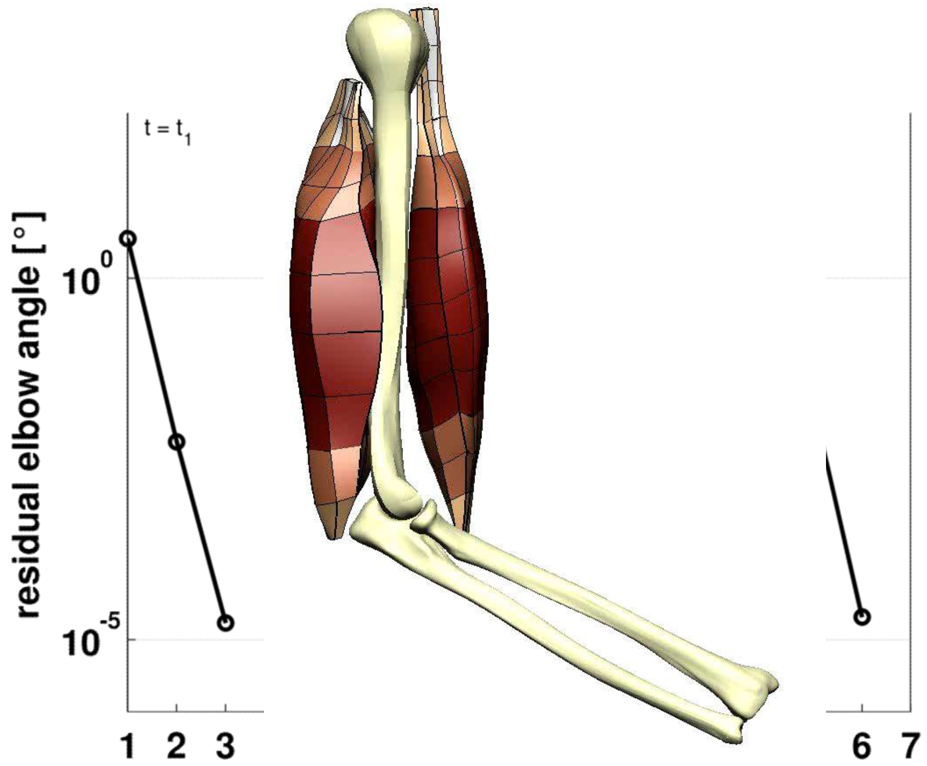
(b) fully extended, $\theta = 10°$, and $\alpha = 1$

(c) fully flexed, $\theta = 150°$, and $\alpha = 0$

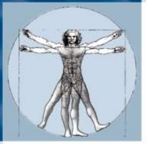
(d) fully flexed, $\theta = 150°$, and $\alpha = 1$

Position-Driven Scenario

- By assuming variations in activation, one can achieve „forward dynamics“ simulation, hence
  - with $\bar{\alpha}_T = 0.09, \ \bar{F} = 44\,\text{N}$ and
    $\alpha_B(t_1) = 88.58\% \ \rightarrow \theta_{equi} = 57.47°$
    $\alpha_B(t_2) = 32\% \ \rightarrow \theta_{equi} = 38.27°$
    $\alpha_B(t_3) = 65\% \ \rightarrow \theta_{equi} = 50.10°$



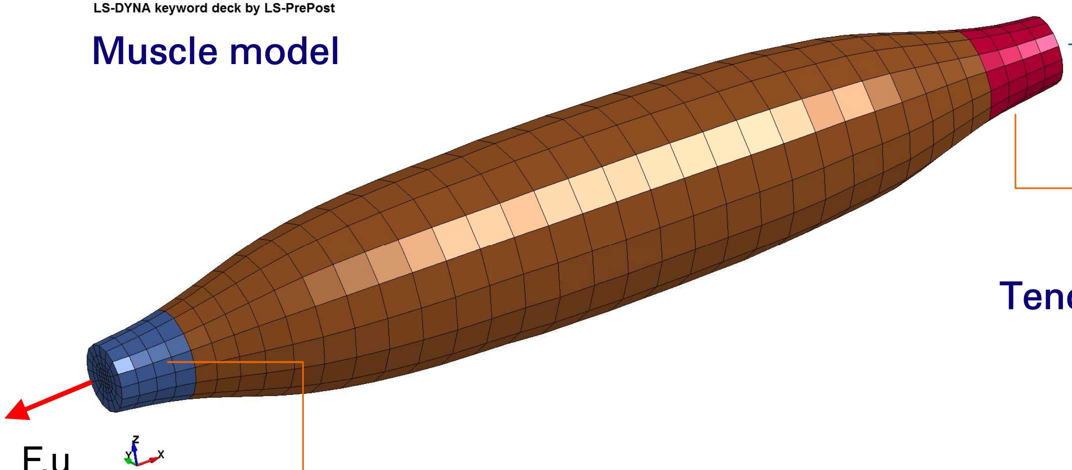
Motivation
Modelling
Simulation
Outlook



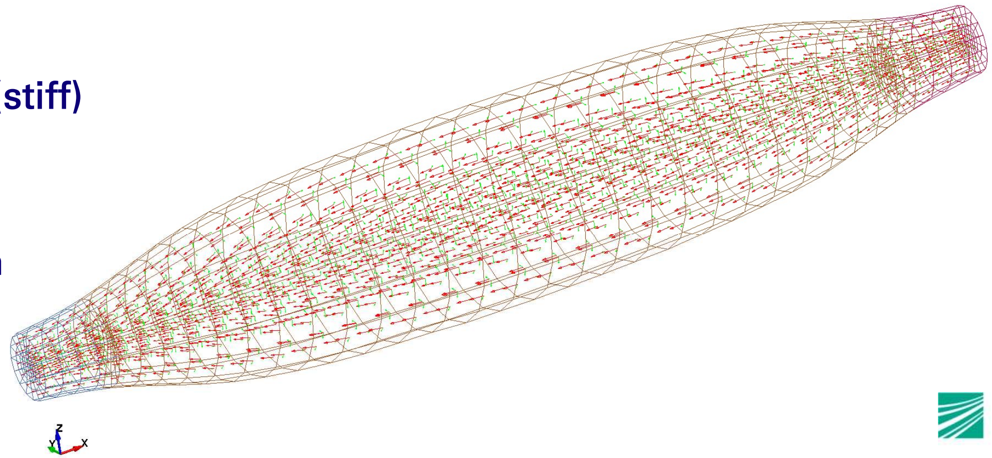
User Material Implementation in LS-DYNA

LS-DYNA keyword deck by LS-PrePost

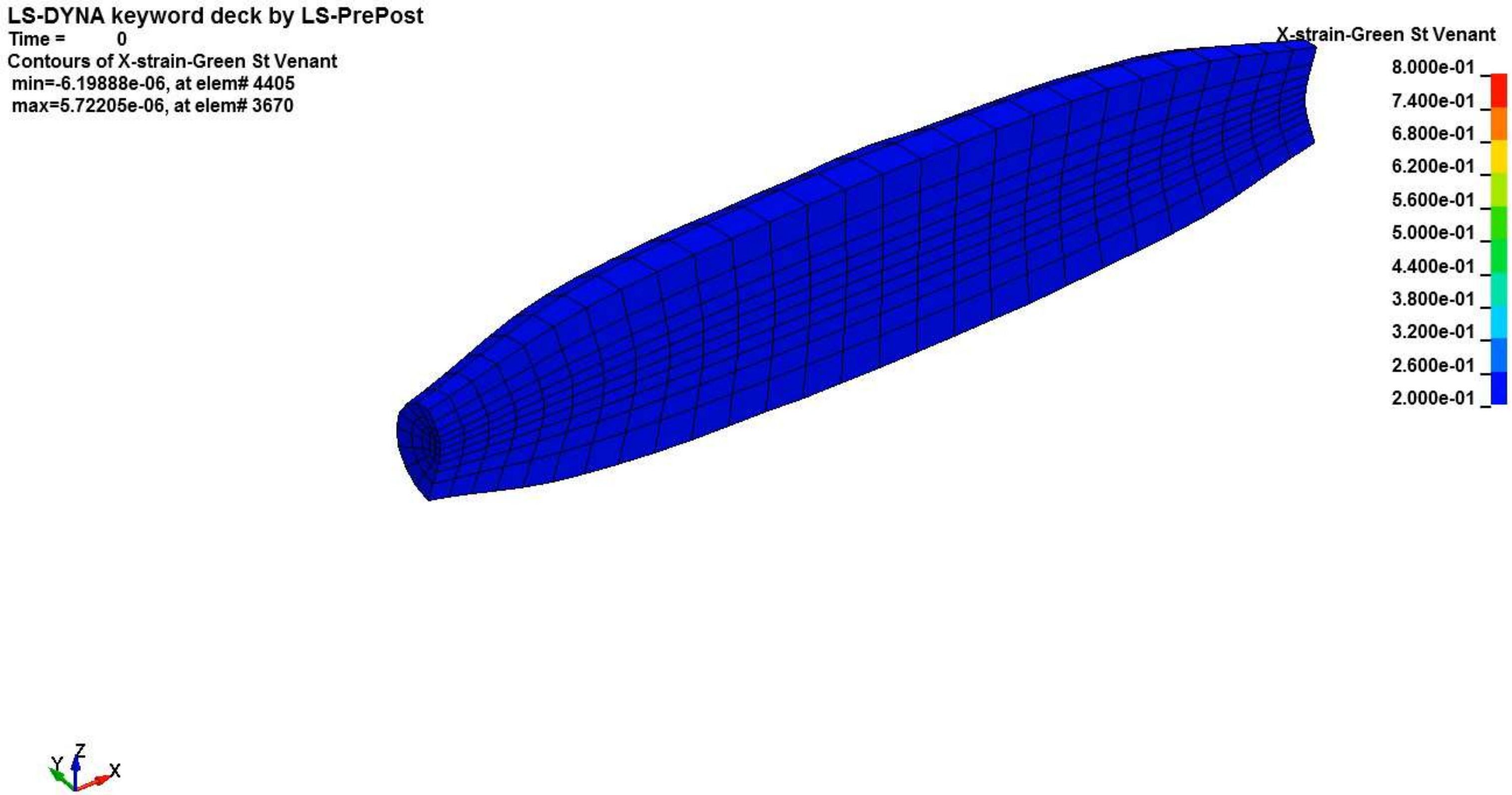
Muscle model



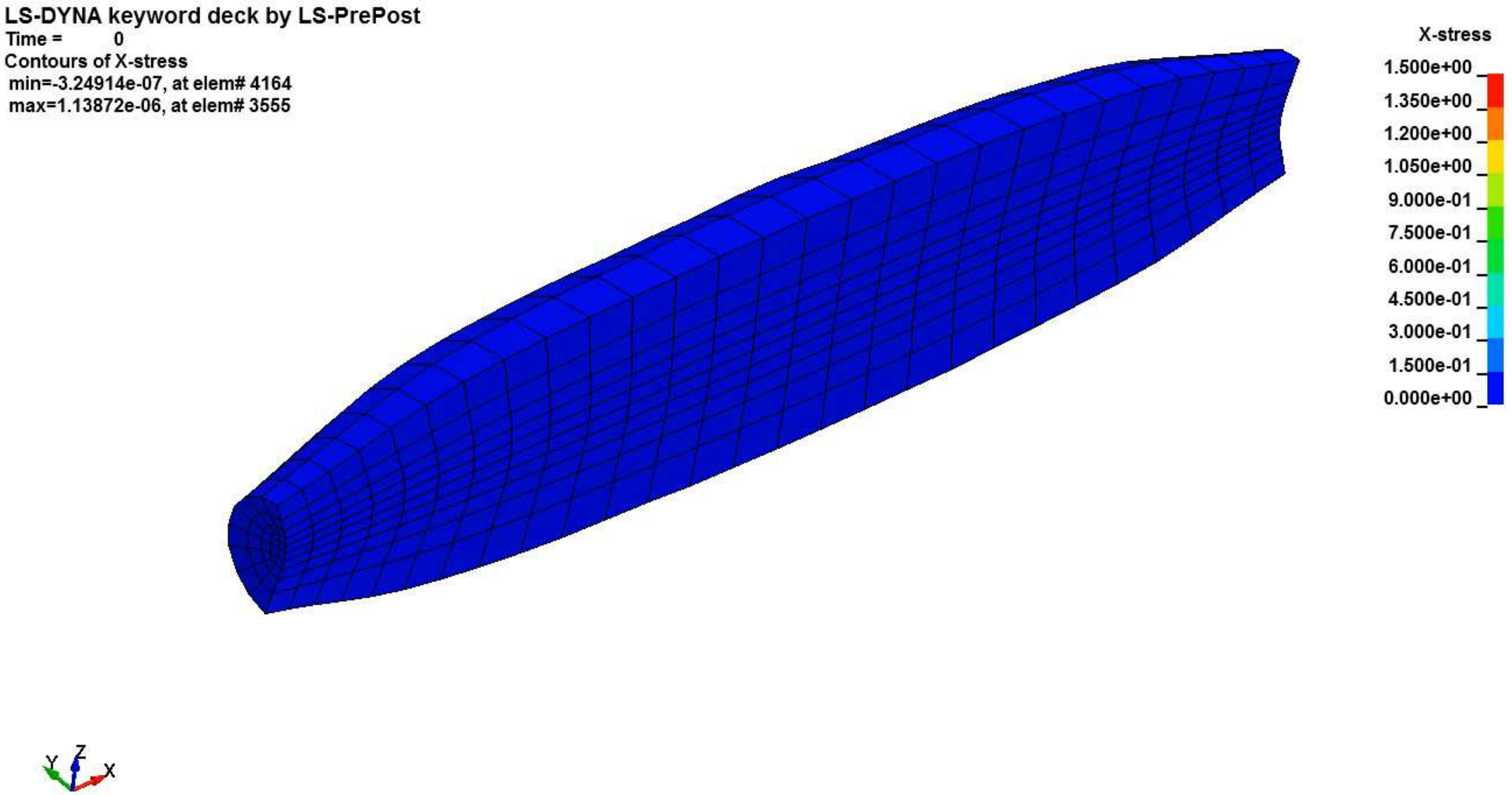
Fiber direction



A Displacement-Driven Scenario

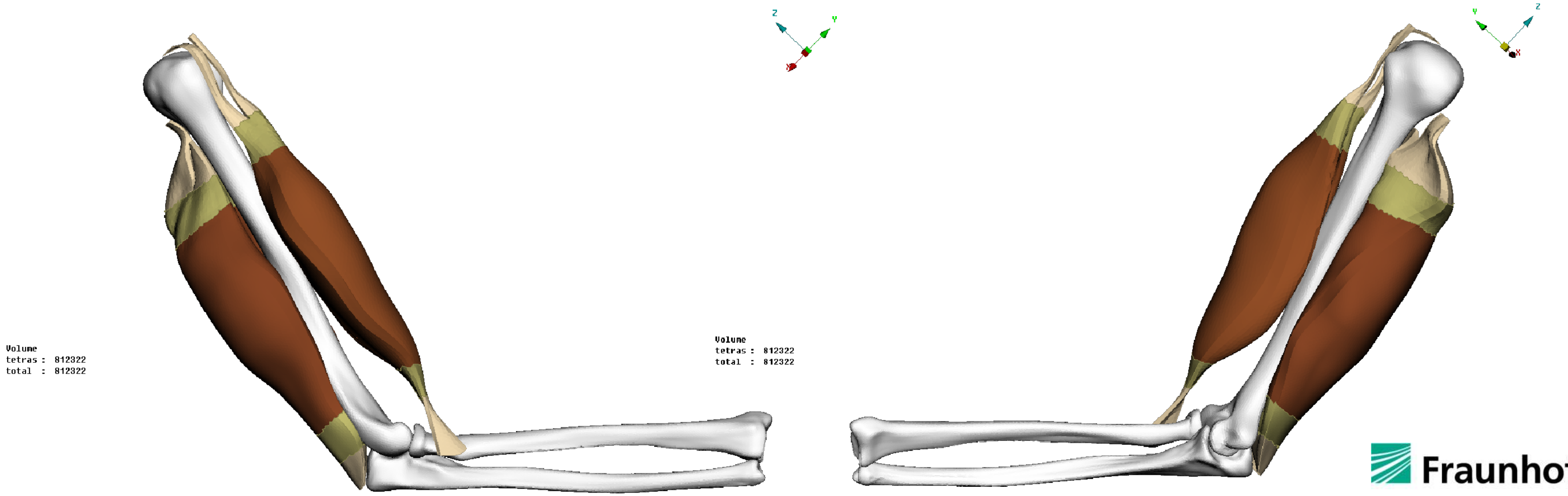


A Force-Driven Scenario



Full Upper Arm Model

- **Implicit dynamic simulation of an upper arm motion**
  - The muscle, muscle-tendon and tendon behavior are modelled with the proposed constitutive law
  - All bones are assumed to be rigid
  - The biceps is assumed to be fusiform.
  - The triceps us assumed to be bipennate.
  - Both muscles are fully activated within the first second of the motion

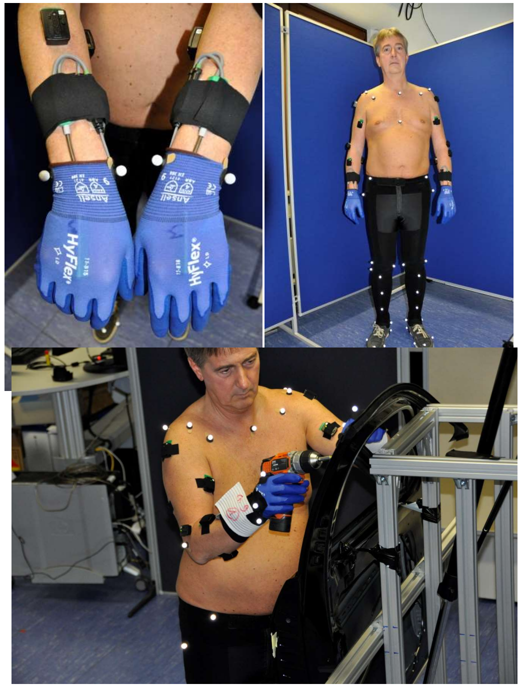


Fraunhofer IPA

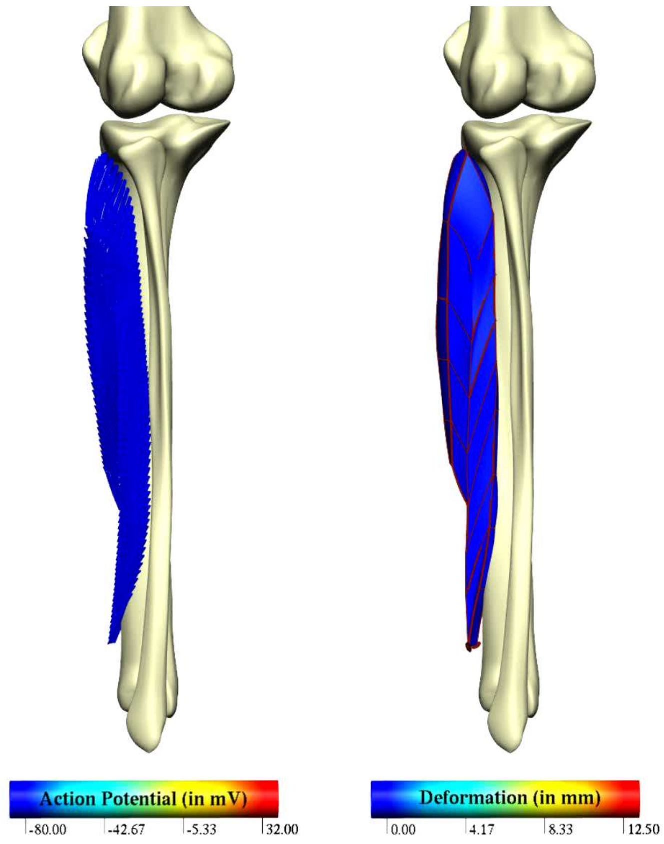
VALIDATION – HIGH DENSITY EMG

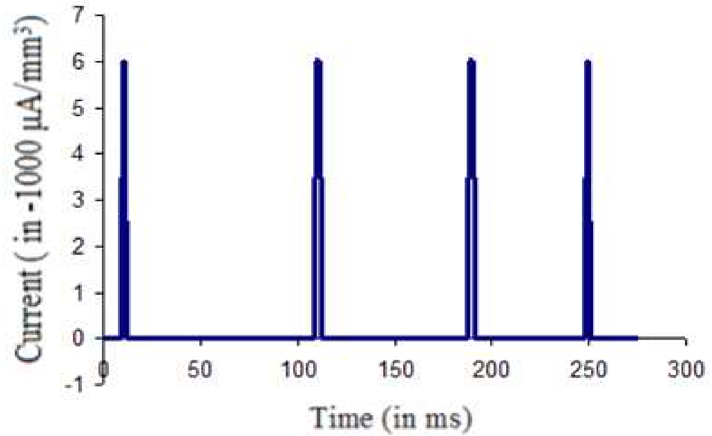
Motivation
Modelling
Simulation
Outlook

- **Part of the Fraunhofer MAVO – EMMA-CC we aim to**
  - Look at research questions arising in ergonomics
  - Use HD-EMG data to determine muscular activation
  - Use Motion Capture analysis techniques to determine movement



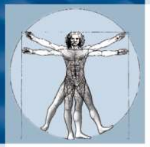
DETAILED CHEMO-ELECTRO-MECHANICAL MODELS





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



OUTLOOK

- Extension to a multiple muscle scenario
  - Contact between multiple muscles
  - Control strategies for multiple muscles? Solving the forward problem
  - Extension to chemo-electro-mechanical skeletal muscle models and biophysical based neuromuscular models for muscle recruitment
  - Couple continuum-mechanical models with Hill-type modelling approaches like the forward-Inverse-dynamics model (Bezier, Lloyd,...) to drive the model (predictor-corrector)
  - Model order reduction for muscles
- Moment arm calculation
  - Currently, the common (analytical) method of An (1992) is used. However, due to the knowledge of the muscle force directions and the resulting geometry, accurate moment arms can be computed
- Validation
  - Biodex experiments for moment arms
  - Linking experimentally determined EMG data to drive the model and validate motion.

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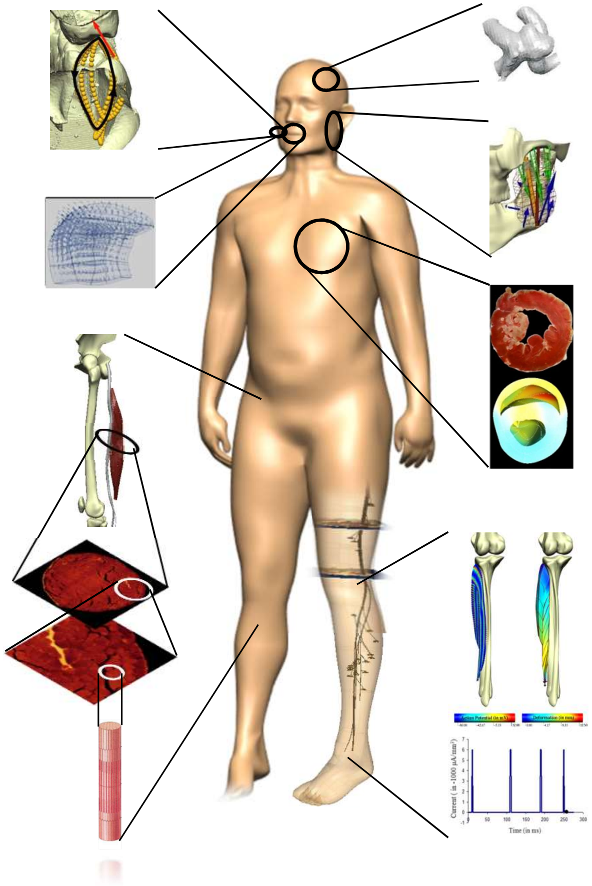

THANK YOU!

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