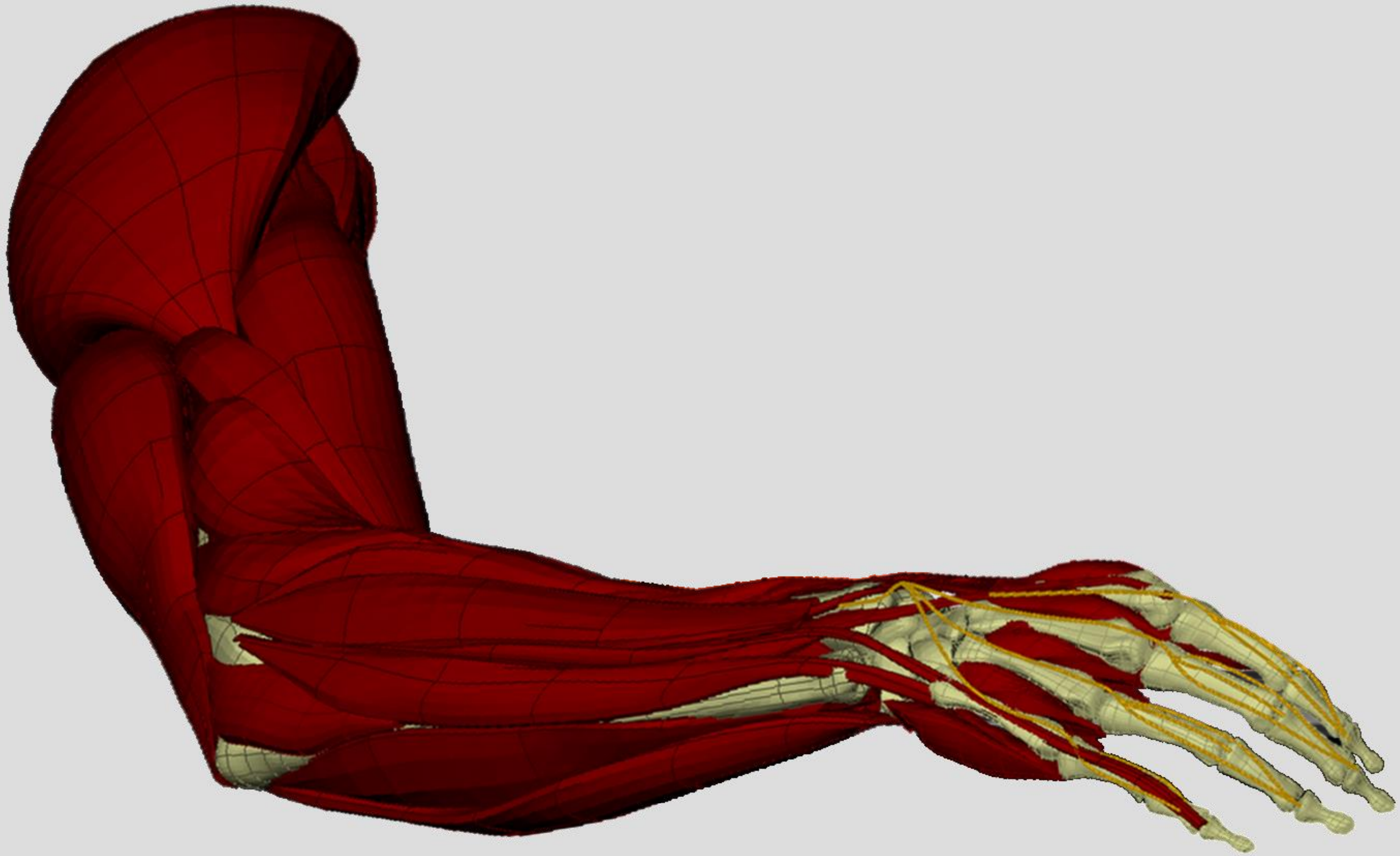
Muscle Modelling in LS-DYNA

O. Röhrle (Fraunhofer IPA/Uni Stuttgart), O. Avci (Fraunhofer IPA)

DYNAMORE INFOTAG
NENSCHMODELLE



Motivation

- **Performance Centre of »Mass Personalization«**
  with personalized Products for Business to User (B2U) Models

Strategic Pooling of Competencies at Stuttgart – with due industrial integration

Fraunhofer IAO

Fraunhofer IBP

Fraunhofer IGB

Fraunhofer IPA

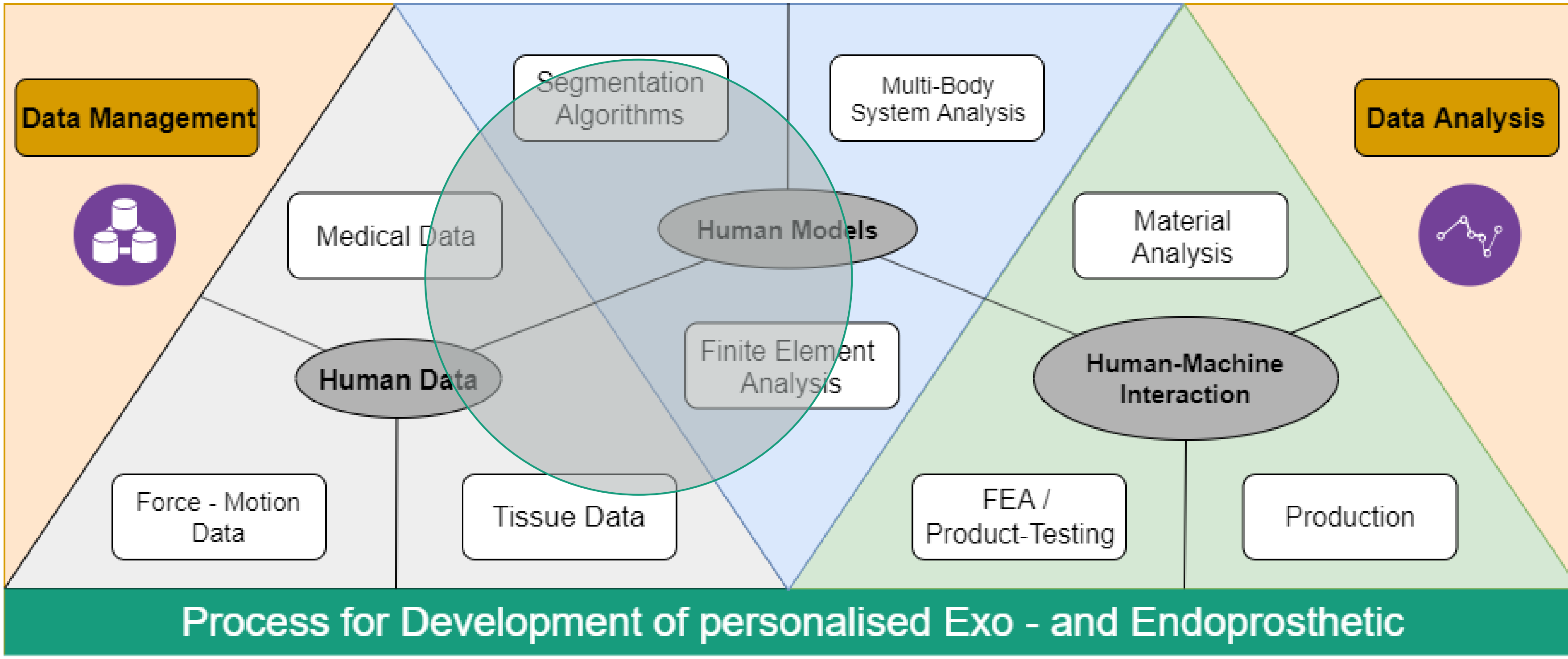
Universität Stuttgart

Industry partners

Goal:

- Development of radically new user-oriented economic value added strategies

Process of (Product) Personalization



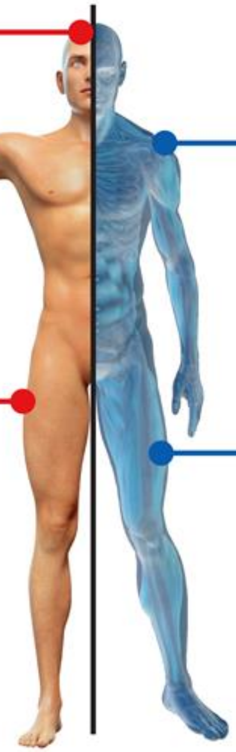
Personalisation in the world of health sciences

SimTech

The real world

Medical doctor
- Personalized data collection
- Decision making
- Personalized treatment

Individualization
- Prosthesis design
- Assistive robotic devices for rehabilitation and ergonomics
- Humanoid robots and interaction with humans



Simulation environments
- High-performance computing
- Data sharing
- Pervasive computing
- Adaptive human-computer interaction

Multi-X modeling
- Subcellular dynamics
- Perfusion, metabolism
- Neural recruitment
- Muscle mechanics
- Cognition, motion

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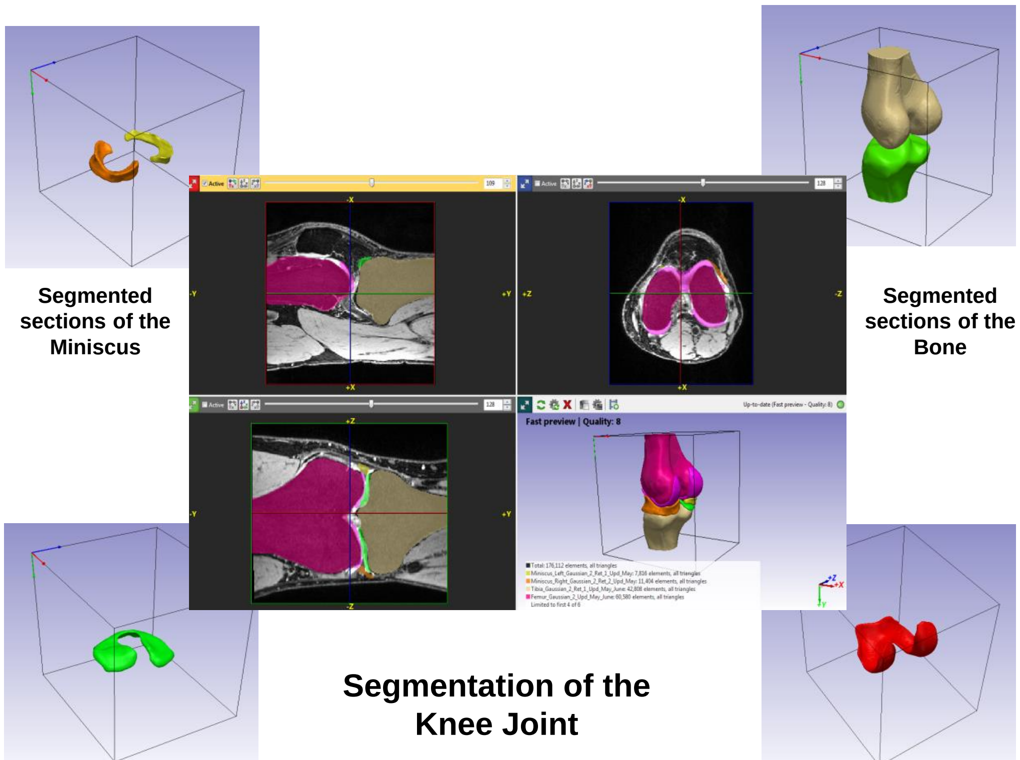
3D-Image Segmentation

Medical Image Segmentation

Mask Generations for the Knee Joint

Implemented as plugin within Simpleware



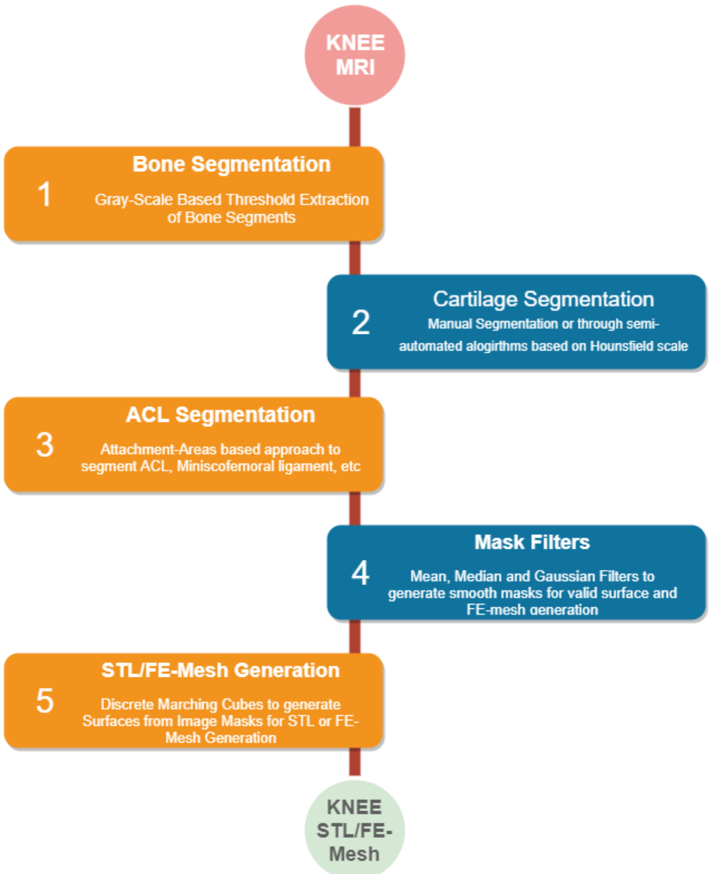
Segmented sections of the Miniscus

Segmented sections of the Bone

Segmentation of the Knee Joint

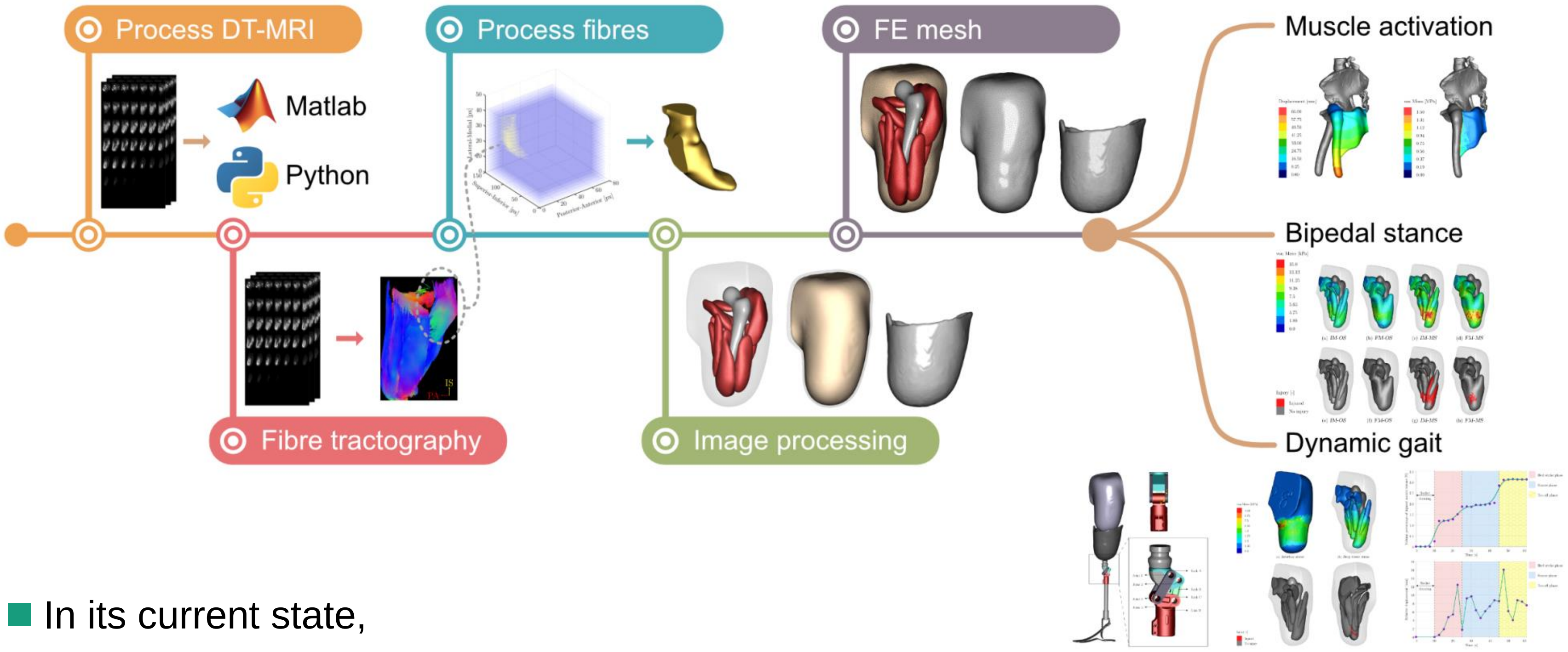
Segmented sections of the Cartilage – Tibia-End

Segmented sections of the Cartilage – Femur-End



Exemplar in Personalised Medicine

Design and Development of Personalised Prosthetics



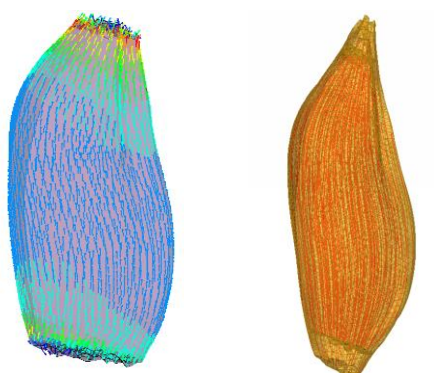
- In its current state,
  - the workflow can automatically process medical images to FE mesh for analyses, and
  - the developed model can predict tissue injury.

Publication:
Ramasamy, E.; Avci, O.; Dorow, B.; Chong, SY.; Gizzi, L.; Steidle, G.; Schick, F.; Röhrle, O.: An Efficient Modelling-Simulation-Analysis Workflow to Investigate Stump-Socket Interaction Using Patient-Specific, Three-Dimensional, Continuum-Mechanical, Finite Element Residual Limb Models. Frontiers in Bioengineering and Biotechnology **6** (2018), 1–17, ISSN 2296-4185

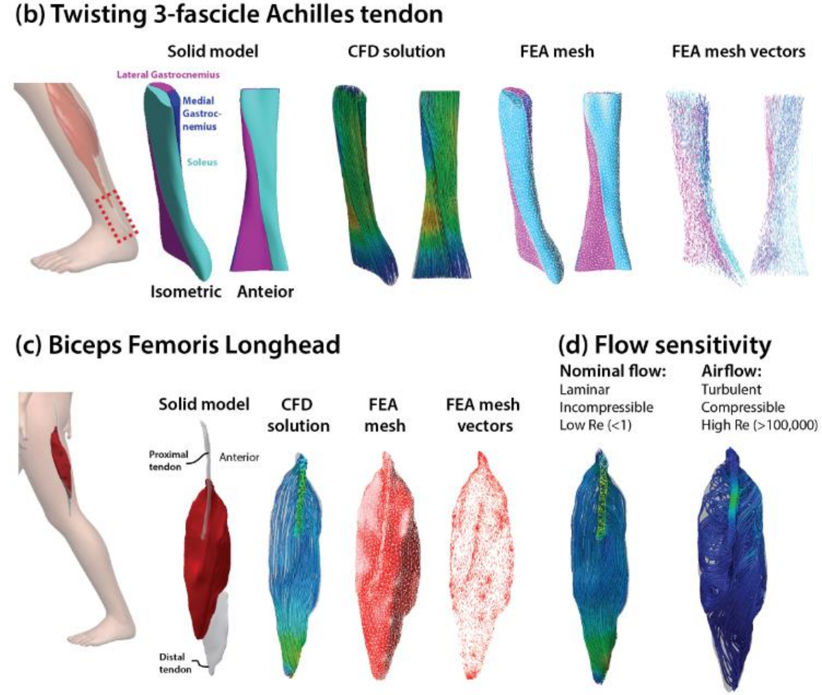
Medical Image Segmentation

Fibre Orientation Modelling Tool

- Application of CFD to determine fibre orientations in muscles and tendons has already been investigated in several literatures
- Potential replacement of CFD solution with a Thermal analysis
- A 3D steady-state thermal analysis is relatively inexpensive compared to a CFD simulation

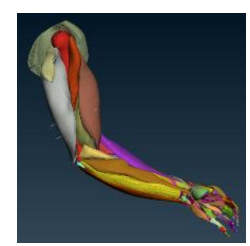


Thermal analysis-based fibre determination



Inouye Joshua, Handsfield Geoffrey, Blemker Silvia, *Fiber Tractography for Finite-Element Modelling of Transversly Isotropic Biological Tissues of Arbitrary Shape Using Computational Fluid Dynamics*, SummerSim'15, pp 1-6, 2015

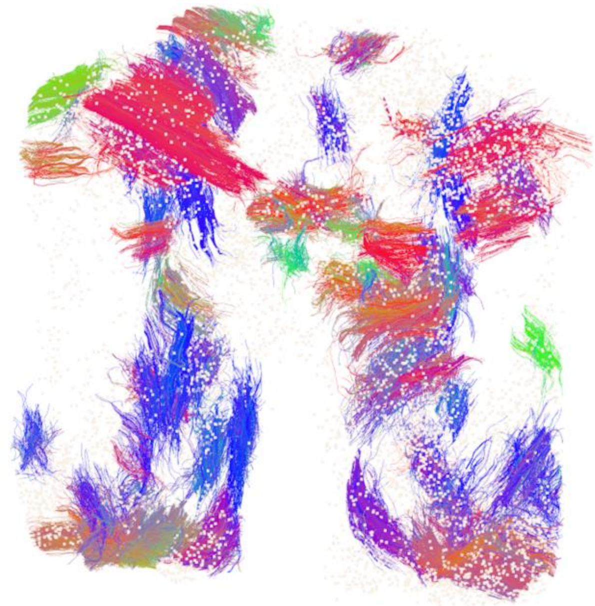
Examples of Human models for witg



Medical Image Segmentation

Muscle Segmentation Tool

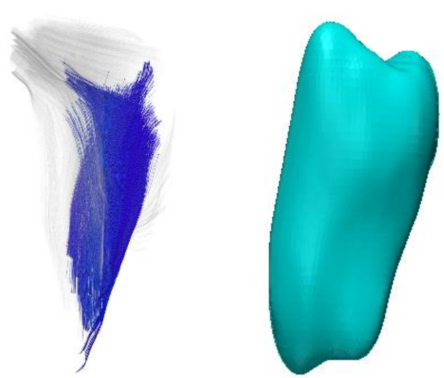
- Estimating Muscle Fibre Directions in Diffusion MRI through Fibre Tractography
- Fibre Clustering based on Machine-Learning algorithms to generate representative muscle volumes
- Validating Muscle Groups through transfer of Muscle fibre groups from DTI-Space to MRI-Space



Muscle Segmentation with Fibre Tractography

In Progress

Algorithm development for automatic fibre clustering and muscle volume generation



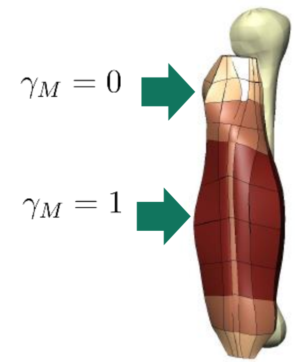
DTI-based muscle and fibre segmentation

3D-Muscle Simulation

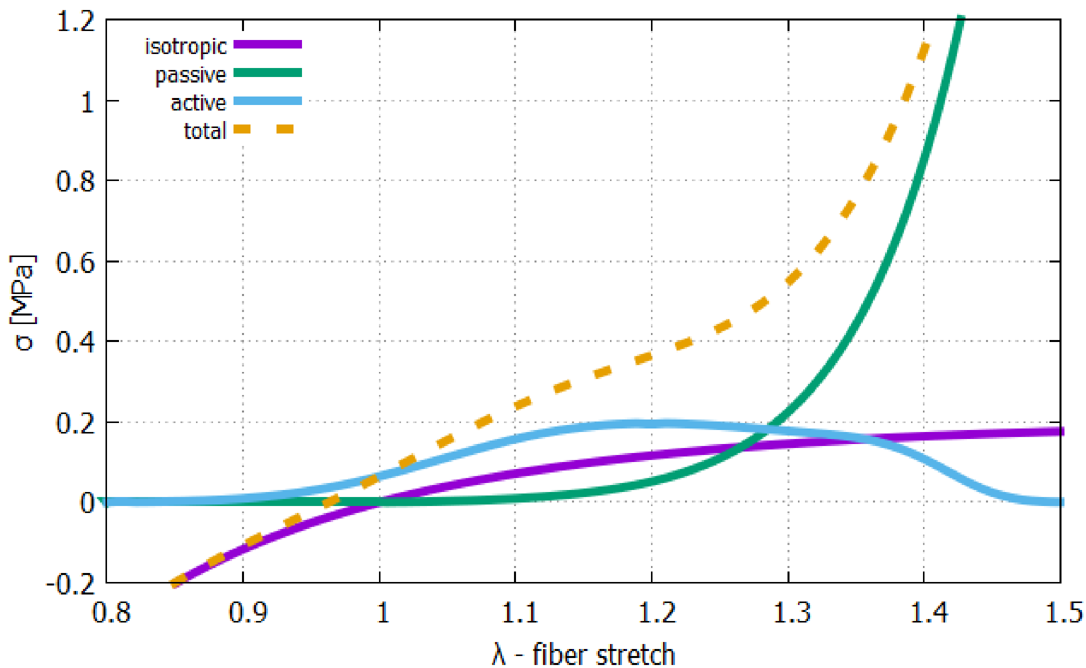
Extended Mooney-Rivlin model (Crisfield)

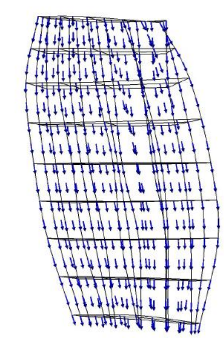
Material Modelling

$$\mathbf{S}_{\text{muscle}} = \underbrace{B_1\mathbf{I} + B_2\mathbf{C} + B_3\mathbf{C}^{-1} - p\sqrt{I_3}\,\mathbf{C}^{-1}}_{:=\mathbf{S}_{\text{iso}}} + (1-\gamma_{\text{ST}})\big(\underbrace{S_{\text{passive}}(\boldsymbol{a}_0 \otimes \boldsymbol{a}_0)}_{:=\mathbf{S}_{\text{passive}}} + \alpha\gamma_{\text{M}}\,\underbrace{S_{\text{active}}(\boldsymbol{a}_0 \otimes \boldsymbol{a}_0)}_{:=\mathbf{S}_{\text{active}}}\big)$$



[Sprenger 2015]





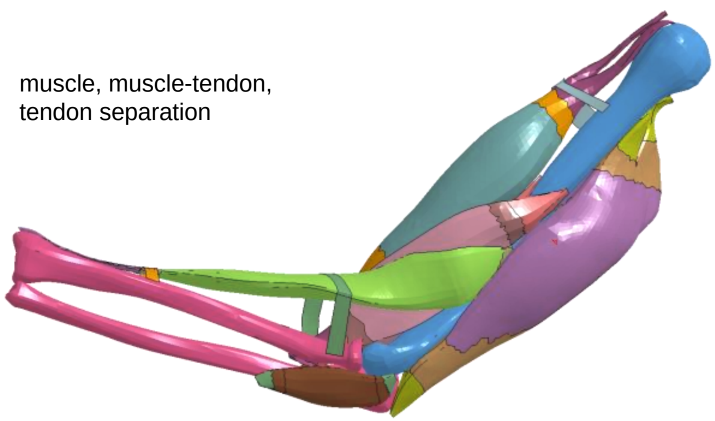
Fiber directions $\mathbf{a}_0$

Muscle Modelling and Simulation

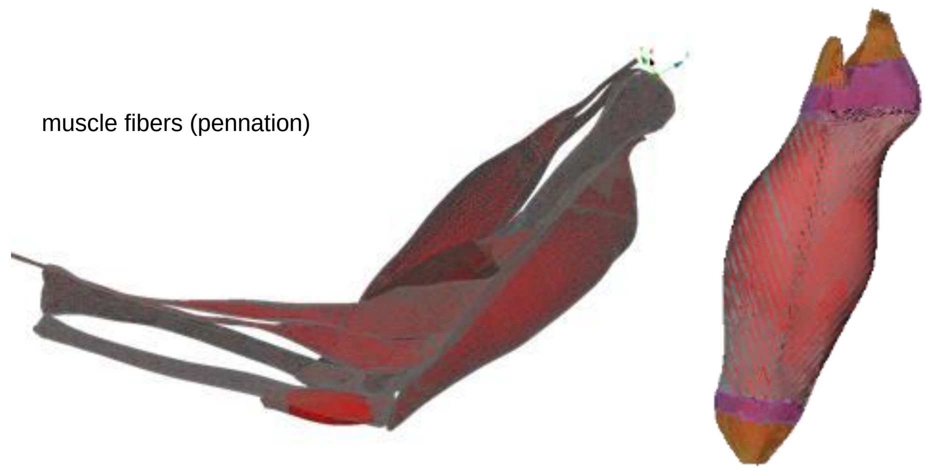
Determination and Assessment of Muscle Activations

- **Goals**: Find the right pre-stretches of the muscle-tendon system and the right combination of muscle activations in time for the motion of the lower arm
- The Finite-Element model of the arm

muscle, muscle-tendon,
tendon separation



muscle fibers (pennation)



- The model consist of 5 muscles and their individual fibre orientations
- Muscles are separated into muscle, muscle-tendon intermediate zone and tendon

Challenges in Modelling the Musculoskeletal System

- Modelling the musculoskeletal system in three dimensions
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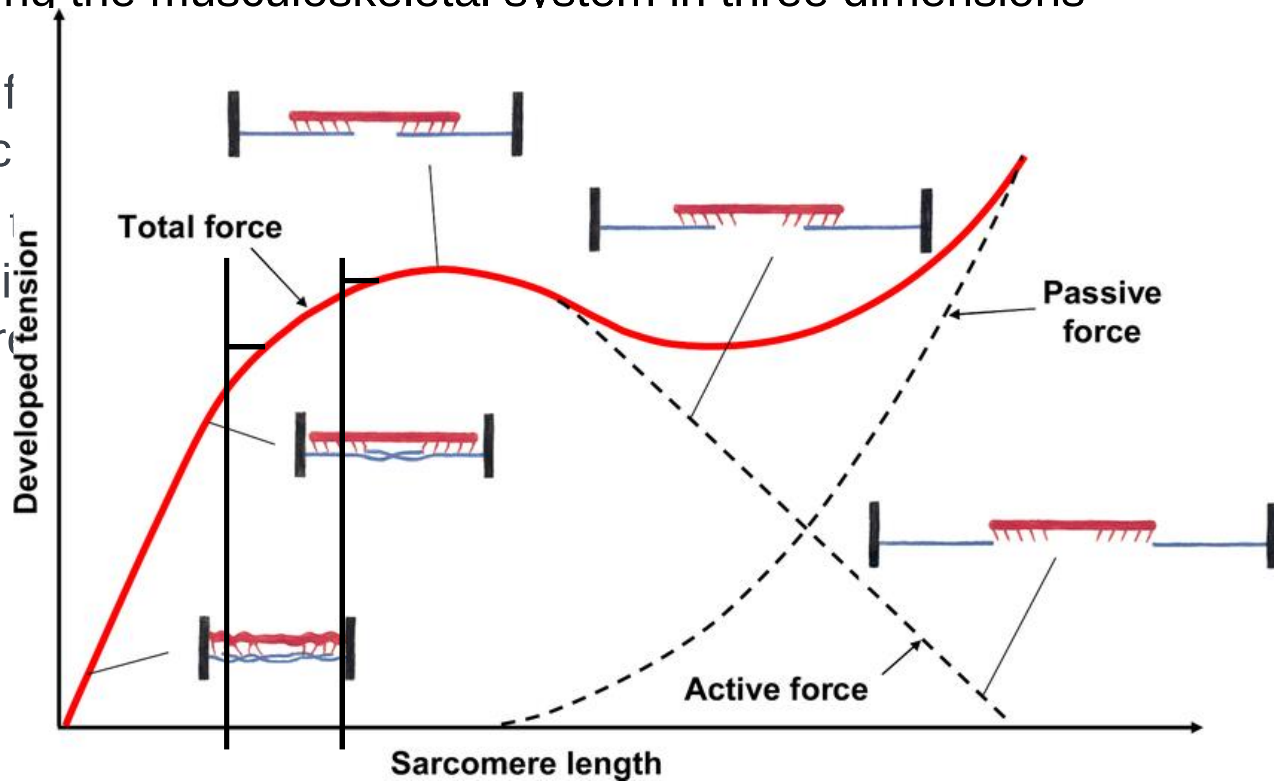
  - Due t ... duced from medi ... uscle the refer



How to find the reference configuration?

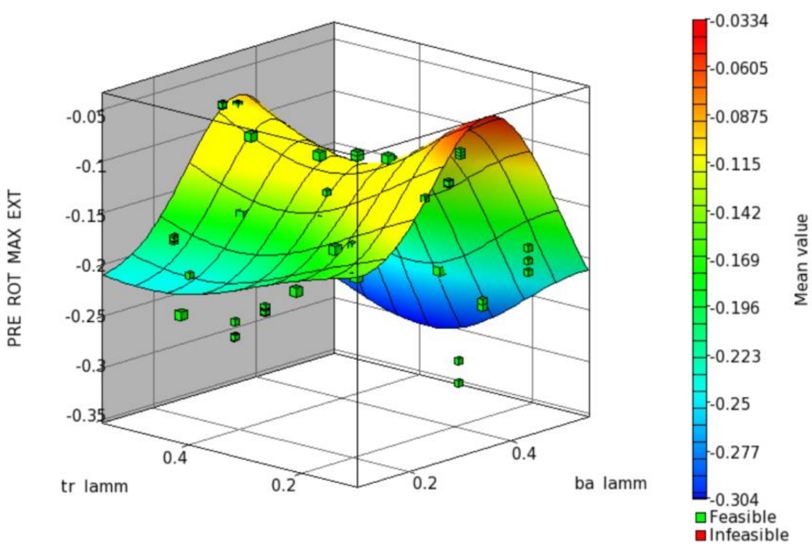
- **Modelling the muscle-tendon pre-stretch (PS)**
  - All muscles have initial pre-stretches and pre-strain, which are not known
  - The pre-stretch state for the initial arm position is important to generate the arm motion by the muscle forces triggered by activation

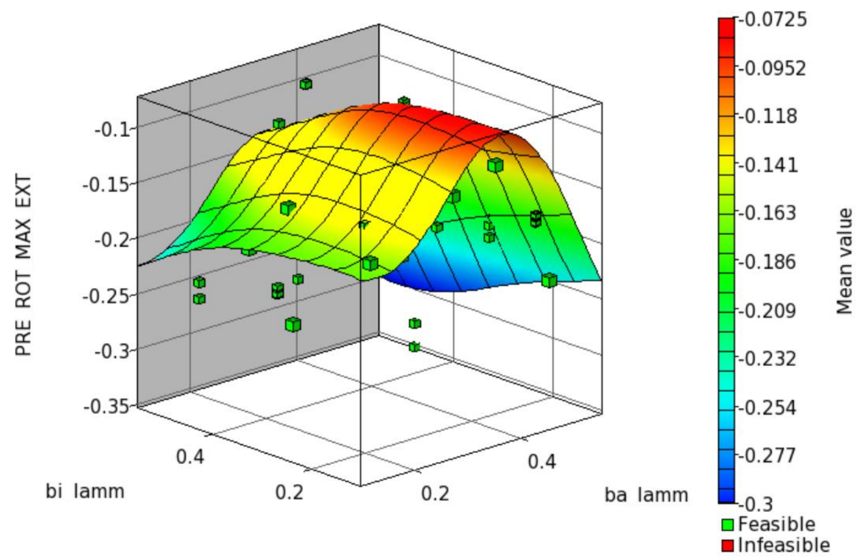
- **Nested optimization of the pre-stretches**
  - Conditions of the outer optimization:
    1. Setting the pre-stretches of muscles and tendons and rotate back by applying a momentum force at the elbow joint, which is determined by an inner optimisation
  - Conditions of the inner optimization:
    1. Setting the pre-stretches of muscles and tendons

       → given by the outer optimization
    2. The resulting rotation is back rotated by momentum force at elbow joint

Surrogate modelling for finding optimal pre-stretches

- META-models: regression surfaces of the dominant variable in respect to the others





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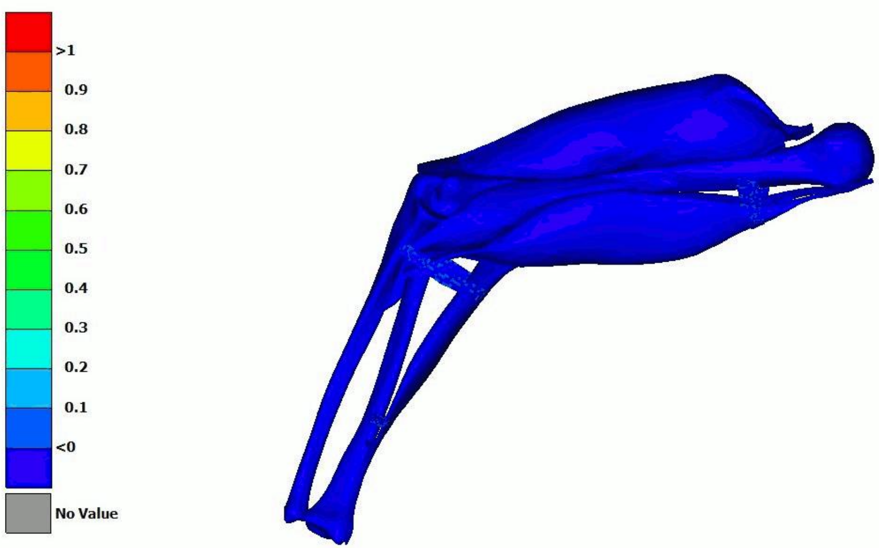
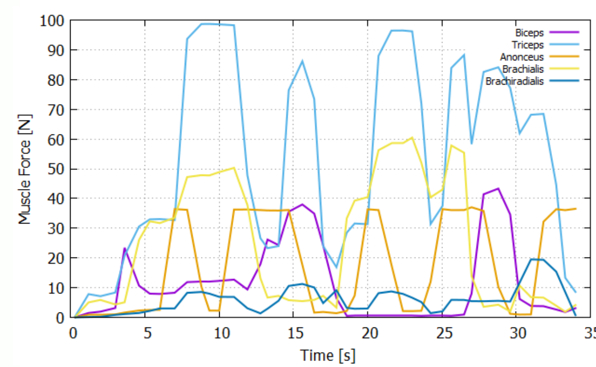
Muscle Modelling and Simulation

Determination and Assessment of Muscle Activations

- Simulation of defined set of activation patterns for analysis with the multi-grid optimization method
  - Load conditions: 1. Phase: setting pre-stretch; 2. Phase: back rotation; 3. Phase: gravitation force; 4. Phase: muscle activations
  - Sensitivity analysis with 1052 design points for muscle activation

    → optimizing the motion on a meta model in real time





uscle forces over time

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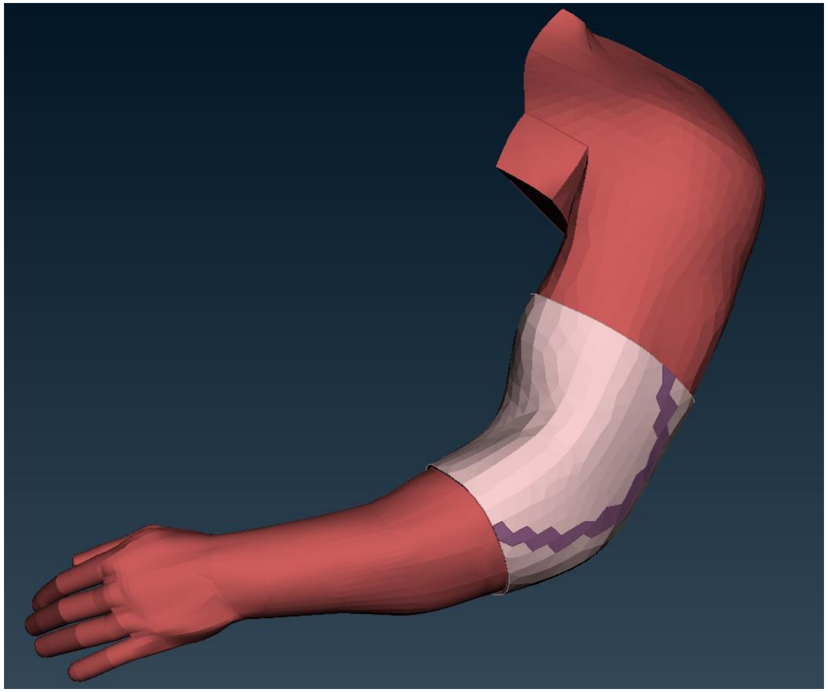
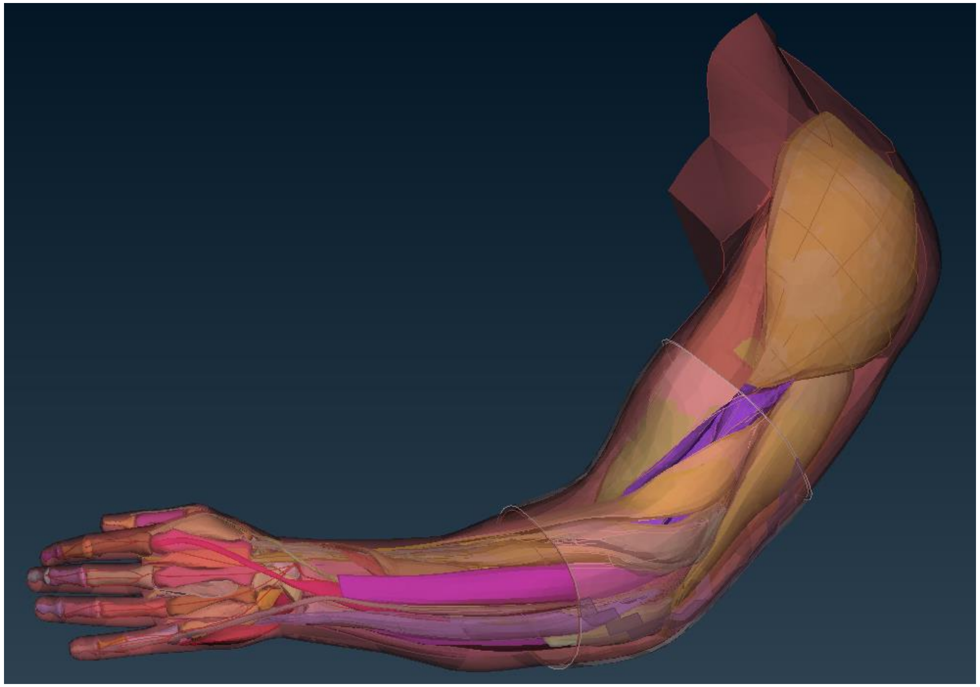
Future Applications:

Optimization of Function and Comfort of Orthopedic Textile Bandage during Dynamic Loading

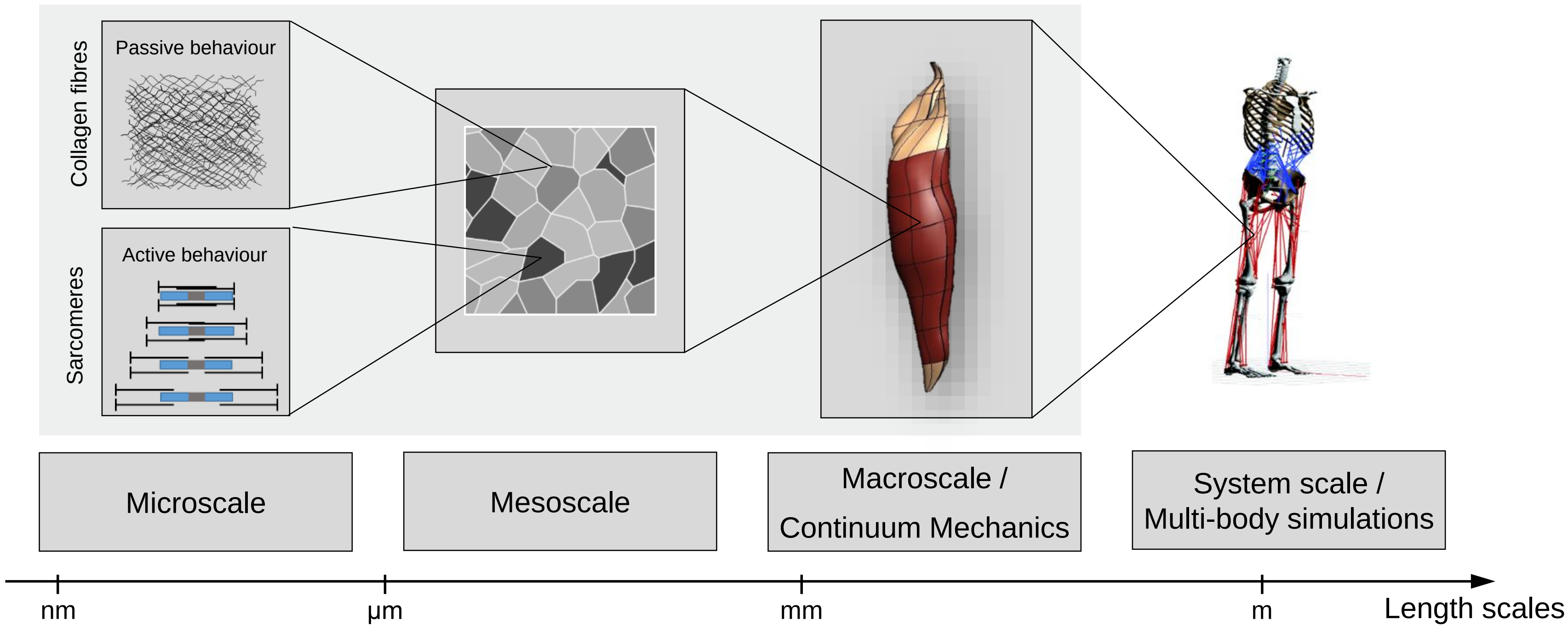




Motivation

SimTech

Skeletal muscle modelling across the scales: multiscale modelling



Multiscale modelling based microstructural features, e.g. collagen stiffness/alignment/volume fraction, …

Microstructural properties ↔ Macroscopic material behaviour

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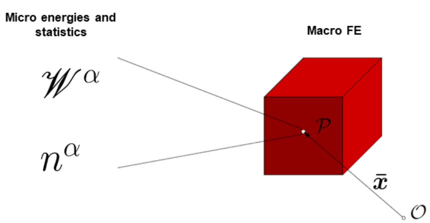
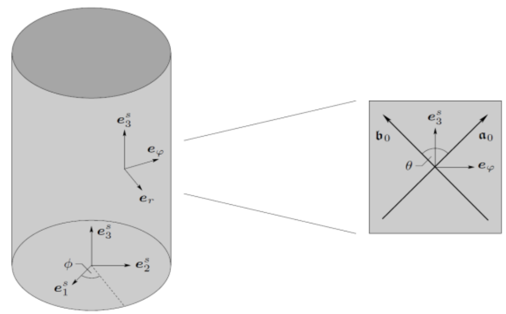
Constitutive Modelling of the Micro-Constituents

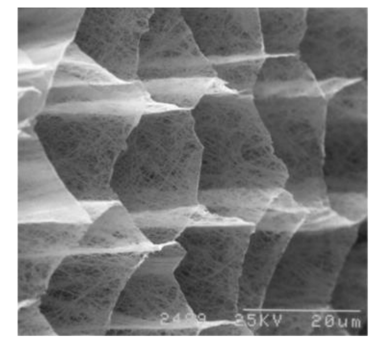
- Muscle matrix: Collagen fibre families and orientation distribution function

Assumptions for the description of the muscle-matrix constituent

passive behaviour of the matrix is mainly influenced by helically arranged collagen fibres around the muscle fibre







[Purslow, 2002]

a single collagen fibre may be described in spherical coordinates by

$$\begin{aligned} \mathfrak{a}_0(\theta,\phi) &= -\sin\theta\sin\phi\,\boldsymbol{e}_1^s + \sin\theta\cos\phi\,\boldsymbol{e}_2^s + \cos\theta\,\boldsymbol{e}_3^s \\ \mathfrak{b}_0(\theta,\phi) &= \sin\theta\sin\phi\,\boldsymbol{e}_1^s - \sin\theta\cos\phi\,\boldsymbol{e}_2^s + \cos\theta\,\boldsymbol{e}_3^s \end{aligned} \quad \text{with} \left\{ \begin{array}{lcl} \boldsymbol{e}_3^s & = & \boldsymbol{a}_0 \\ \theta & : & \text{polar angle} \\ \phi & : & \text{azimuthal angle} \end{array} \right.$$

Dispersion is modelled by an orientation distribution function (ODF) $\mathfrak{p}(\mathfrak{a}_0) = \mathfrak{p}(\mathfrak{b}_0) = \mathfrak{p}(\theta,\phi) = \mathfrak{p}_\theta(\theta)\mathfrak{p}_\phi(\phi)$

[Lanir, 1983]

INDIVIDUALISATION

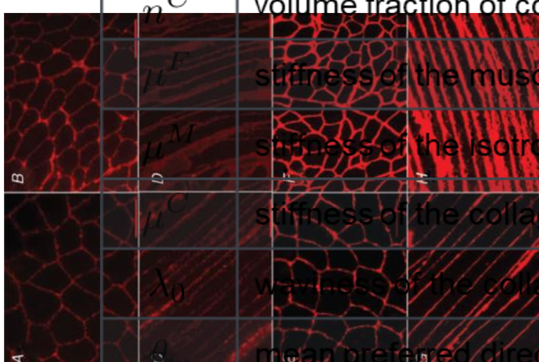
- Towards a person-specific constitutive law based on homogenisation techniques

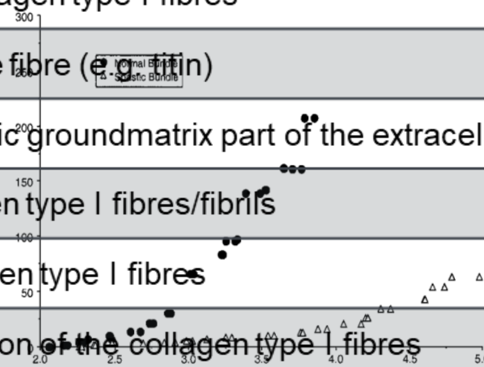
microscopic experiments → μ^F, μ^M, μ^C → $\mathscr{W}$ ← $n^F, n^C, \lambda_0, \theta_m, b$ ← micro-structural data

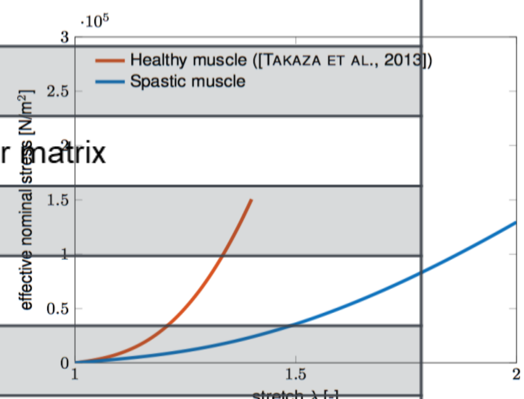
material data from data-rich scales

structural data (ideally from in vivo imaging)

n^M	volume fraction of the extracellular matrix
n^C	volume fraction of collagen type I fibres
μ^F	stiffness of the muscle fibre (e.g. titin)
μ^M	stiffness of the isotropic groundmatrix part of the extracellular matrix
μ^C	stiffness of the collagen type I fibres/fibrils
λ_0	waviness of the collagen type I fibres
θ_m	mean preferred direction of the collagen type I fibres
b	distribution function parameter accounting for the spreading around the mean direction







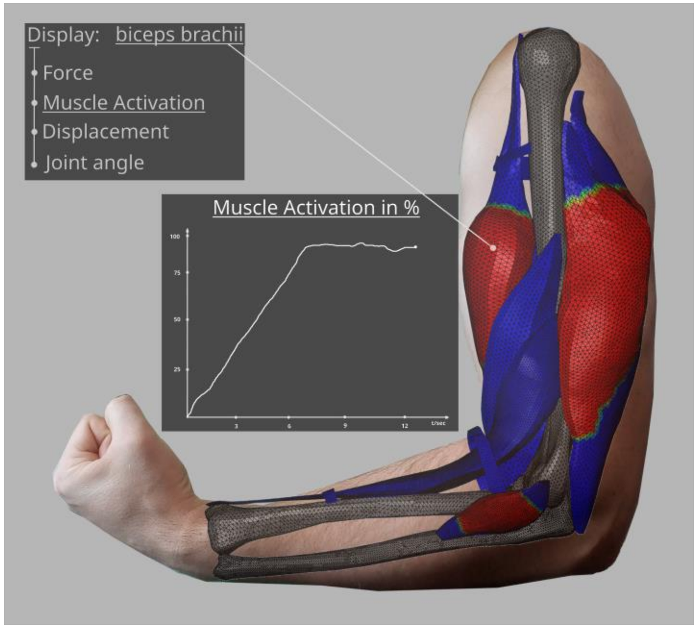
PerSiVal: Pervasive Simulation and Visualization

A SimTech project just recently started (in collaboration with JP Sedelmair und Prof. Rothermel)

Goals:

- Real-time visualization of complex but realistic biomechanical models in AR/VR
- Pervasive Computing (cloud, edge, HPC)
- Surrogate modelling workflow:
  - Data interpolation using sparse grids
  - Distributed machine learning
- Quantifiable data, e.g. muscle deformations
- Model information and annotations

Applications: Rehabilitation, Ergonomics



Human-Socket-Interaction

Numerical Example II: Human-Socket-Interaction

BMBF – Joint Venture Project

Patch2Patient

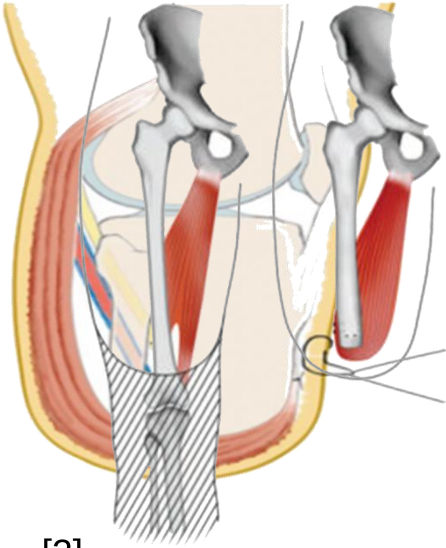
Automated individual-based Manufacturing of patient-specific CFRP-Components by Fiber Patch Placement

Motivation: Transfemoral amputation – improving comfort of prostheses

Source: http://www.schildkroet-fitness.com/home.html

Non-traumatic amputation

Clinical procedure: *Myodesis*



[1] [2]

[1] Source: http://www.physio-pedia.com/File:Foot_amputation_levels_(2).png

[2] Source: https://de.pinterest.com/pin/77827899782052326/

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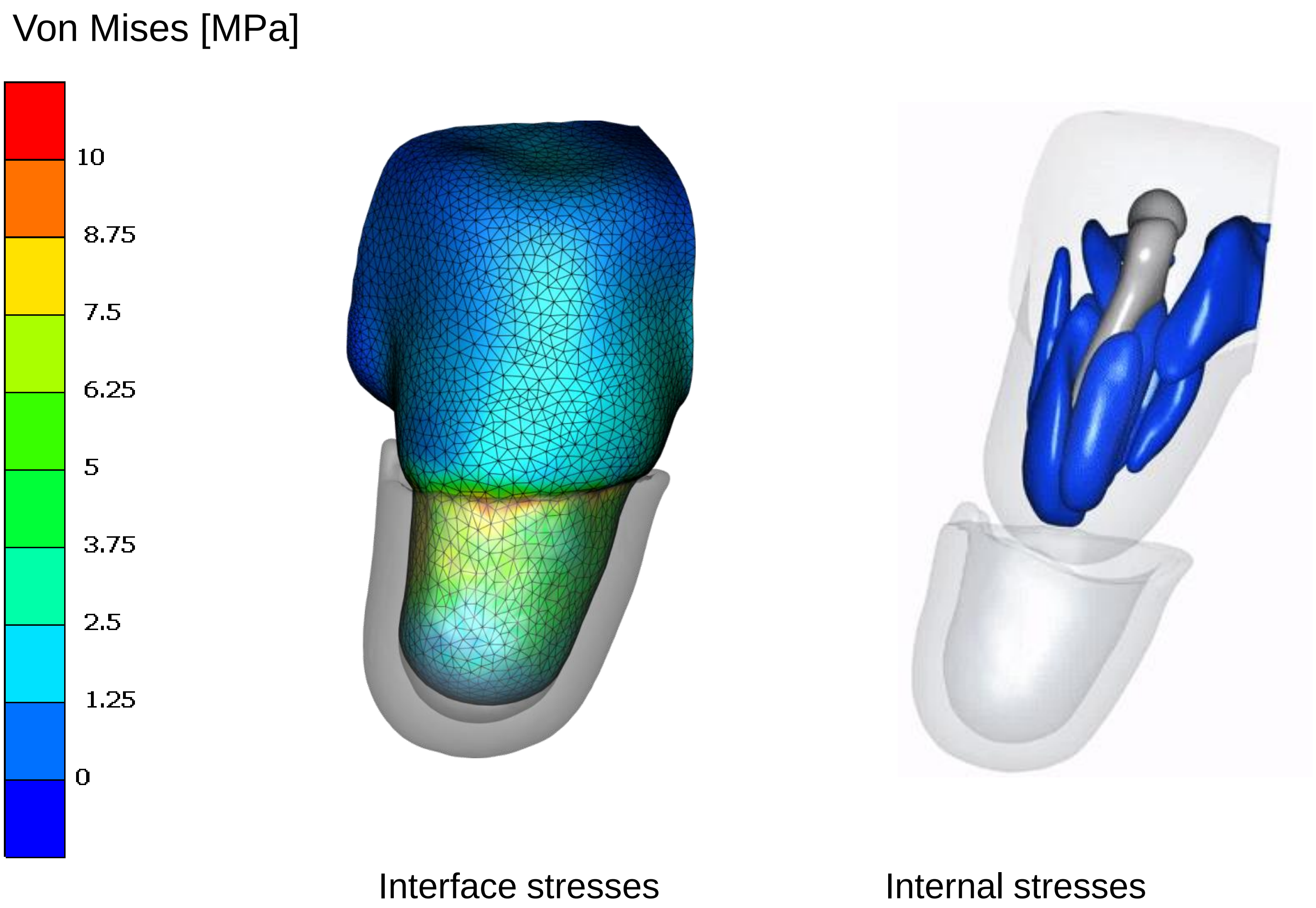
Limb Simulation

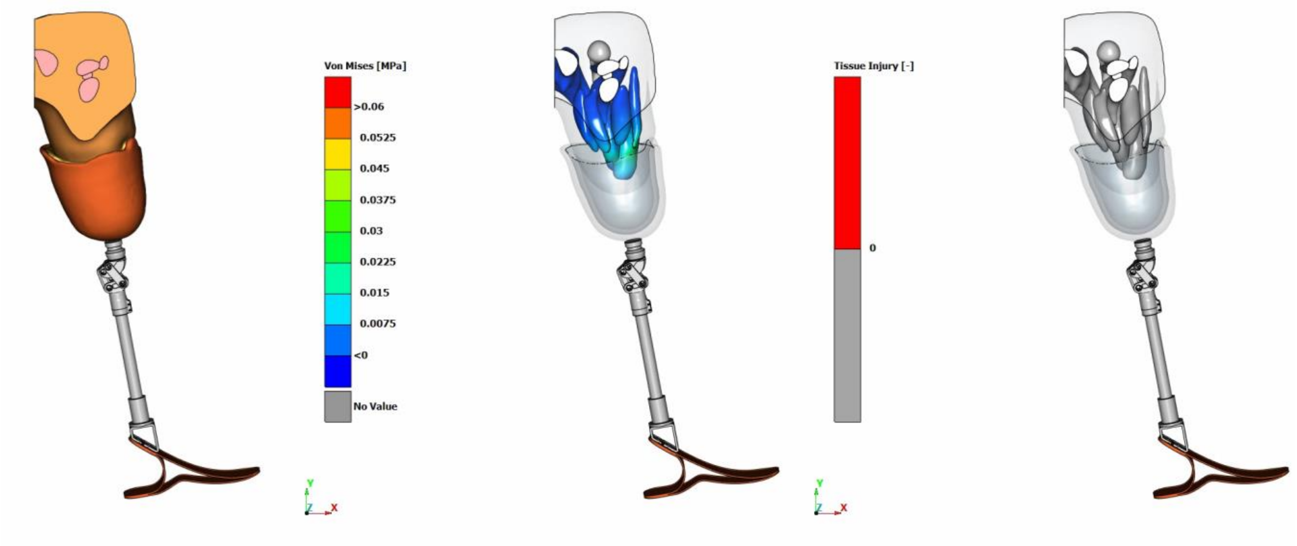
Example 1 Results – Donning prosthetic socket



Selected Applications: Above Knee Amputee Modelling

Example: socket donning

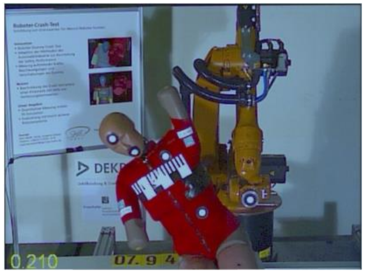
- Investigating internal pressures to assess muscle-stump interaction for above-knee amputees.



Ramasamy, Avci, Dorow, Chong, Gizzi, Steidle, Schick, Röhrle. *An efficient modelling-simulation-analysis workflow to investigate stump-socket interaction using patient-specific, three-dimensional, continuum-mechanical, finite element residual limb models*, Front. Bioeng. Biotechnol., 2018.

Mass Personalization B2U

Human-Machine Interaction



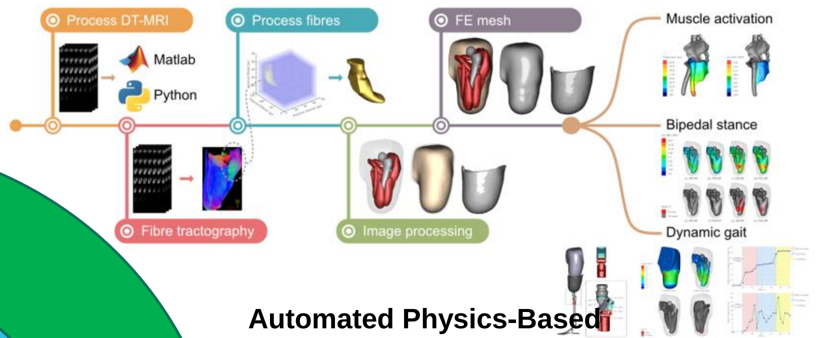
Human-Robot-Collusion (S. Oberer - IPA)

Motion apparatus

Exoprosthetics & Sport

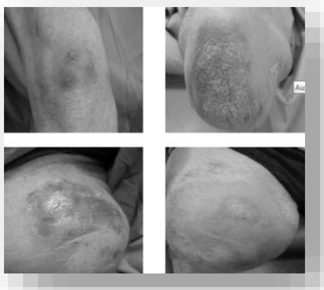
Endoprosthetics

Personaliza-tion in Medicine and Sport

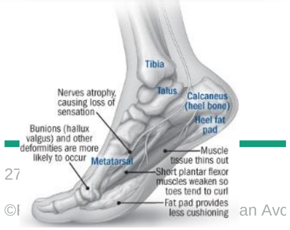


Automated Physics-Based Orthopedic Workflows

Personalized Products

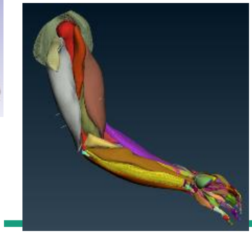


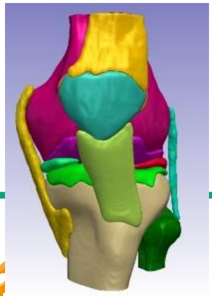
Limb-Prosthetic-Interaction

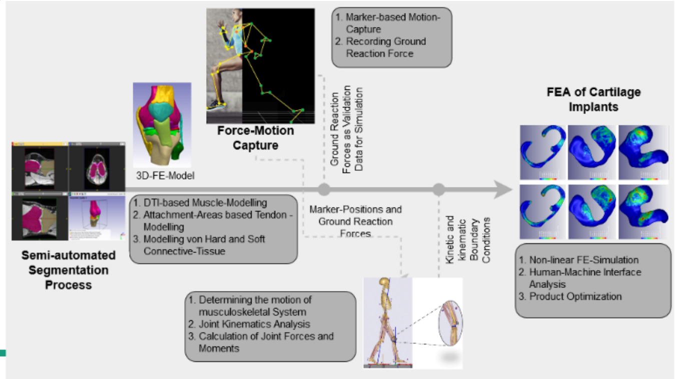


Foot-Shoe-Interaction

Biomechanics - Human







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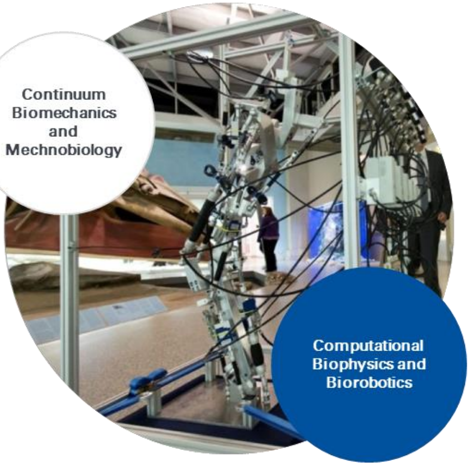
First International Musculoskeletal System Symposium

Organised by Institute for Modelling and Simulation of Biomechanical Systems at the University of

1. International
Musculoskeletal
System Symposium
Stuttgart
July 16-18, 2020

First International Musculoskeletal System Symposium



On June 1, 2019, the University of Stuttgart established the new **Institute for Modelling and Simulation of Biomechanical Systems**. We would like to take this occasion to invite you to Stuttgart for a "Musculoskeletal System Symposium". The goal is to bring together young and renowned international researchers to discuss and improve our understanding of the musculoskeletal system as a whole. The symposium will take place from July 16 - 18, 2020. We are all looking forward to welcoming you in Stuttgart.

Please register online
https://www.imsb.uni-stuttgart.de/Musculoskeletal_System_Symposium_2020/

Registration fee (before May 31, 2020):
360 Euro (delegates)
150 Euro (students)

International Speakers

We welcome scientists in the field of the musculoskeletal system.

Confirmed Keynote Speakers

- Bilston, Lynne, NeuRA, Sydney, Australia
- Blemker, Silvia, University of Virginia, USA
- Ehlers, Wolfgang, University of Stuttgart, Germany
- Enoka, Roger, University of Colorado, USA
- Fridén, Jan, Paraplegie.ch, Schweiz
- Geyer, Hartmut, CMU, Pittsburgh, USA
- Gollhofer, Albert, Albert-Ludwigs-Universität Freiburg, Germany
- Heckman, CJ, Northwestern University, USA
- Hunter, Peter, Auckland Bioengineering Institute, NZ
- Lieber, Richard, Shirley Ryan AbilityLab, Chicago, USA
- Lloyd, David, Griffith University, Gold Coast, Australia
- Pivonka, Peter, QUT, Brisbane, Australia
- Taylor, William, ETH, Zürich, Switzerland
- Viceconti, Marco, University of Bologna, Italy
- Willie, Bettina, McGill, Montreal, Canada

Interested in Advertising?

Venue

The conferen
the Staatsgale

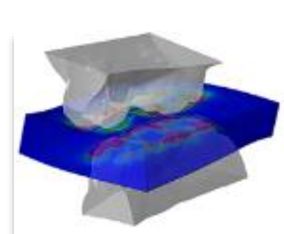
The Staatsgalerie, built in 1843, belongs to the most popular art museums in Germany. In 1984 the new state gallery has been added.

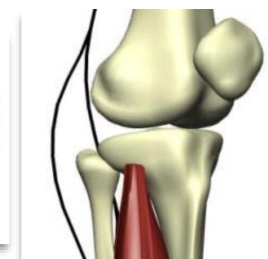
The gallery exhibits paintings from the 14th to the 21st century, interlinks traditional and modern art, and presents many historical highlights from the region. Located in the centre of Stuttgart, it stands out with its great architectural design. From the central station, it's only a ten-minute walk.

SimTech

Our Competencies

- Finite Element Simulation
- Material modeling and testing
- Simulation of the muscle apparatus
- Computer Vision & Medical Image Segmentation
- Workflow- and Video-Overlay-Technique
- Virtual development of implants and prostheses
- Virtual ISO-testing procedures
- Stress analysis and structural optimization
- Dental biomechanics
- Simulation of biting power





„The *Virtual Orthopedic Lab* develops simulation concepts for development and optimization of products in orthopedics, prosthetics and dentistry.“

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Thank you!

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