UNIVERSITÄT DES SAARLANDES

APPLIED MECHANICS

OPTIMIZING FRACTURE HEALING: REALISTIC BOUNDARY CONDITIONS

Annchristin Andres – annchristin.andres@uni-saarland.de
Kerstin Wickert
Michael Roland
Stefan Diebels

Applied Mechanics

- Modeling of microstructured **continua** and the **simulation** of their mechanical properties
- Research topics cover the three areas of **theory**, **numerics**, and **experimentation**
- Material behavior of metals, polymers, and **biomaterials** on different scales

- **BIOMECHANICS:**
  - Bone healing
  - Patient monitoring
  - Experimental validation
  - Personalized simulation
  - Clinical application of biomechanics

Applied Mechanics - Current projects

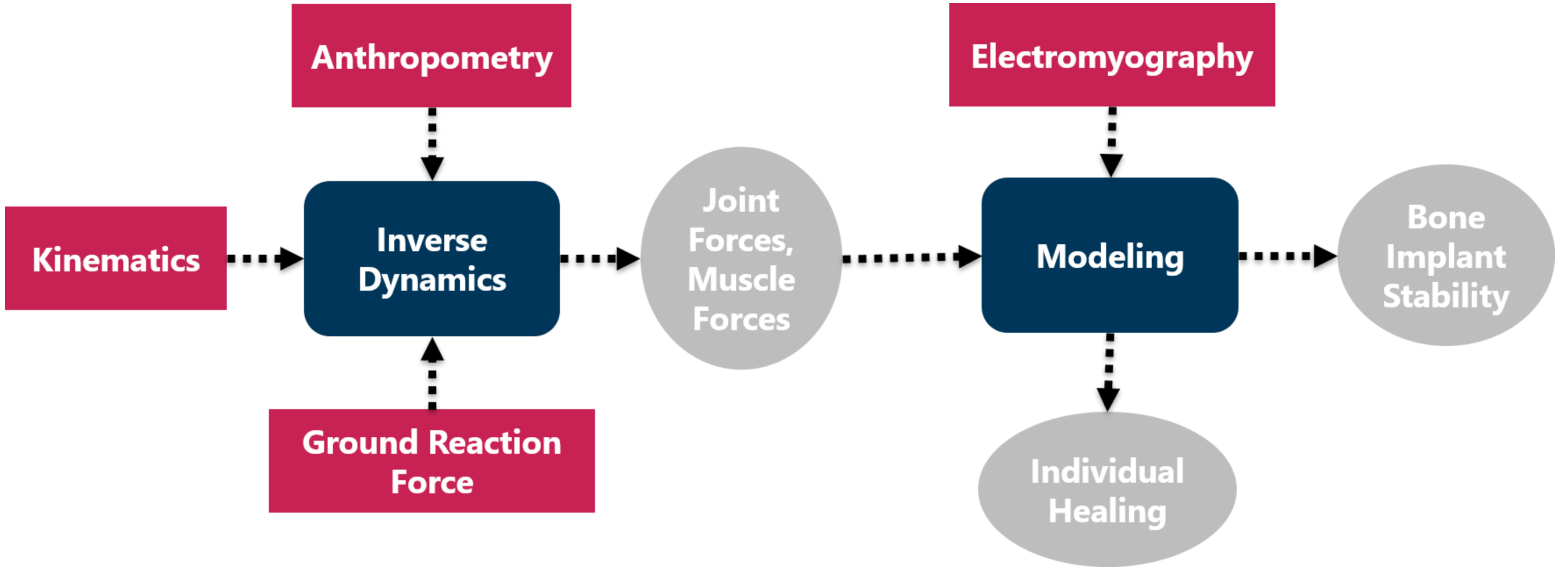
- VirtuS
- Smart Implants
- GO-FIT-FAST
- SPP 2311

Introduction

Interfragmentary movement (IFM) is a key parameter for fracture healing and changes due to individual external influences (mechanical loading, type of fixation, fracture type, and location).

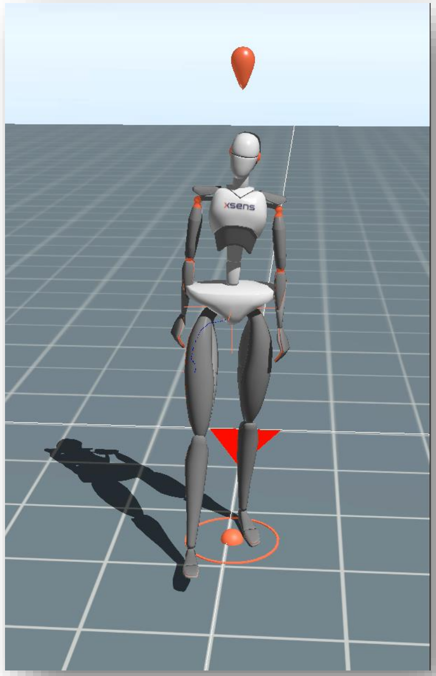
IFM = micromotion between bone fragments at a fracture site during the healing process.

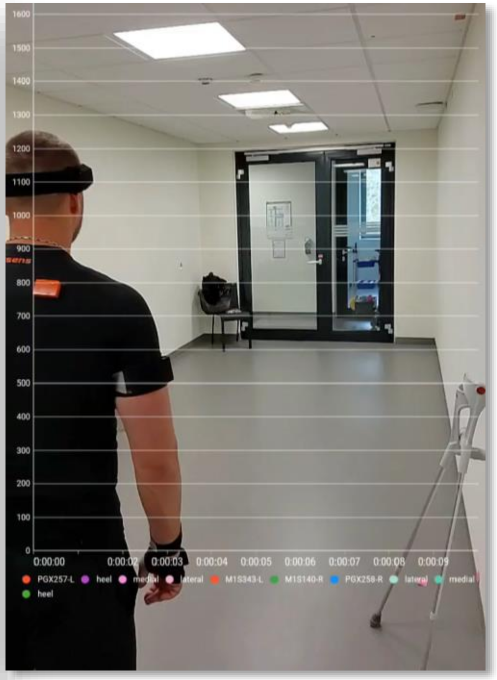
- **Controlled interfragmentary movement** can actually **stimulate callus formation**
- **Too much movement** can lead to **non-union or delayed healing**.
- **Too little movement** (i.e., rigid fixation) can prevent proper callus development

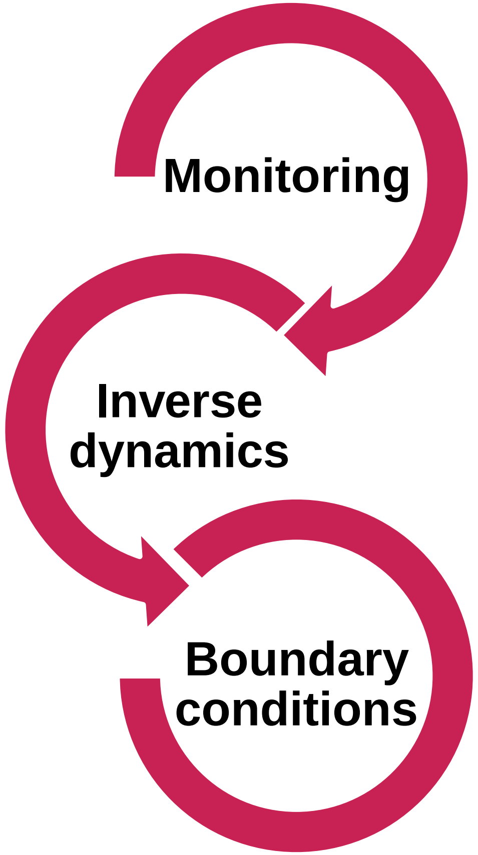


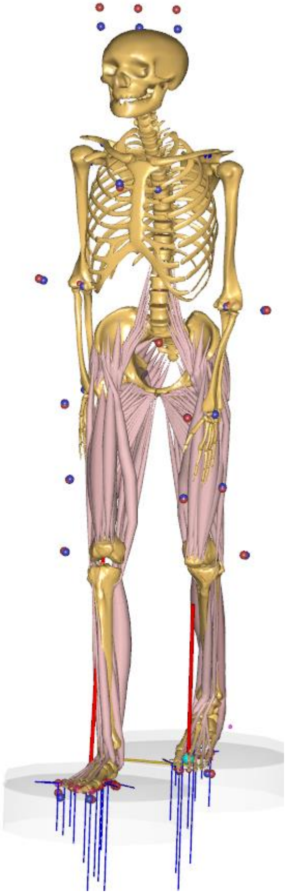
[1] Werner Siemens Stiftung/Oliver Lang

Methods – Part 1





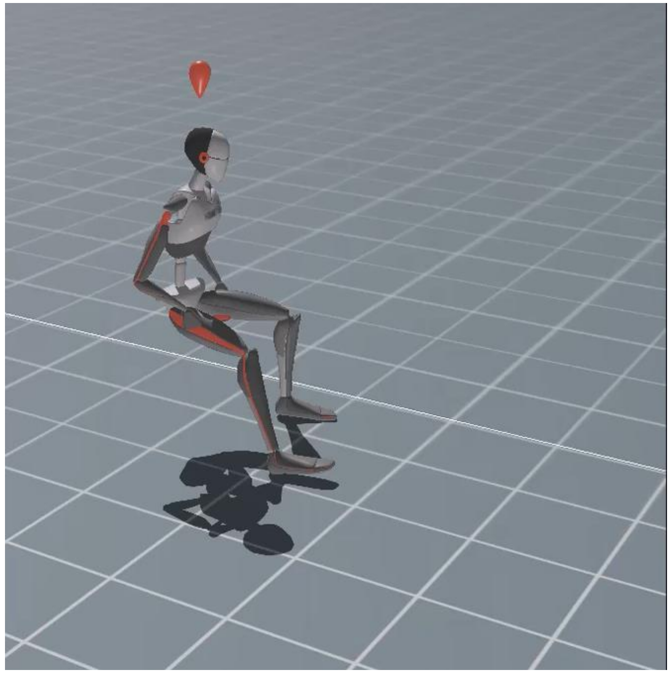


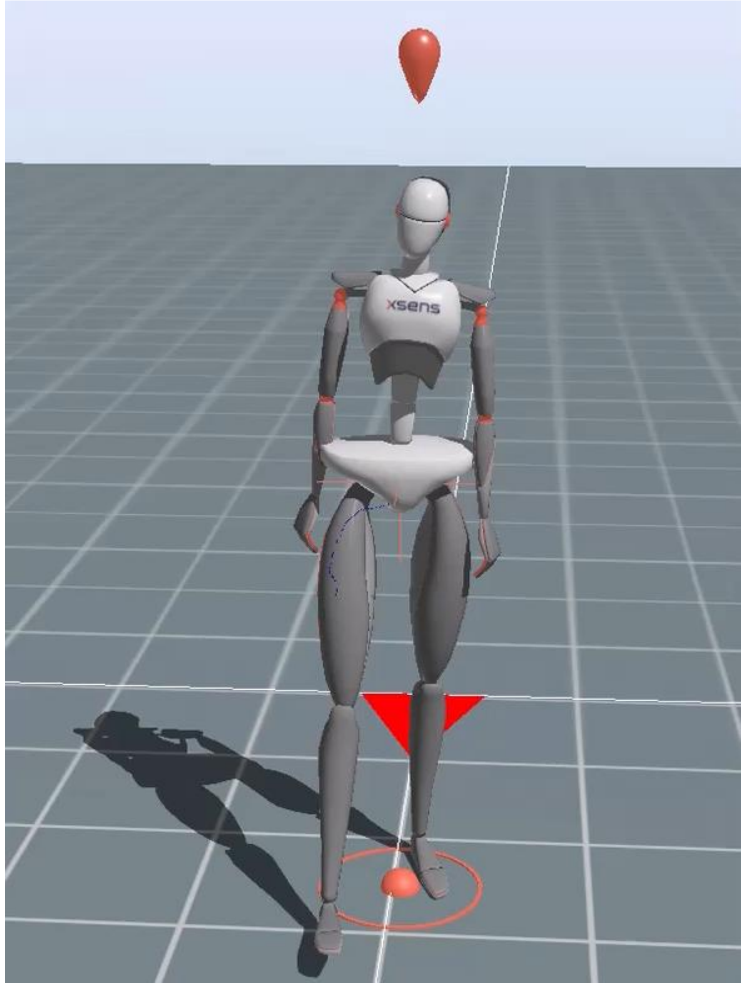


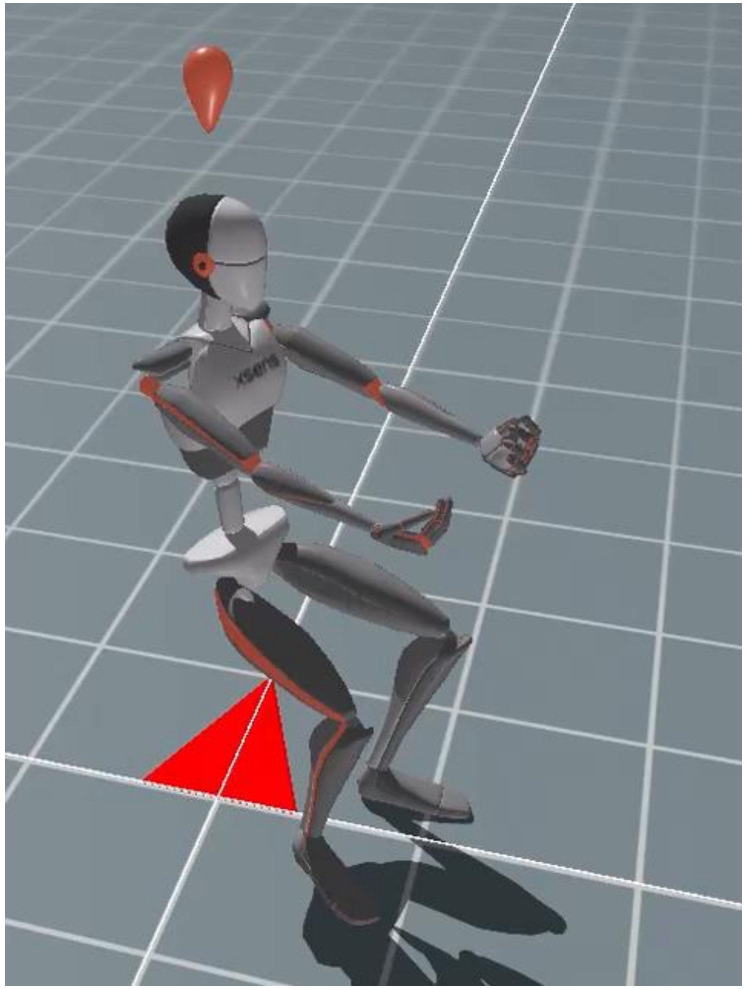
Monitoring: Kinematic - Xsens™

- 17 inertial measurement units
  - additional prop
- Frequency: 240 Hz/100 Hz
- Kinematic output:
  - Acceleration
  - Velocity
  - Joint angle
  - Position
  - Orientation

Monitoring: Kinematic - Xsens^{TM}

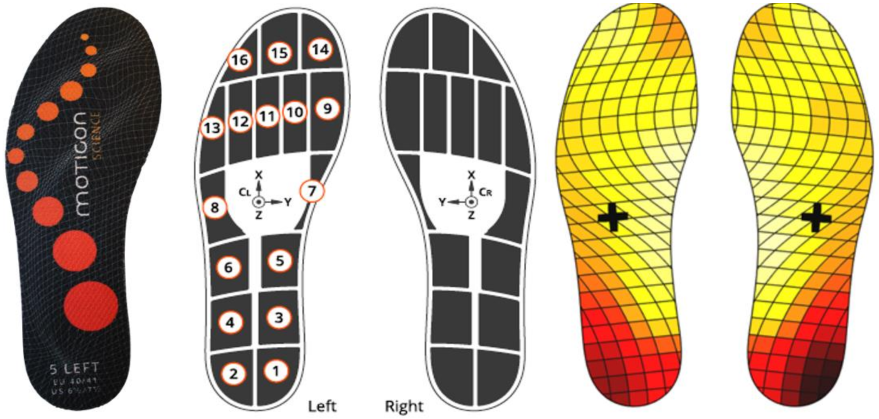


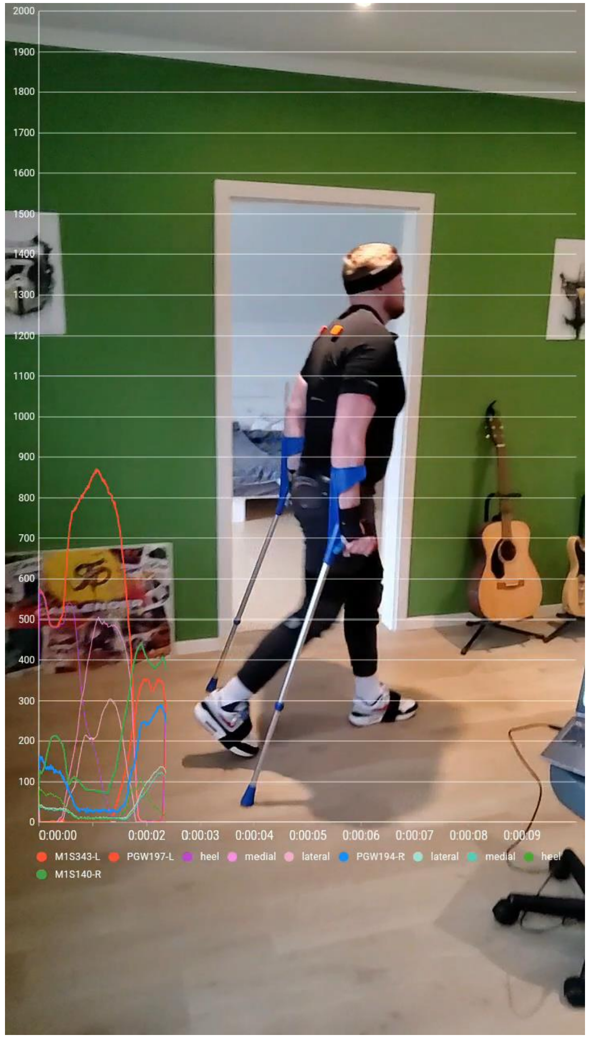




Monitoring Kinetic

- Frequency: 100 Hz
- Kinetic output:
  - Ground reaction force
  - Center of pressure
  - Contact forces
    - Crutch/Hand

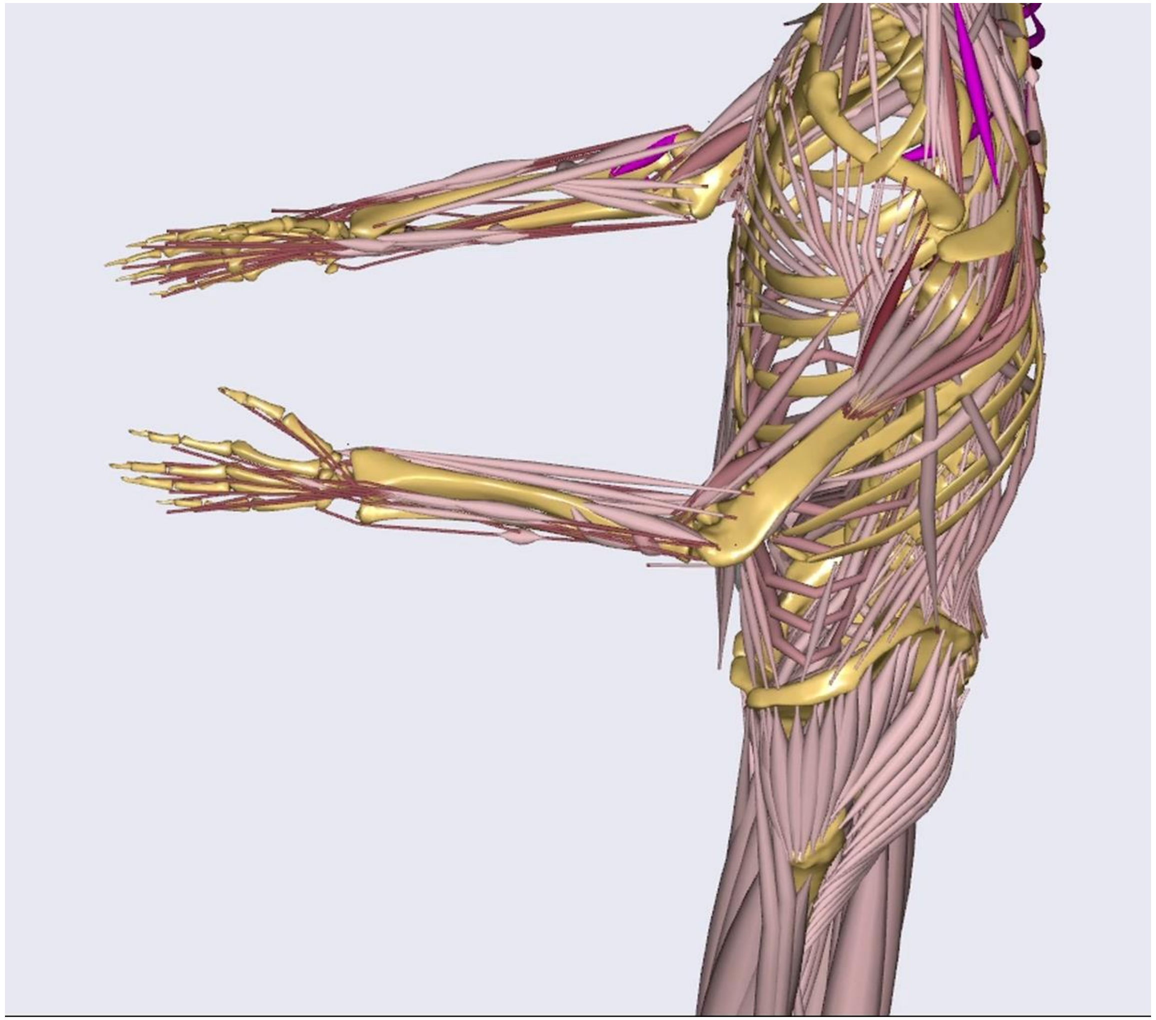


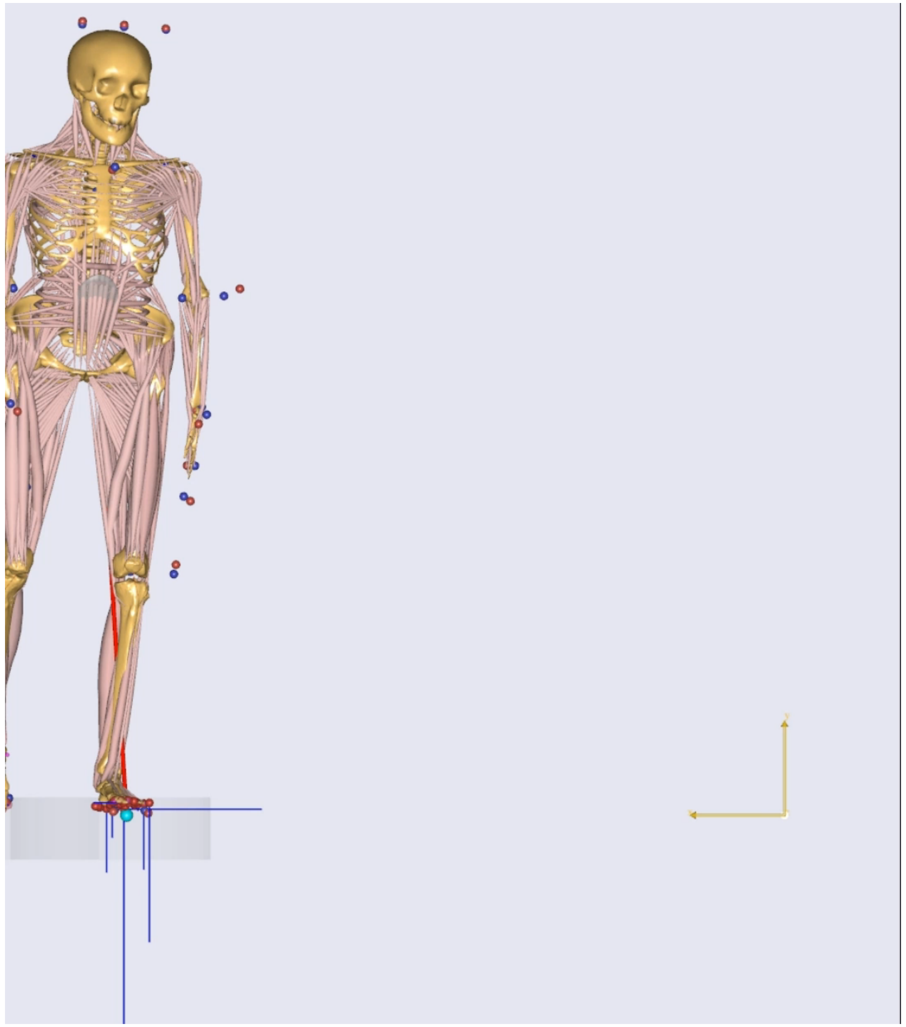


Inverse Dynamics

- Xsens™ → exports .bvh files
- Import using the AMMR (**A**nyBody **M**anaged **M**odel **R**epository)
- Kinematic data do drive the musculoskeletal model
- Individual models scaled based on anthropometric data

Inverse Dynamics

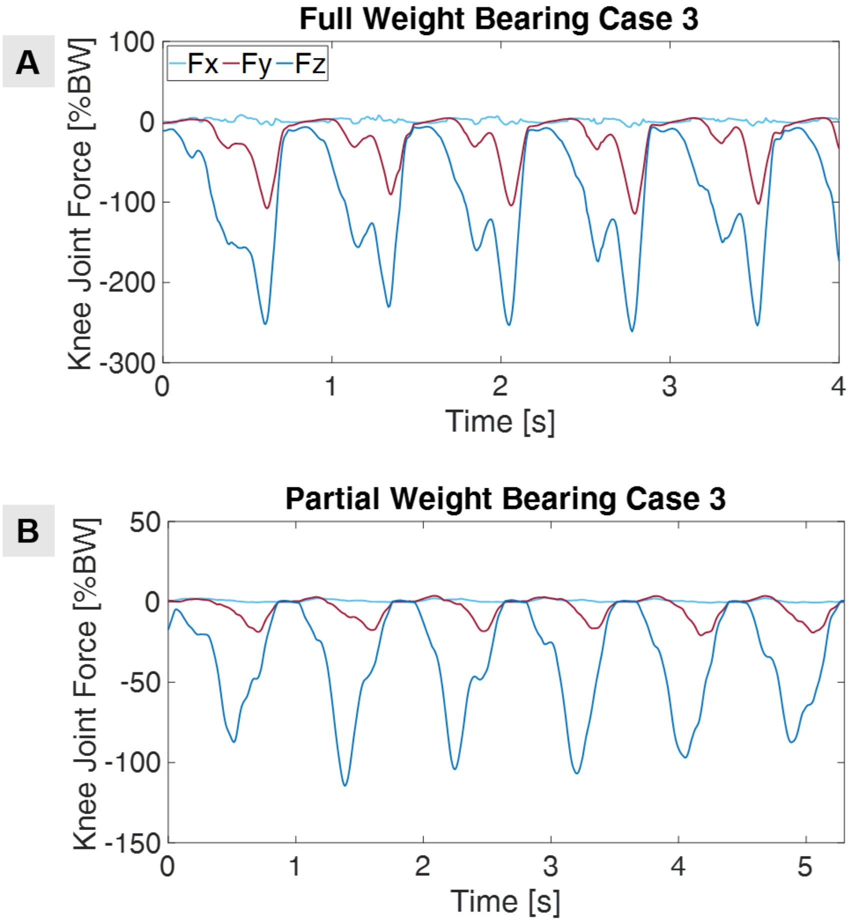




Boundary Conditions

Force components are distributed to the nodes and scaled to body weight

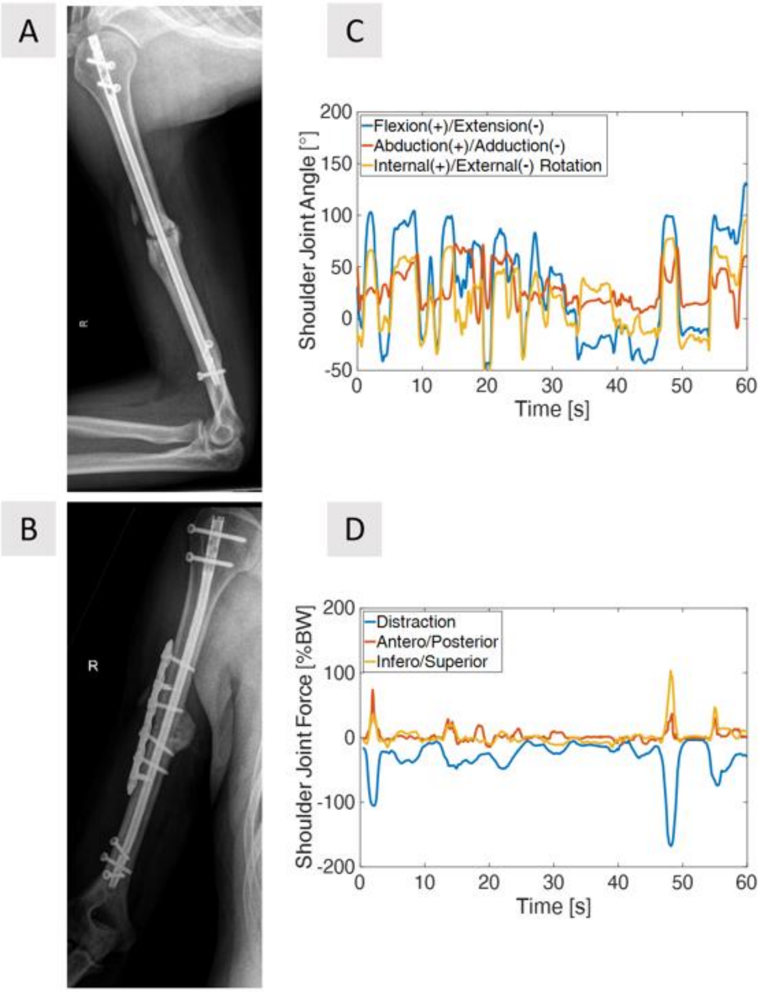
Fixing on the distal side



Boundary Conditions

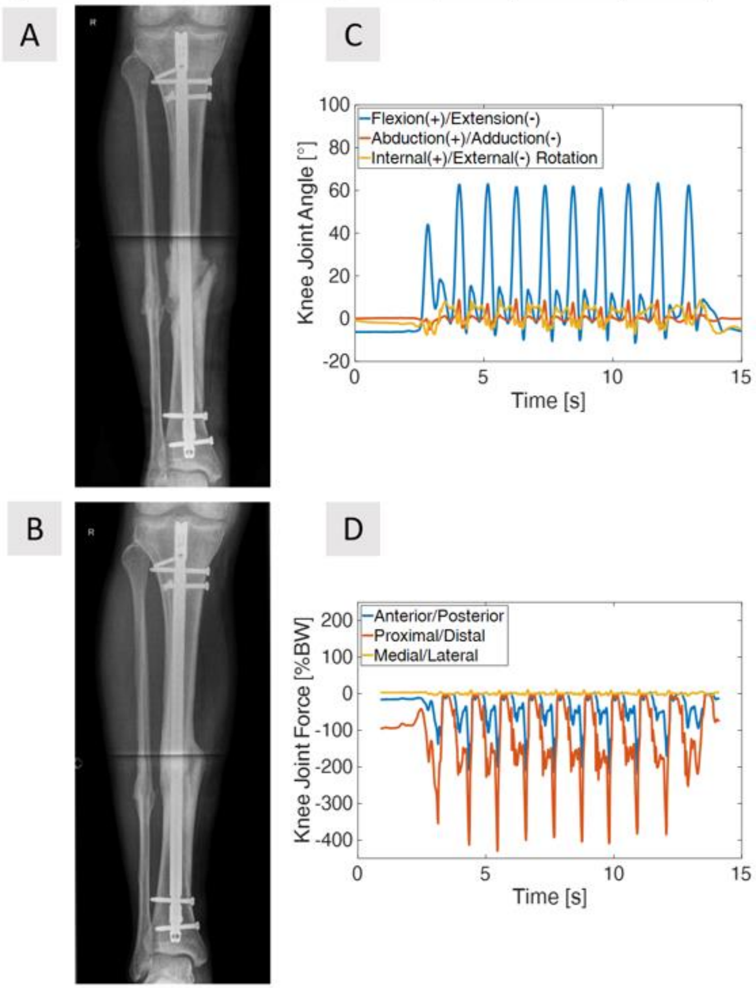
Use Case 2 - Augmentative plate for a humeral fracture

Monitoring Measurements	Body weight [kg]	Birth Year	Sex	Height [cm]	Position
14.06.2021	100	1944	male	178	right



Use Case 1 - Variation of the thickness of an intramedullary nail

Monitoring Measurements	Body weight [kg]	Birth Year	Sex	Height [cm]	Position
19.07.2021	95	1969	male	184	right



Andres, A., Roland, M., Wickert, K. *et al.* Advantages of digital twin technology in orthopedic trauma Surgery – Exploring different clinical use cases. *Sci Rep* **15**, 19987 (2025)

Methods - Part 2

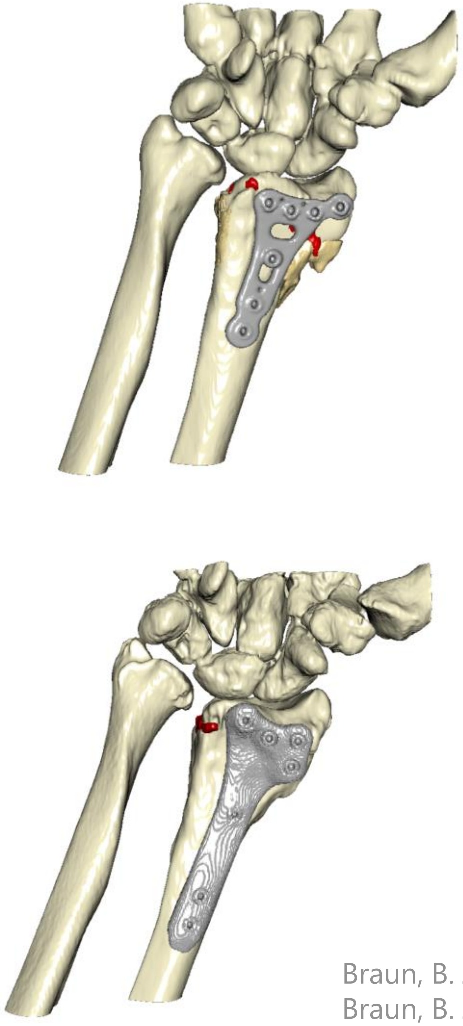
CT Images

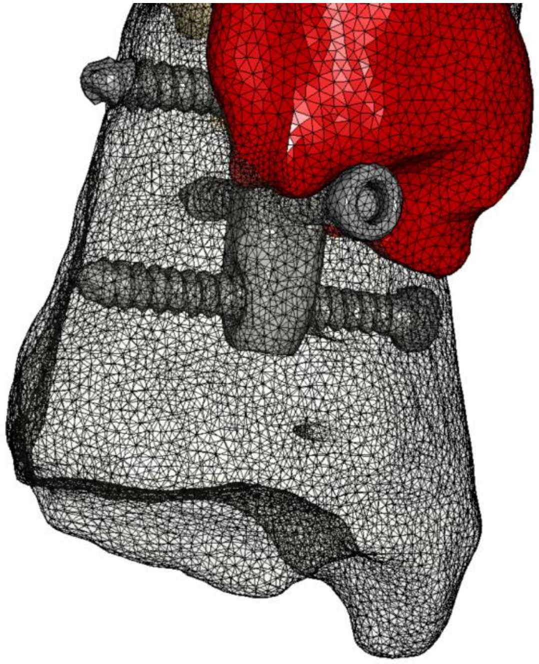
Segmentation

Digital Twin

FE simulation

Analysis



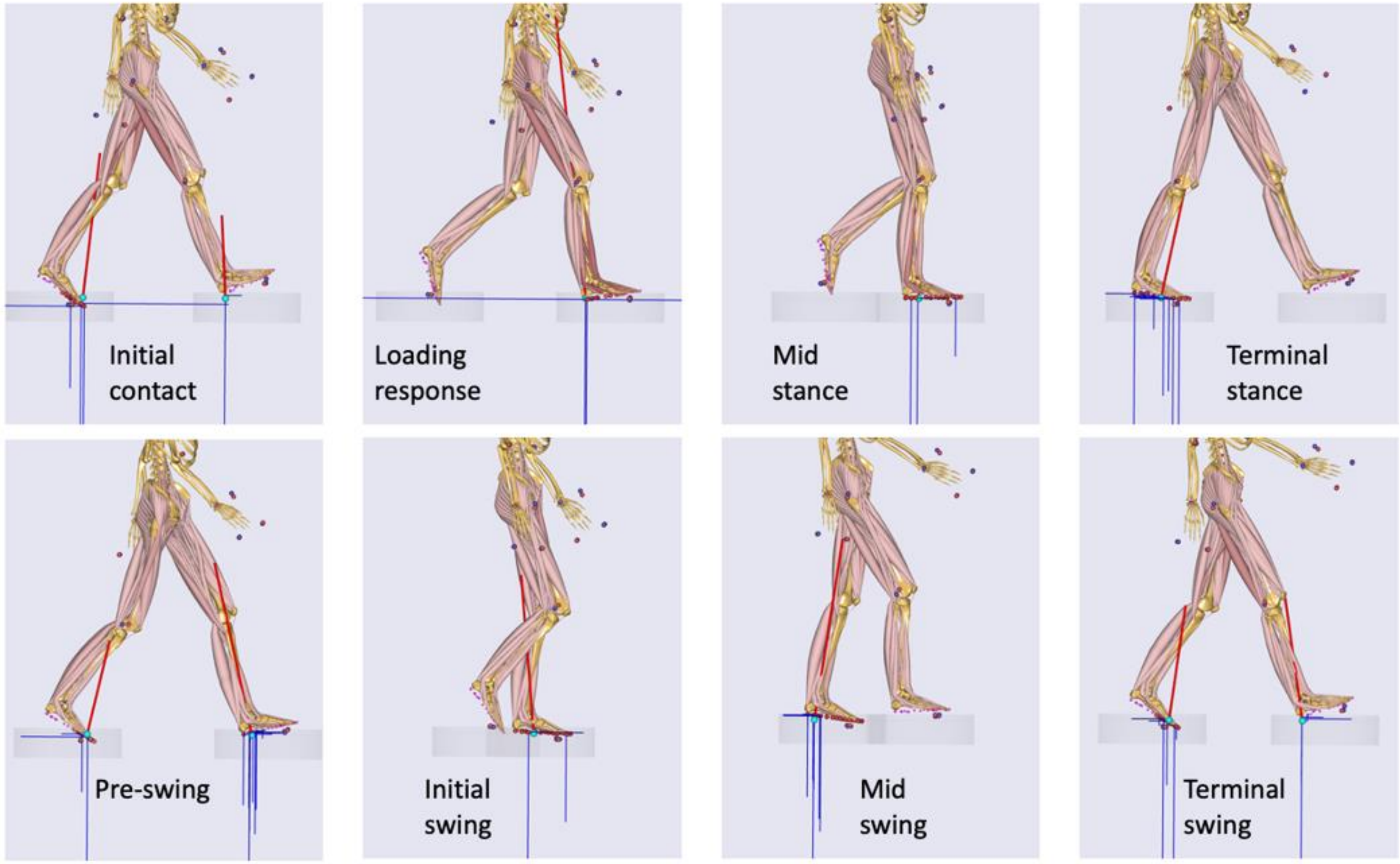


Braun, B. J. *et al.* (2021), *Frontiers in Surgery*, 8(September), pp. 1–9.
Braun, B. J. *et al.* (2022), *Die Unfallchirurgie*, 125(8), pp. 619–627
Orth, M. *et al.* (2023), *Front. Bioeng. Biotechnol.*, 11(February), pp. 1–13.
Andres, A. et al. (2025) Clin. Biomech. 106503.
Roland, M. et al. (2024) Front. Bioeng. Biotechnol. 12, pp. 1–14.

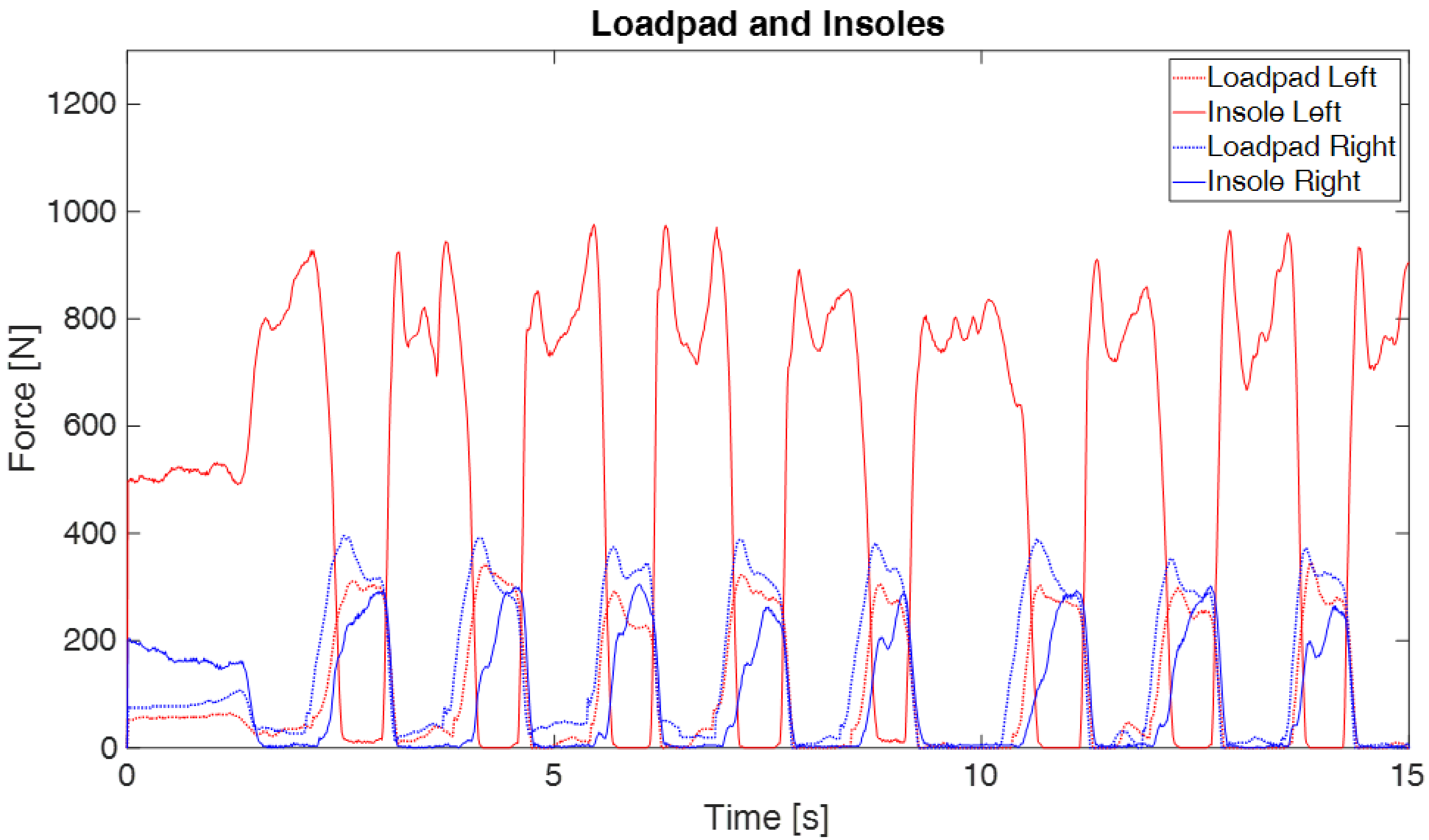
Gait Analysis

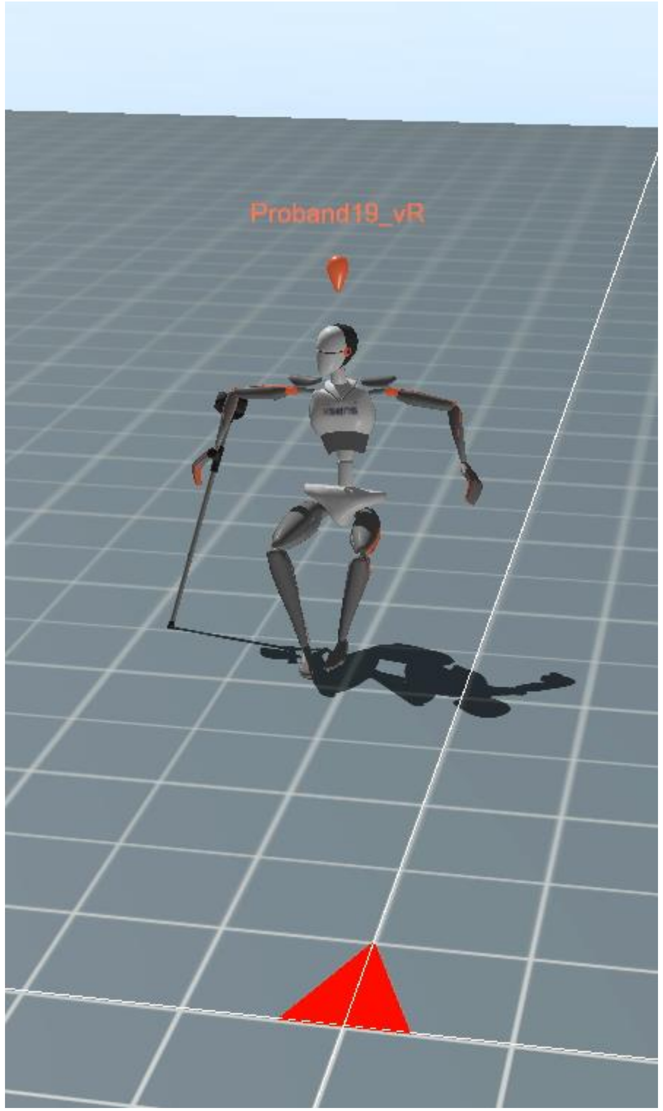
For fractures of the lower extremities, accurately assessing and guiding walking patterns during the healing phase is critical for reliable simulation outcomes.

This includes accounting for the effects of crutches and partial weight bearing.



Weight Bearing Scenarios



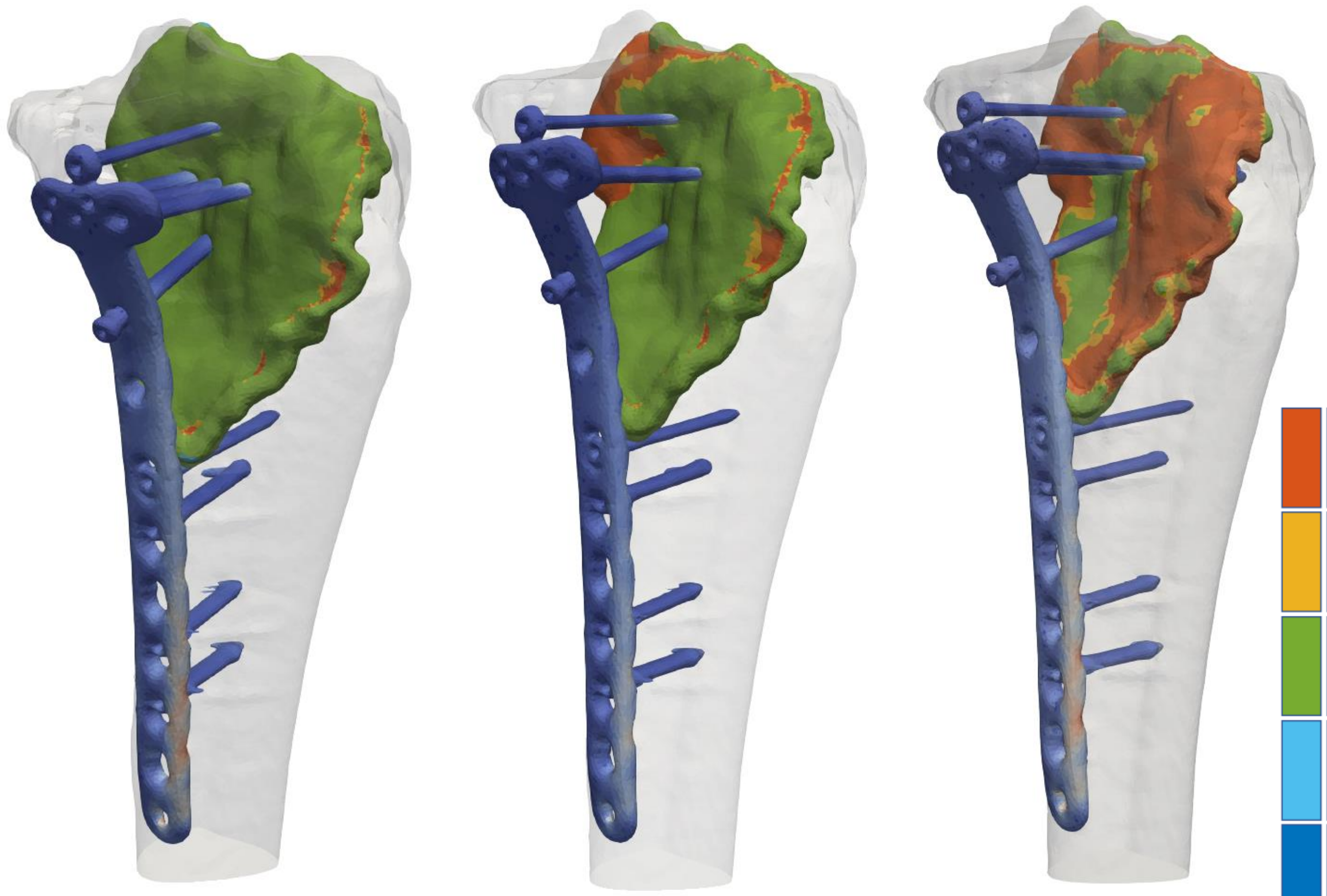


Treatment: Patient P_T_036

20kg

50% Bodyweight

Full weight bearing: 63kg



[1], [2], [3]

too much movement

maybe too much transition zone

perfect healing bone formation

maybe too lazy transition zone

too lazy bone resorption

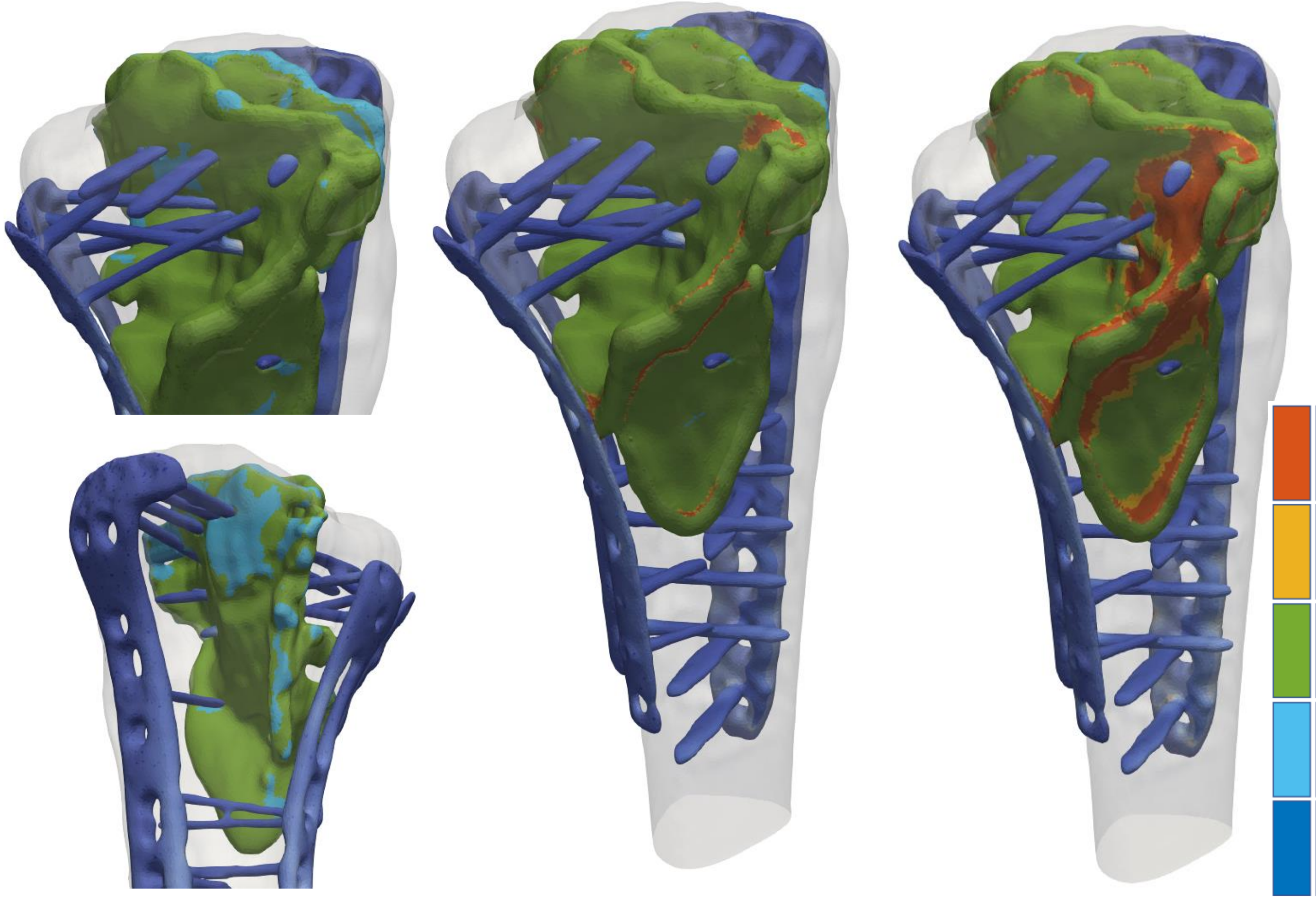
[1] Shefelbine, S.J. et al. J. Biomech. 38:12, 2440-2450 (2005)
[2] Claes, L.E. et al. J Biomech. 32:3, 255-266 (1999)
[3] Braun, B.J. et al. Frontiers in Surgery. 8 (2021)

Treatment: Patient P_T_040

20kg

50% Bodyweight

Full weight bearing: 71kg

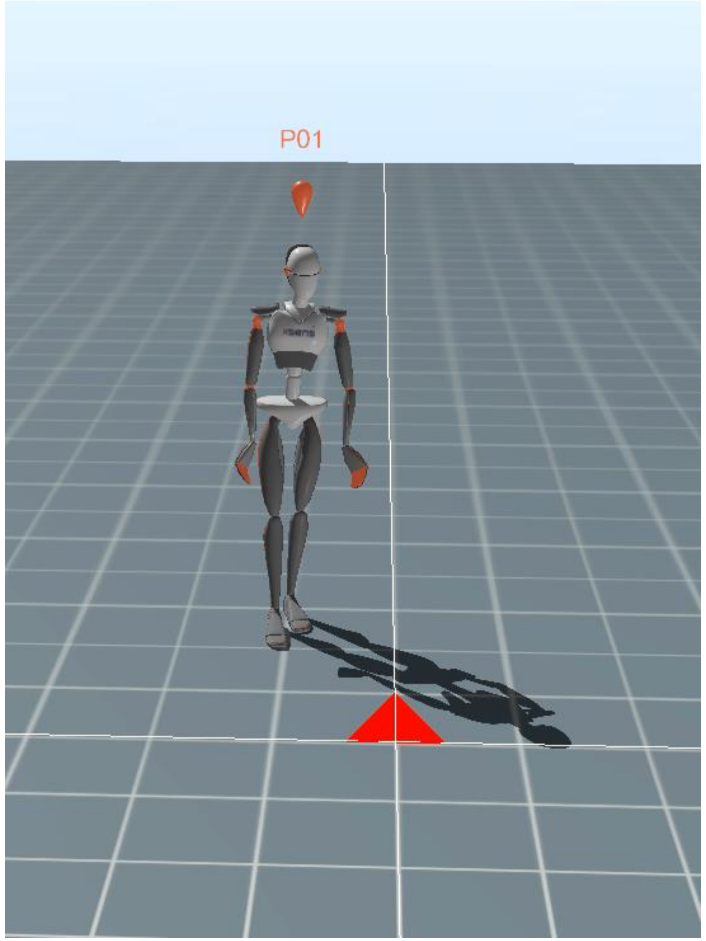


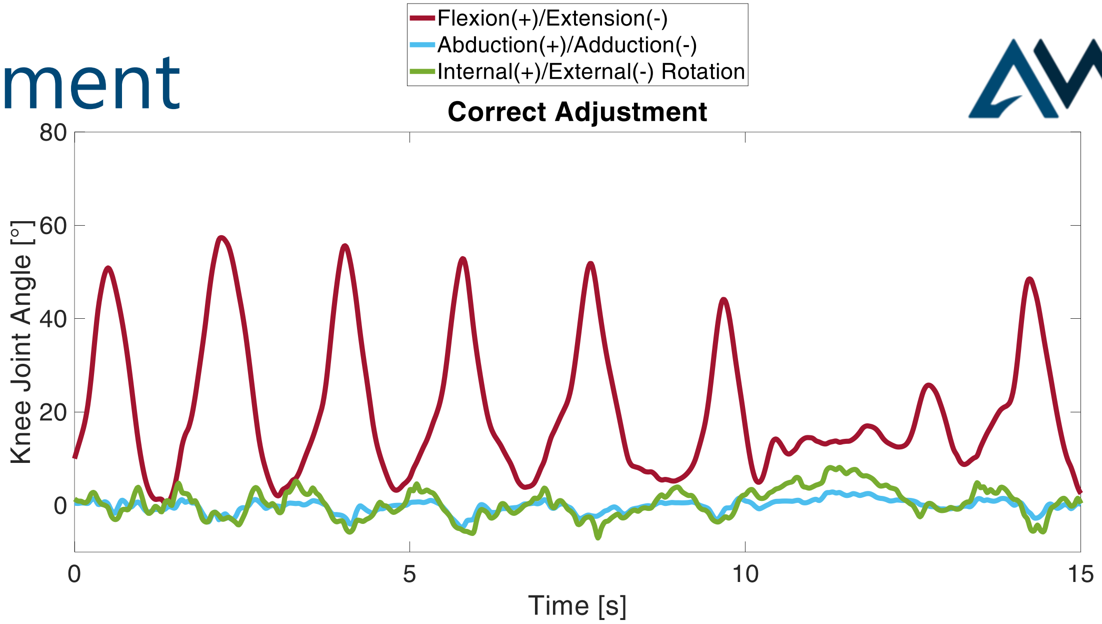
[1], [2], [3]

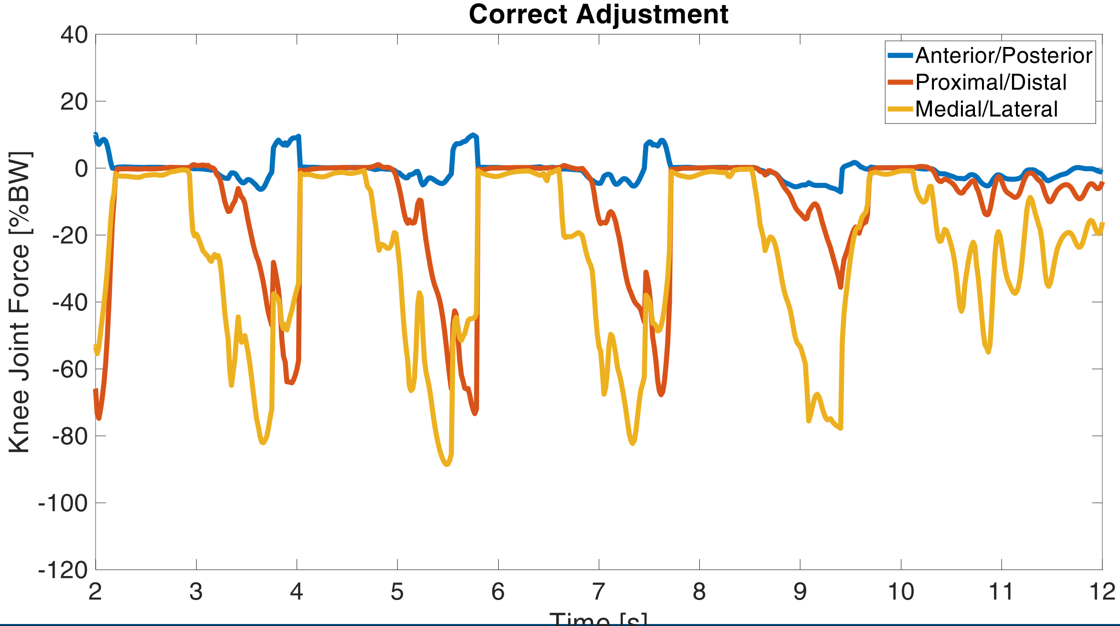
- too much movement
- maybe too much transition zone
- perfect healing bone formation
- maybe too lazy transition zone
- too lazy bone resorption

[1] Shefelbine, S.J. et al. J. Biomech. 38:12, 2440-2450 (2005)
[2] Claes, L.E. et al. J Biomech. 32:3, 255-266 (1999)
[3] Braun, B.J. et al. Frontiers in Surgery. 8 (2021)

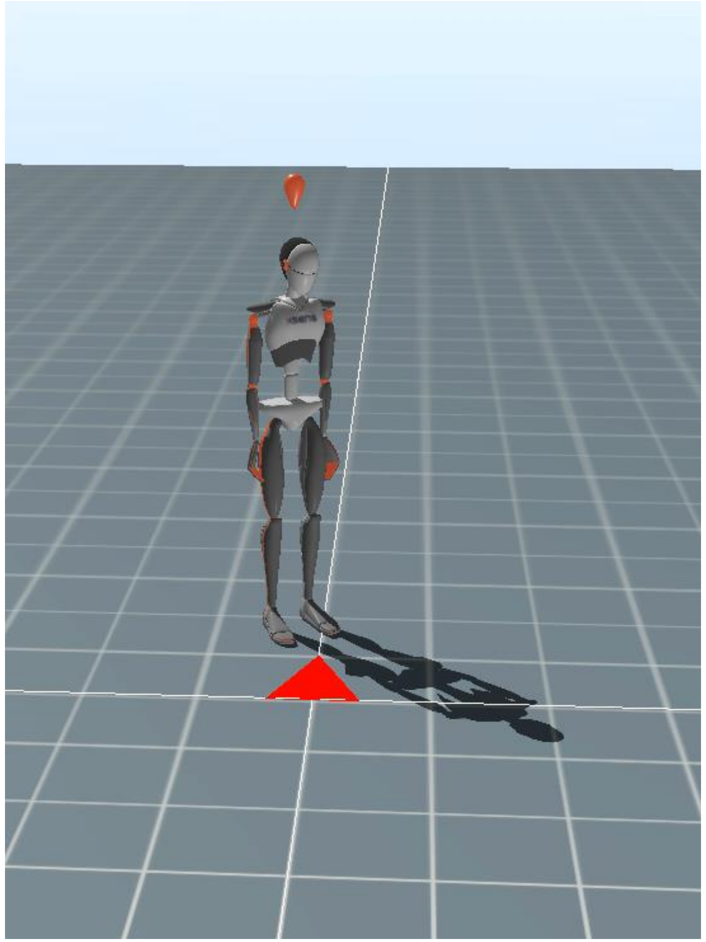
Walking Aids: Correct Adjustment

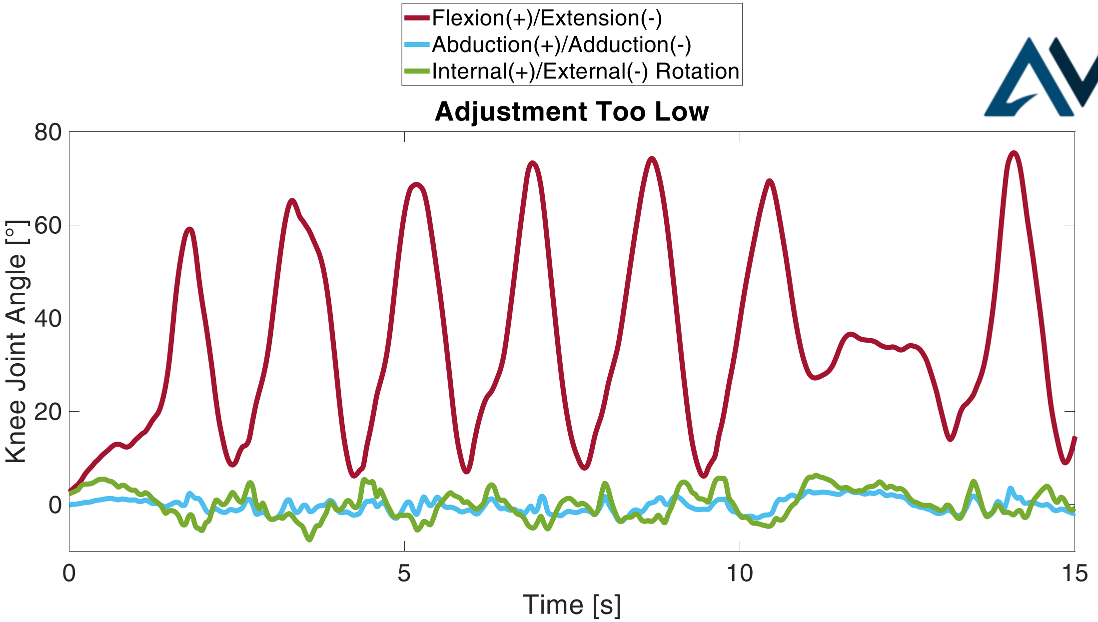


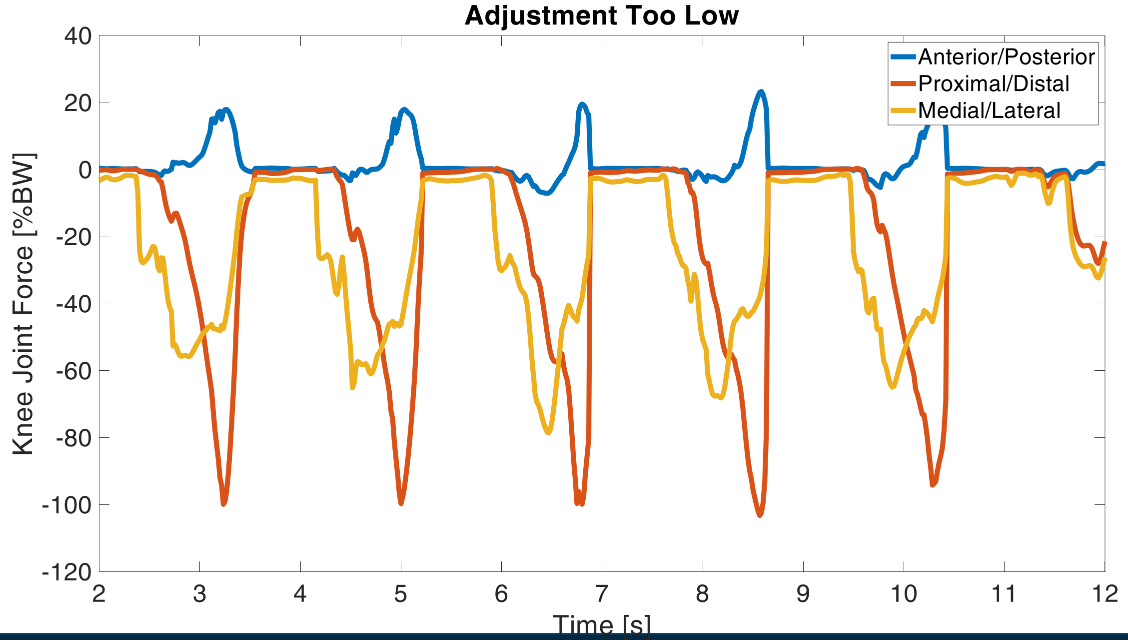




Walking Aids: Too Low



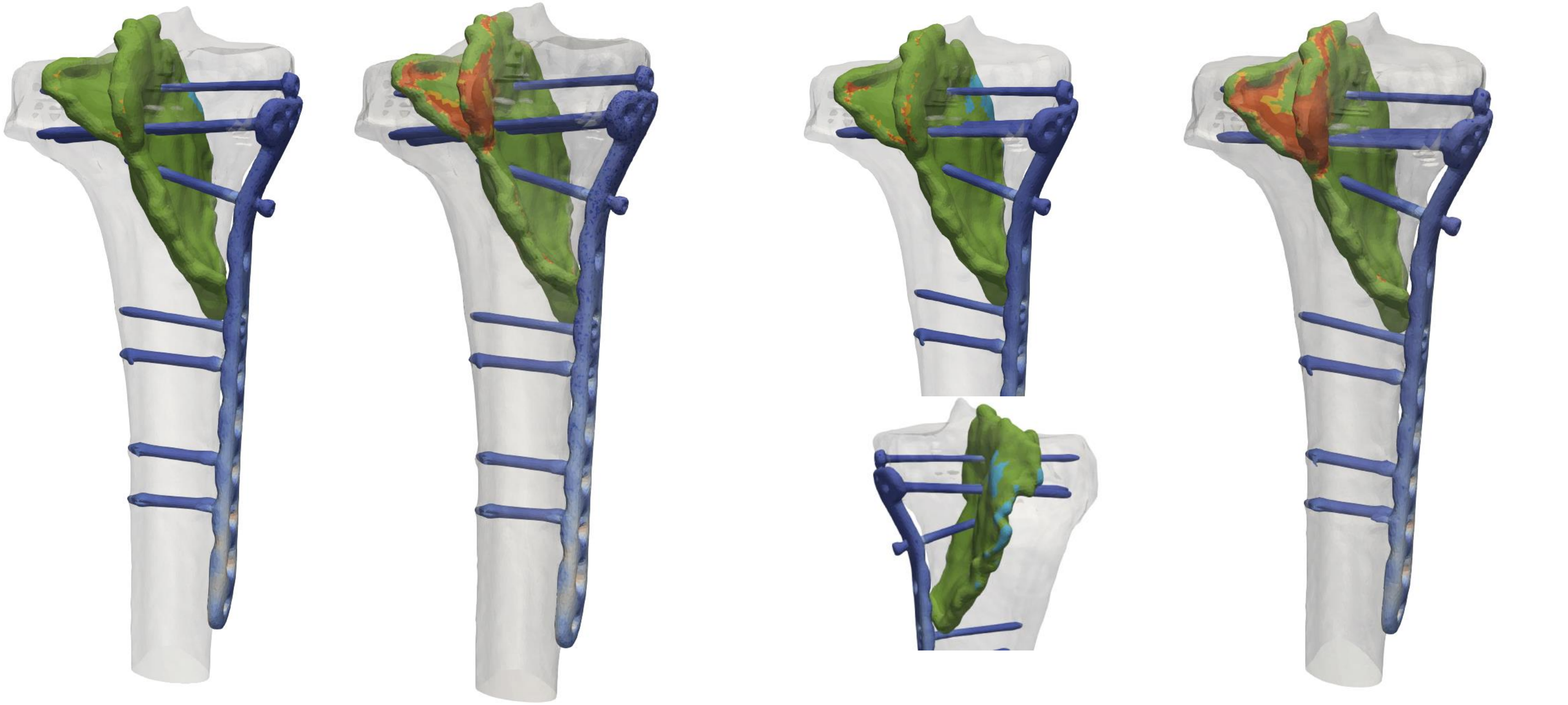




Walking Aids: Patients Results

Correct Adjustment:
20kg 50% bodyweight

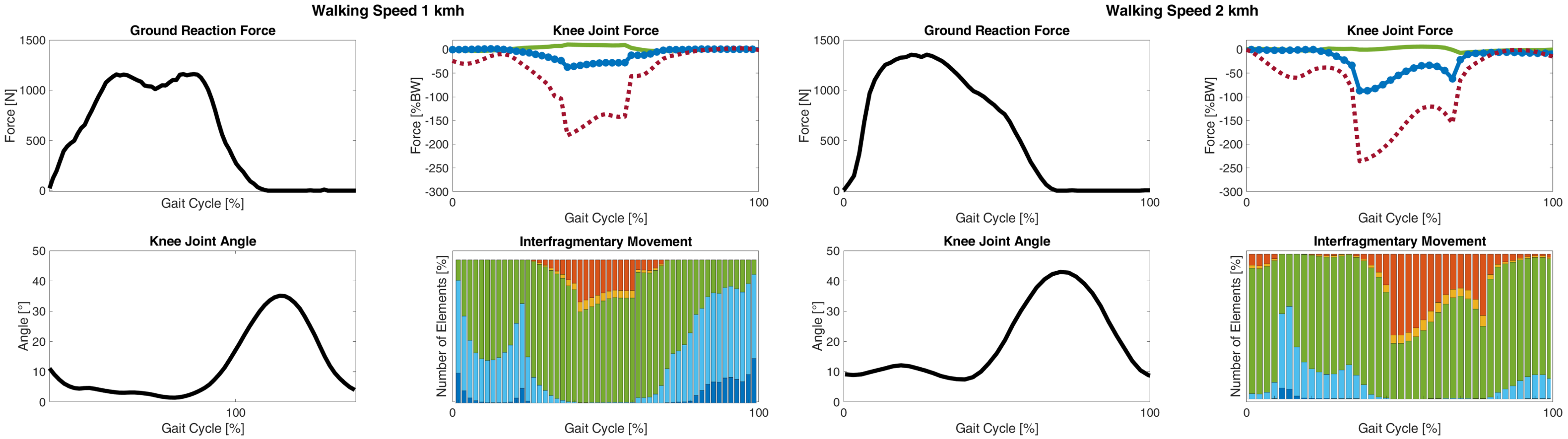
Adjustment too low:
20kg 50% bodyweight



The increase in the proportion in the “too much movement” area is 12%

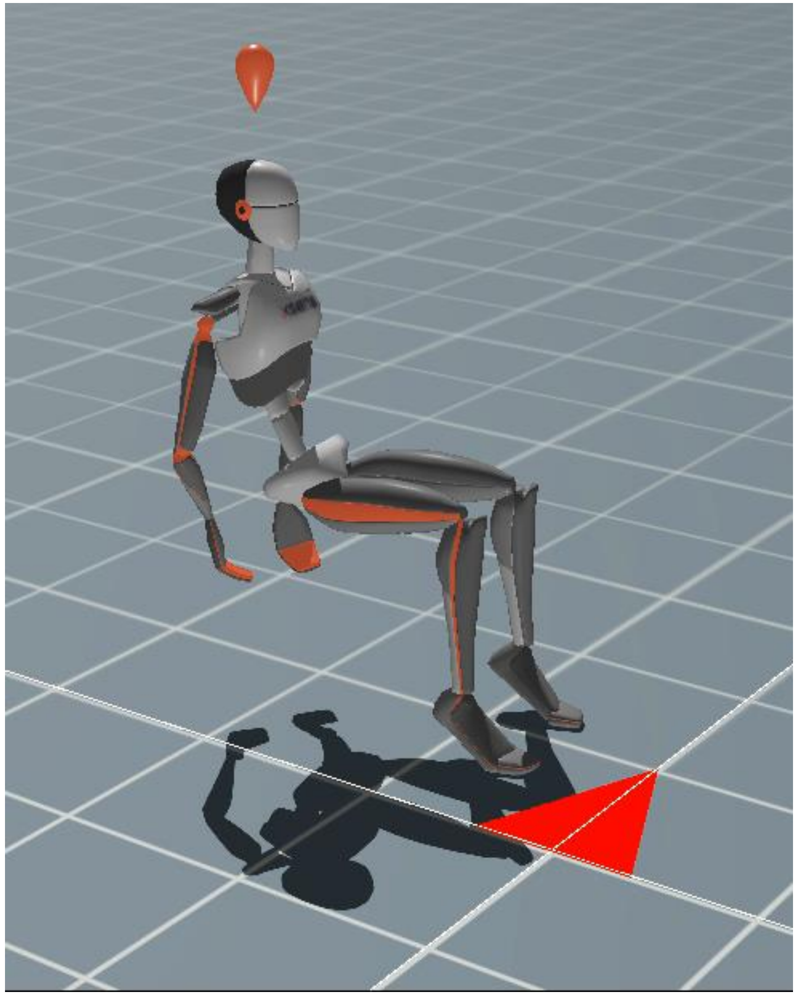
Treatment Situation

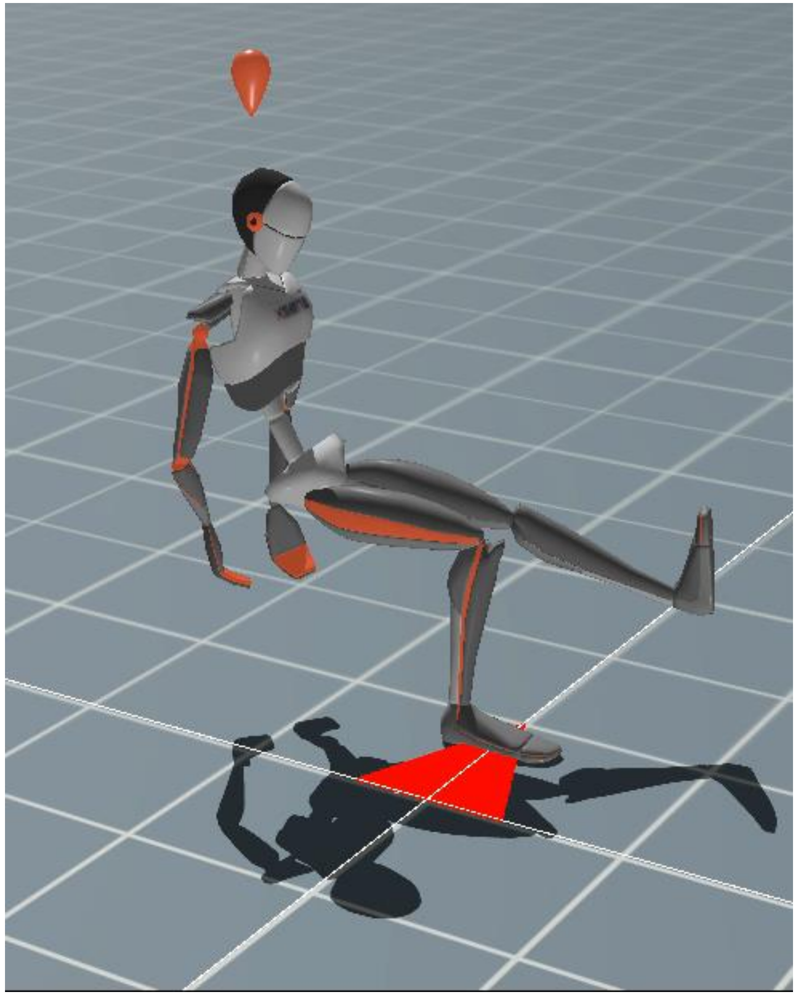
Walking Speed

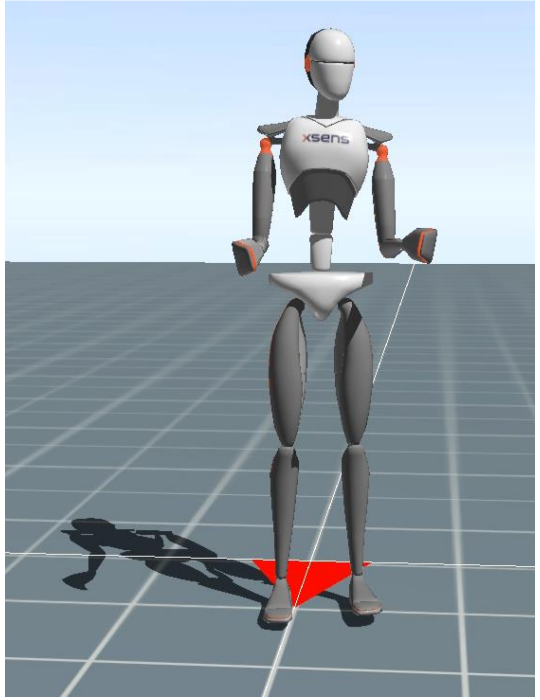


Andres, A., Roland, M., Wickert, K., Ganse, B., Pohlemann, T., Orth, M., & Diebels, S. (2025). Individual postoperative and preoperative workflow for patients with fractures of the lower extremities. *Clinical Biomechanics*, 106503.

Muscle Attachments

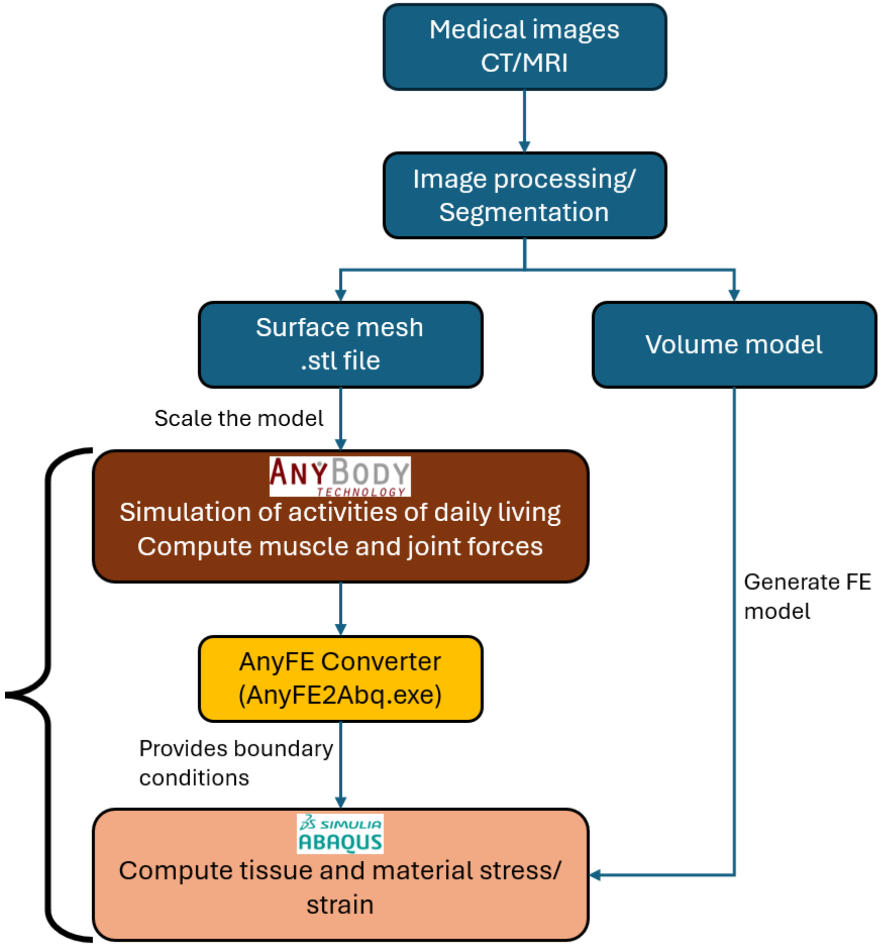






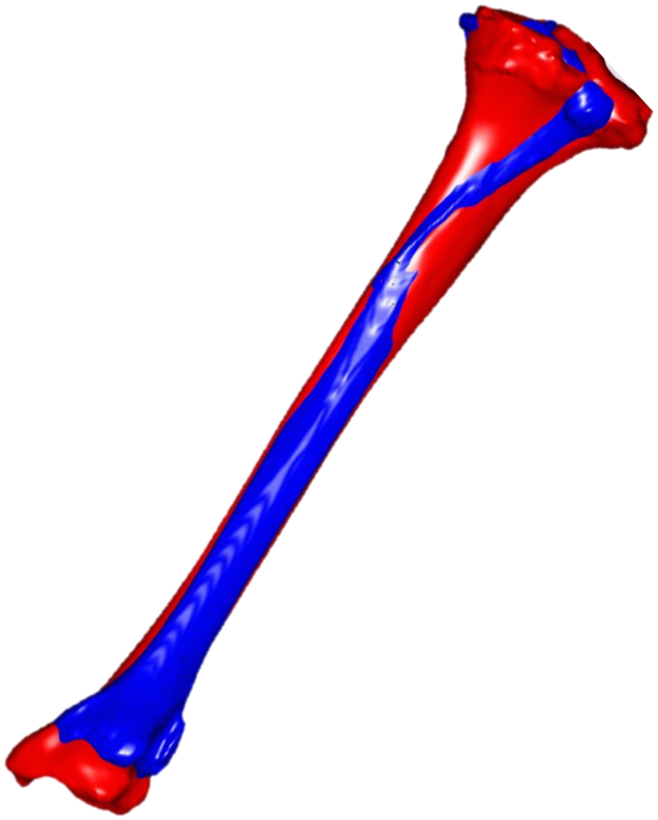
Muscle Attachments

- Finite Element Analysis Interfacing



+

- Scaling and Personalizing your model

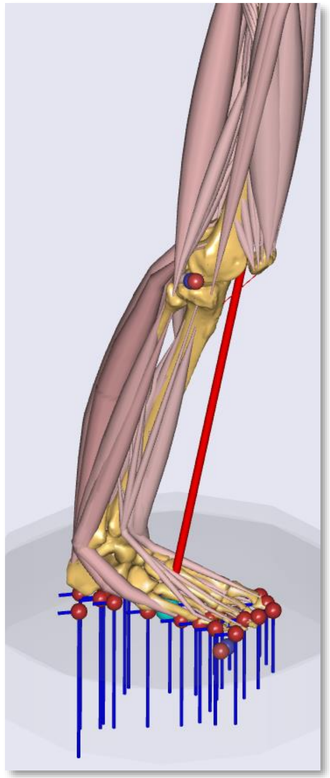


https://anyscript.org/tutorials/Finite_element_analysis/lesson3.html
https://anyscript.org/tutorials/Scaling/index.html

Muscle Attachments

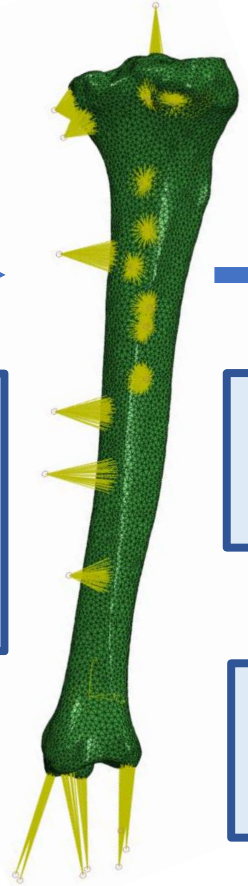
Simplified Boundaries → **Realistic Boundaries via Muscle Attachments**

Loading conditions



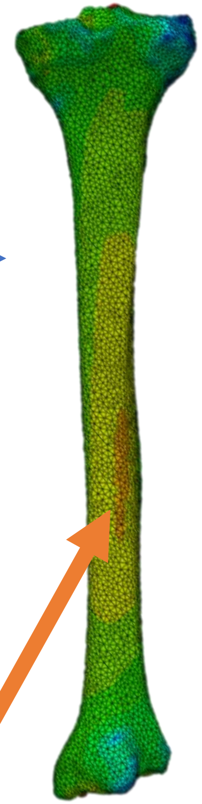
Fully fixed on the distal side

Force export and connection with volume mesh

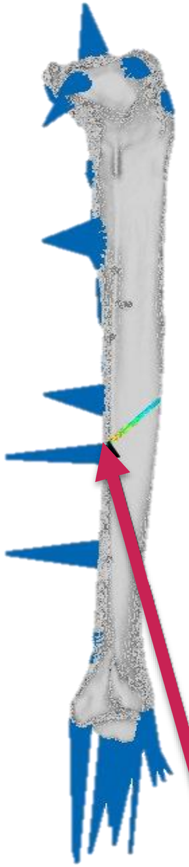


Simulation result: Two leg stance

Von Mises stress: $\approx 25\ MPa$

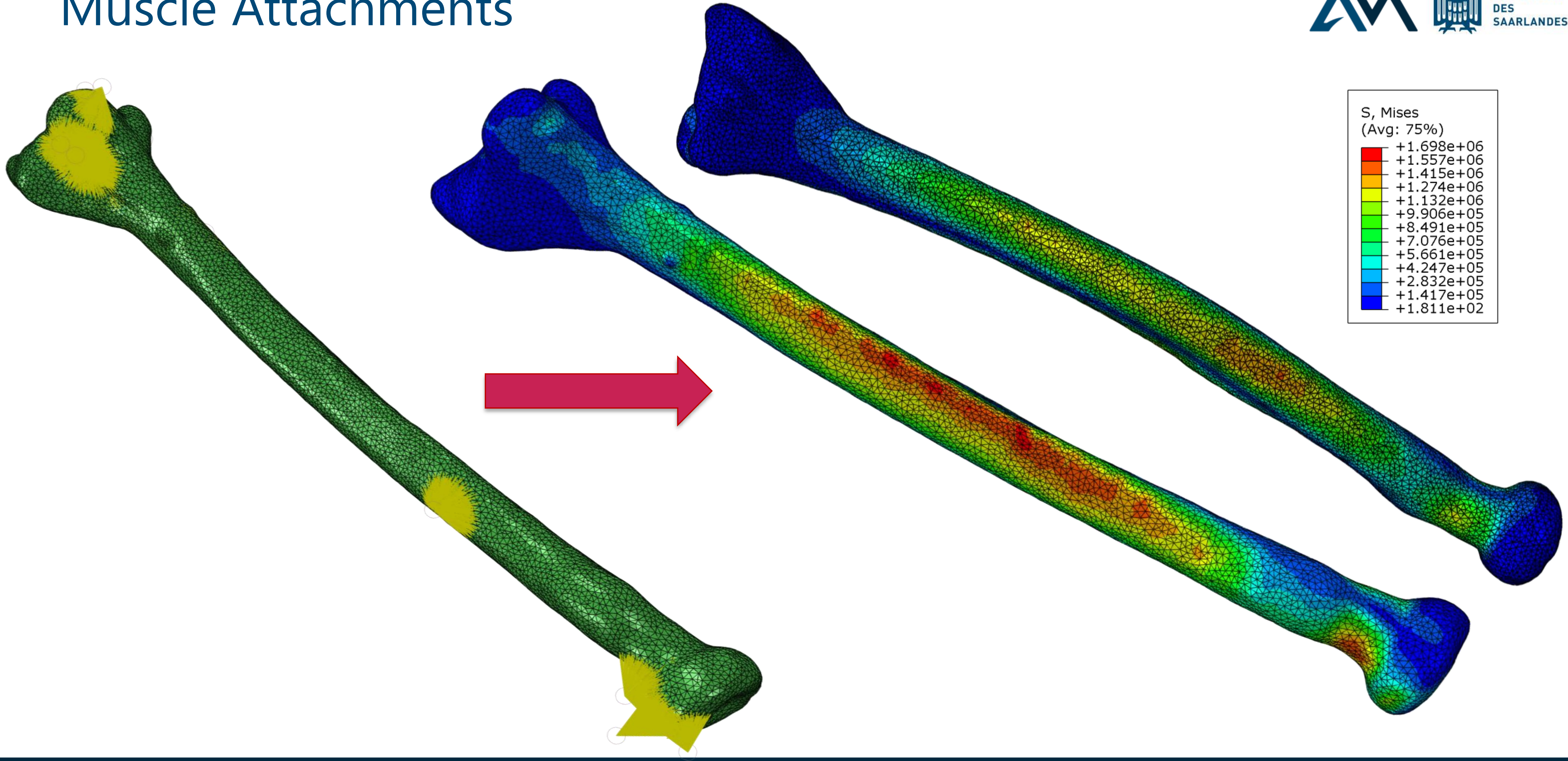


Muscles' influence on the fracture gap

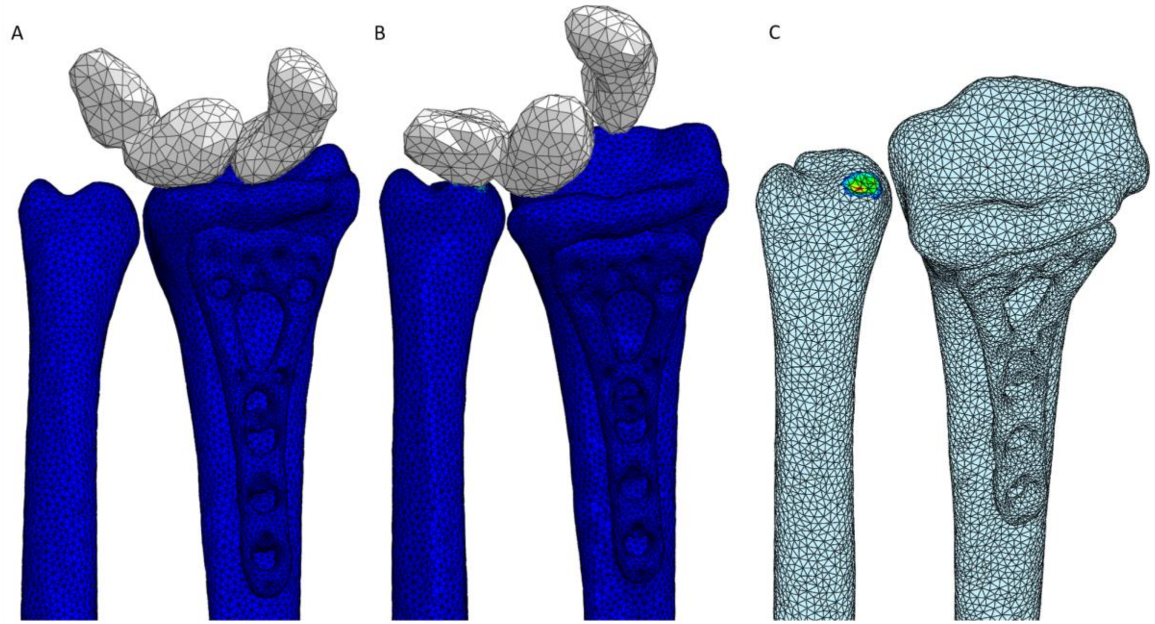


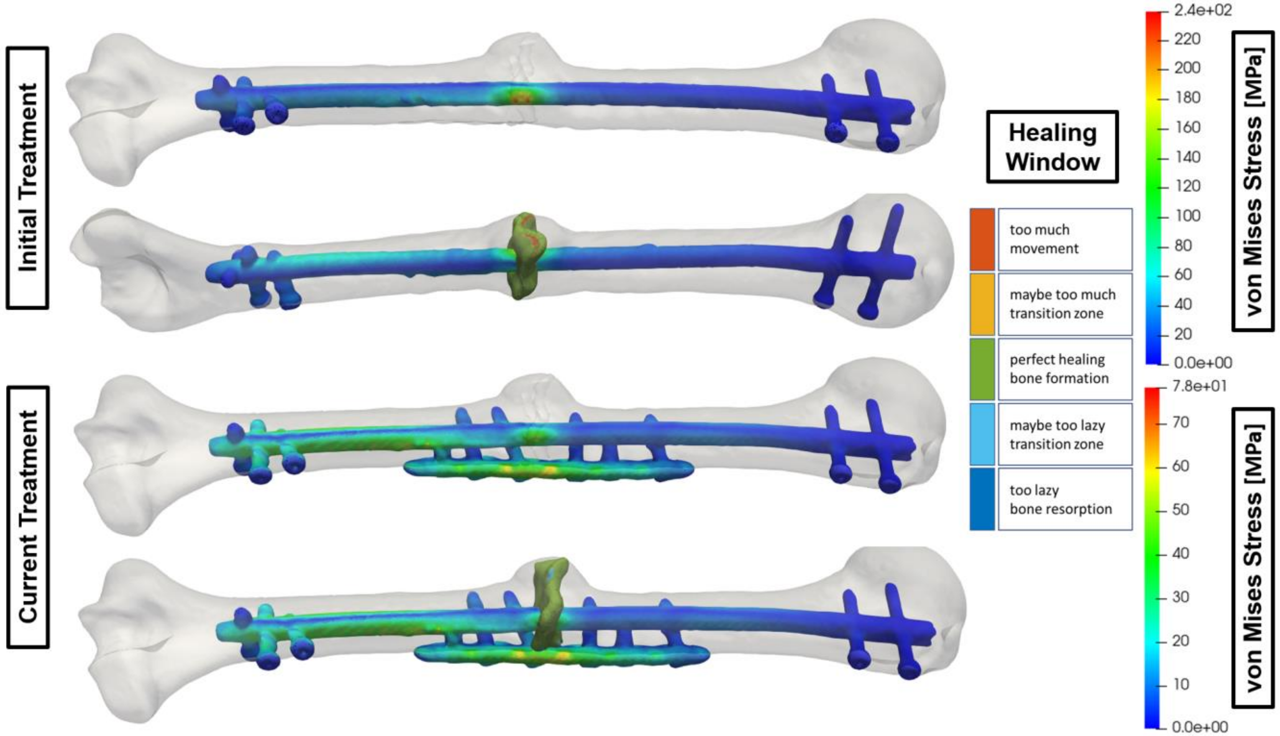
Strain (max) = 0.14

Muscle Attachments



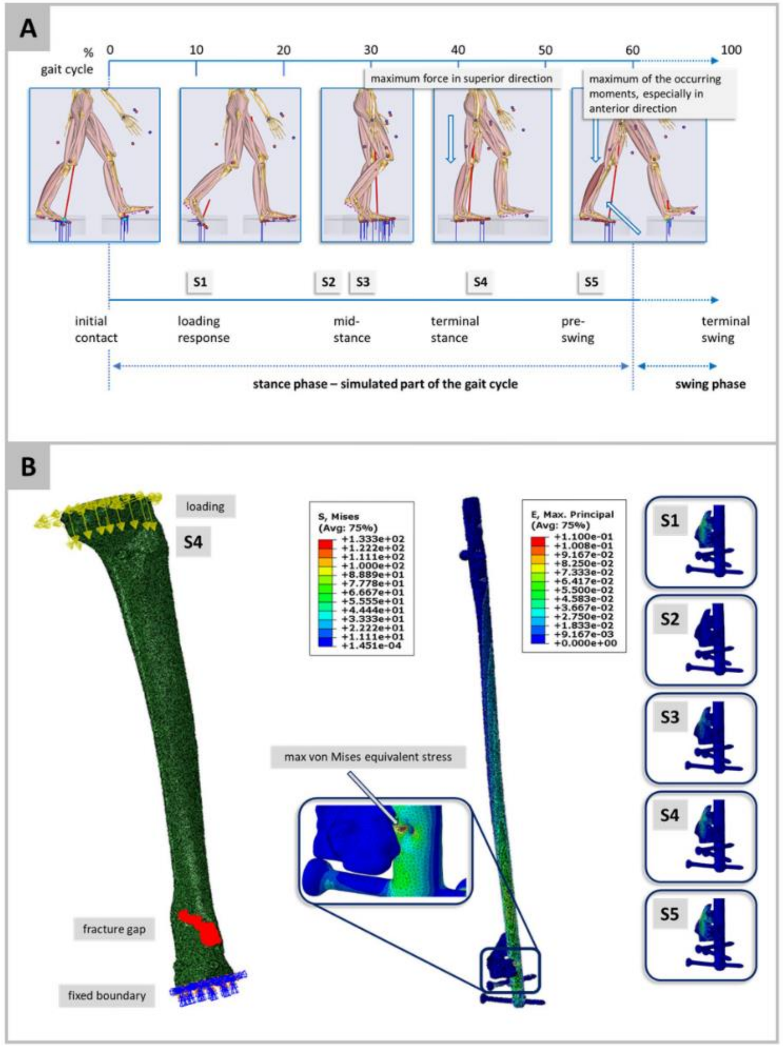
Results



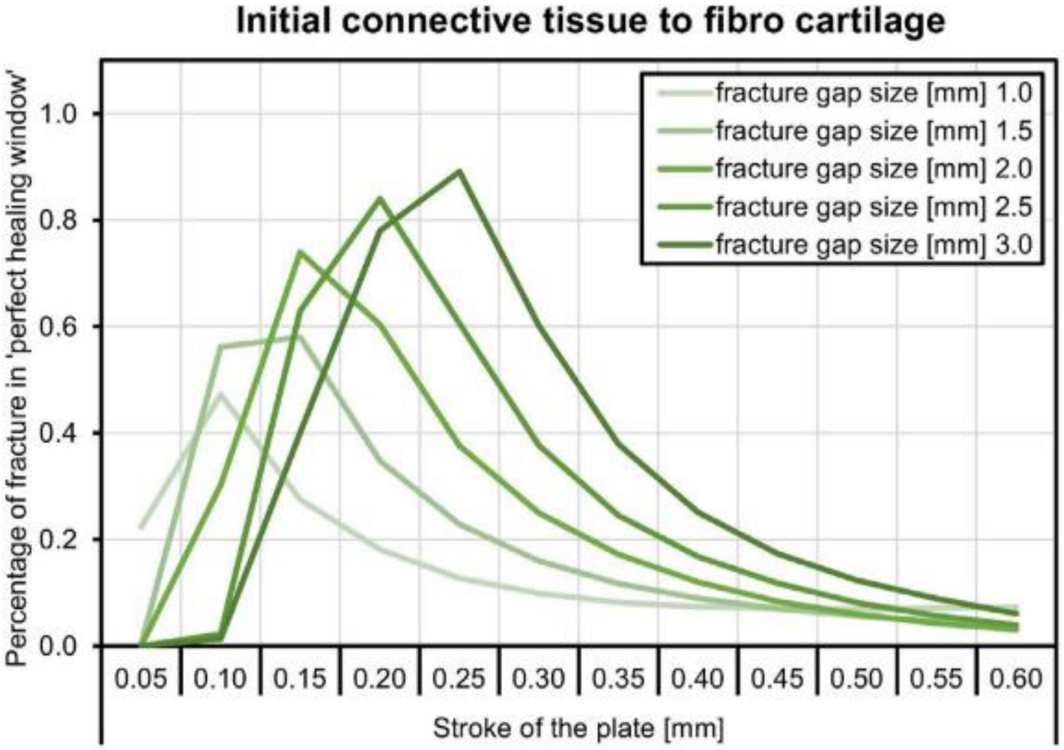


Andres, A., Roland, M., Wickert, K. *et al.* Advantages of digital twin technology in orthopedic trauma Surgery – Exploring different clinical use cases. *Sci Rep* **15**, 19987 (2025)

Results

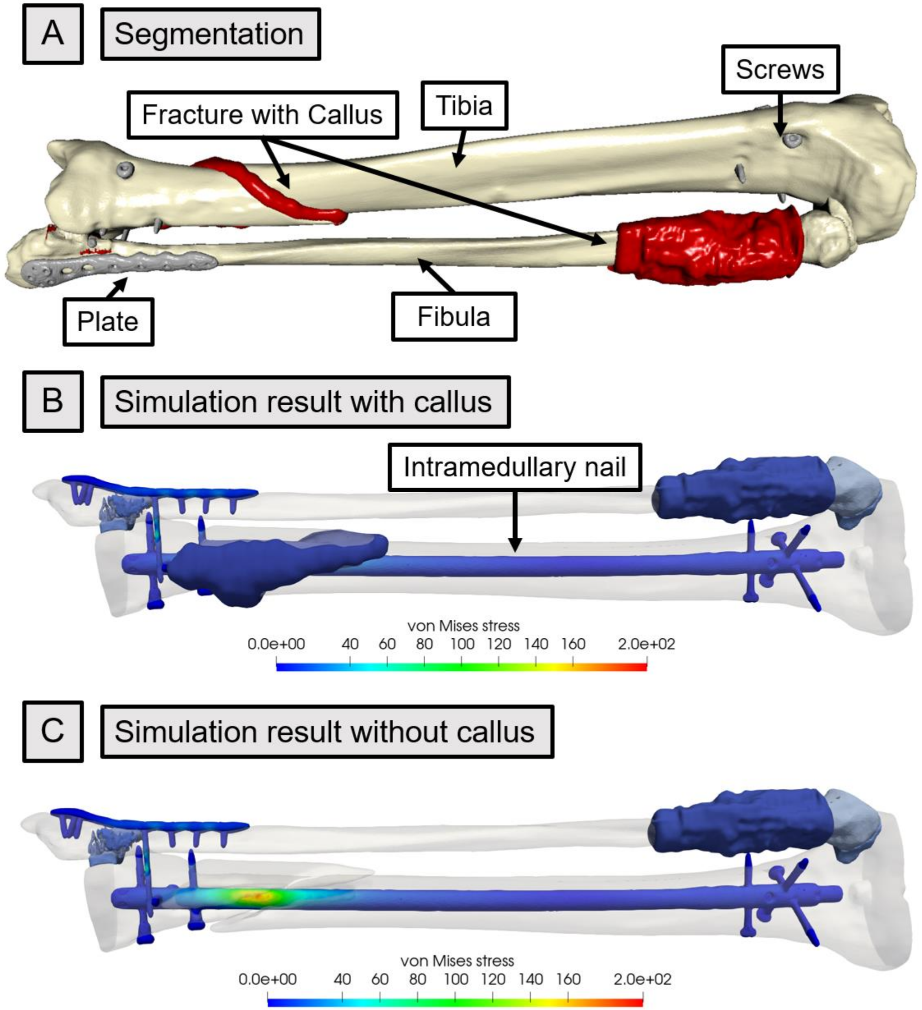


Roland, M., Diebels, S., Orth, M., Pohlemann, T., Bouillon, B., & Tjardes, T. (2023). Reappraisal of clinical trauma trials: the critical impact of anthropometric parameters on fracture gap micro-mechanics—observations from a simulation-based study. *Scientific Reports*, *13*(1), 20450.



Roland, M., Diebels, S., Wickert, K., Pohlemann, T., & Ganse, B. (2024). Finite element simulations of smart fracture plates capable of cyclic shortening and lengthening: which stroke for which fracture?. *Frontiers in Bioengineering and Biotechnology*, *12*, 1420047.

Results



Andres, A., Roland, M., Wickert, K., Ganse, B., Pohlemann, T., Orth, M., & Diebels, S. (2025). Individual postoperative and preoperative workflow for patients with fractures of the lower extremities. *Clinical Biomechanics*, 106503.

Human Cadaveric Specimen - Experiments

Motivation

Investigation bone and bone-implant systems

Experiments to validate simulated results

Fracture generation

What happened during fracture generation? Definition of failure load

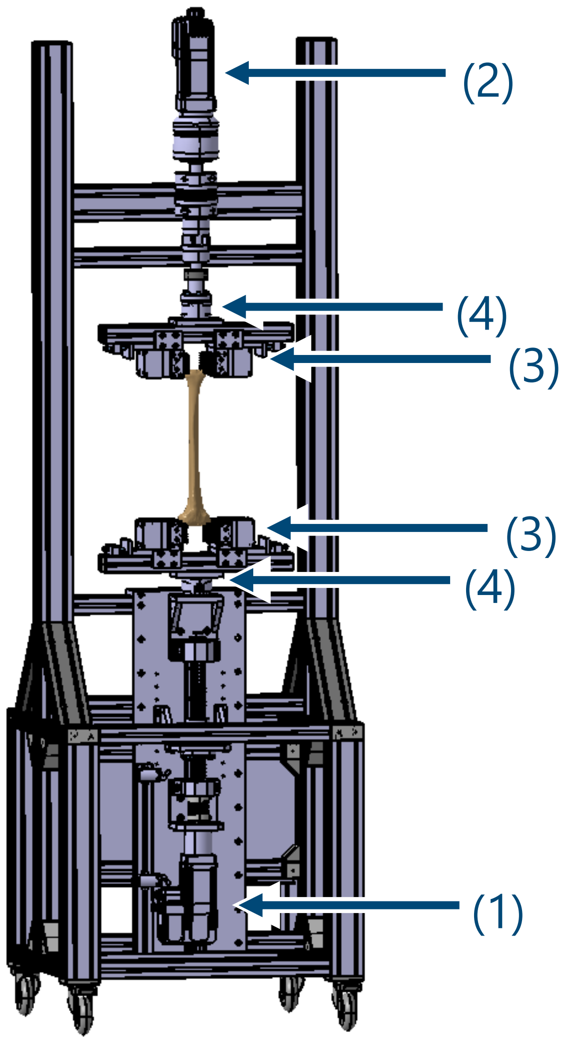
Loading scenarios

Testing of different loading scenarios (full weight bearing, partial weight bearing,…)

Why do fractures not heal? ➡ Investigate bone under physiological loading scenario

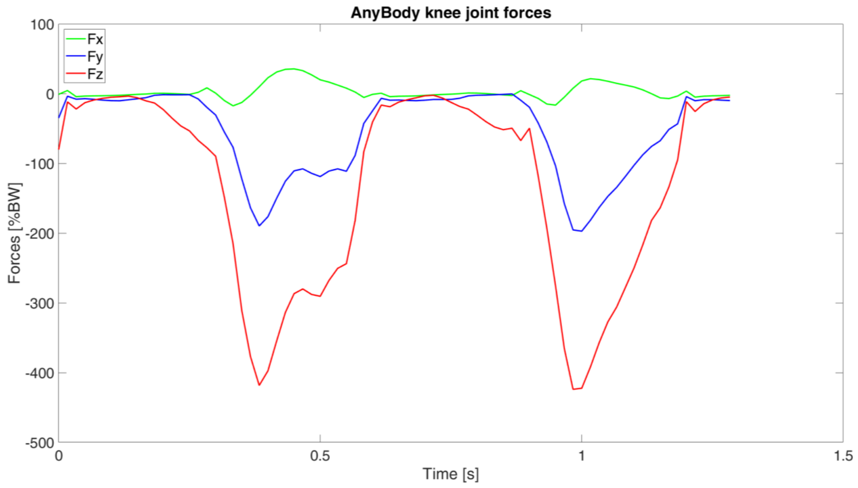
Fracture Generation

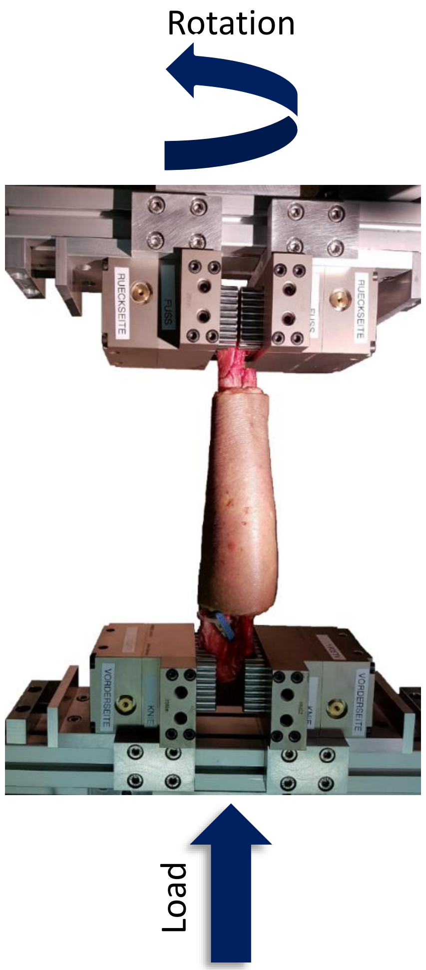
Fracture Generation



- Compression axis (1)
- Torsion axis (2)
- Clamping (3)
- Six axis force sensor (4)

- Production of reproducible distal tibiae fractures
- Fracture event caused by axial preload and rotation

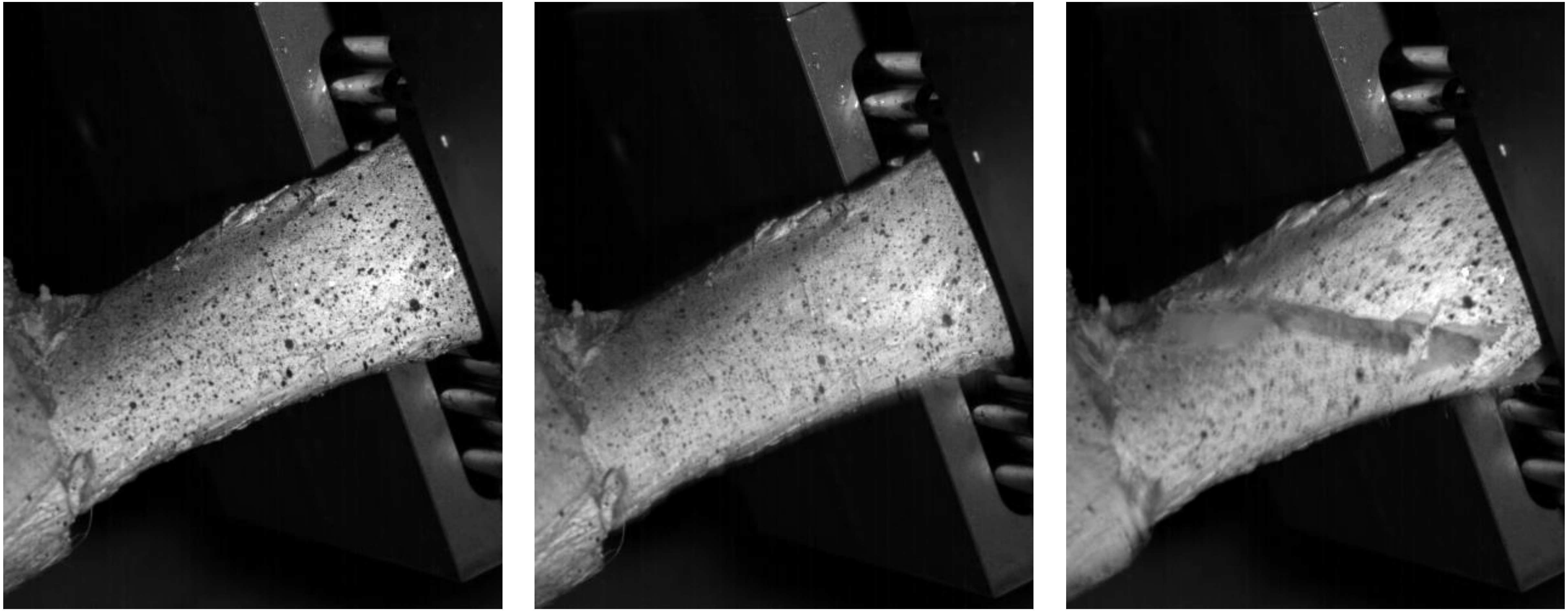




Video Fracture Generation

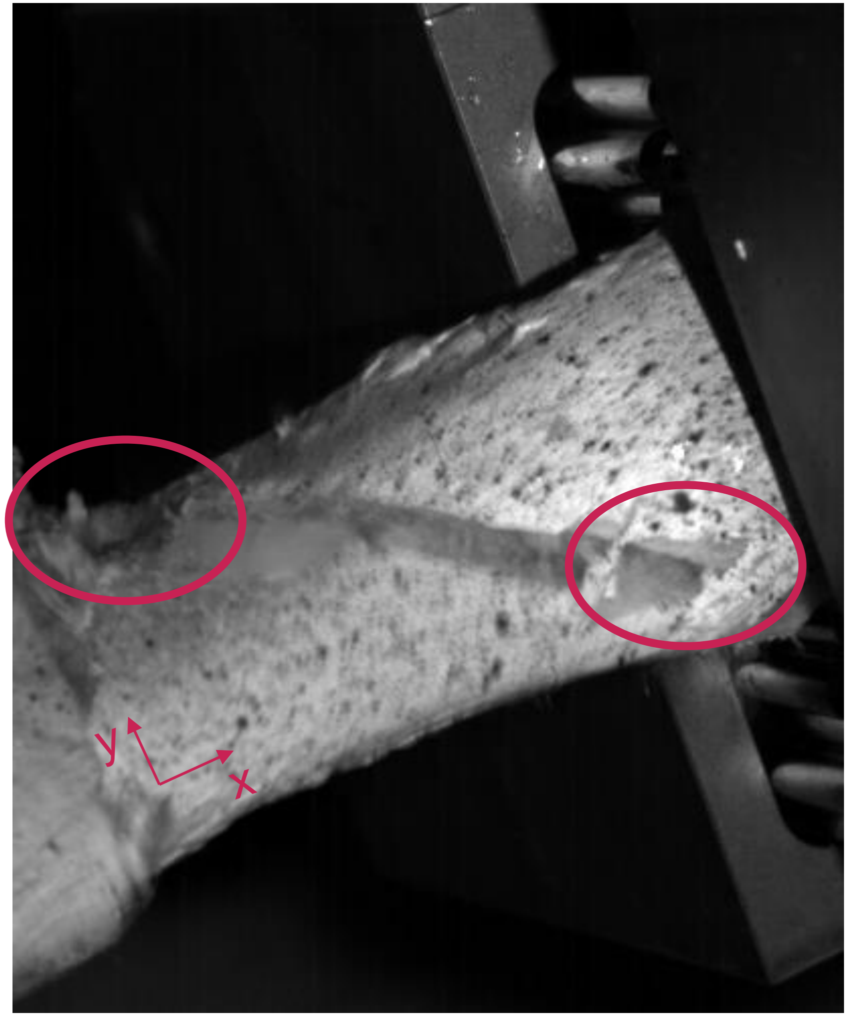
Experiment – Fracture Generation

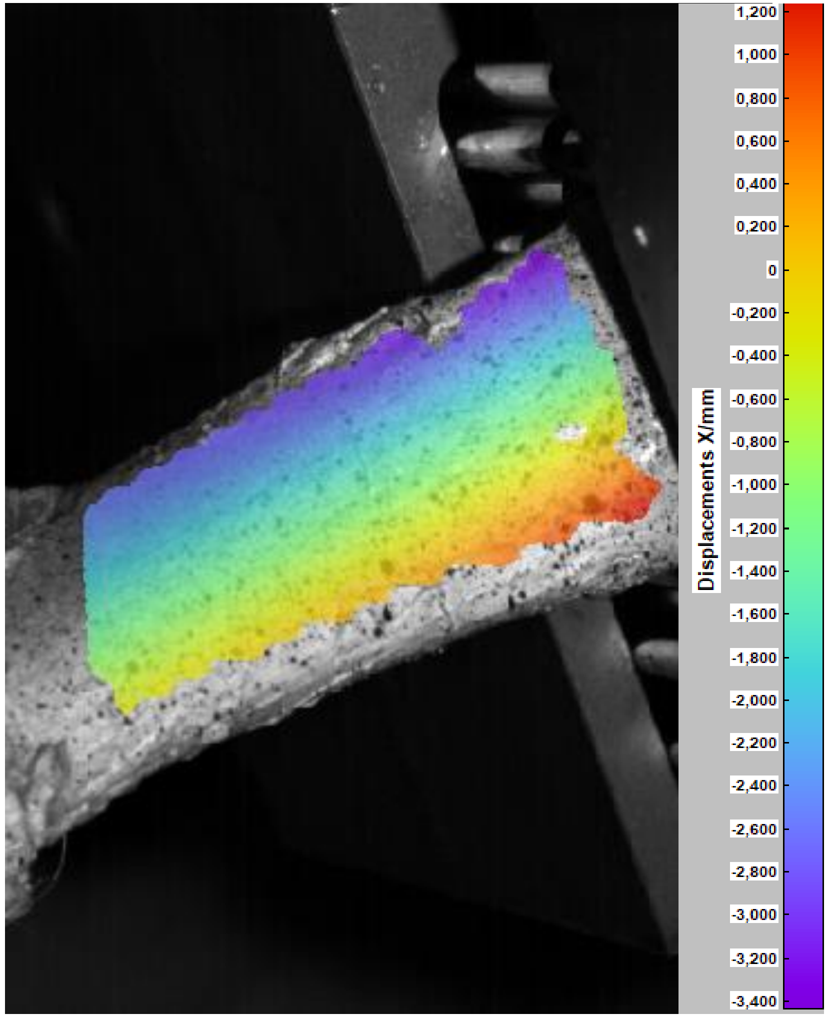
UNIVERSITÄT DES SAARLANDES

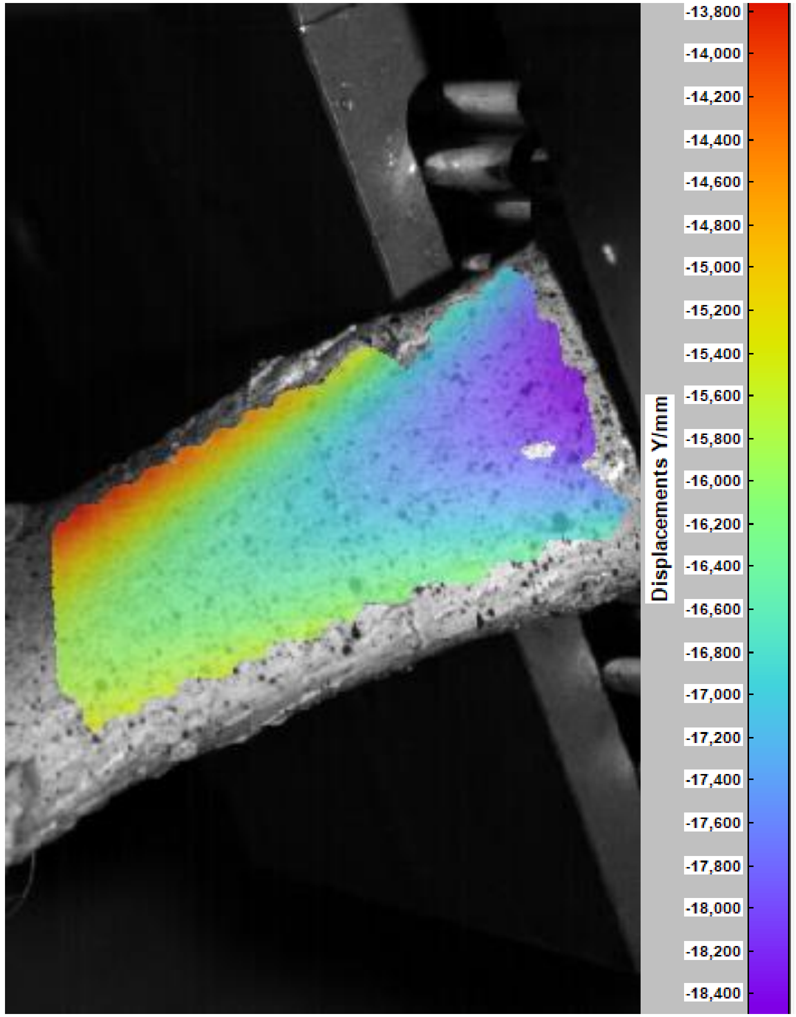


Focus on fracture formation: consecutive images

Results – Displacement in X and Y Direction

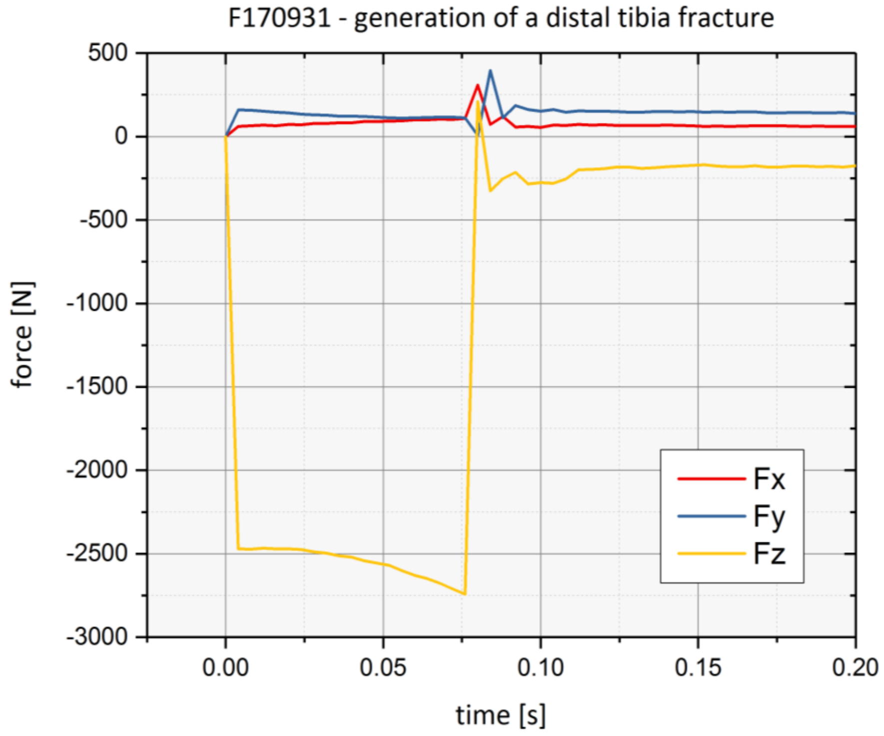


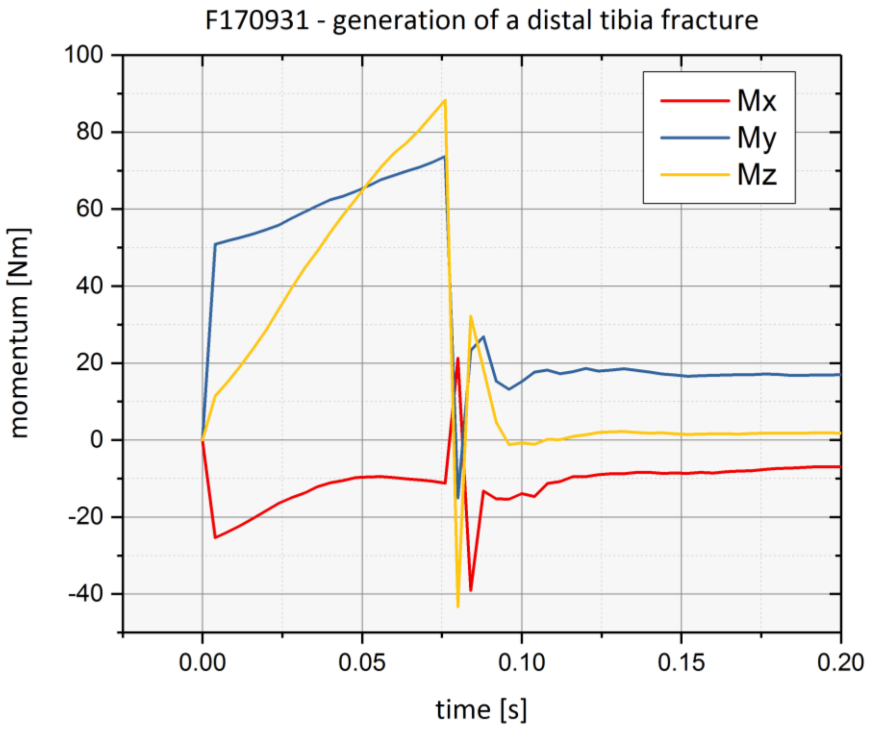




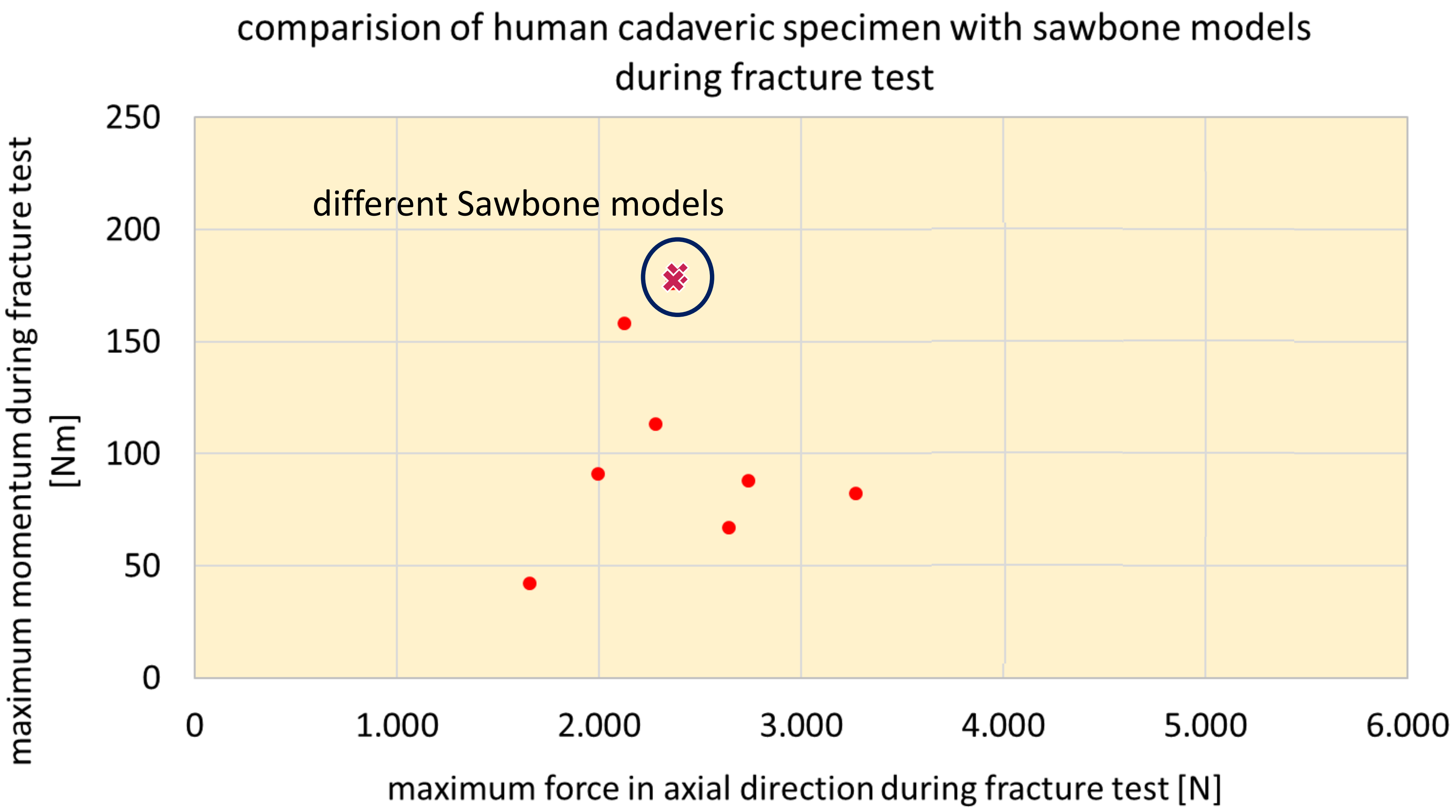
Maximum displacement at outer fracture edges in x and y direction

Reproducible Generation of Distal Tibia Fractures



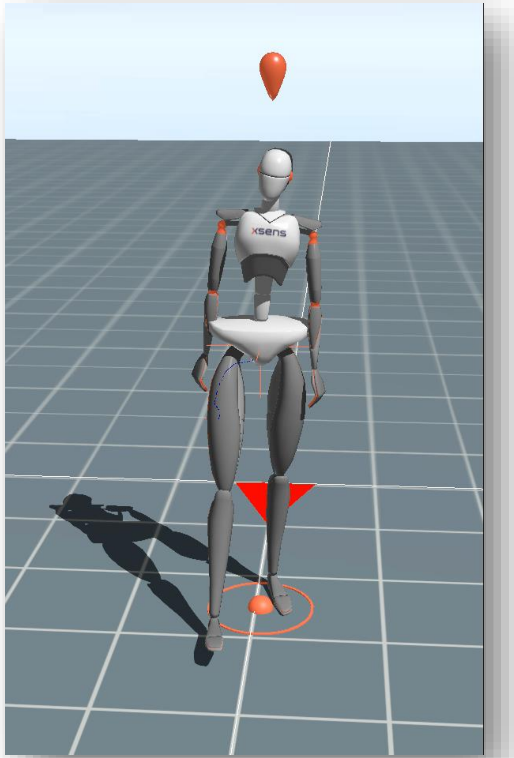


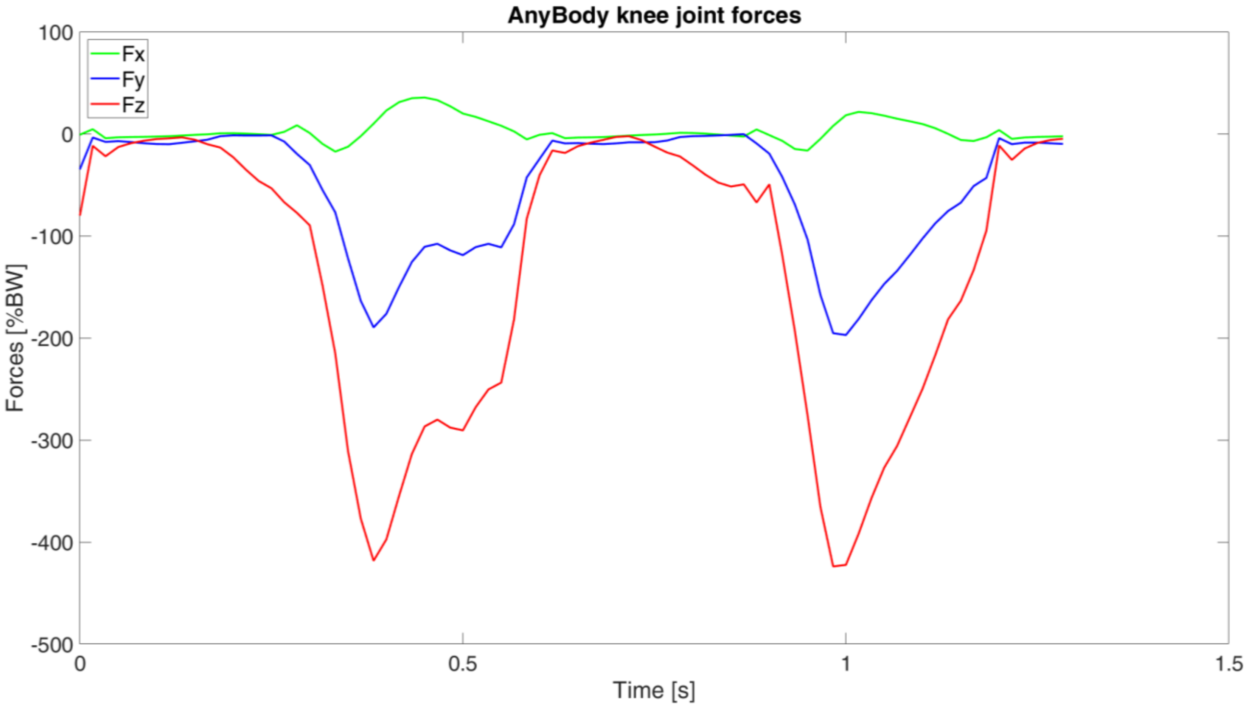
Results for a Series of Distal Tibia Fractures



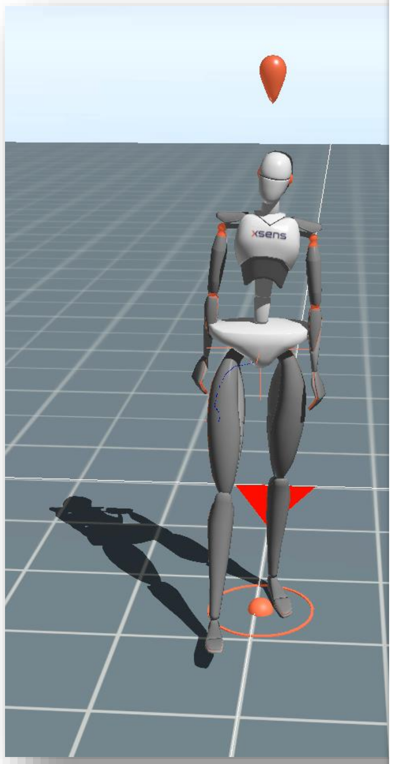
Testing Bone-Implant Systems

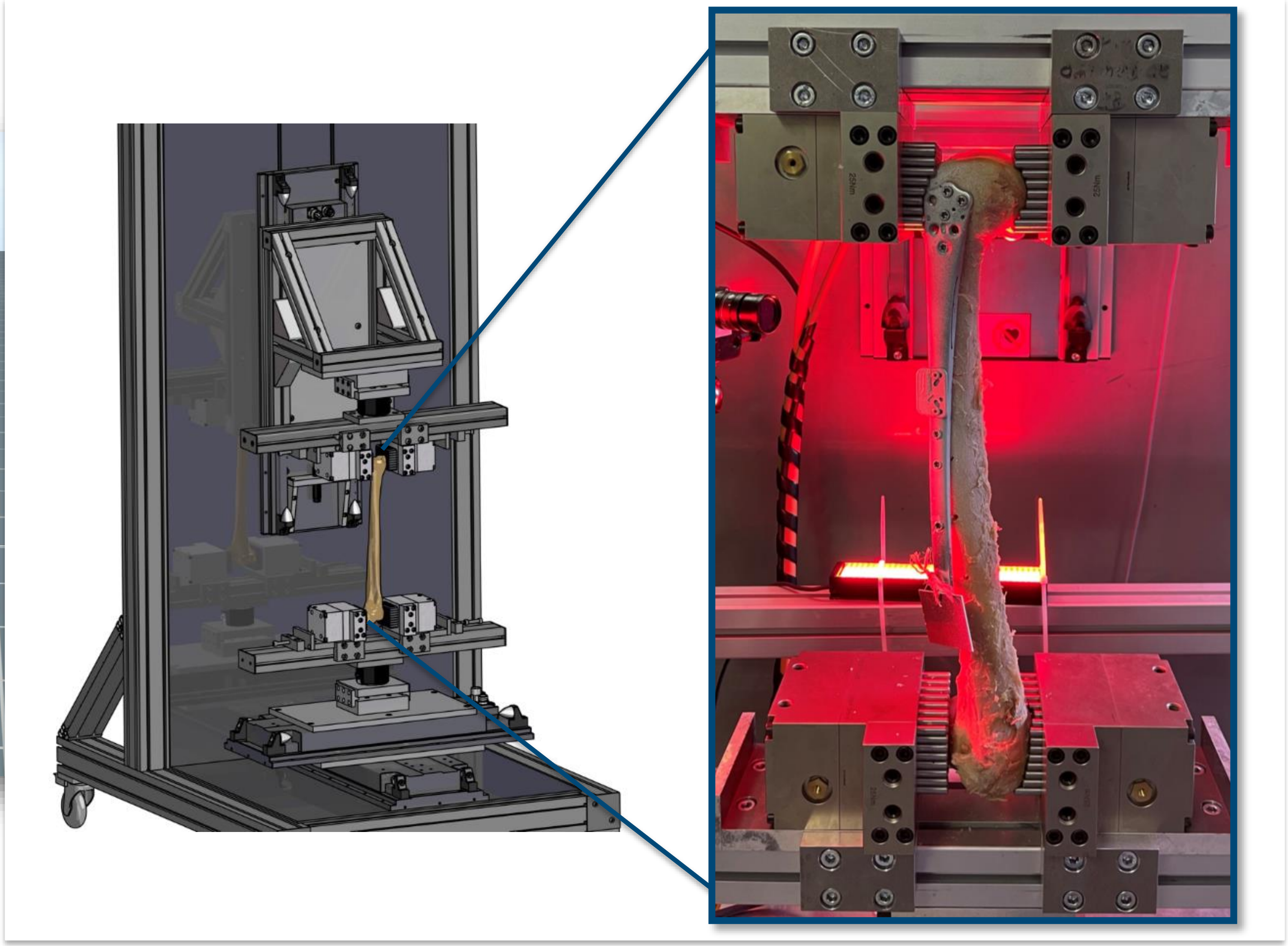
Aim: Replicate loading scenarios of human bone during gait cycle



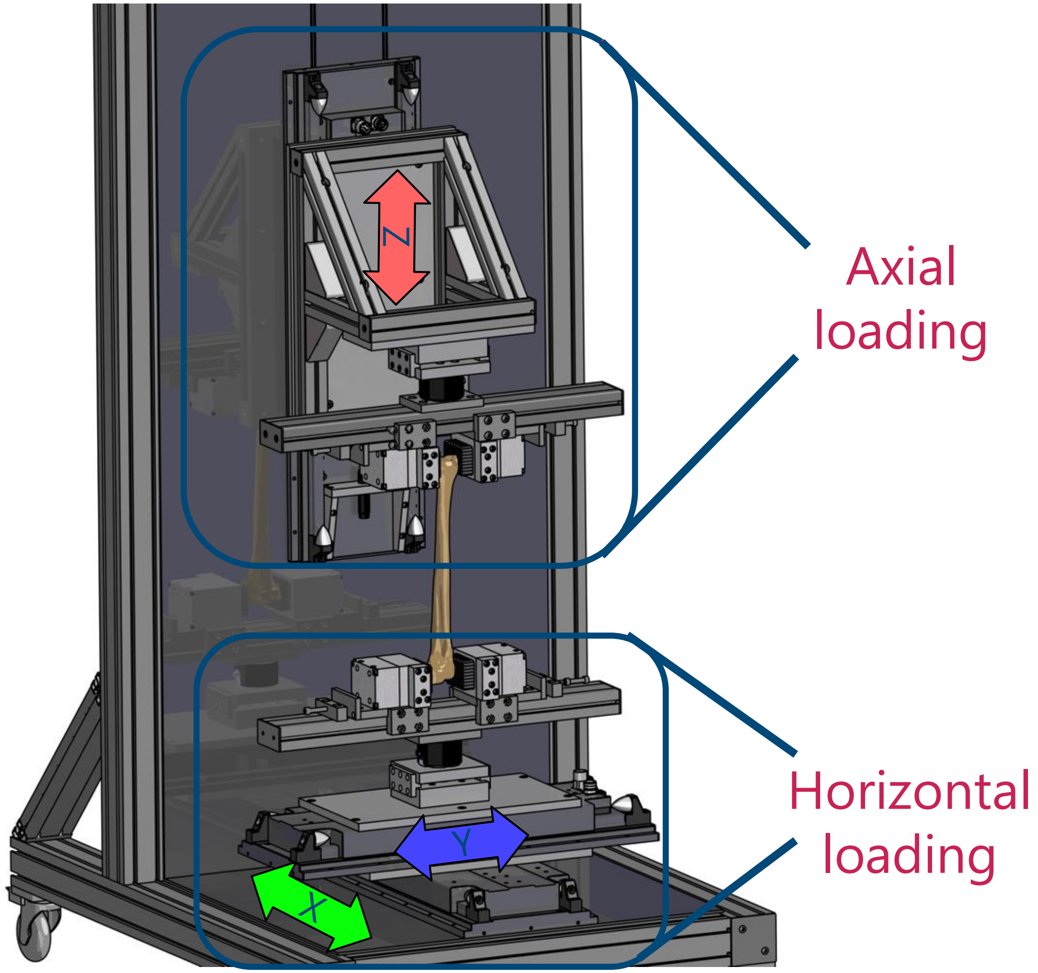


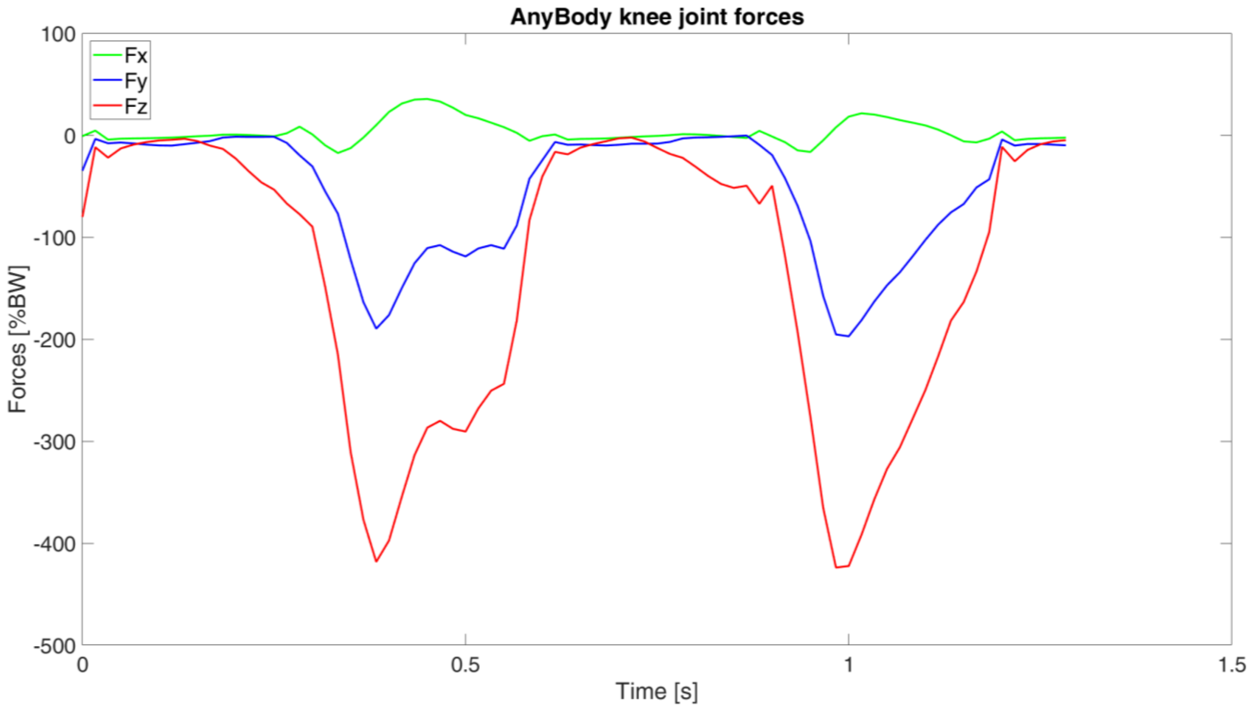
Aim: Replicate loading scenarios of human bone during gait cycle





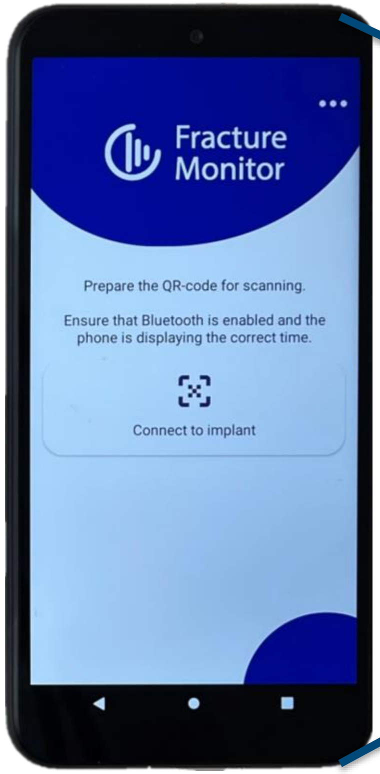
Testing Device for Force-Driven Scenarios

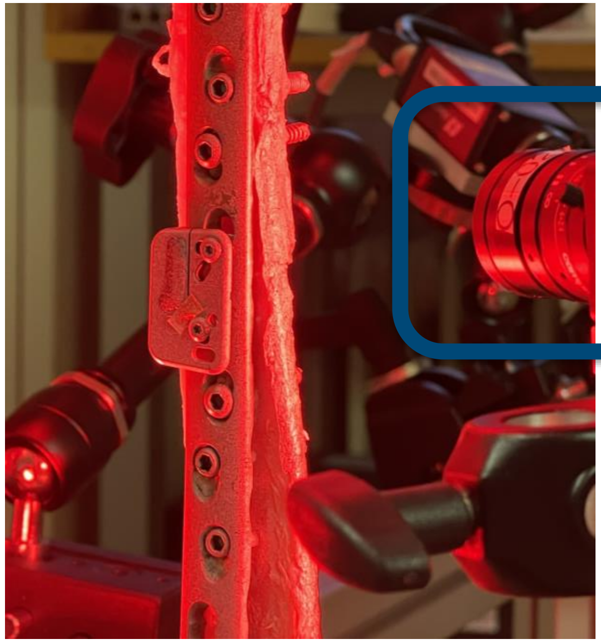




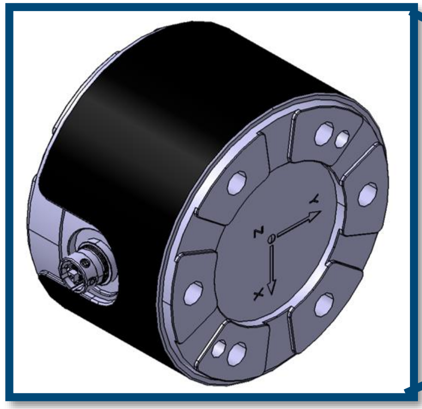
Goal: Experimental validation data for the simulation of bone-implant system

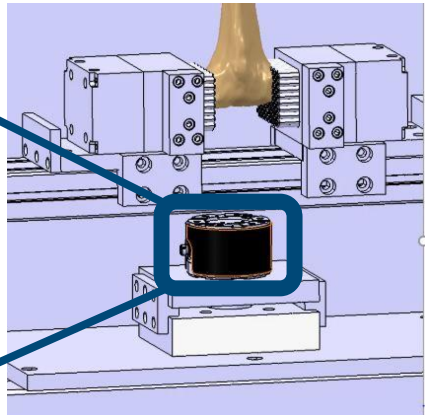
Evaluation Methods



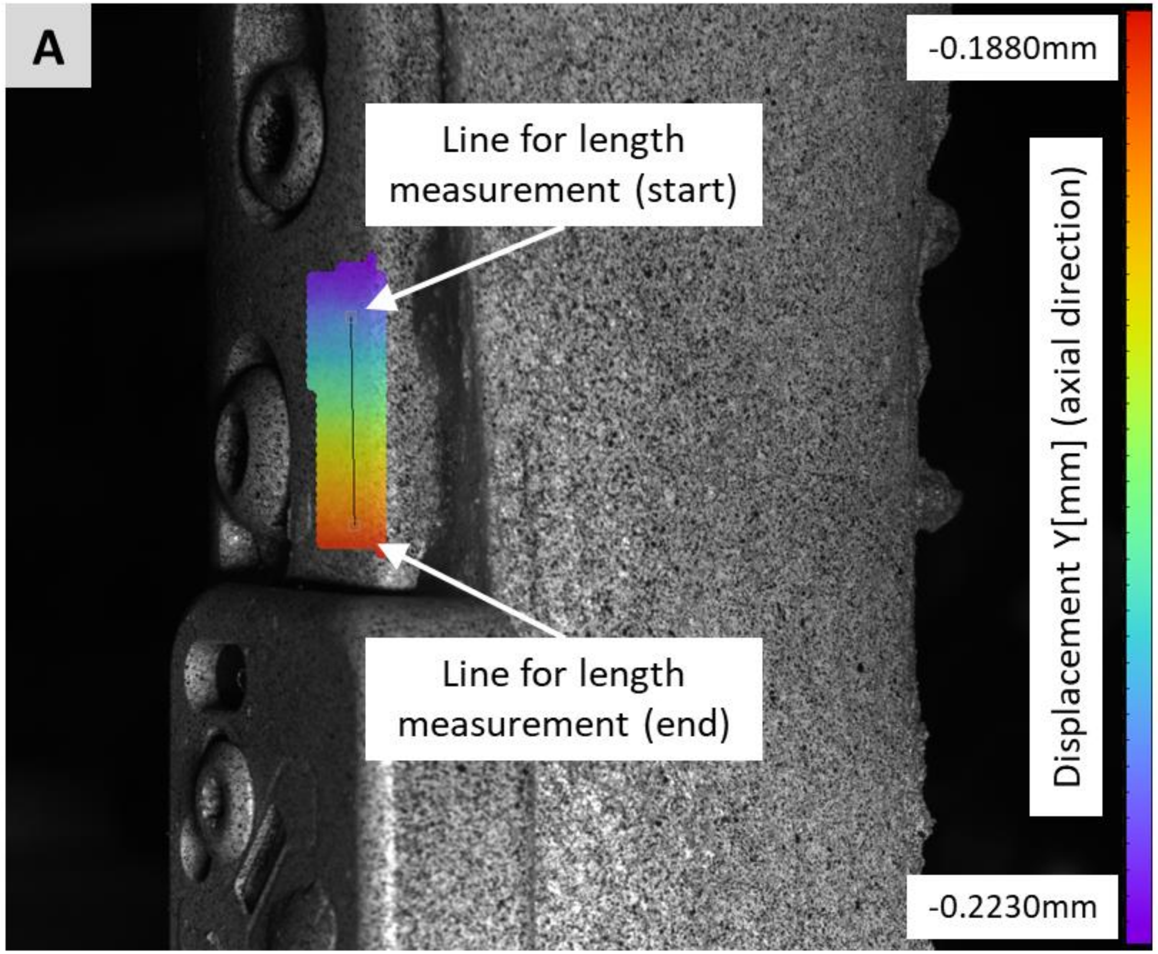


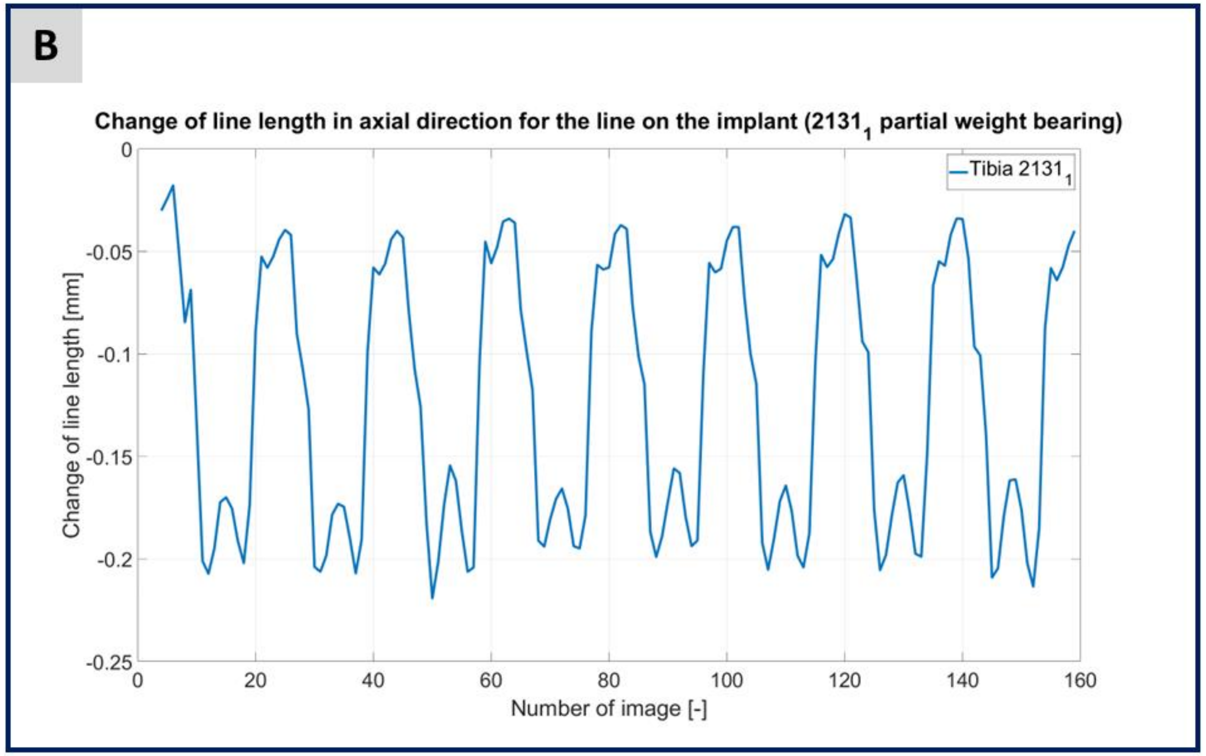
Camera system (DIC)



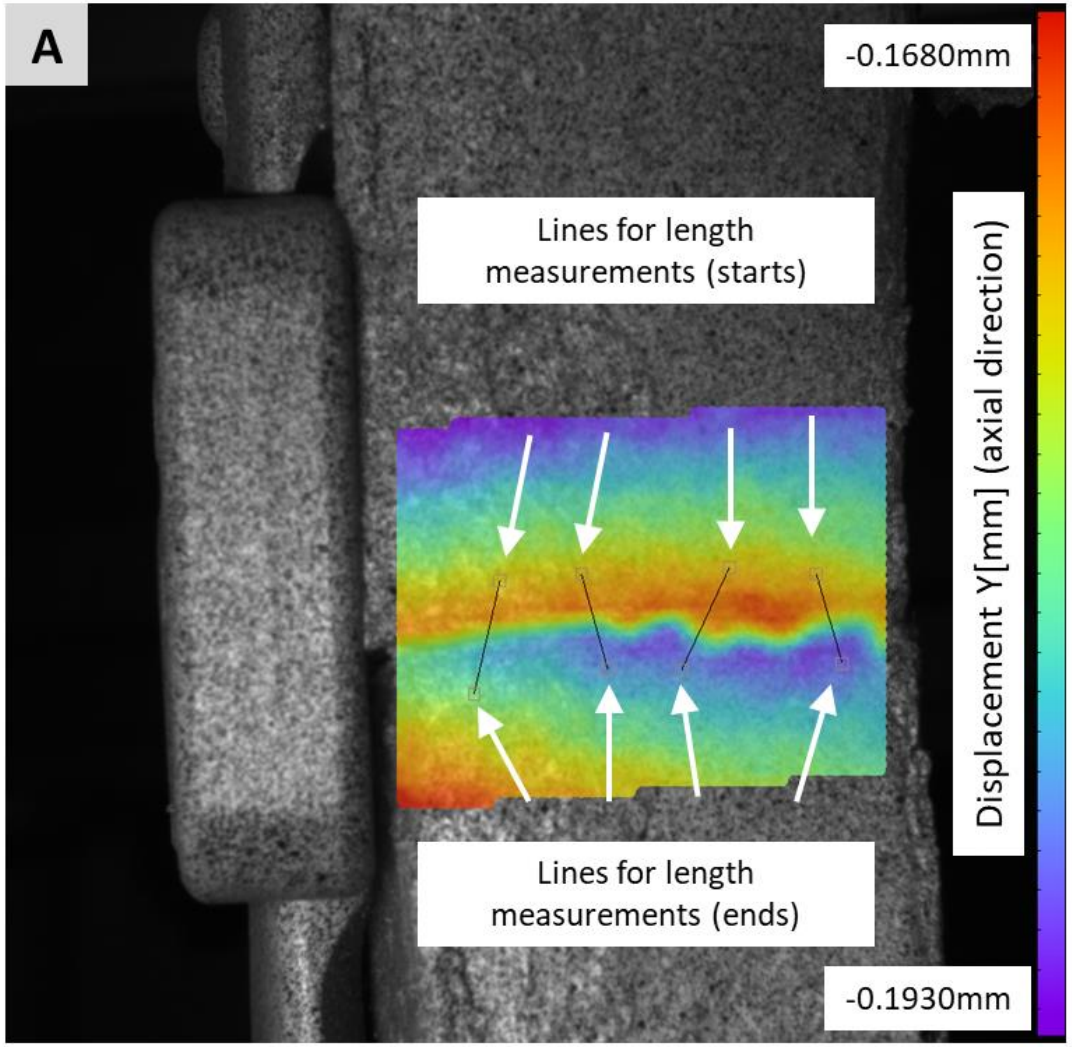


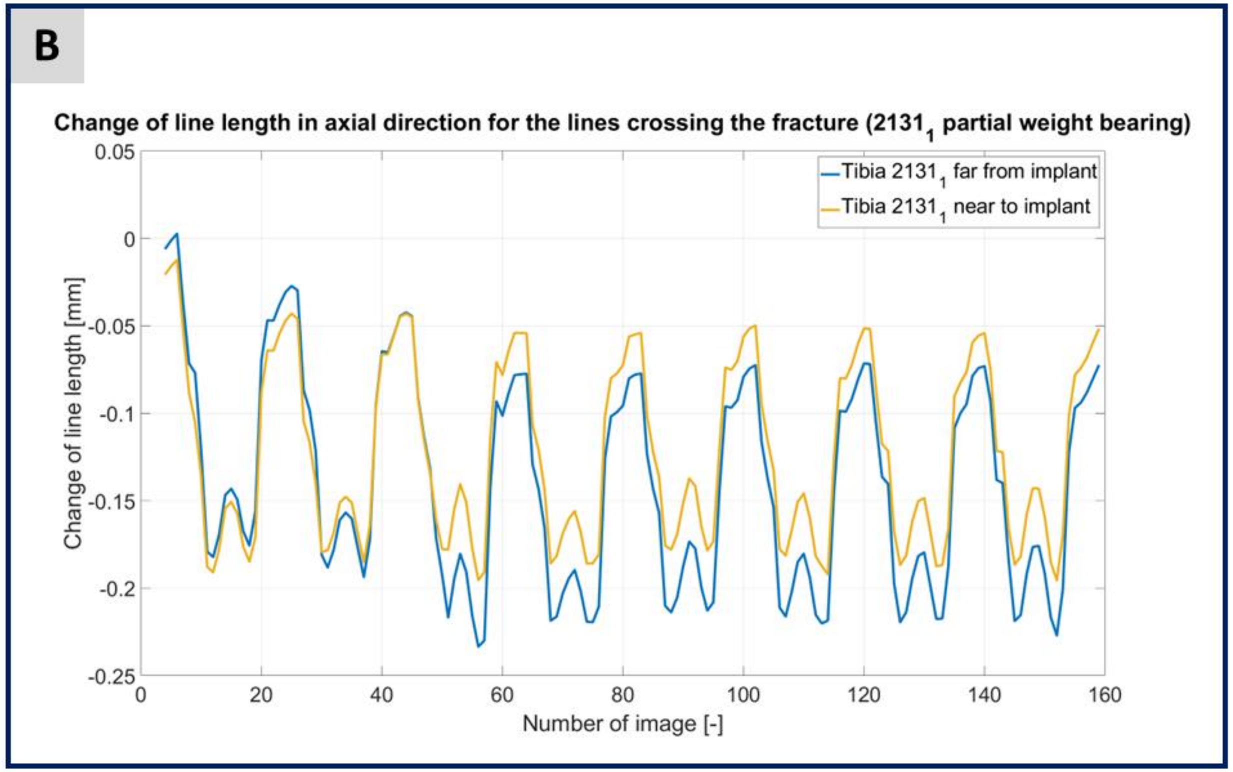
Results Experiment



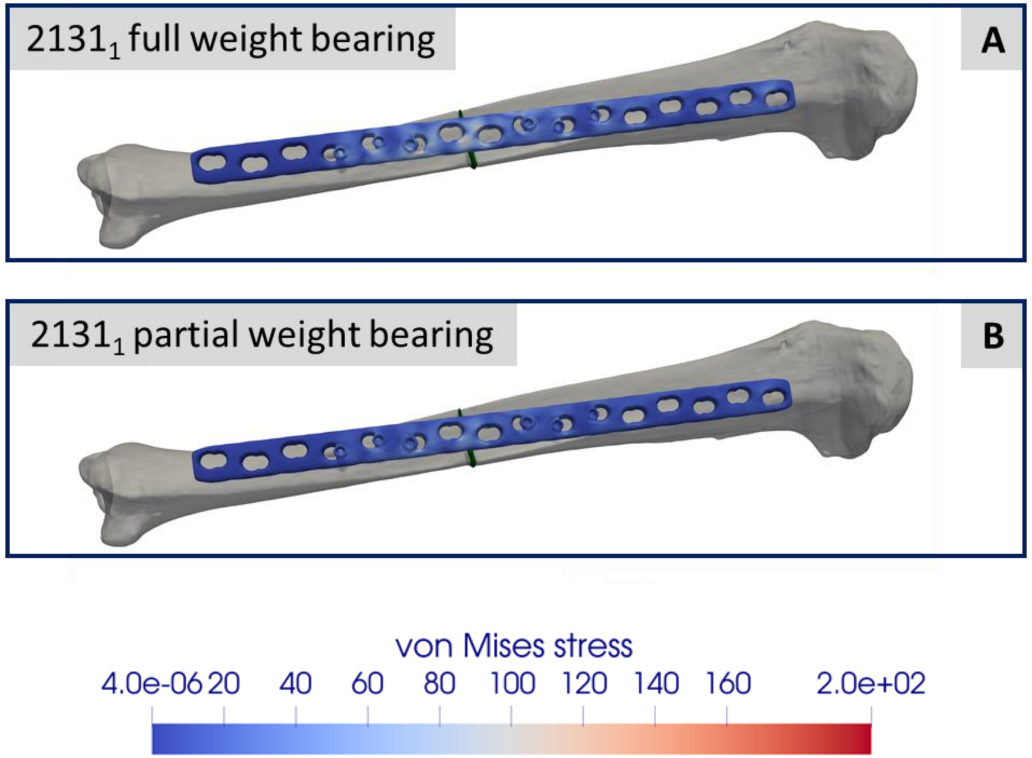


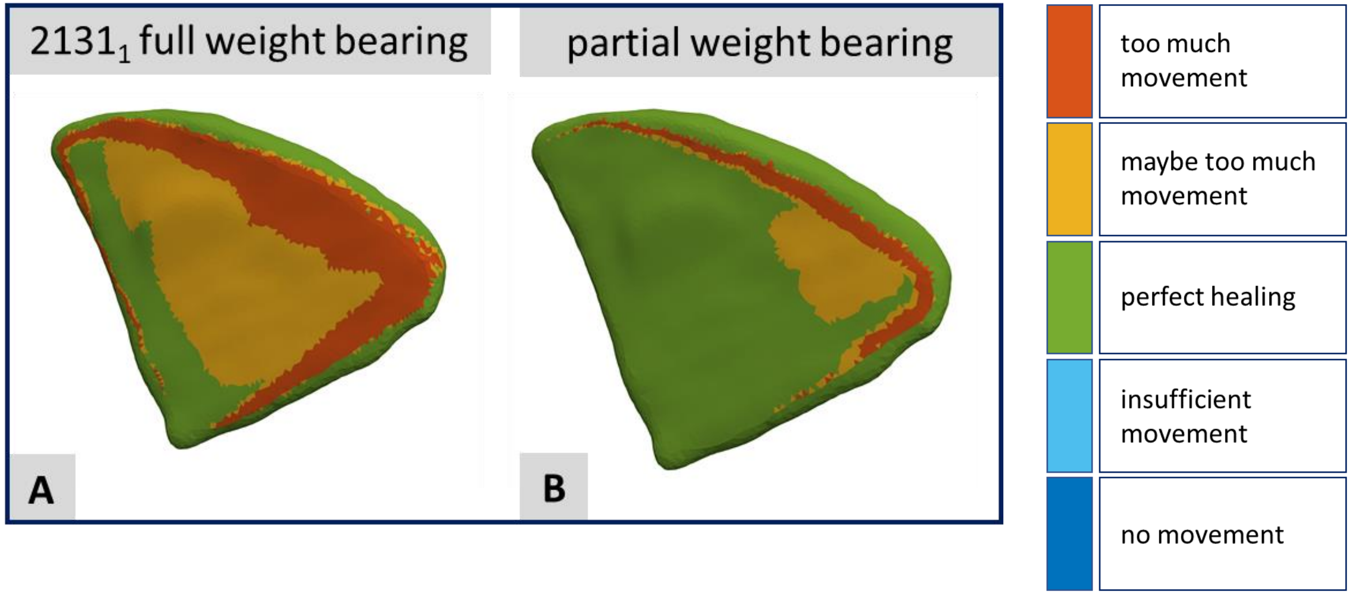
Results Experiment





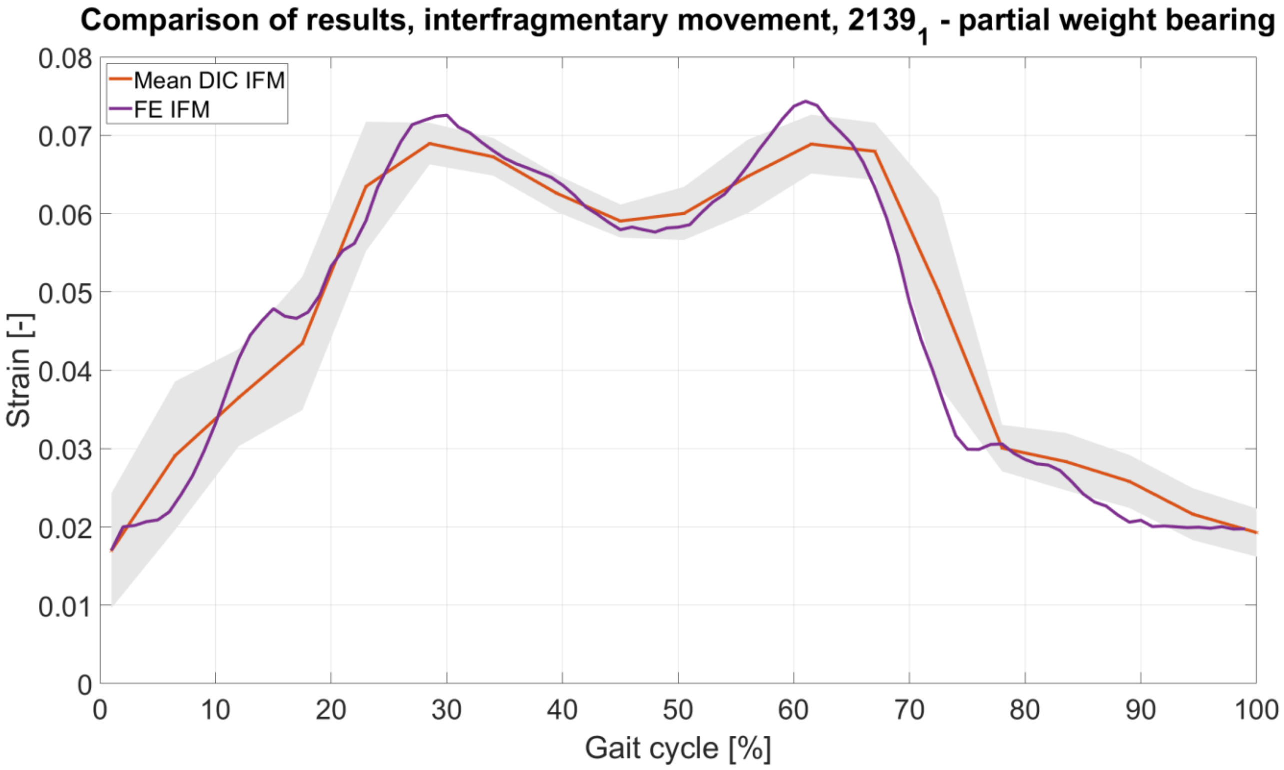
Results FEM Simulation





Claes, L.E. et al. *J. Biomech*. **32**:3, 255-266 (1999)

Results – Experiment vs Simulation



Wickert, K., Roland, M., Andres, A., Diebels, S., Ganse, B., Kerner, D., ... & Orth, M. (2024). Experimental and virtual testing of bone-implant systems equipped with the AO Fracture Monitor with regard to interfragmentary movement. *Frontiers in Bioengineering and Biotechnology*, *12*, 1370837.

Custom-Made TMJ Prosthesis

Custom-Made TMJ Prosthesis – Introduction

- 35-year-old female patient with a fracture of the condylar process due to trauma

- Custom-made TMJ prosthesis, consisting of a titanium alloy (Ti-6Al-4V) condyle and fossa component with ultra-high molecular weight polyethylene as joint surface, was inserted.

bioengineering MDPI

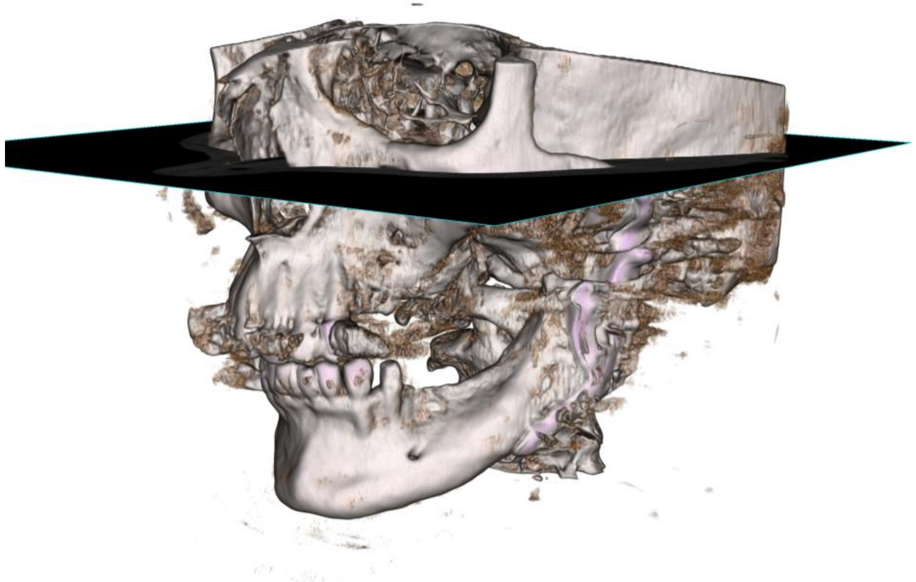
Article

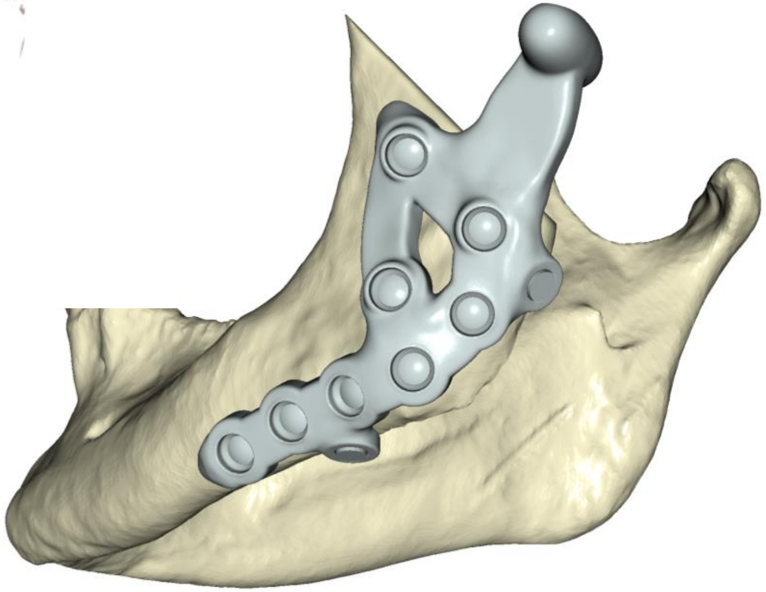
Simulation of a Custom-Made Temporomandibular Joint—An Academic View on an Industrial Workflow

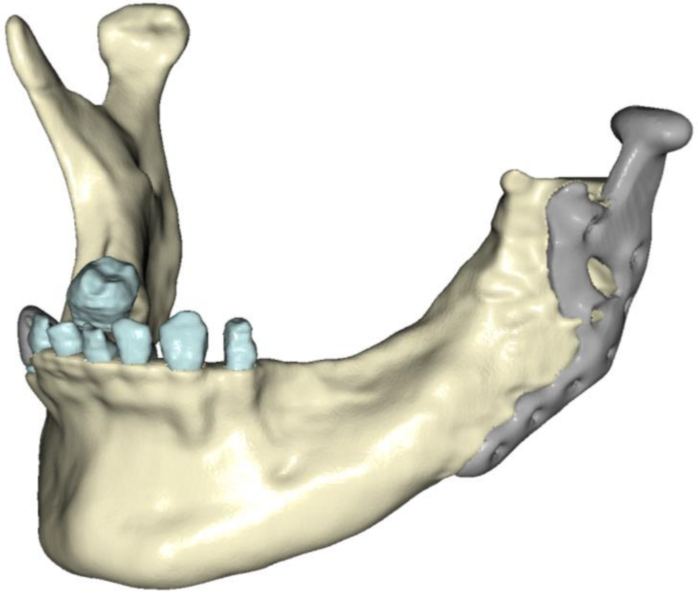
Annchristin Andres [1,†], Kerstin Wickert [1,†], Elena Gneiting [2], Franziska Binmoeller [2], Stefan Diebels [1] and Michael Roland [1,*]

KLS martin GROUP

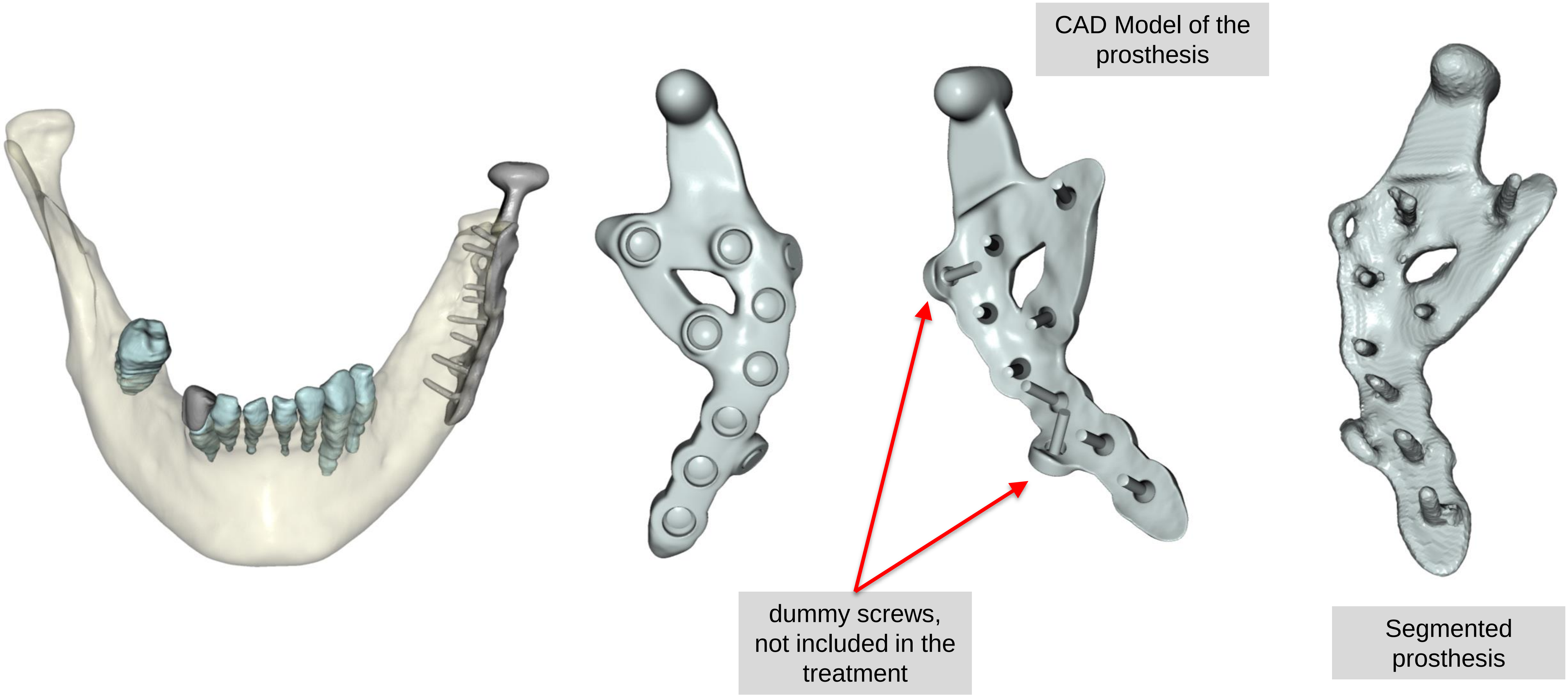
Custom-Made TMJ Prosthesis – Surgical Planning



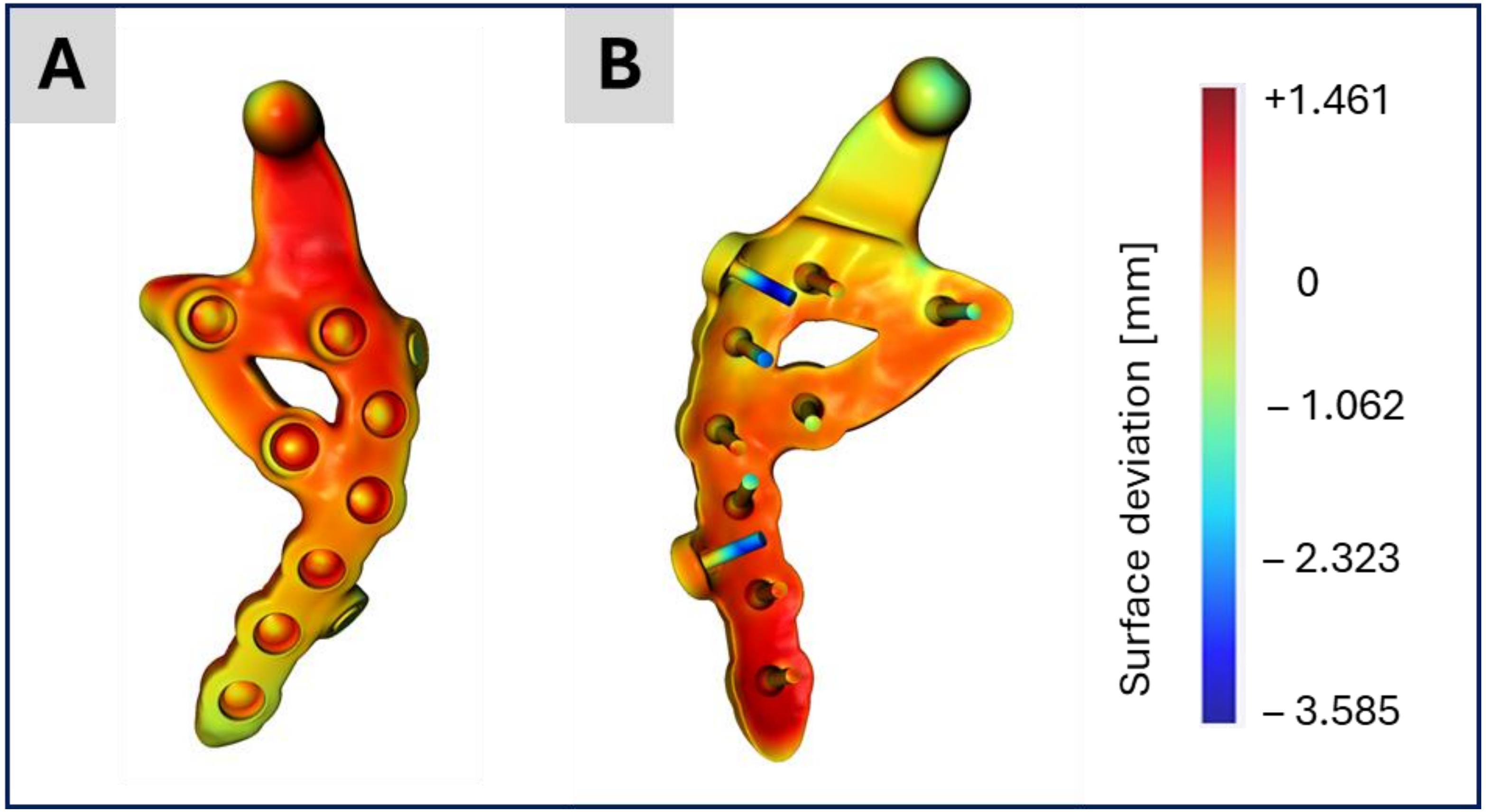




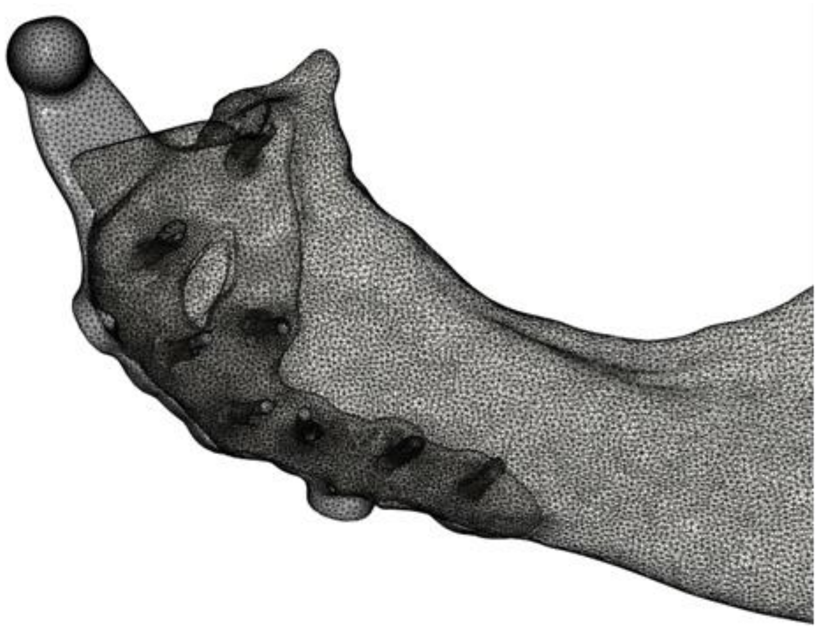
Custom-Made TMJ Prosthesis – Segmentation

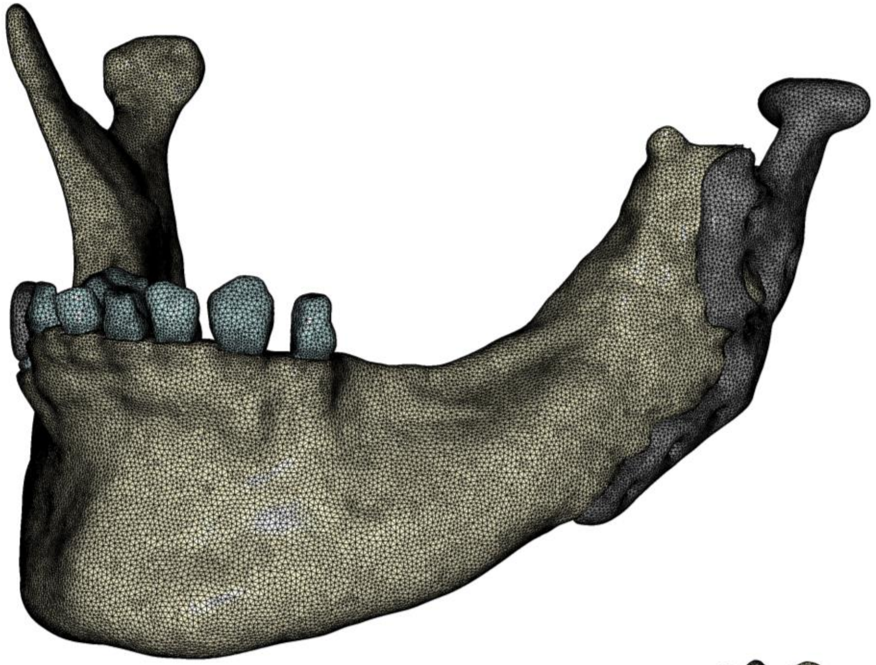


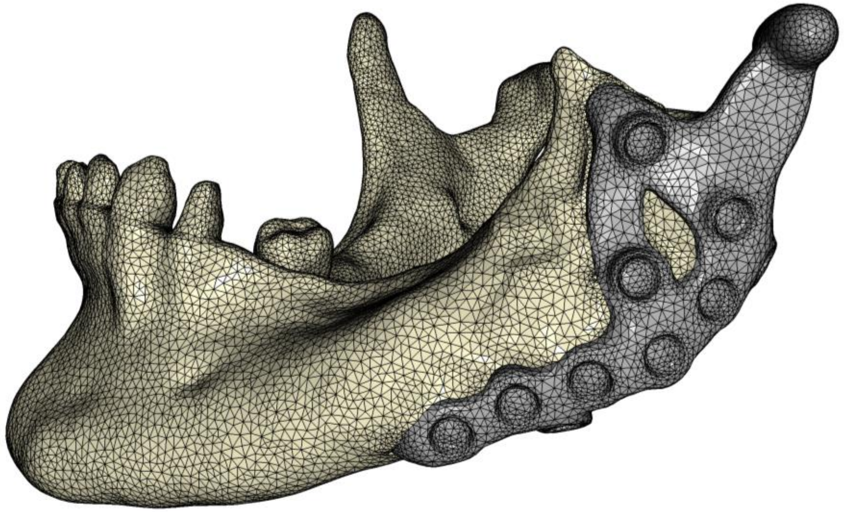
Custom-Made TMJ Prosthesis – Segmentation



Custom-Made TMJ Prosthesis – FE Models



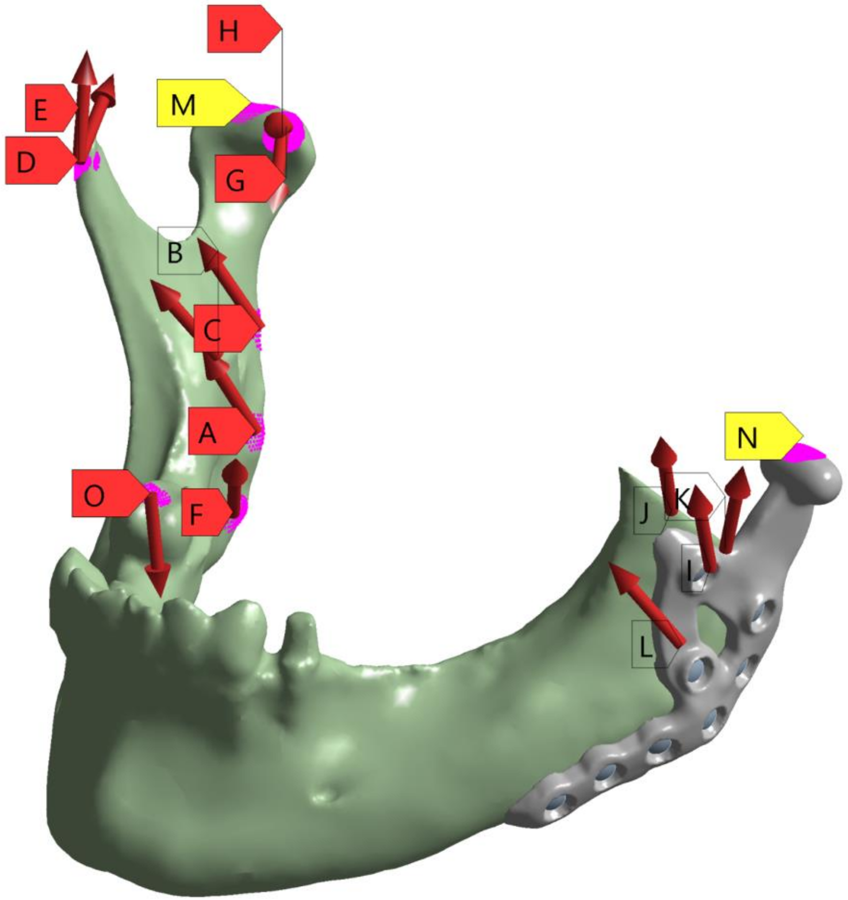


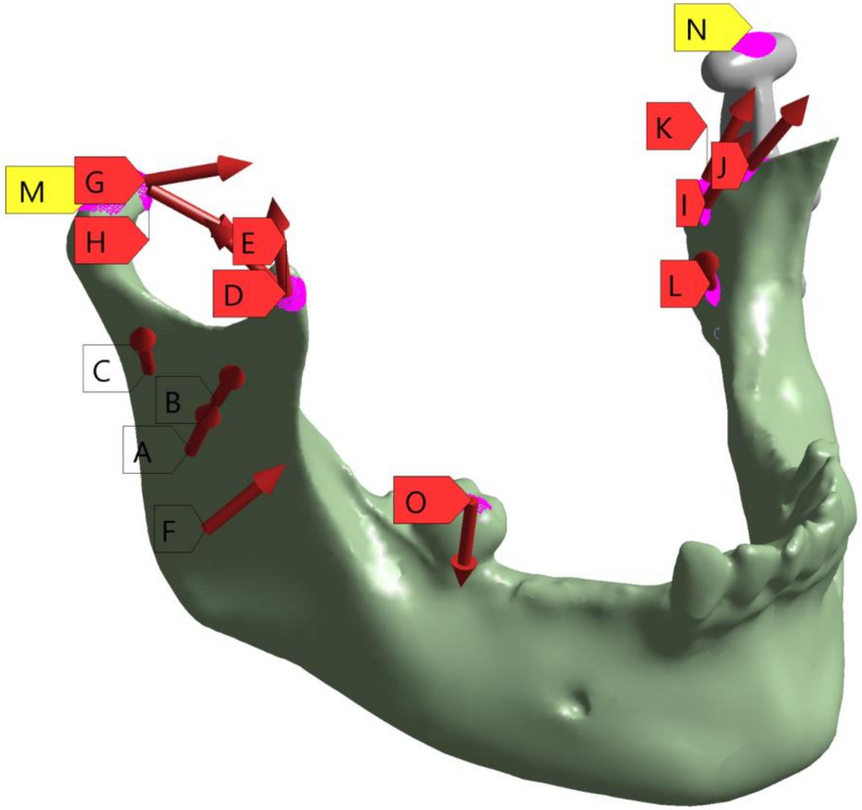


Custom-Made TMJ Prosthesis – Boundary Conditions

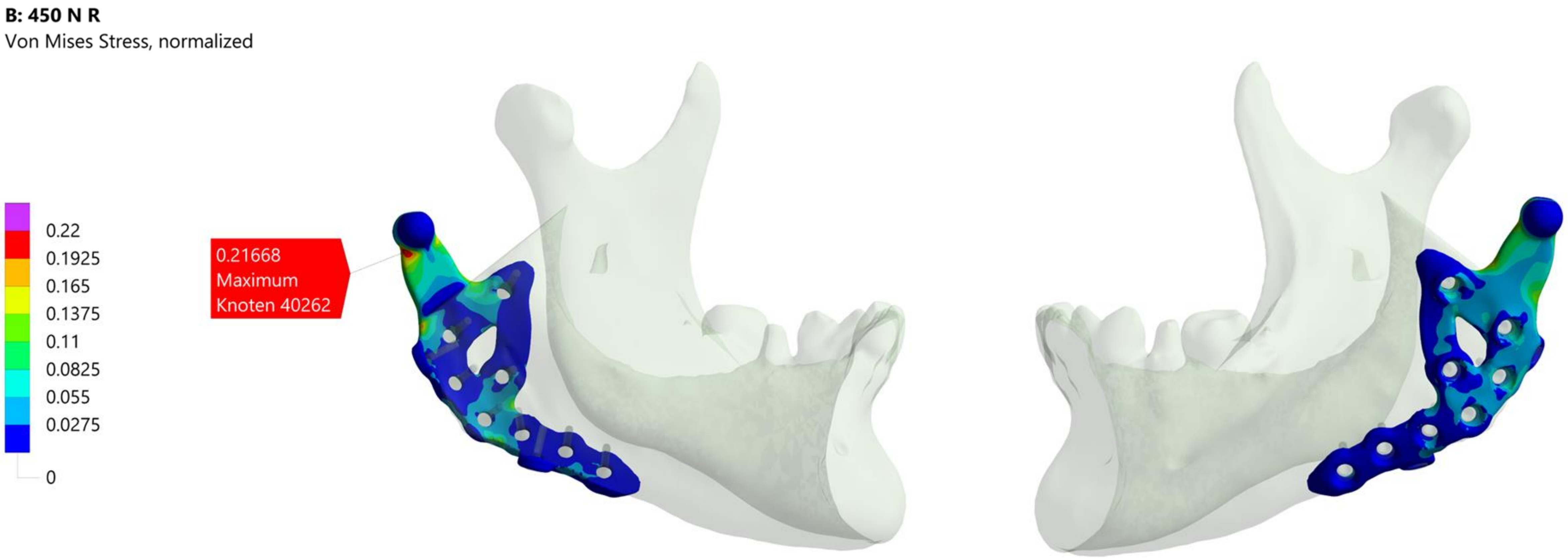
Boundary Conditions

- **A** Right Superficial Masseter: 149,68 N
- **B** Right Deep Anterior Masseter: 19,811 N
- **C** Right Deep Posterior Masseter: 9,2488 N
- **D** Right Anterior Temporalis: 174,63 N
- **E** Right Posterior Temporalis: 47,085 N
- **F** Right Medial Pterygoid: 137,68 N
- **G** Right Superior Lateral Pterygoid: 6,1164 N
- **H** Right Inferior Lateral Pterygoid: 28,424 N
- **I** Left Superficial Masseter: 123,21 N
- **J** Left Deep Anterior Masseter: 18,378 N
- **K** Left Deep Posterior Masseter: 5,5056 N
- **L** Left Medial Pterygoid: 104,44 N
- **M** Right Support
- **N** Left Support
- **O** Molar Bite Force: 450, N

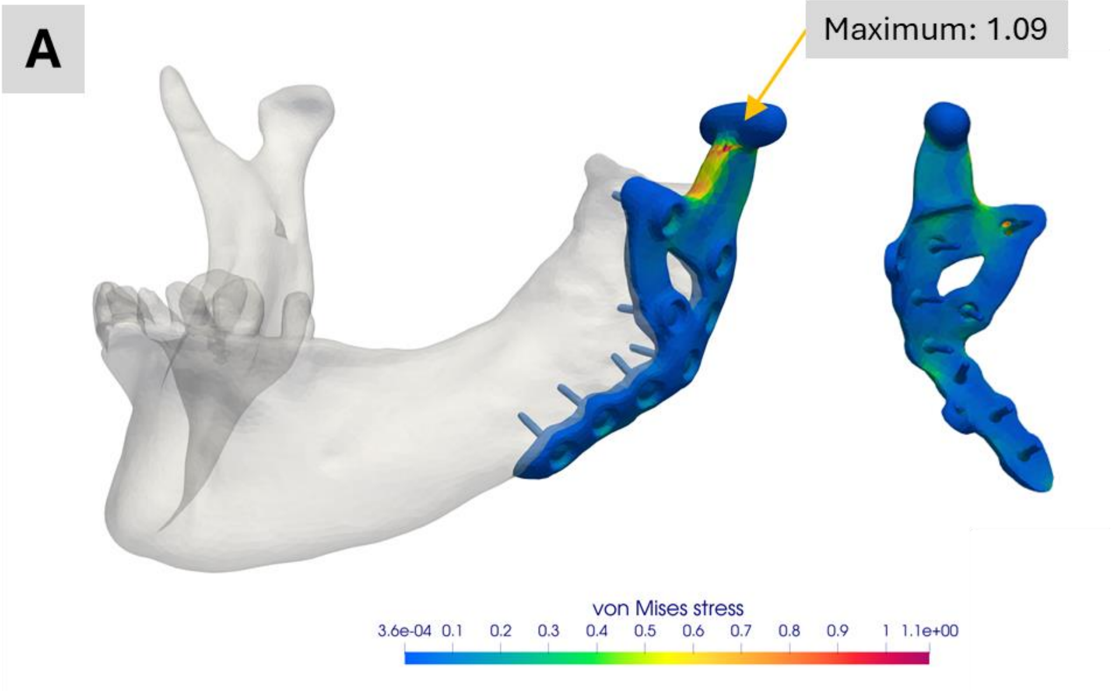


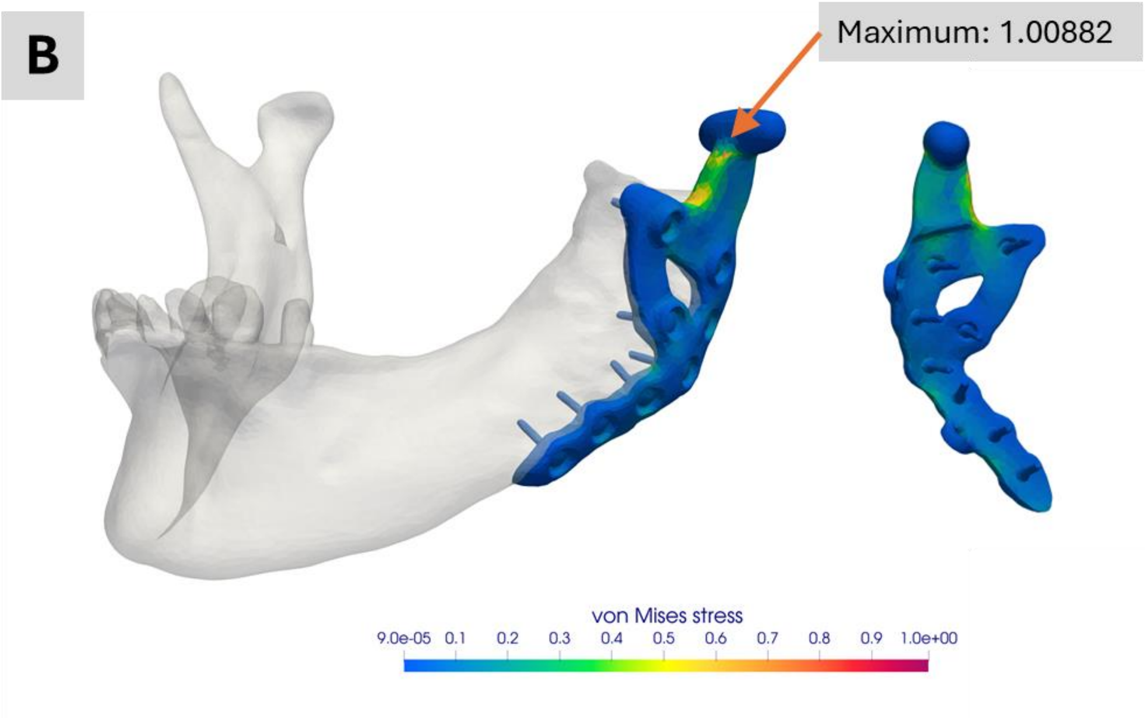


Custom-Made TMJ Prosthesis – FEA Results

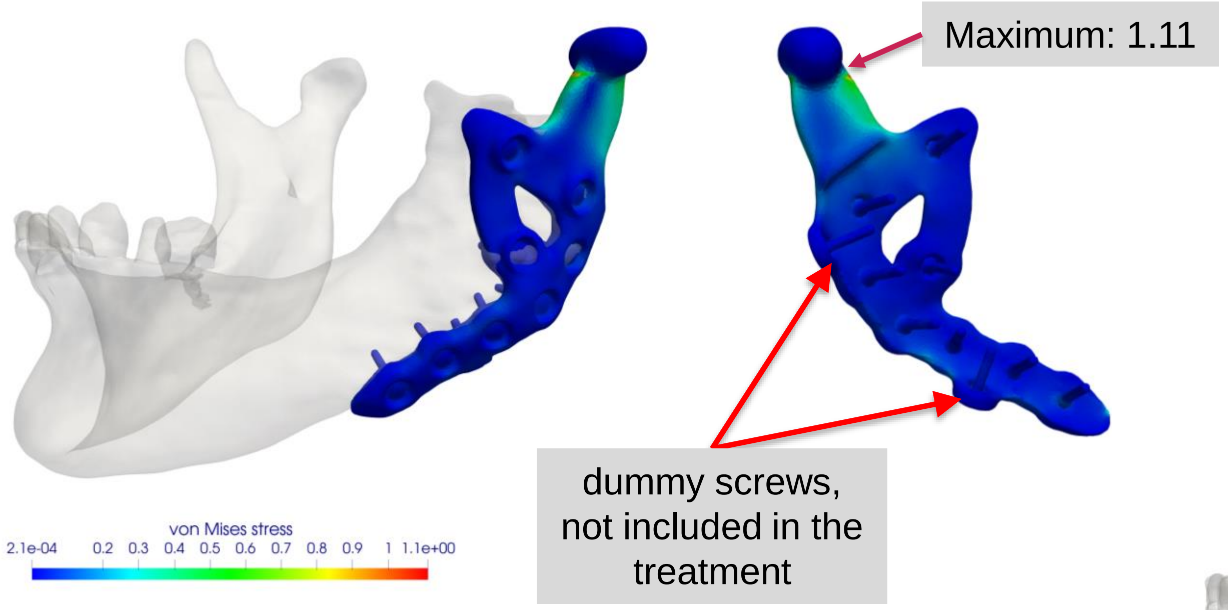


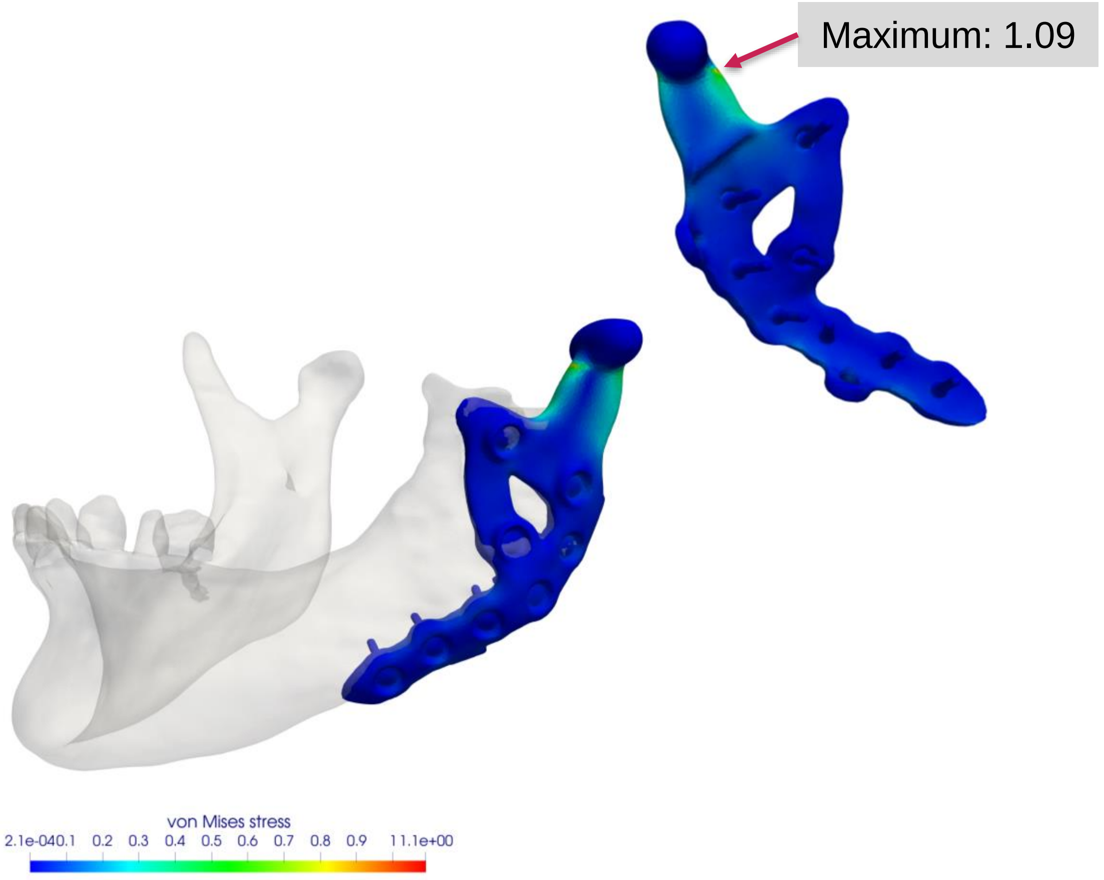
Custom-Made TMJ Prosthesis – FEA Results





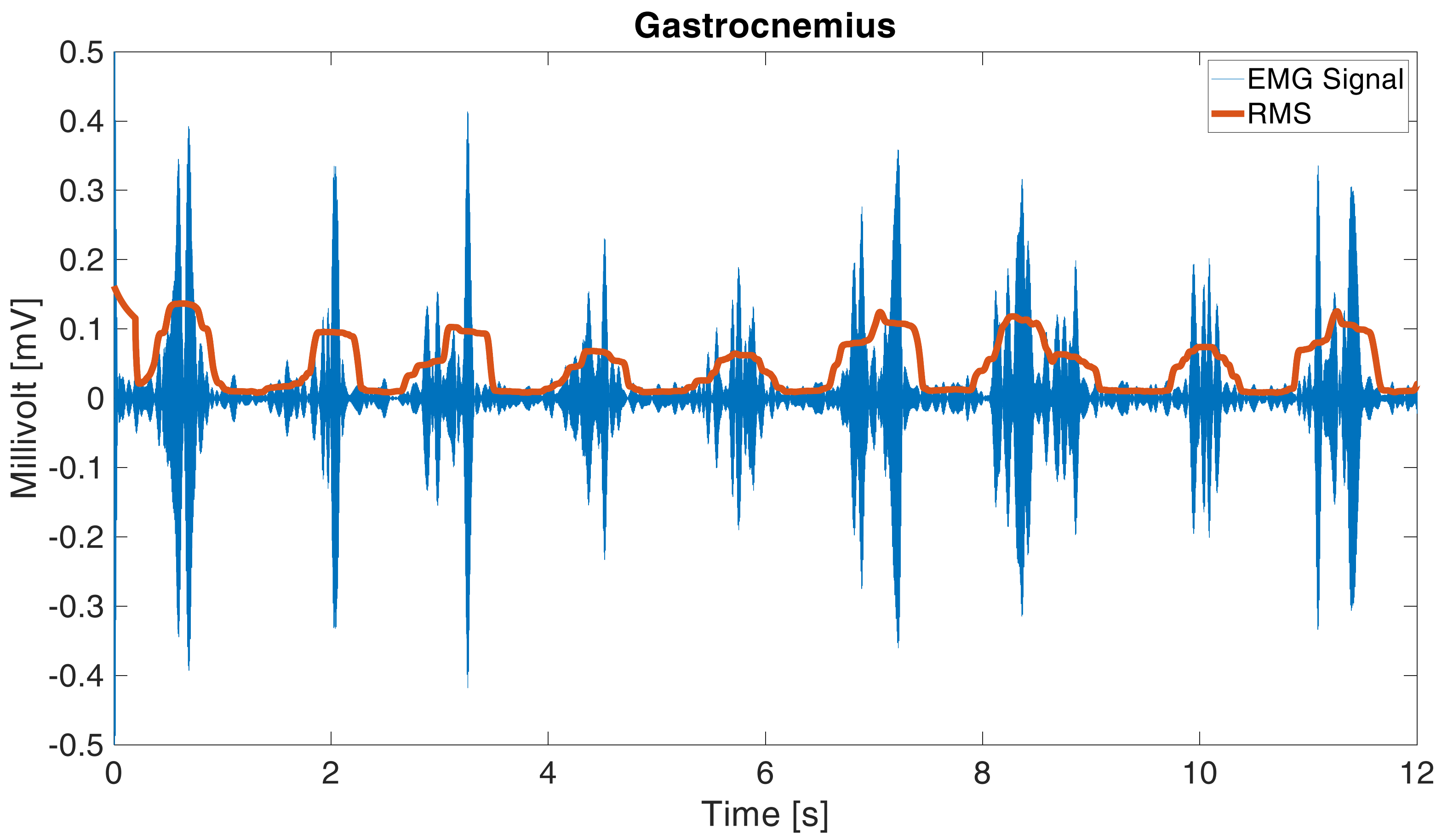
Custom-Made TMJ Prosthesis – FEA Results





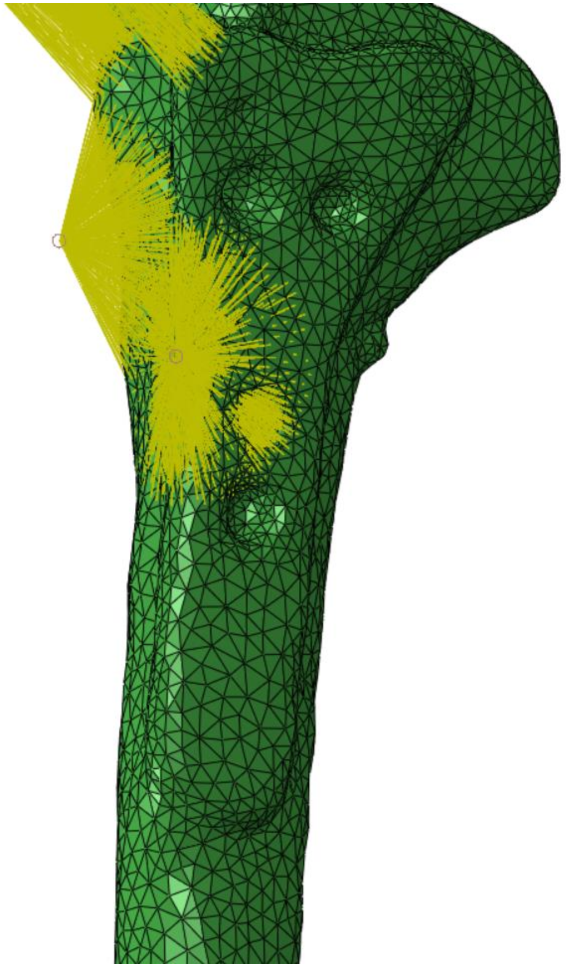
Outlook: EMG Data

- Synchronous recording of movement and EMG data (Delsys™)
- EMG data for initial rehabilitation exercises to investigate the muscle pull on the fracture gap
- Additional input for simulation and to define the boundary conditions



Outlook: Muscle Attachments

- Solving artefacts regarding the implant and fracture with OptiStruct™ and Ansa™
- Automatic workflow



Take Home Message

Doubts

- Close to reality?
- Validation
- Focus on best practice
- Blackbox

How to build trust?

- Comparison with real data
- Clear explanations
- Clear benefits

What are the key elements of a good simulation?

- Appropriate
- Reliable
- Valid
- Relevant

APPLIED MECHANICS

UNIVERSITÄT DES SAARLANDES

Thank you for your attention! Any Questions?

Contact: annchristin.andres@uni-saarland.de