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Fachhochschule Salzburg University of Applied Sciences

FE Simulation and Analysis of Shoulder Implants with Bone Remodeling

MSc. DI(FH) Werner Pomwenger

Salzburg University of Applied Sciences
A-5412 Puch, Urstein Süd 1, AUSTRIA
werner.pomwenger@fh-salzburg.ac.at

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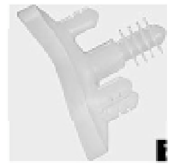
Introduction

- Need for joint replacement
  - Rheumatoid arthritis
  - Traumatic injuries
  - Rotator cuff tear
- Two types of arthroplasty
  - Hemiarthroplasty - replacement of articular surface of the humeral head
  - Total shoulder arthroplasty (TSR) – additional replacement of glenoid surface
  - Prequesite: intact rotator cuff
  - Primary fixation: bone cement, screws, press fit
  - Secondary fixtation: bone ingrowth



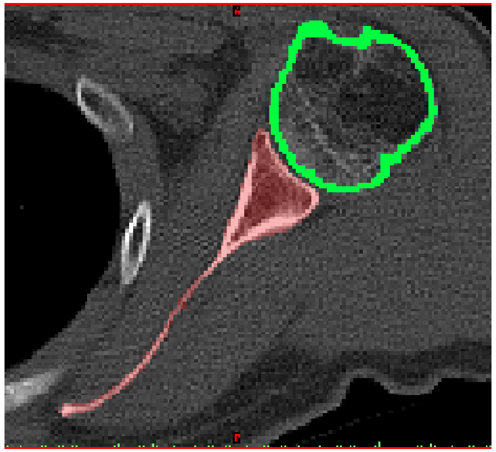
Introduction

- Problems
  - Prosthesis failure due to
    - Loosening
    - Inlay wear
    - Breaking of parts, especially screws
- Goals and investigations
  - Know-How in the field of FE-analysis, 3D modelling, biomechanics and biogenic structures
  - Virtual 3D surgery
  - Highly accurate, realistic 3D modelling from CT to FE-analysis
  - Optimal preoperative implant angle and position
  - Statistic methods for evaluation and validation
  - Patient-specific prosthesis design

Modelling

- CT segmentation
  - Software: Mimics V13.0, 3matic V5.01
  - Thresholding, Region grow
  - Manual refinement
  - Generation of 3D model
  - STL-Export
  - Import STL to 3matic V5.01
  - Smoothing and compensate for defects

Fig. 1: Model after segmentation and 3D reconstruction



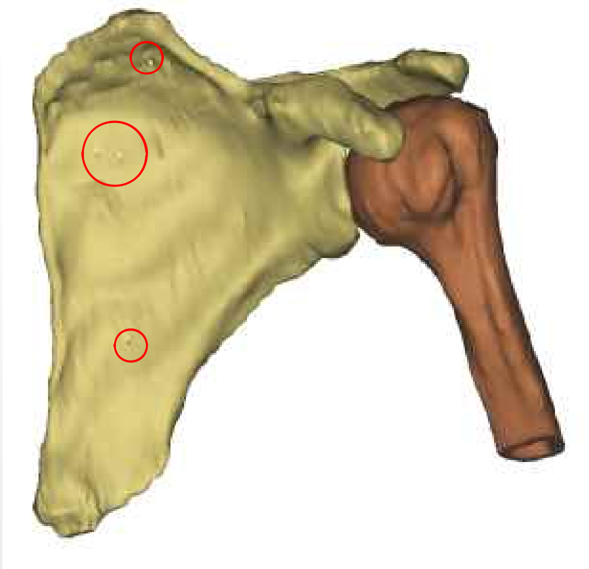


Fig. 2: Model after segmentation and 3D reconstruction

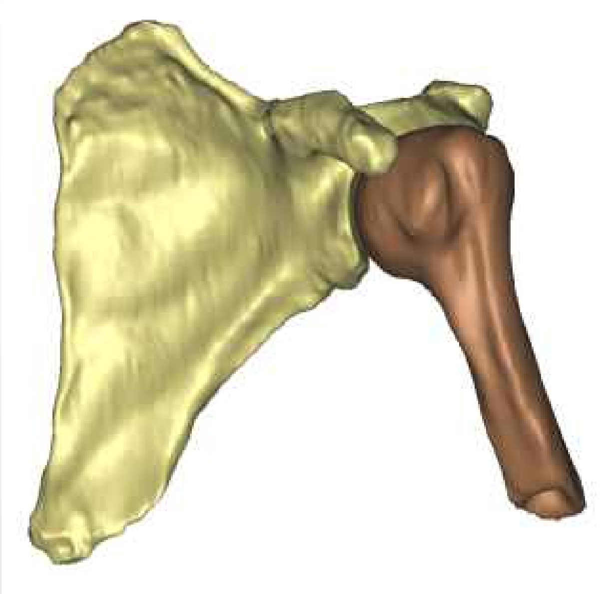


Fig. 3: Final 3D model after compenstion

Modelling

- 3D modelling
  - Positioning of implant (HAS-Prothesis - Stryker Howmedica Osteonics)
    - Reconstruction of anatomical or pathological state?
    - Definition of the neutral position
      - According to De Wilde et. al. (2010) using the inferior glenoid plane (API-plane) is most reliable and accurate
      - Inferior plane and scapular plane used for measurement of retroversion and inclination
      - Eventually repositioning due to anatomical issues (perforation)

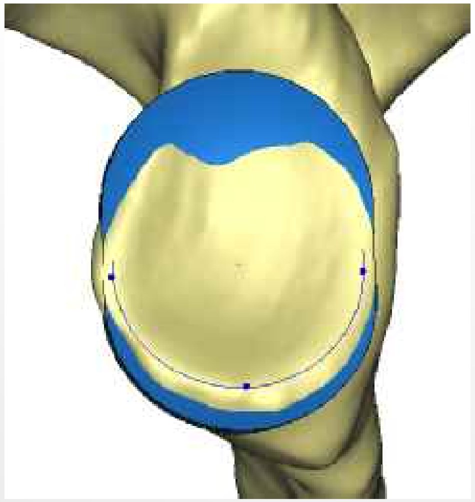


Fig. 4: Implant positioning by using the inferior glenoid plane

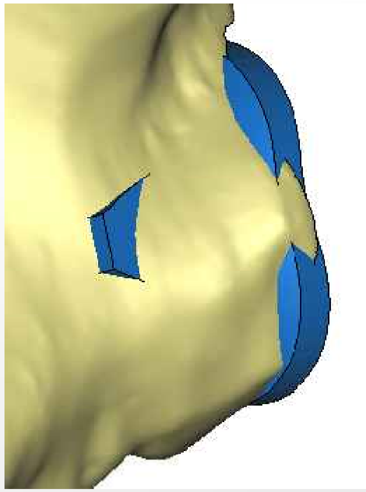


Fig. 5: Perforation of the scapular neck

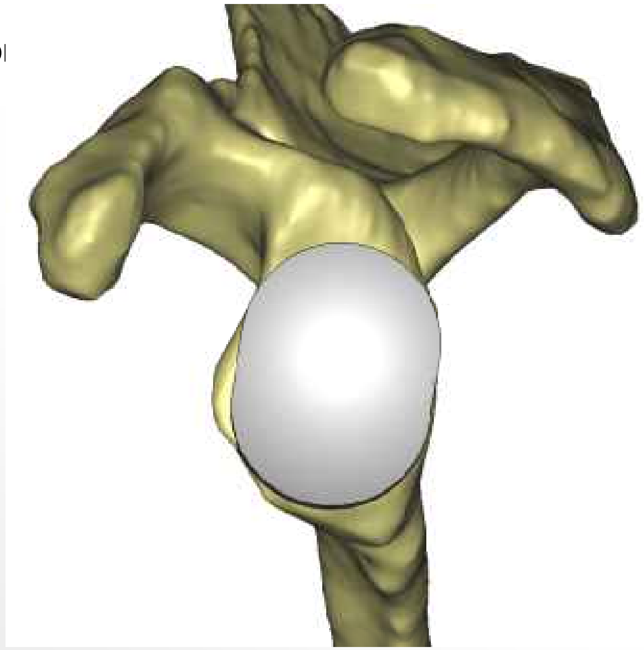


Fig. 6: Implant position after correction

- Virtual surgery procedure
  - Preparation of glenoid surface with two tools (surface reamer and stencil)
  - Modeling of bone cement
    - Ideal cement thickness ~1-1.5mm
    - Approach by using a constructed surface reamer and a stencil
    - Boolean operation for bone cement
      - Cement block \ scapula
      - Cement block \ implant

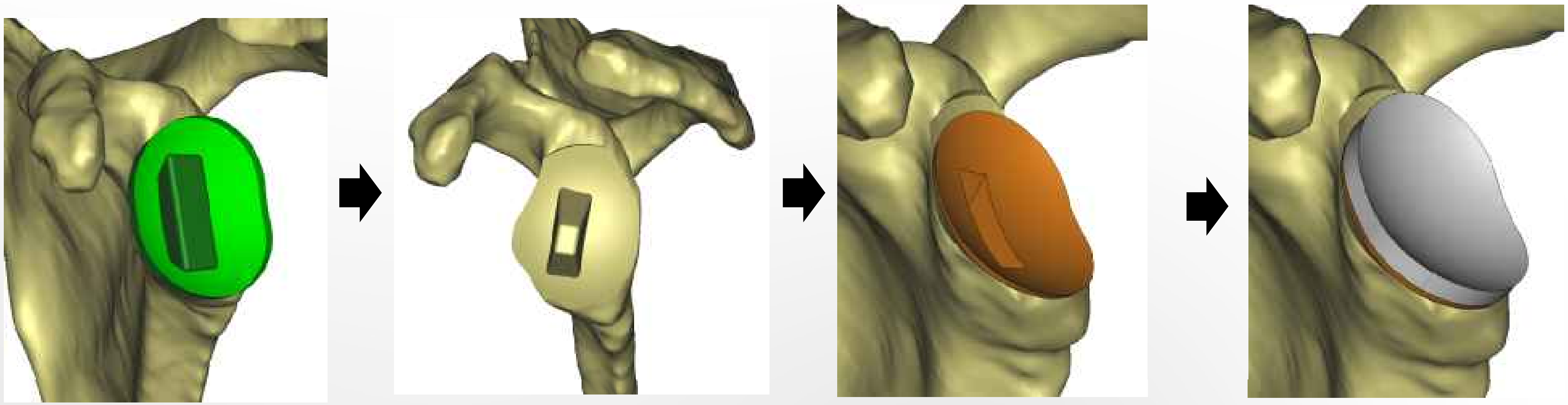


Fig. 7: Virtual surgery procedure

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Modelling

- Meshing
  - Software: ICEM CFD
  - Main steps
    - STL-Import & create geometry/topology
    - Define all curves of intersecting surfaces
    - Define body points in all parts and intersecting parts
    - Define meshing (max/min size, etc.) parameter

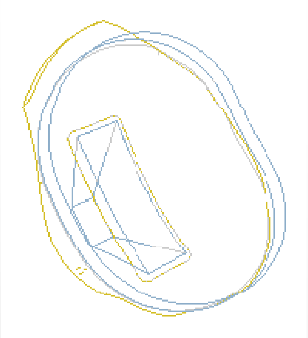

Fig. 8: Create geometry & intersecting surfaces

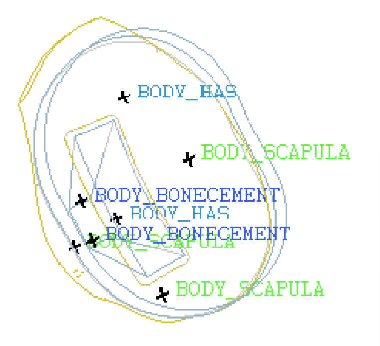

Fig. 9: Define body points

Fig. 10: Shoulder model – final mesh, ~380k elements

Modelling

- Meshing
  - Meshing by penetration
    - Boolean operations done by ICEM
    - Consistent nodes at part boundaries
    - Only for bonded contacts
  - Meshing part by part
    - Boolean operations in 3matics
    - Contact definition with eg. friction coefficients for micromotion possible
  - Check mesh for errors
  - Smooth mesh concerning element quality
  - Export mesh
  - Import mesh to Ansys Classic and write CDB file for input to Ansys Workbench

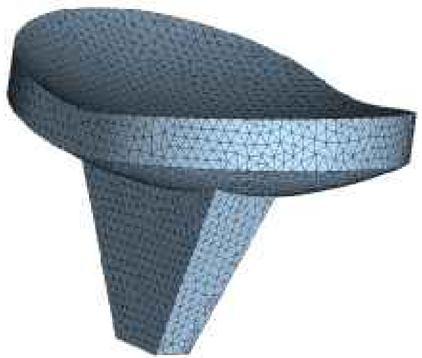

Fig. 11: Implant volume mesh

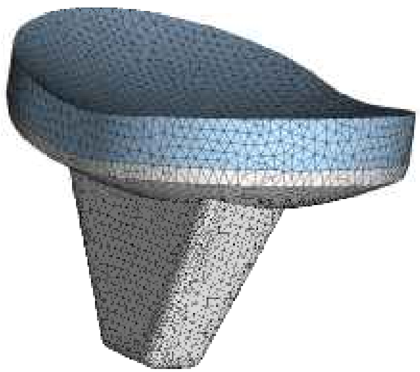

Fig. 12: Prothesis & bone cement volume mesh

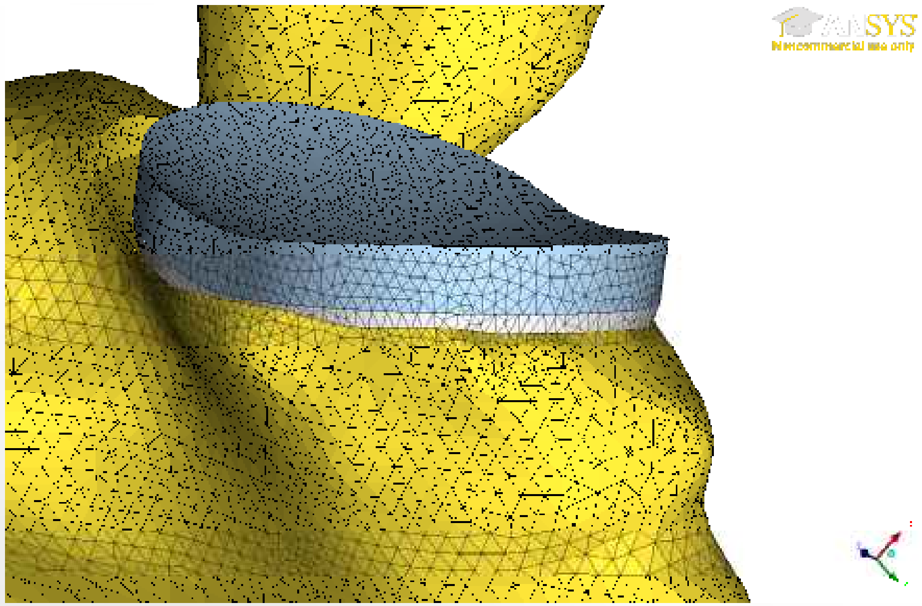

Fig. 13: Volume mesh of Implant, bone cement, and scapula

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FEM – Definition

- FE-Modeller
  - Define surfaces for bearing and loads
    - Flexion/Abduction (30°, 60°, 90°, 120°, 150°, 180°)
    - Positions according to Van der Helm (1994)
    - Entry surfaces of M.Trapezius and M.Rhomboideus
- Static Simulation
  - Define material parameter

Material	Young's Modulus [MPa]	Poisson Ratio
Compacta	13.700	0.3
Bone cement	2.000	0.33
Polyethylene	500	0.3

  - Define boundary conditions
    - Fixed bearing simulate M. Trapezius and M. Rhomboideus
    - Apply forces for flexion/abduction angle according to values and direction of Van der Helm (1994)
  - Solve and evaluate Van Mises stress and deformation

Fig. 14: Define component for forces (30° flex.)

Fig. 15: Fixed bearing

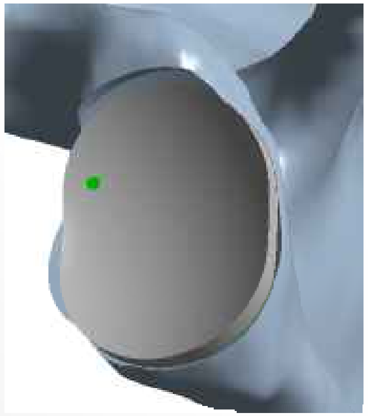


Fig. 16: Forces at 90° abd.

FEM – Results

- Validation
  - Results are within the range of comparable studies from Terrier, Farron, Murphy, Prendergast and others.
  - Reflect only a certain point in time
- Actual work
  - Different angles and positions
  - Probability of failure according to Murphy & Prendergast (2000)
  - Result analysis and statistical evaluation

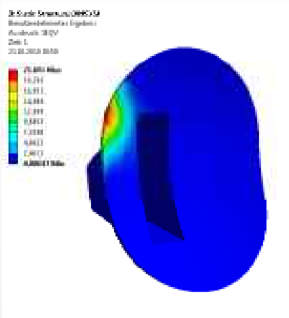


Fig. 17: Define component for forces (30° flex.)

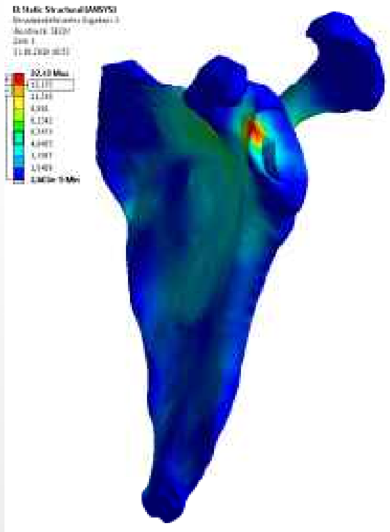


Fig. 18: Fixed bearing

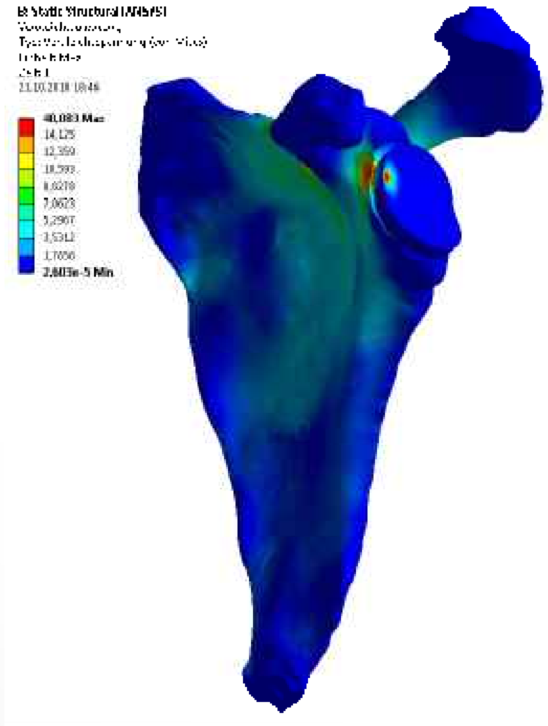


Fig. 19: Forces on 90° abd. and flex.

FEM – Bone Remodeling

- Adaptive bone remodeling
  - Wolff's law, a mechanical stimulus is responsible for bone remodeling, hence bone growth
  - Formulation by Weinans (1992), Huiskes (1994) by using strain energy density (U) as the mechanical stimulus.

$$U = \frac{1}{2}\sigma \bullet \varepsilon$$ *For one load step*

$$U_{TOT} = \frac{1}{n}\sum_{i=1}^{n} U_i$$ *For n-load steps, e.g. several humeral positions (abduction & flexion from 30° - 180°)*

- Local bone adaption function

$$\frac{d\rho}{dt} = \begin{cases} B\left(\frac{U}{\rho} - (1+s)K\right) & if \quad \frac{U}{\rho} > (1+s)K \\ 0 & if \quad (1-s)K \le \frac{U}{\rho} \le (1-s)K \\ B\left(\frac{U}{\rho} - (1-s)K\right) & if \quad \frac{U}{\rho} < (1+s)K \end{cases}$$

U… strain energy density
B… remodeling constant
K… reference stimulus
s… lazy zone factor

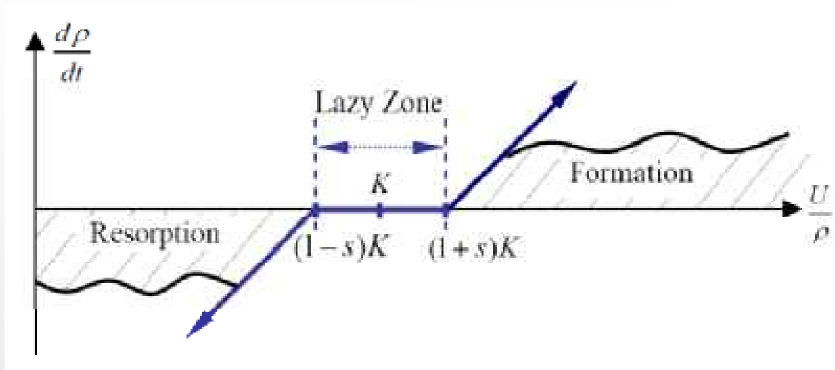
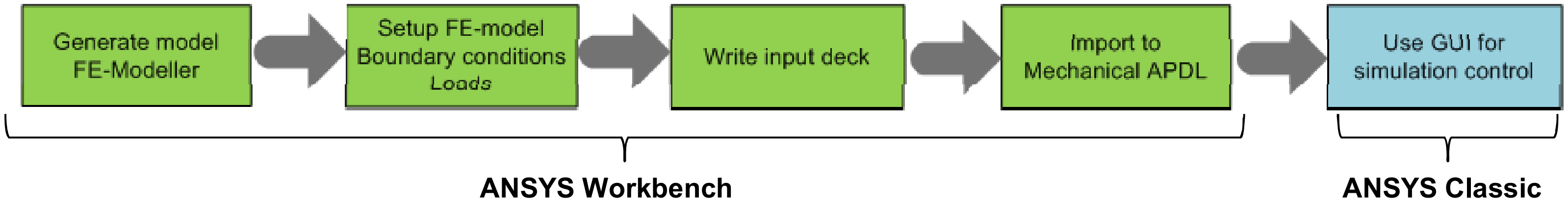


Fig. 20: Bone remodeling function (Lian et. al, 2010)

FEM – Bone Remodeling

- Adaptive bone remodeling
  - Steps



- ANSYS User Interface Design Language (UIDL)
  - GUI implementation for parameter control of bone remodeling algorithm
- APDL macros implementing bone modeling algorithm
- APDL specials
  - First implementation: ~90s per iteration for a 1.600 element test plate (solving time: ~3s)
  - Modifications:
    - Avoiding *DO-loops and exploit masking and vector operations: *VMASK, *VOPER (especially for *IF and mathematical operations)
    - Using element tables to display density results
  - Result: ~4s per iteration

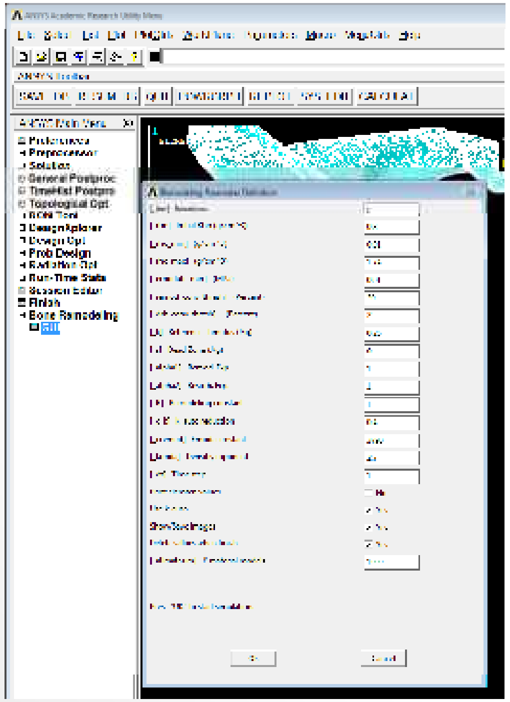


Fig. 21: UIDL GUI for algorithm control

FEM – Bone Remodeling

- Adaptive bone remodeling
  - APDL specials
    - One material assigned per element for individual density change
      - Number of elements for scapula model ~380k
      - Restriction in ANSYS: 100.000 material models
      - Algorithm runtime increases by using a high number of material models
    - Discretisation of density, hence on E-module scale

$$\Delta\rho_{Sim} = \frac{\rho_{Max}}{n_{Mat}} = \frac{1.74 g/cm^3}{1000} = 0.00174 g/cm^3$$

ρ_{Sim} … Density step
ρ_{MAX} … Maximum bone density
n … Number of material models

$$E_n = c\Delta\rho^{\gamma}_{Sim} n \qquad for\ n = 1 \ldots n_{Mat}$$

E_n … E-module
c, γ … Constants

$$\rho_{Max\_Err} = 0.05\% \qquad for\ n_{Mat} = 1000$$

ρ_{MAX_ERR} … Maximum density error

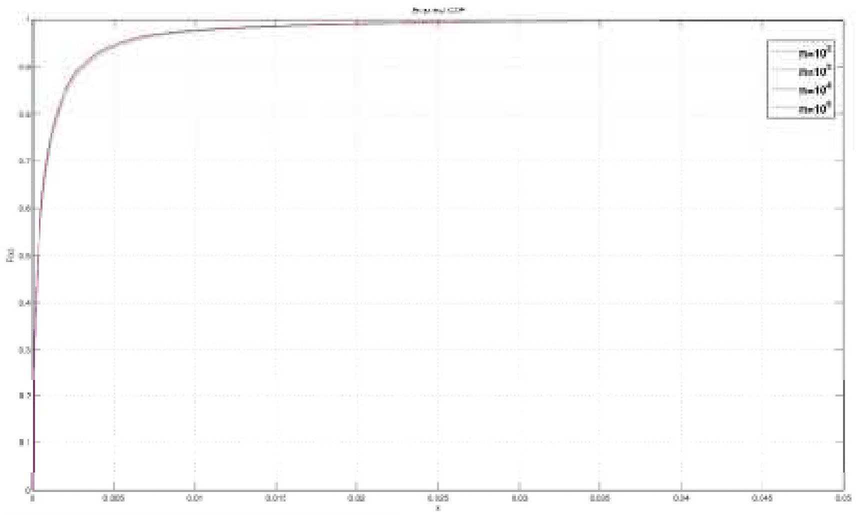


Fig. 22: CDF-Plot of SED-values

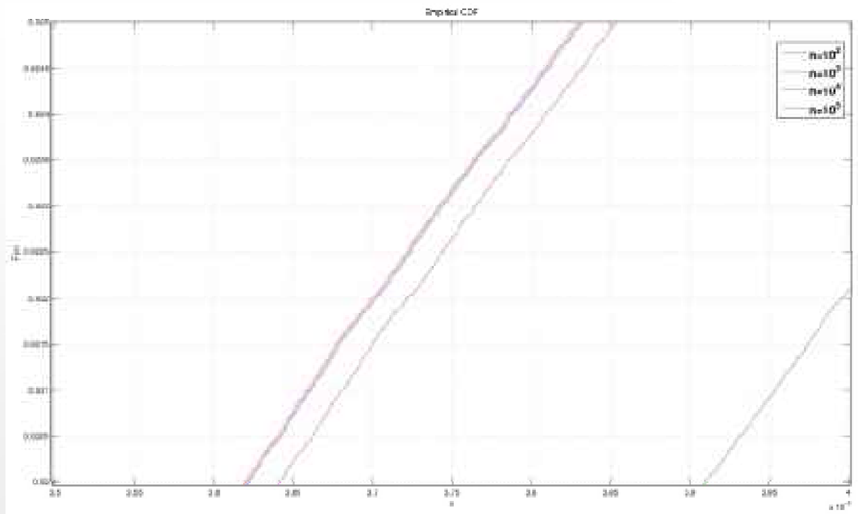


Fig. 23: CDF-Plot of SED-values (zoomed)

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•Adaptive bone remodeling

- Flow diagram

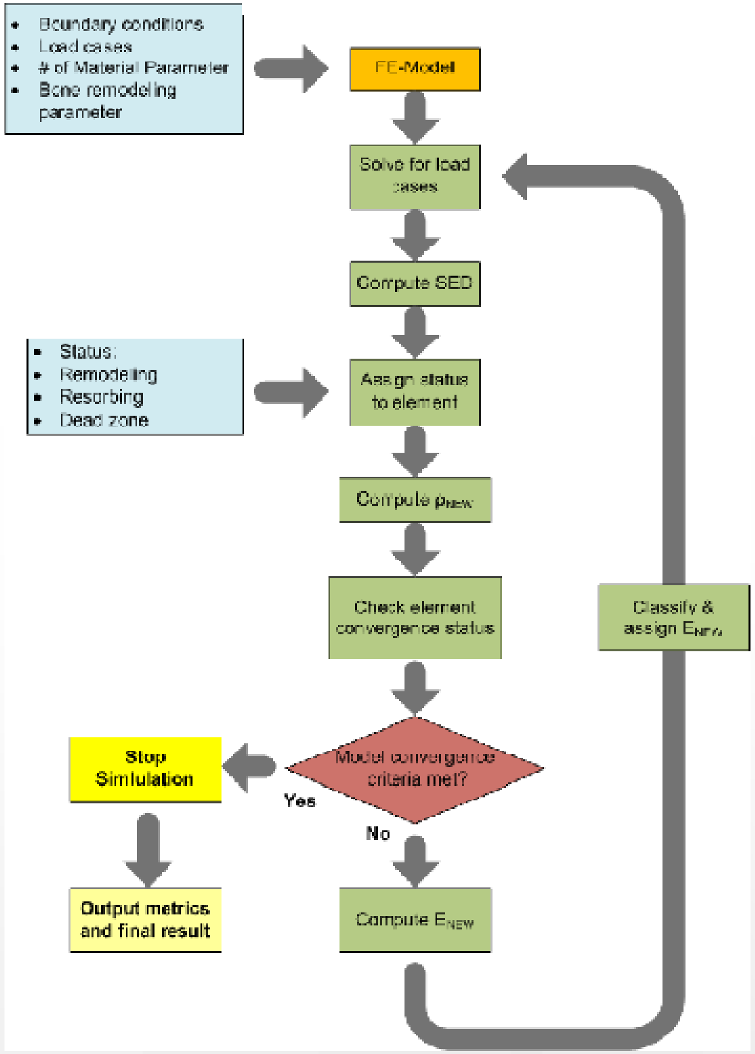

Fig. 24: Flow diagram for bone remodeling algorithm

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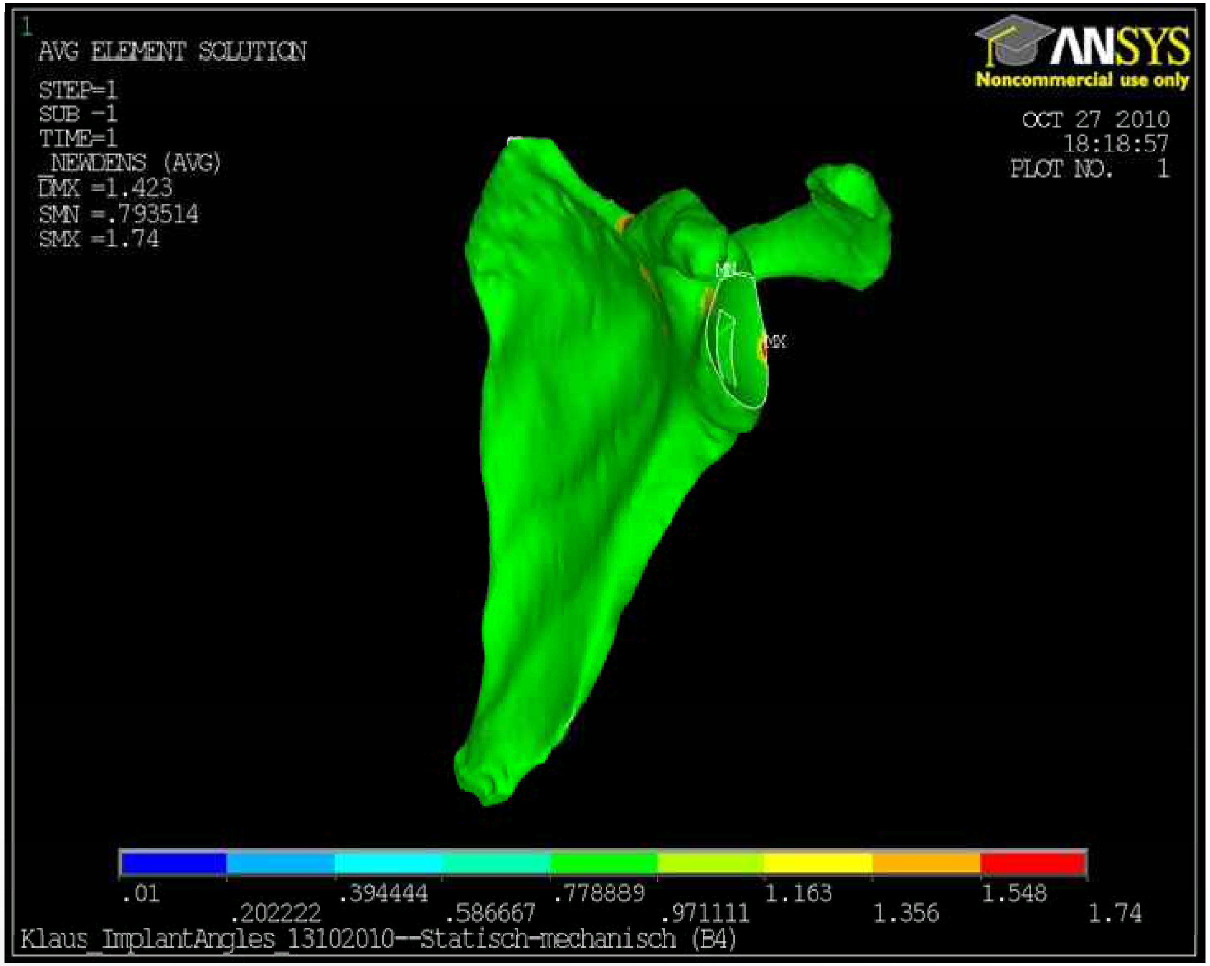
Results

- Setting
  - 96k nodes, 380k elements
  - Forces at 90° flexion and abduktion alternating
  - Iterations: 300
  - Time step: *dt=10*

- Statistics
  - Solving time: 140 (avg./iter.)
  - Bone remod:. 90s (avg./iter.)
  - Total time incl. overhead: ~42h



Results

- Setting
  - 96k nodes, 380k elements
  - Forces at 90° flexion and abduction
  - Iterations: 150
  - Time step: *dt=10*
- Statistics
  - Solving time: 138s (avg./iter.)
  - Bone remod:. 95s (avg./iter.)
  - Total time incl. overhead: ~42h
  - First results meet expectations according to applied forces, but are subject of further validation

Fig. 25: Bone remodelled scapulaing – posterior view

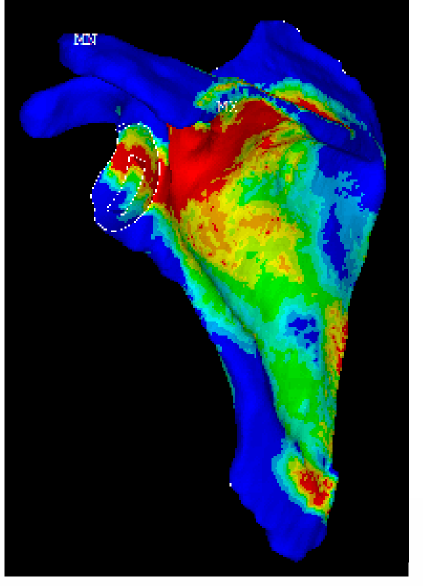


Fig. 26: Bone remodelled scapula – anterior view

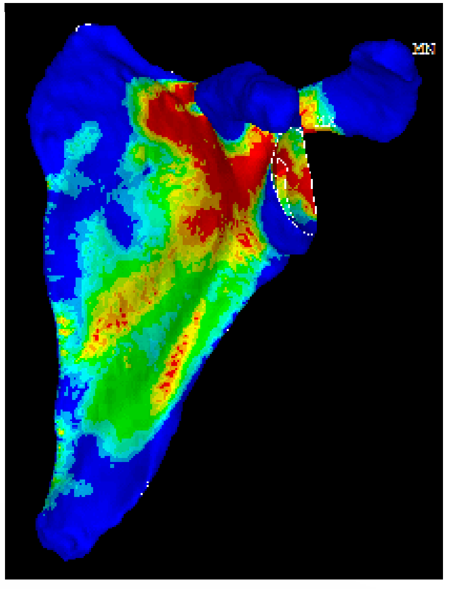


Fig. 27: Bone remodelled scapula – lateral view

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Actual & Future Work

- Further testing and validation of the bone remodeling algorithm
- Assignment of bone density according to CT-Data
- Expansion of the FE-Model with humeral prosthesis part, muscular load and different prosthesis position
- Application on different anatomic shoulder models
- Comparison with a reverse shoulder implant

Fig. 28 : Reverse shoulder implant (DePuy)

Acknowledgments

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Project Homepage: http://ctfem.fh-salzburg.ac.at

Contact: werner.pomwenger@fh-salzburg.ac.at

Research Team:

Univ.-Doz.Dr. Karl Entacher
Salzburg University
Task: Project Leader FHS, Senior Researcher

Prim.Univ.-Prof.Dr. Herbert Resch
Paracelsus Medizinische Privatuniversität
Task: Medical Advisor

DI(FH) Werner Pomwenger, MSc.
Salzburg University
Task: Junior Researcher

DDr. Peter Schuller-Götzburg aHCM
Paracelsus Medizinische Privatuniversität
Task: Project Leader PMU, Senior Researcher

ANSYS

Materialise Software

FWF

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