骨梁リモデリングの
生体力学シミュレーション

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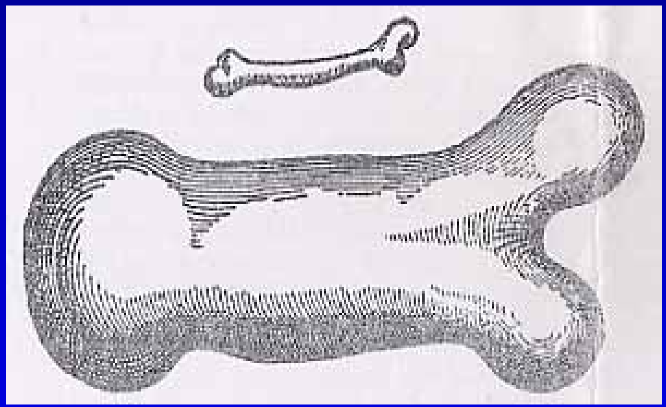
理研シンポジウム「生体力学シミュレーション」
2003.5.27-28, 東京

Bone: Structure ⟷ Function

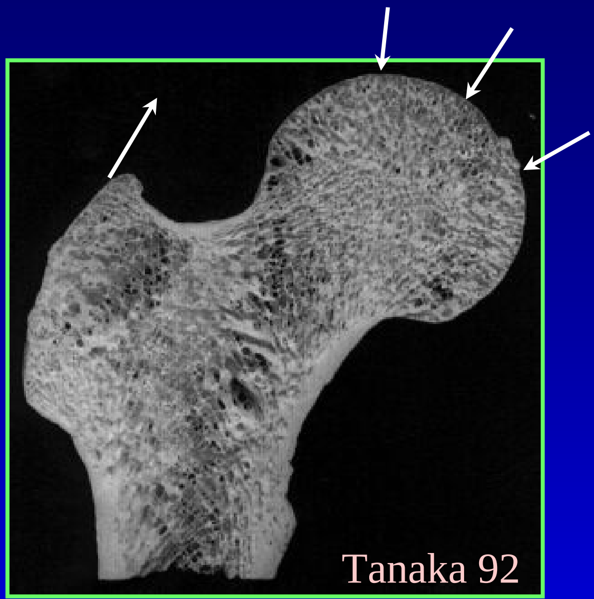


Galileo Galilei, 17C

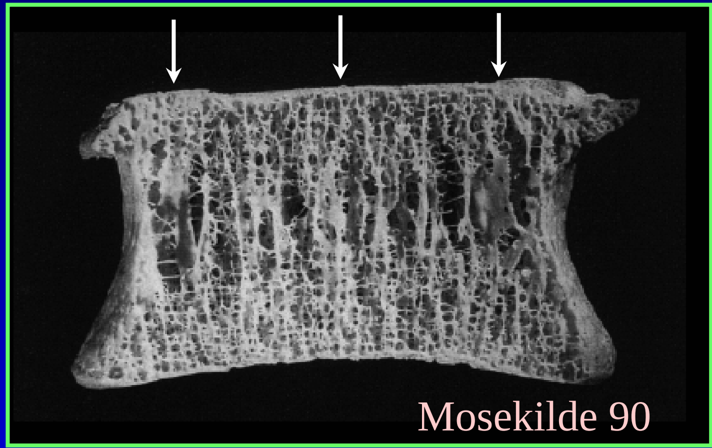
Bone size - specimen size (Ascenzi93)

個体の大きさ→ 体重, 筋力, etc.→ 骨に加わる荷重→ 骨の大きさ (形態)

Bone: Structure and function (cont.)



Proximal femur
(大腿骨近位部)



Vertebral body
(椎体)

- Complicated three-dimensional structure
  (External shape, Internal structure)
- Functional adaptation to mech. env. (Roux 1881)
- Load bearing structure

Computational Biomechanics: Bone Remodeling

Purposes:

- To understand mechanism of adaptive bone remodeling
- To predict remodeling, around bone-implant interface
- To design implant, screw ...
- To apply in bone tissue engineering, design scaffold
- …

Approaches:

- Phenomenological modeling and simulation "Macro"
- Down toward mechanism at cellular level "Micro"

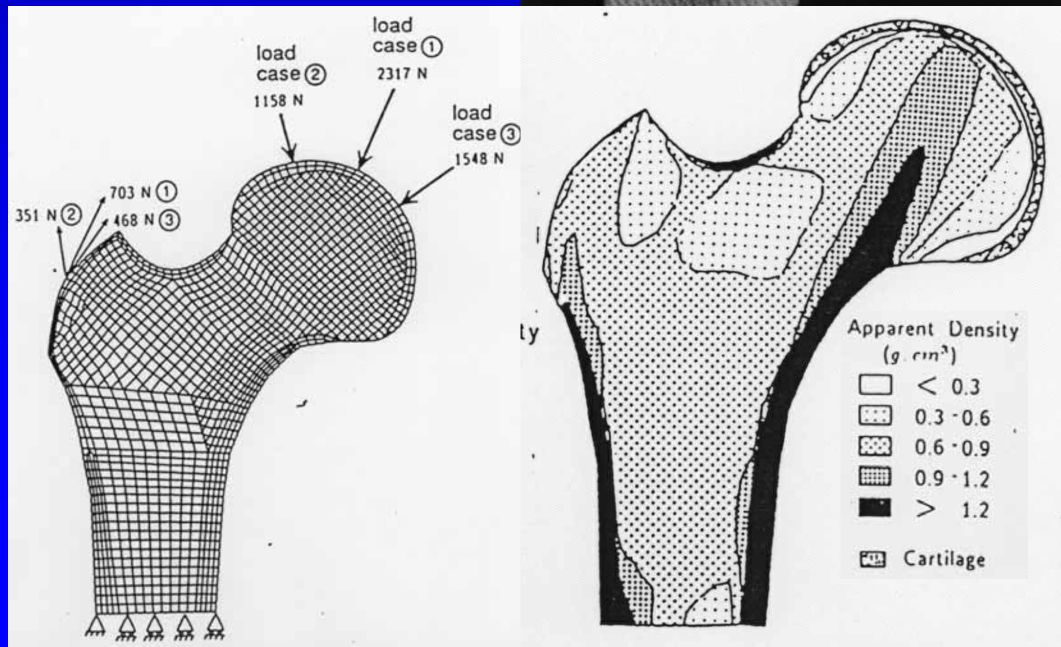
Macroscopic Model: Cowin, Carter *et al.*

Adaptive elasticity (Cowin76)

$$\boxed{\frac{de}{dt} = a(e) + A(e)_{ij}(\varepsilon_{ij} - \varepsilon^0{}_{ij})}$$

Self optimization model (Carter87)

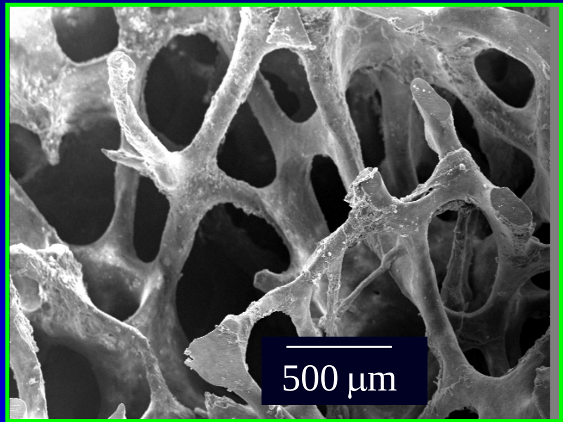
$$\boxed{\frac{d\rho}{dt} = c(\Psi_b - \Psi_{bAS})}$$



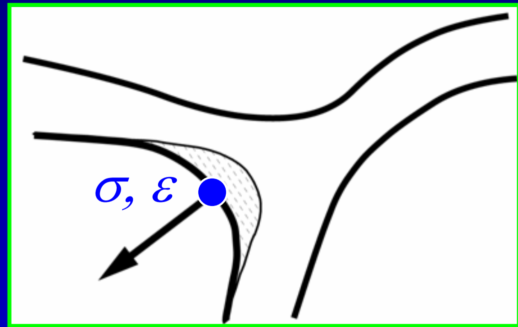
Trabecular adaptation by surface remodeling

Whole bone (Macro)

Trabecular structure (骨梁構造)



Single trabecula (Micro)



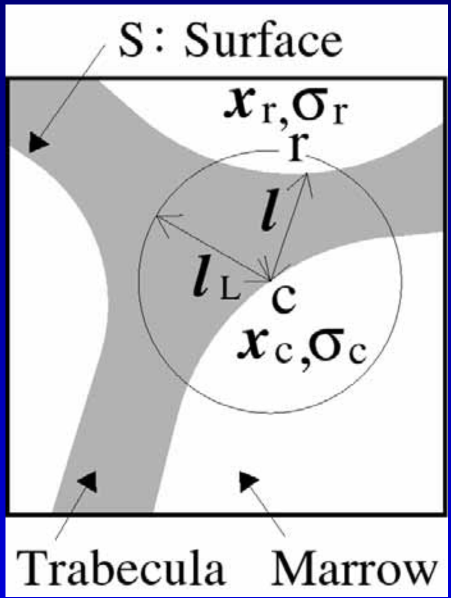
Mech. env. (σ, ε)

Struc. Change ($\swarrow$)

- **Trabecular microstructural changes by remodeling**
- **Local mechanical stimulus** (Cowin 91)
- **Structural adaptation at macrostructural level** (Wolff 1869)
- **Hierarchy from micro- up to macro- structure**

Mathematical and Computational Modeling of Trabecular Surface Remodeling

Model of Trabecular Surface Remodeling



- Local stress nonuniformity

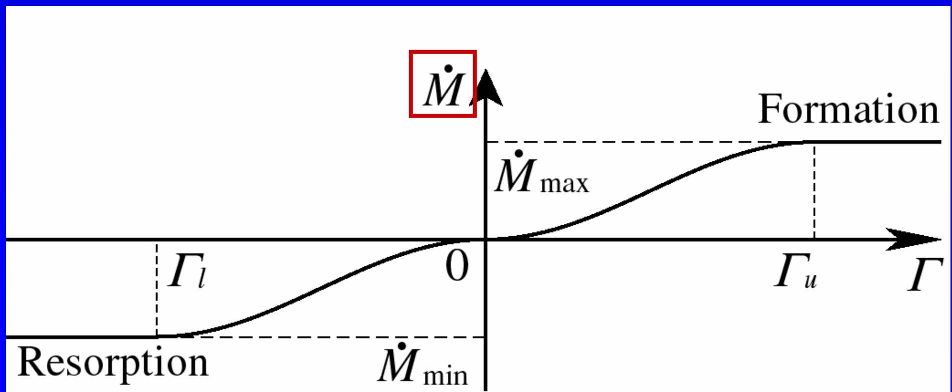
$$\Gamma = \ln(\sigma_c / \sigma_d)$$

$\longrightarrow$ **Driving force of remodeling**

- Representative stress

$$\sigma_d = \int_S w(l)\sigma_r dS \Big/ \int_S w(l) dS$$

- Surface movement toward uniform stress state



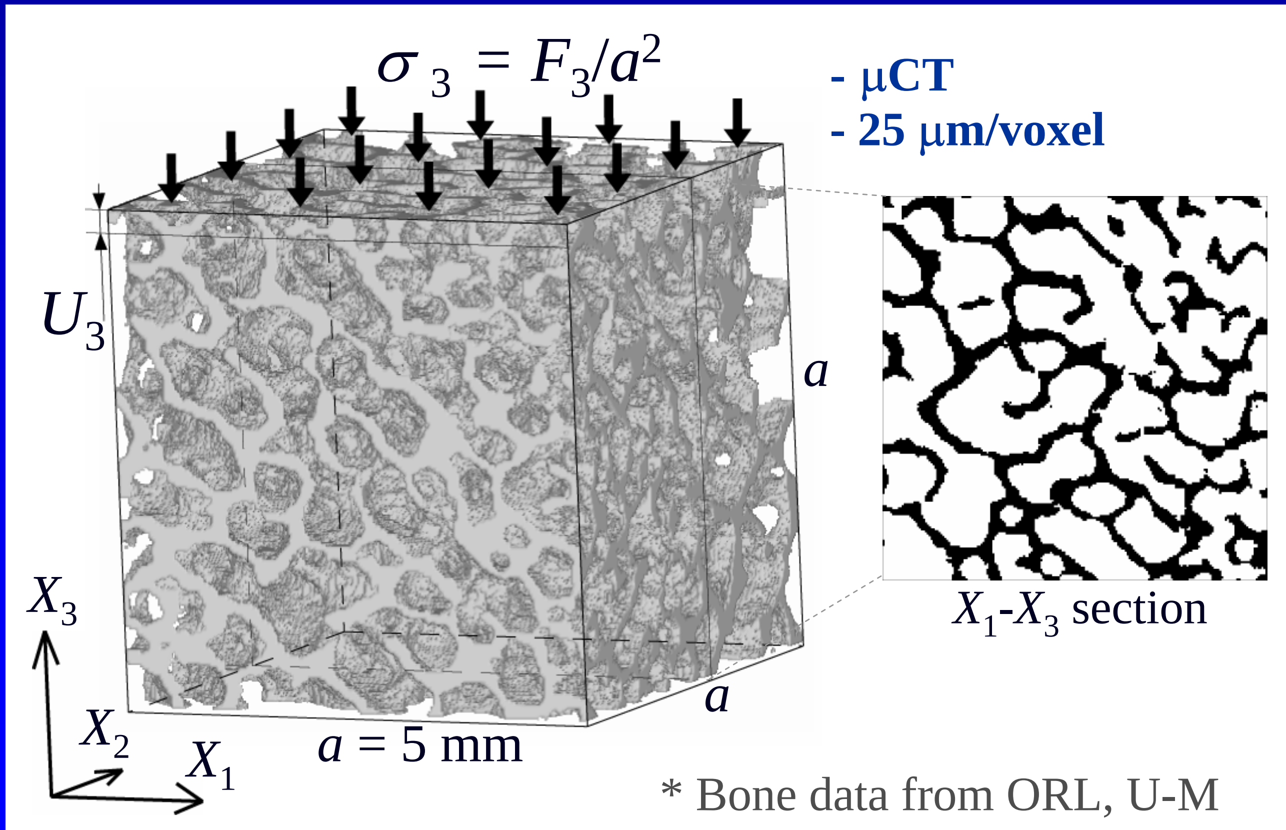
Rate of surface movement

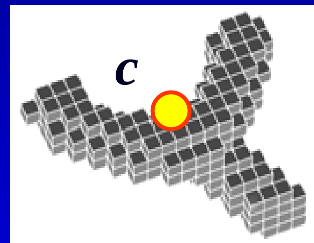
$$\dot{M} = \dot{M}(\Gamma)$$

$$= \begin{cases} \Gamma > 0 \quad \text{(Formation)} \\ \Gamma < 0 \quad \text{(Resorption)} \end{cases}$$

Digital image-based model of cancellous bone cube combined with large-scale finite element method

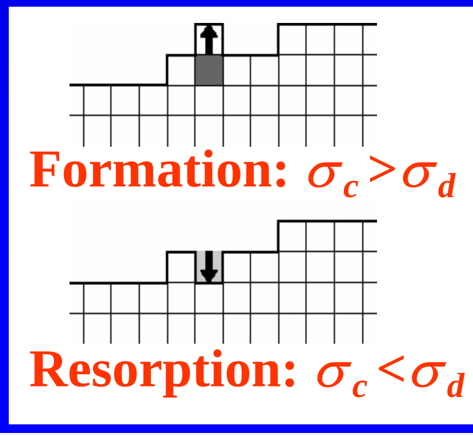
- **Canine distal femur under compressive loading** (Guldberg97)
- **Repetitive calculation of FEM and Morphological changes**



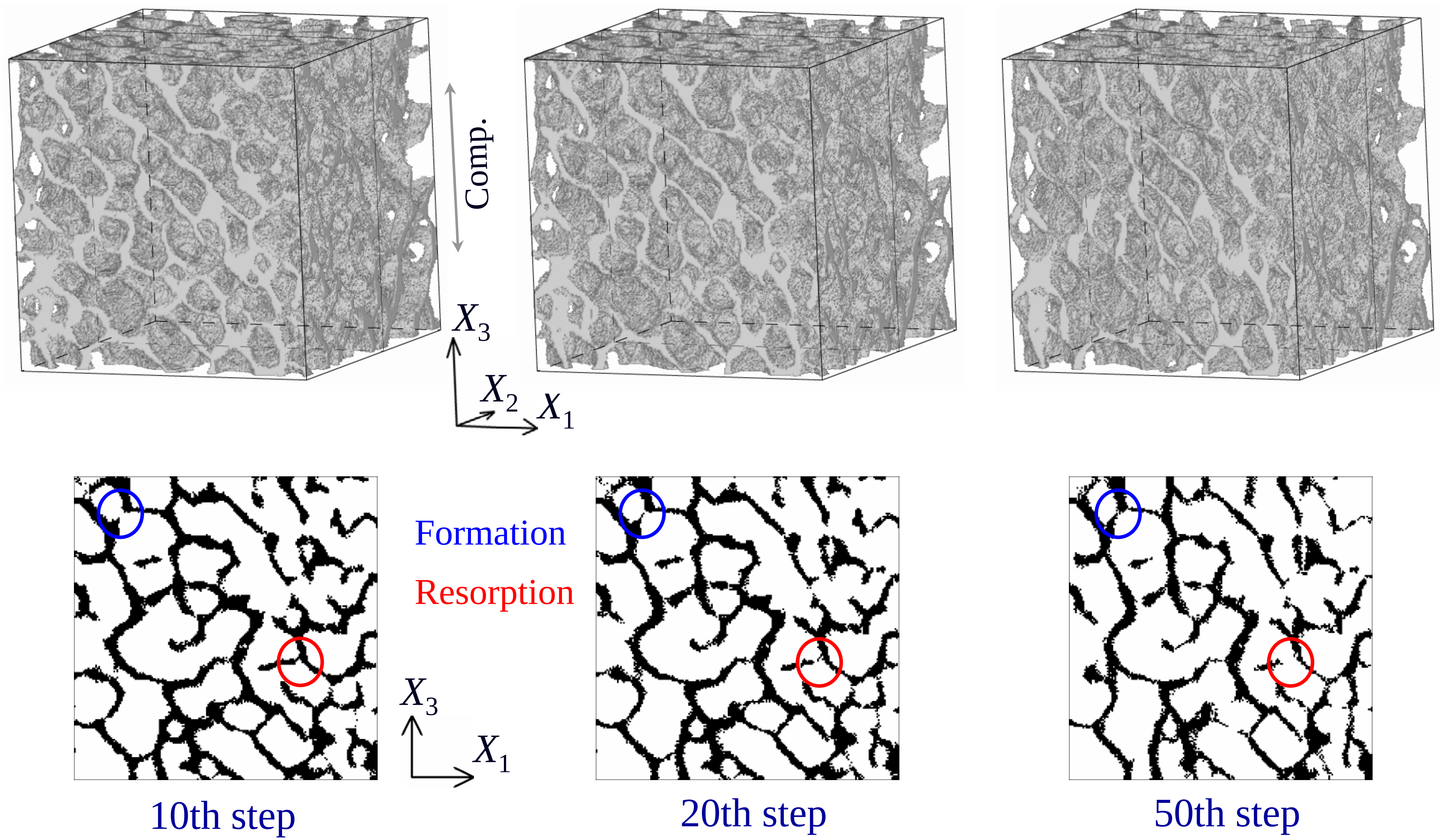


σ_c : Stress at point c

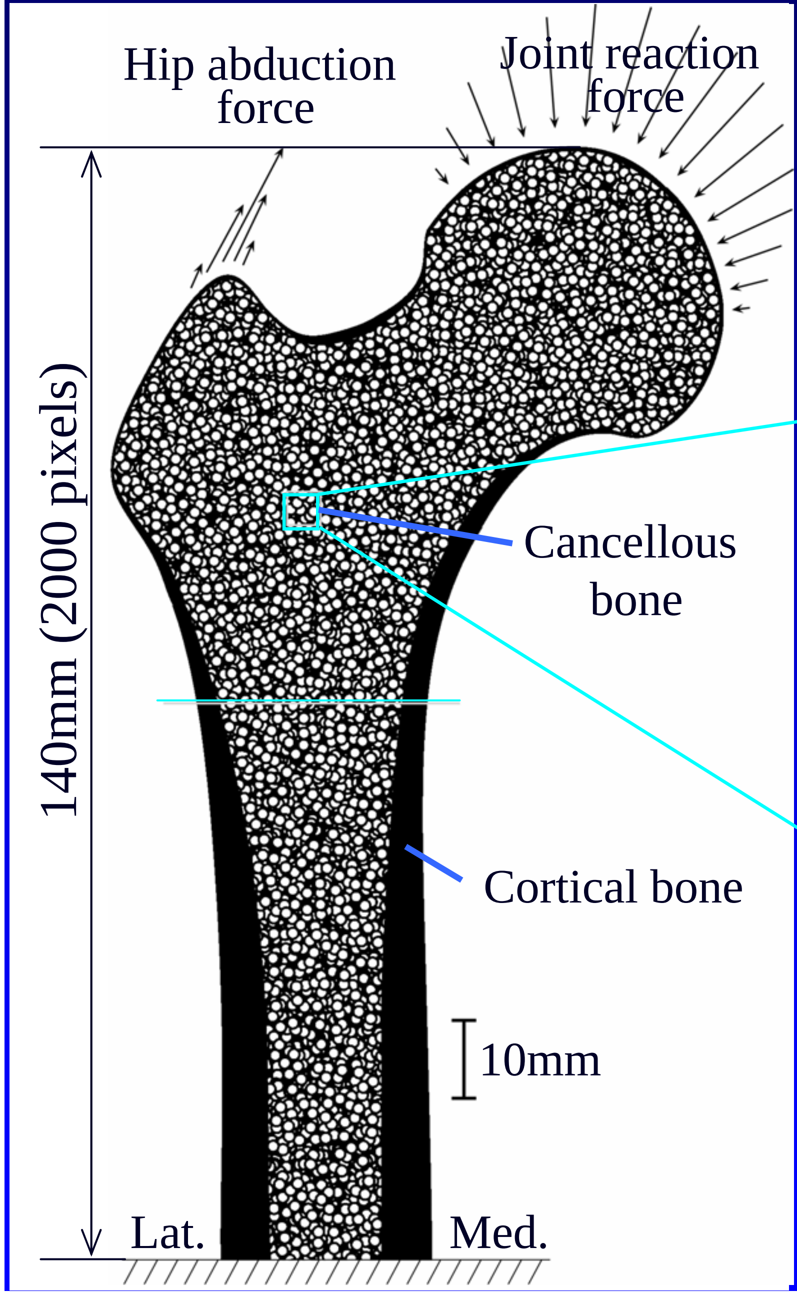
σ_d : Representative stress around c



Trabecular structural changes under compressive loading

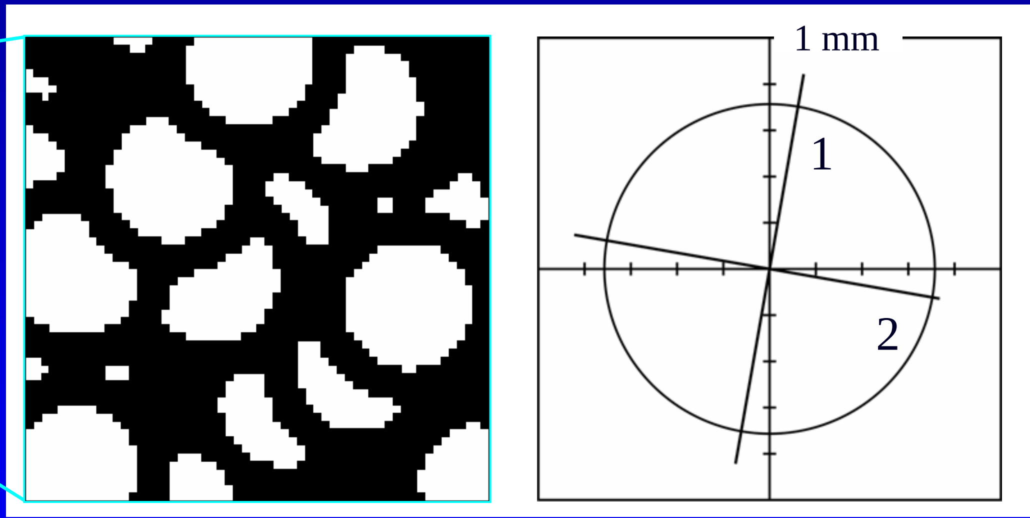


Pixel FE model of proximal femur



- **Bone part: 0.67 million elements**
- **Pixel size: 70 μm**

4mm × 4mm　　Fabric ellipse



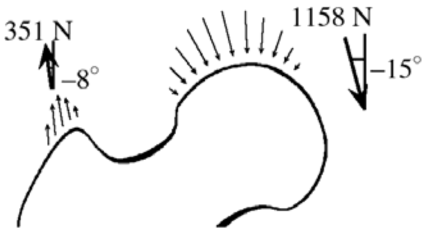
H_1 = 714μm, H_2 = 713μm
H_1/H_2 = 1.00

*Model parameters
(1) Threshold values: $\Gamma_u = 1.0$, $\Gamma_l = -2.0$
(2) Sensing distance: l_L = 1.0mm (14 pixels)

Trabecular surface remodeling for proximal femur

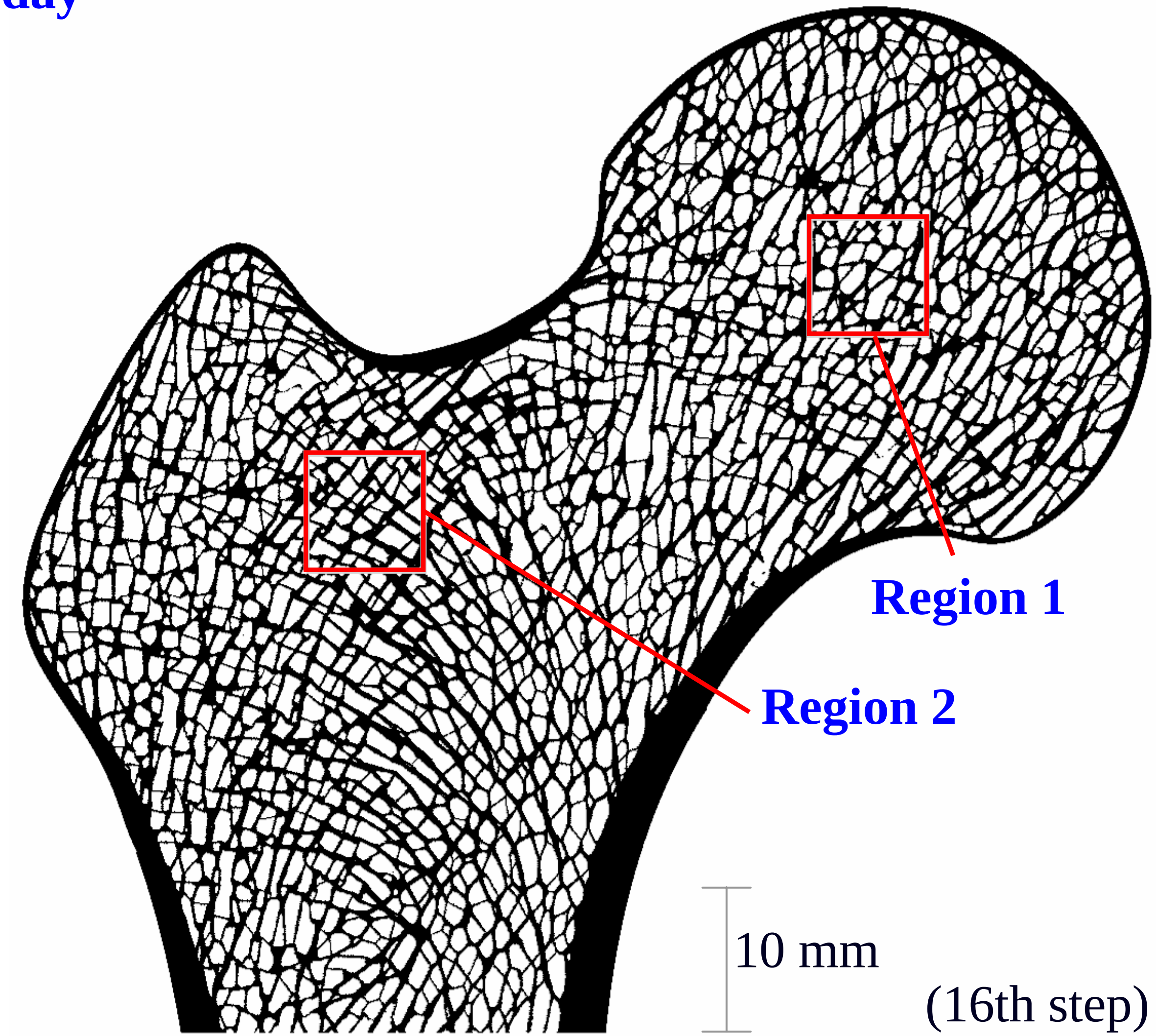
(1) One-legged stance: 6000/day

(2) Abduction: 2000/day

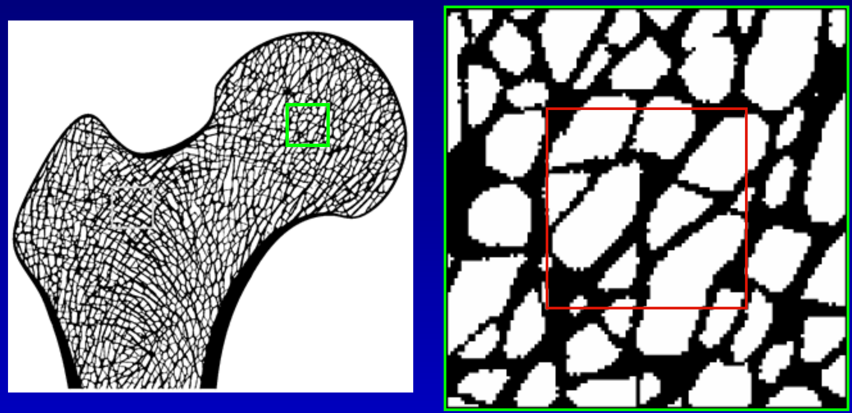


(3) Adduction: 2000/day

* Boundary condition:
Beaupré 1990



Mechanical environment at trabecular level



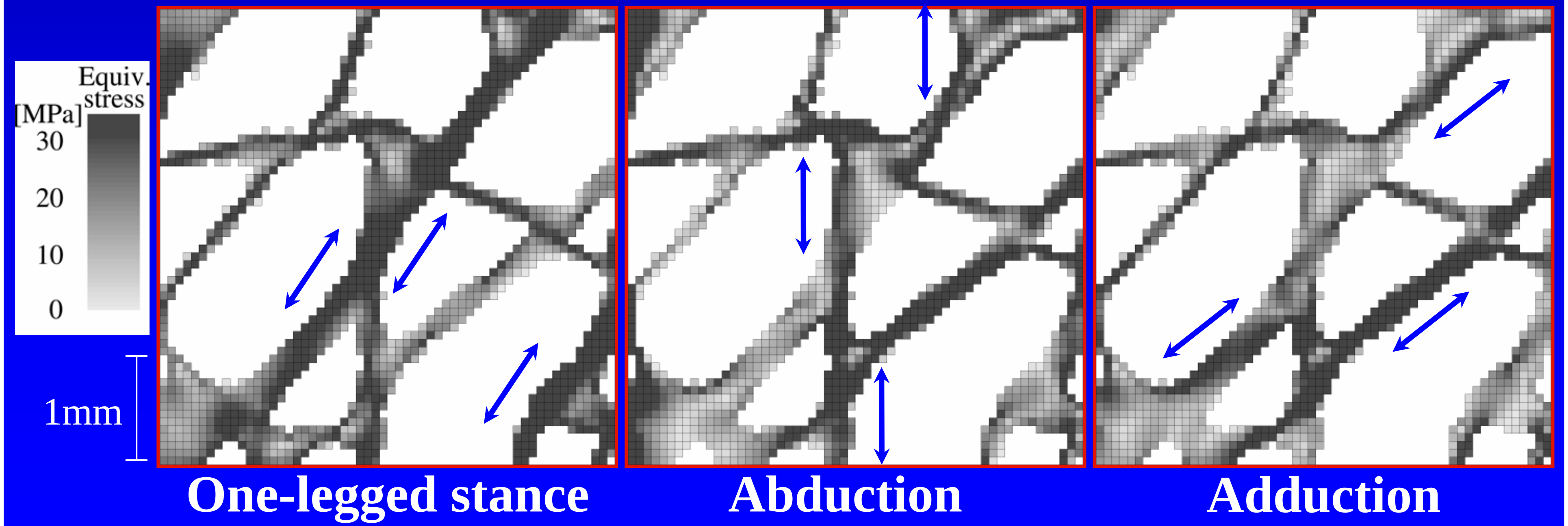


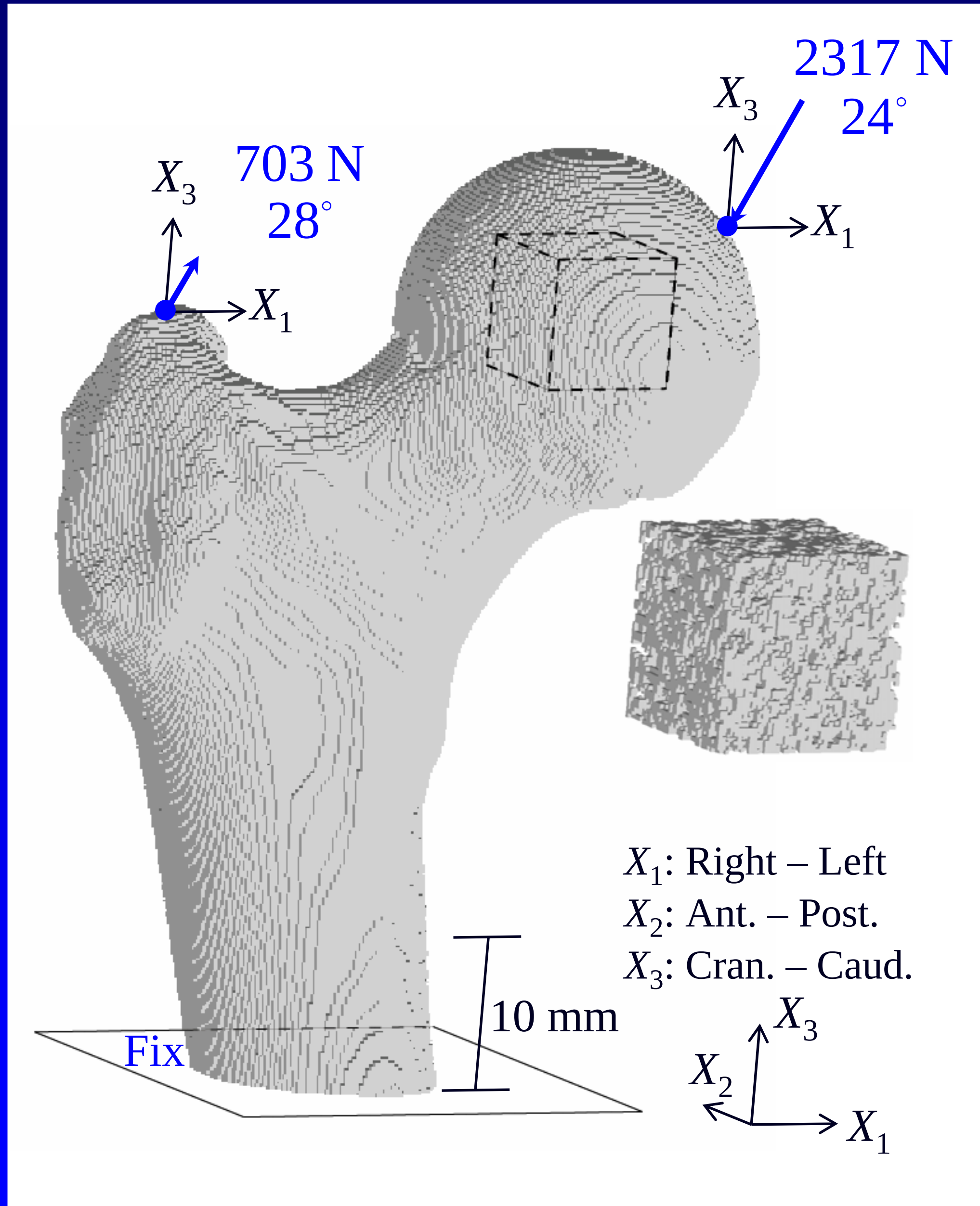
Image-based model of human proximal femur

- CT image data

(Research systems inc.)

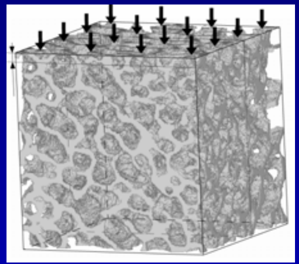
- One million voxels
- 250 mm/voxel

- Isotropic structure
- Volume fraction of cancellous bone: 0.51

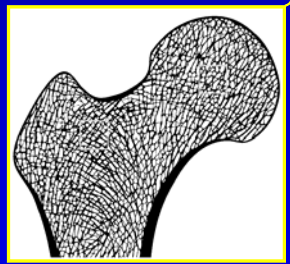


Future works

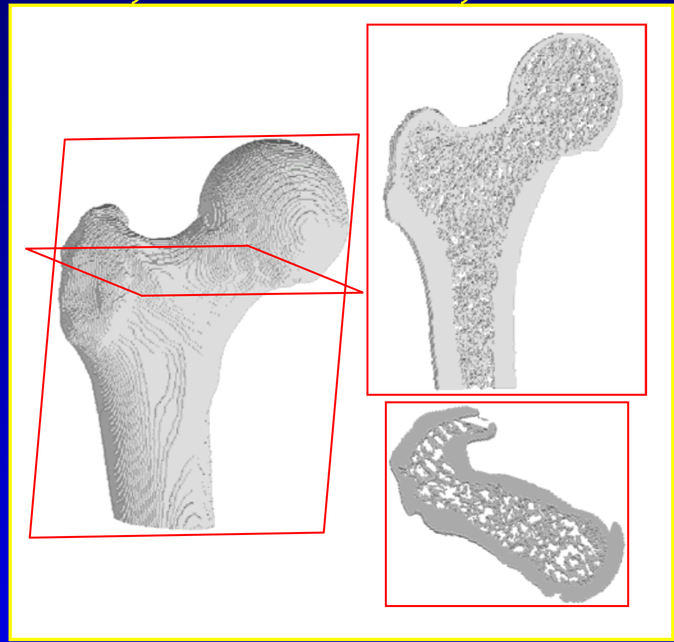
3D, bone tissue, fine



2D, whole bone, fine



3D, whole bone, coarse



3D, whole bone, fine

Under construction …

- Imaging
- Morph. modeling
- L.S. FEM
- …

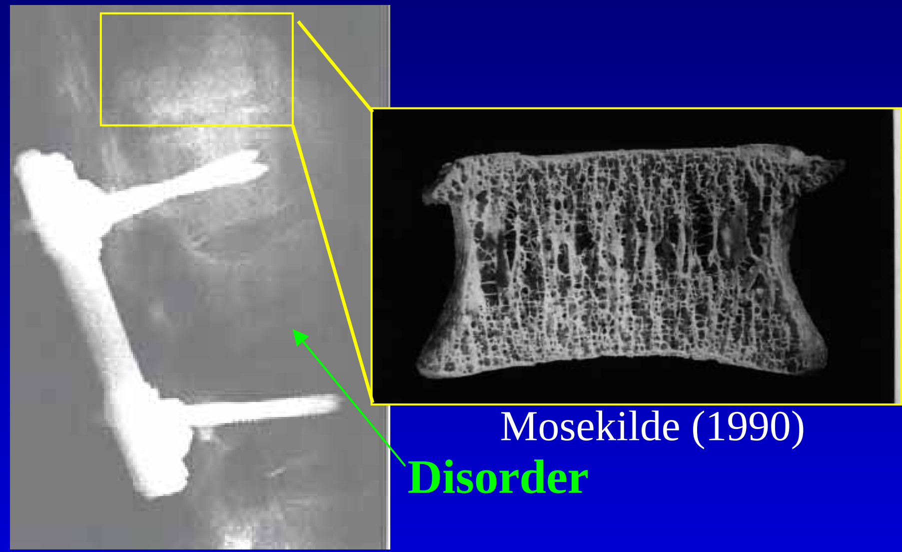
Evaluation and Design of Bone-Implant with Trabecular Remodeling Simulation

Evaluation of trabecular structural change around spinal fixation screw

- **Spinal reconstruction**

  for Neoplasm, Fracture, ...

- **Fixation Screw**
  - Infection
  - Fatigue fracture (Bone, Screw)
  - Loosening   Order of month-year



Mosekilde (1990)

Meyer & Cotler (1991)

- **Time-course change in bone structure by remodeling**

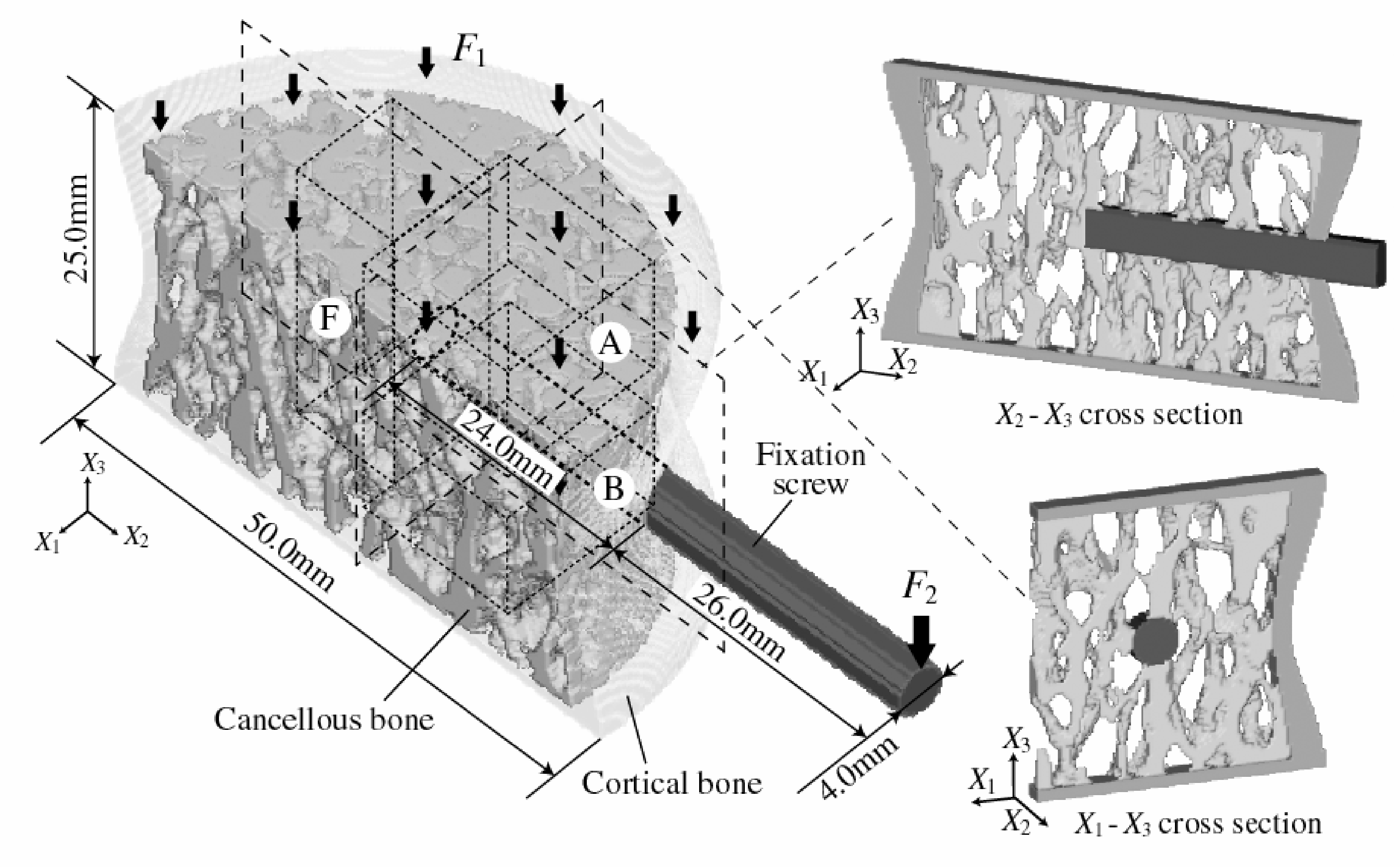
  (1) Change in mechanical environment of bone

  (2) Adaptive bone remodeling

  (3) Change in bone morphology

  → **Important for proper fixation**

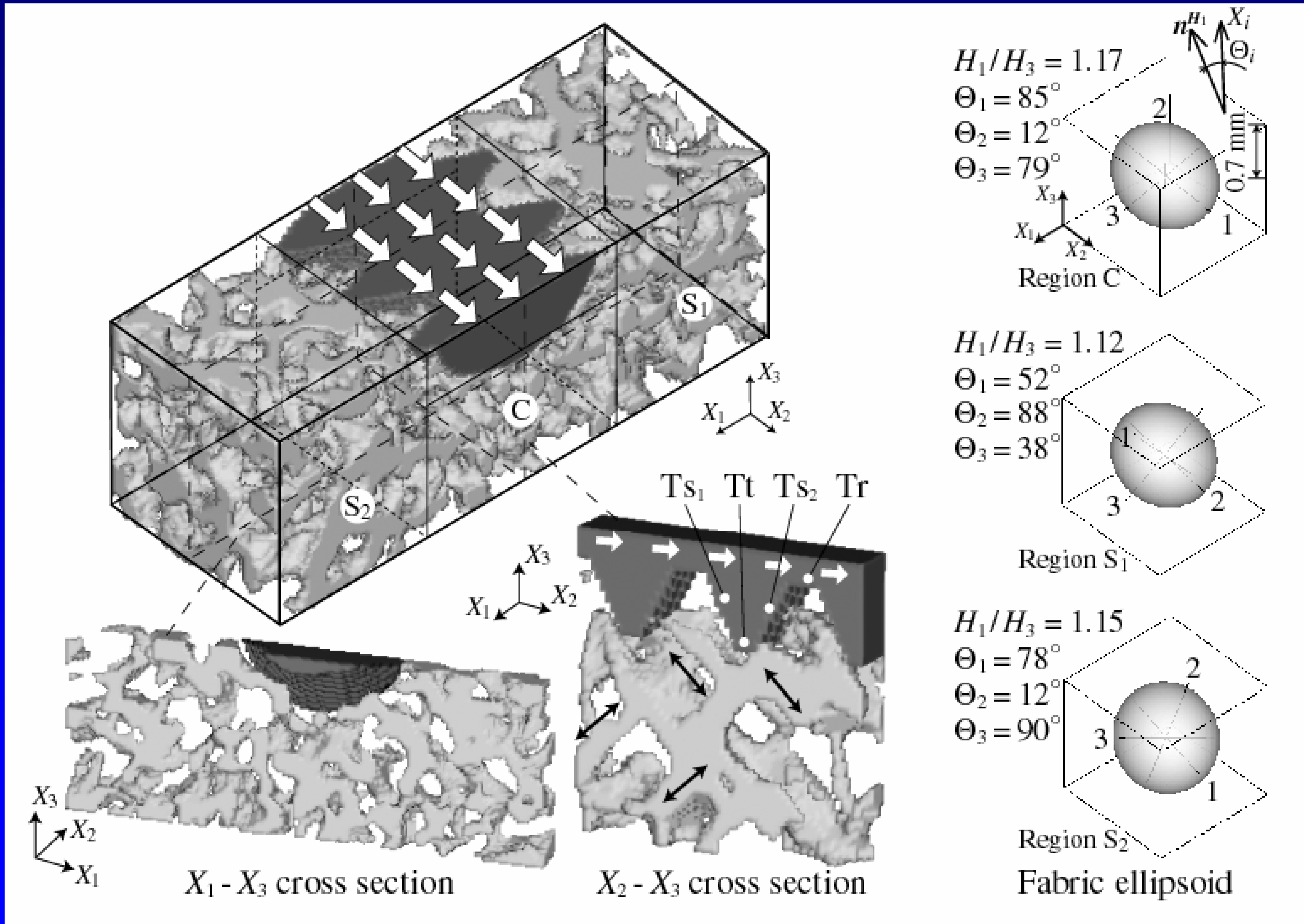
Voxel model of a vertebral body with a fixation screw



* Isotropic elastic material:

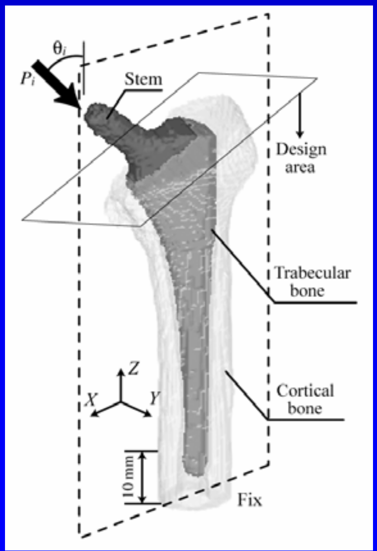
Bone (E_b = 20 GPa, ν_b = 0.3), Screw(E_s = 200 GPa, ν_s = 0.29)

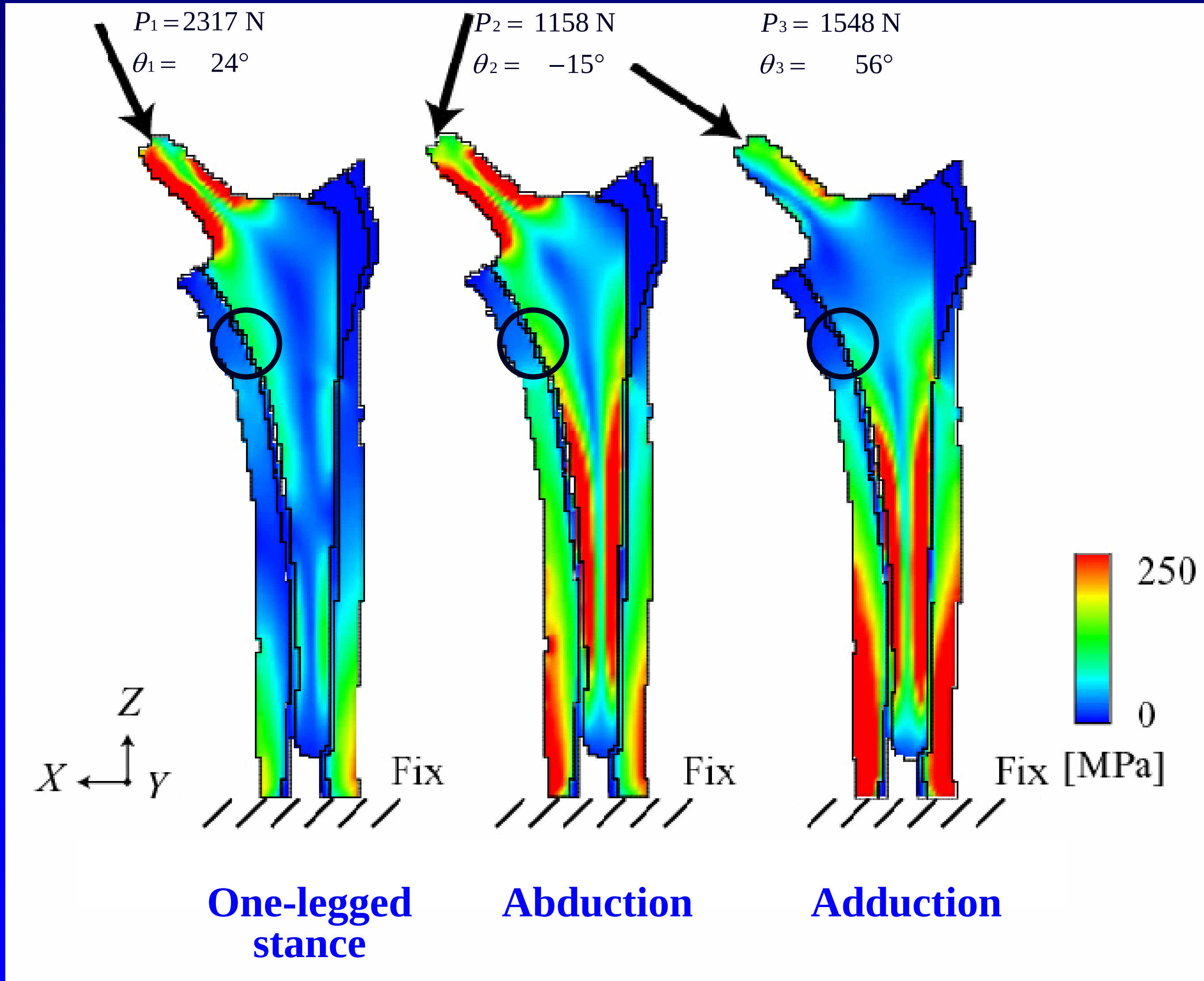
Trabecular structural changes near bone-screw interface: shear loading case



Shape design for artificial hip joint stem

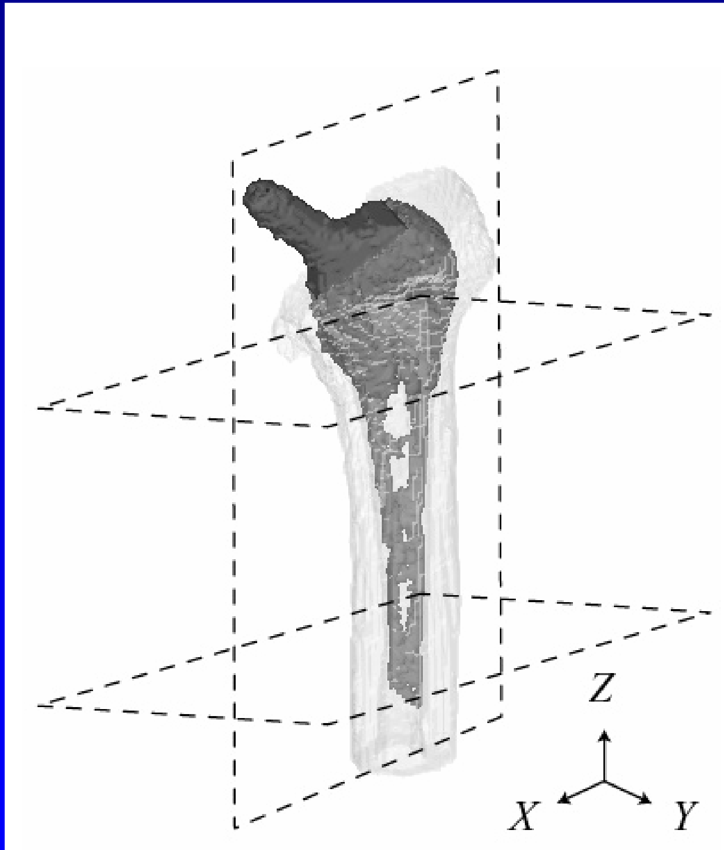
(Kobe Steel Ltd.)



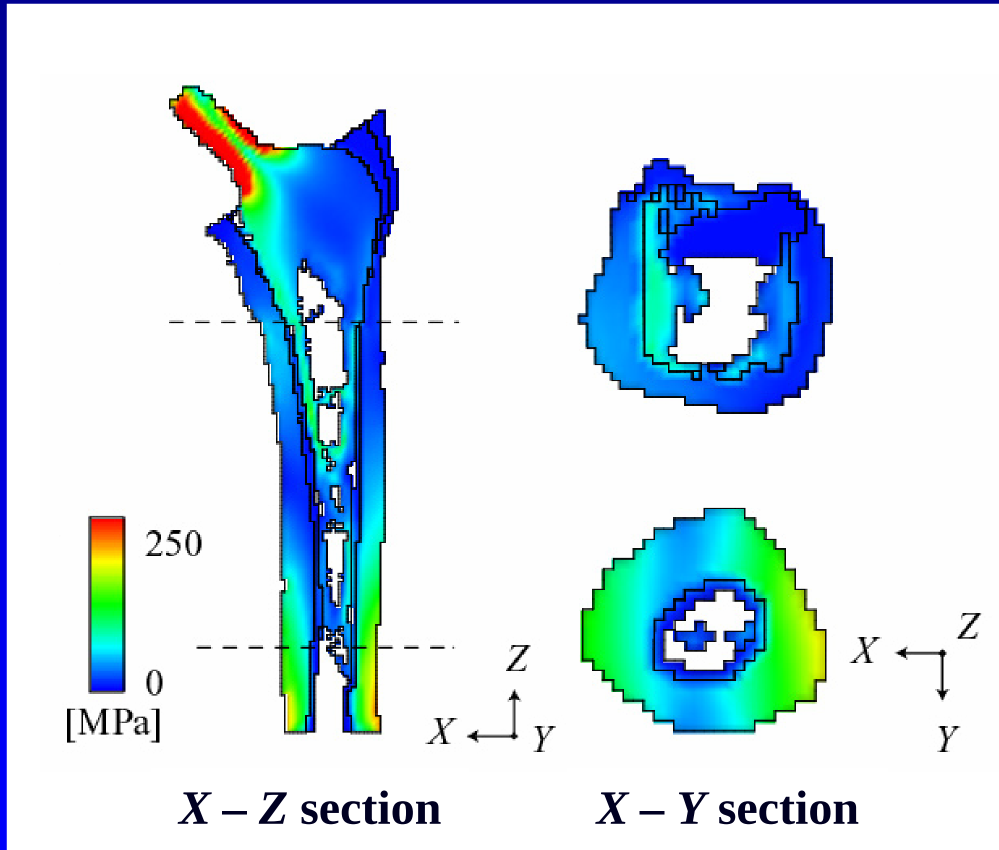


Change in stem shape and equiv. stress

Loading case L1 : L2 : L3 = 3 : 1 : 1



Stem Shape

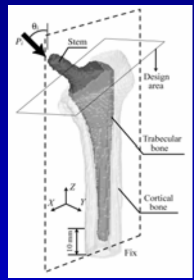


Equivalent Stress

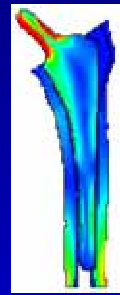
Computational design system for bone implant

Individual modeling of bone and implant

Medical image, 3D CAD data



Evaluation of implant



Choice of the implant type

Design of stem shape

Manufacturing directly from image-based model

Summary

- Trabecular remodeling simulation with digital image-based model combined with large-scale finite element method

- Application to the simulation method to evaluation and design of bone-implant