Computational Simulation of Cancellous Bone Remodeling Using Digital Image-based Model

Ken-ichi TSUBOTA, Taiji ADACHI
and Yoshihiro TOMITA

Kobe University, RIKEN

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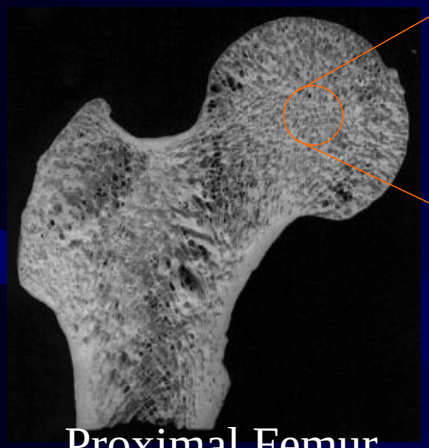
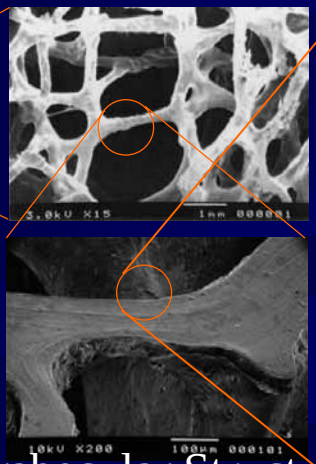
Introduction: Adaptive Bone Remodeling

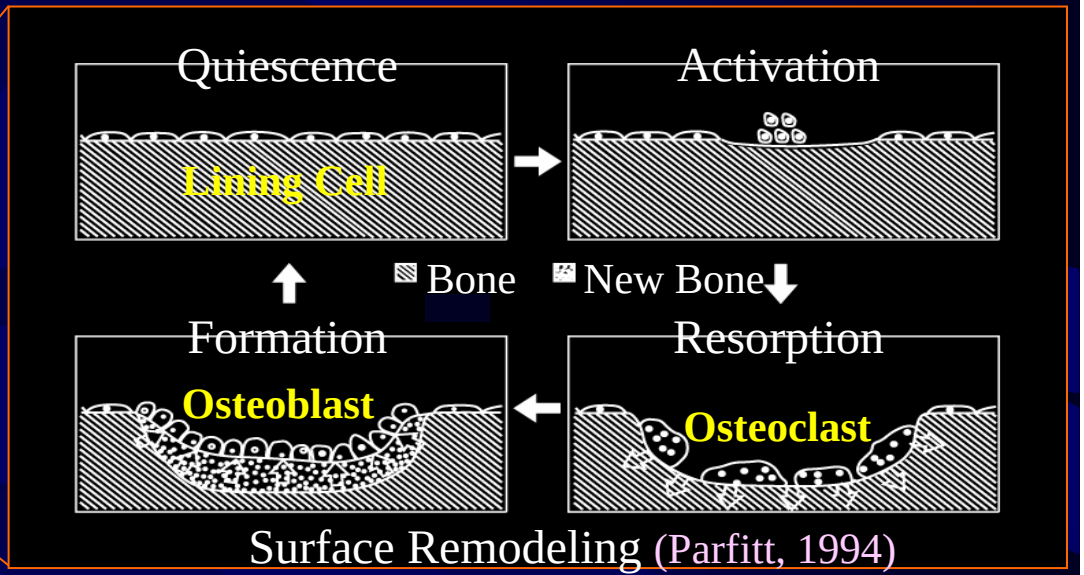
- Macroscopic Phenomenon and Microscopic Mechanism



Proximal Femur
(Tanaka, 1992)



Trabecular Structure

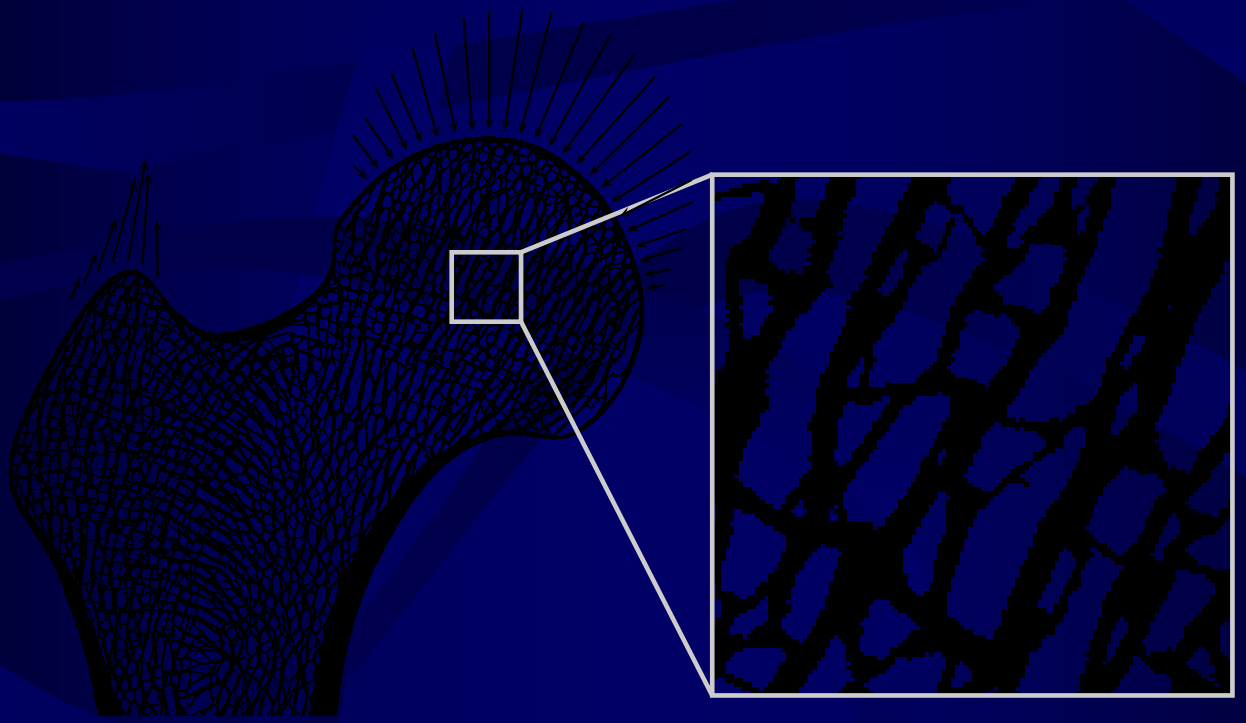


Surface Remodeling (Parfitt, 1994)

Relationship between bone morphological change and a mechanical stimulus should be considered at microscopic level in remodeling rate equation.

Introduction: Trabecular Surface Remodeling Simulation

- Bone Morphological Change Related to Mechanical Stimulus at Trabecular Level
- Large-Scale Pixel Finite Element Model



Trabecular remodeling simulation for proximal femur under multiple loading (Adachi *et al*., 1999)

Purpose

Application of Trabecular Remodeling Simulation to Digital Image-Based Model

(1) Trabecular Remodeling Simulation for 3D Complicated Structure

(2) Quantitative Comparison to Experiment

1. Digital Image-Based Model

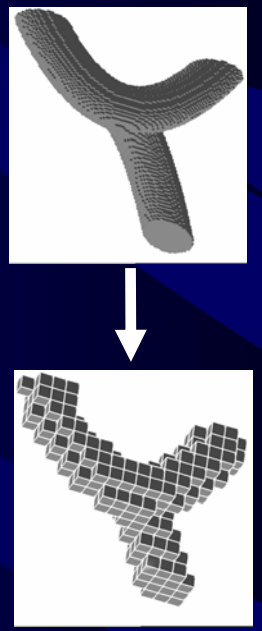
1.1 Digital Image-Based Model

- Model of 3D & Complex Trabecular Structure

  (Hollister *et al*., 1994; van Rietbergen *et al*., 1995; Odgaard *et al*., 1997)

  (1) Voxel Model Generated by Digital Image
  → Direct Modeling of Trabecular Microstructure

  (2) Large-Scale FEM Using EBE/PCG Manner
  → Evaluation of Trabecular-Level Stress/Strain



- Digital Image-Based Model for Remodeling Simulation

Trabecular-Level

Mechanical Stimulus ⟷ **Morphological Change**

1.2 X-Ray μCT System

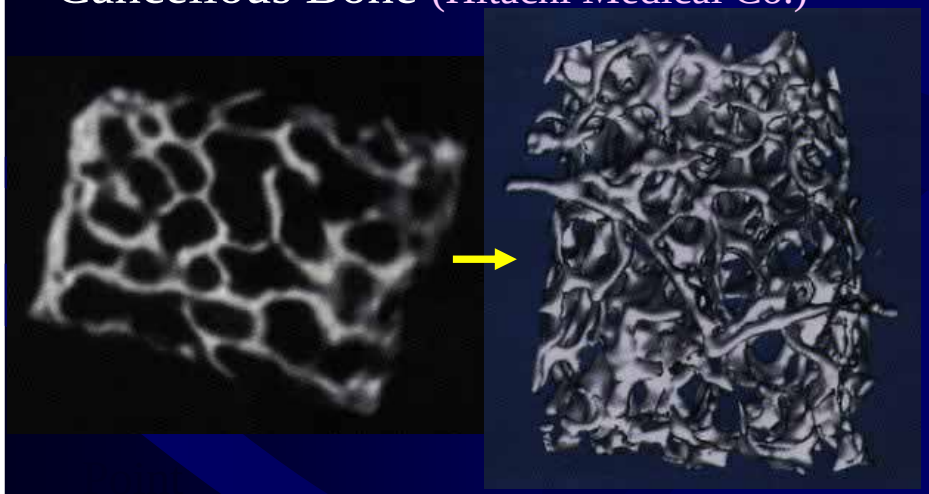
- X-Ray μCT System (Feldkamp *et al.*, 1989)

  (1) Obtaining 2D Cross Sections by Detecting X Ray Photons

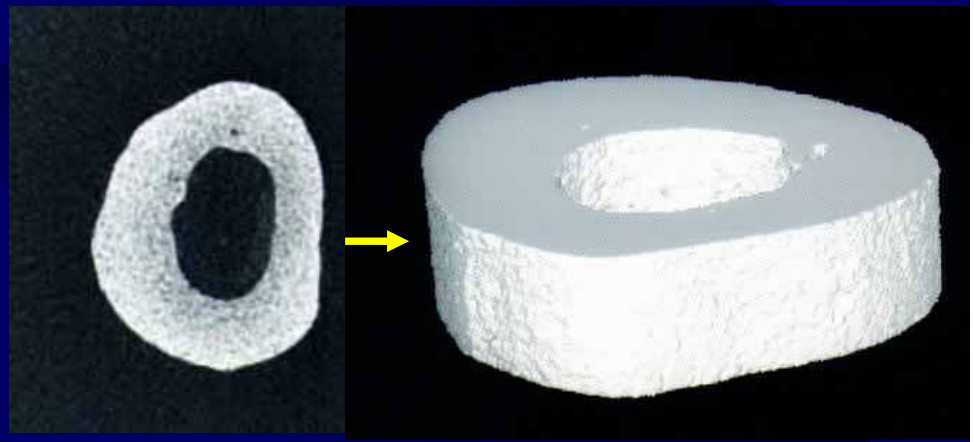
  (2) 3D Reconstruction from 2D Images

Specimen

- Cancellous Bone (Hitachi Medical Co.)

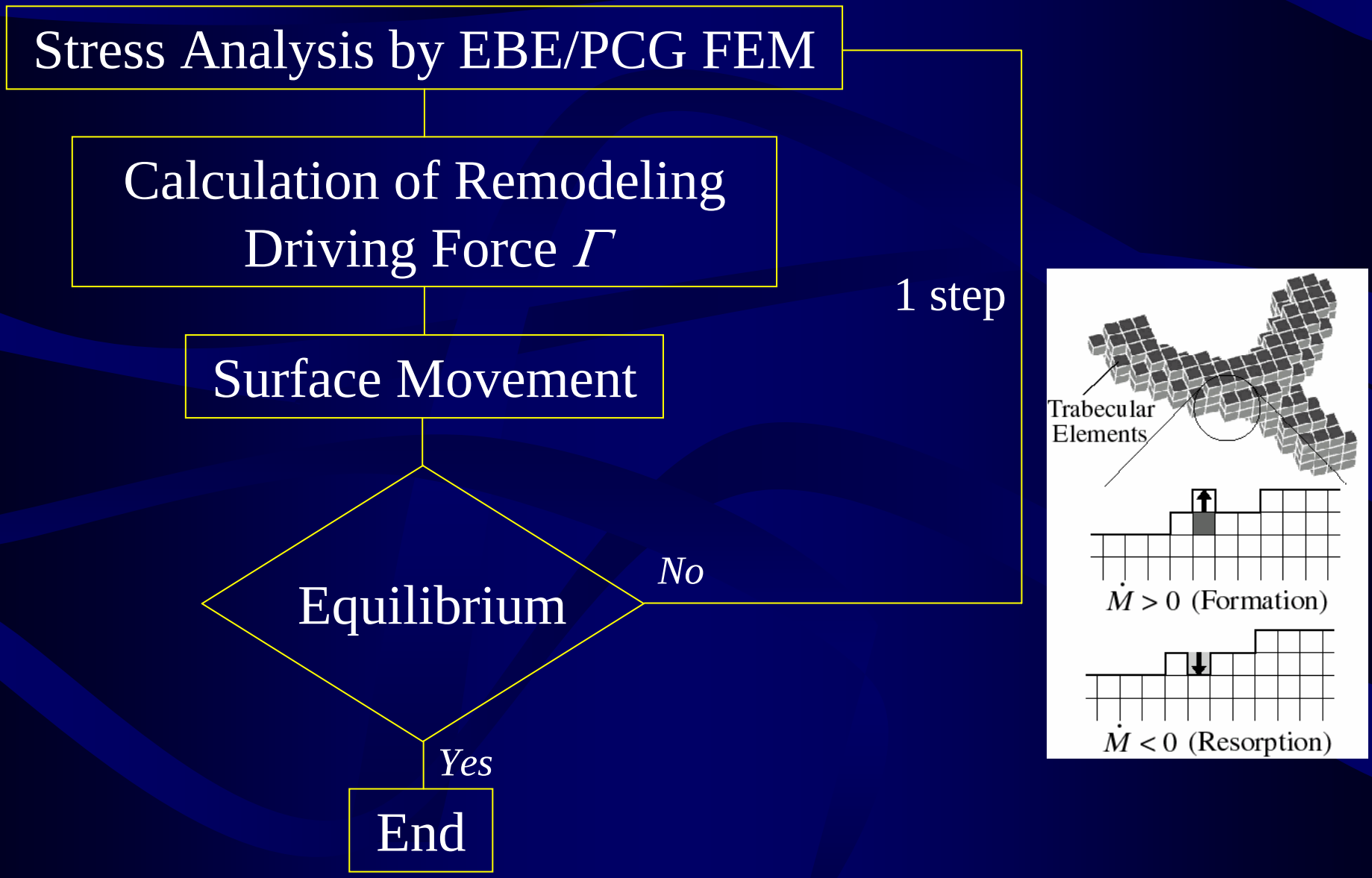


- Cortical Bone*



* Obtained by MCT-CB100MF

1.3 Iterative Algorithm for Surface Remodeling Simulation



2. Simulation Model

2.1 Bone Remodeling at Trabecular Level

- Experimental Study (Goldstein *et al.*, 1991; Guldberg *et al.*, 1997)

  (1) Cancellous Bone in Canine Distal Femoral Metaphysis

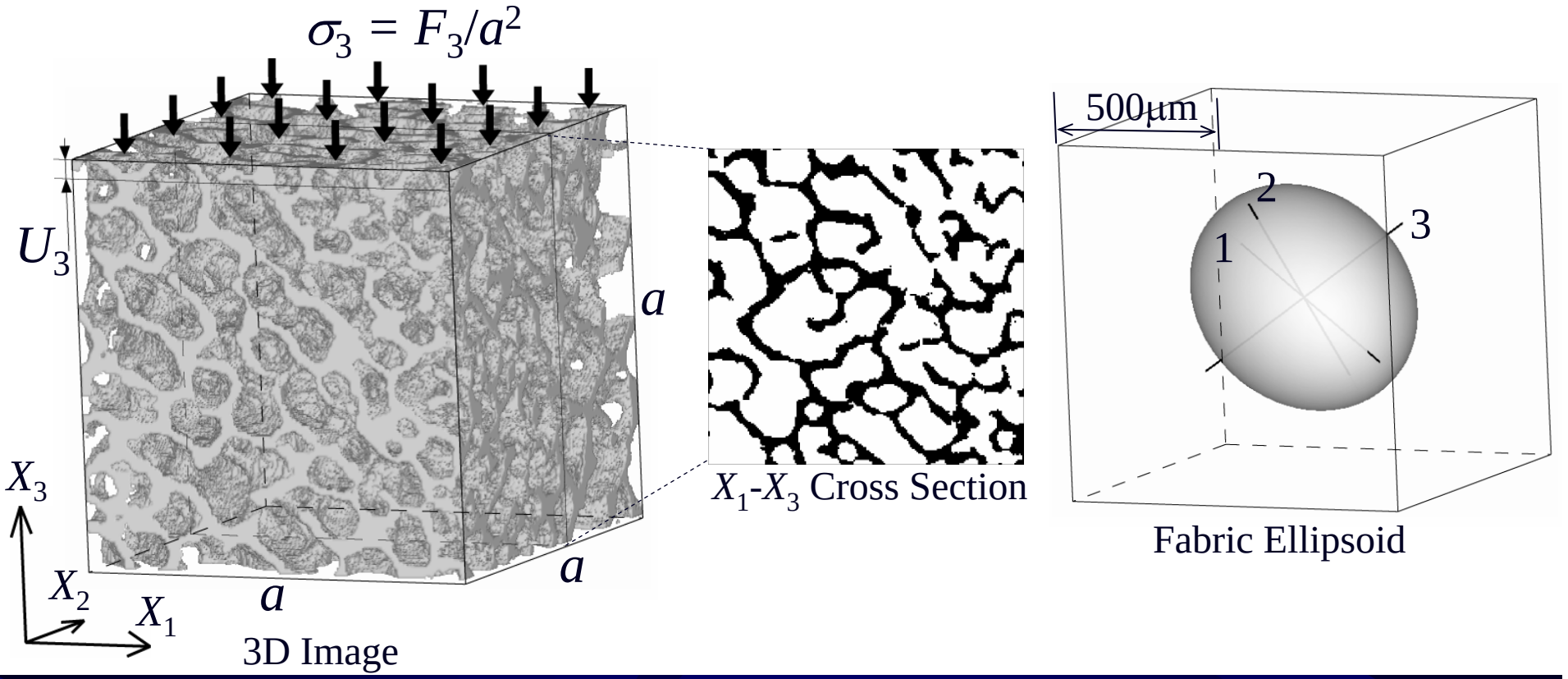
  (2) Hydraulically Controlled Loads Using Platens

  (3) Quantitative Evaluation of Bone Structural Changes Using Digital Image Obtained by μCT

Implant body with five 6mm platen designs (left) and embedded within canine distal femoral metaphysis (right) (Guldberg *et al.*, 1997)

Trabecular structure around porous-coated platen (Guldberg *et al.*, 1997)

2.2 Cancellous Bone Model Under Compressive Loading



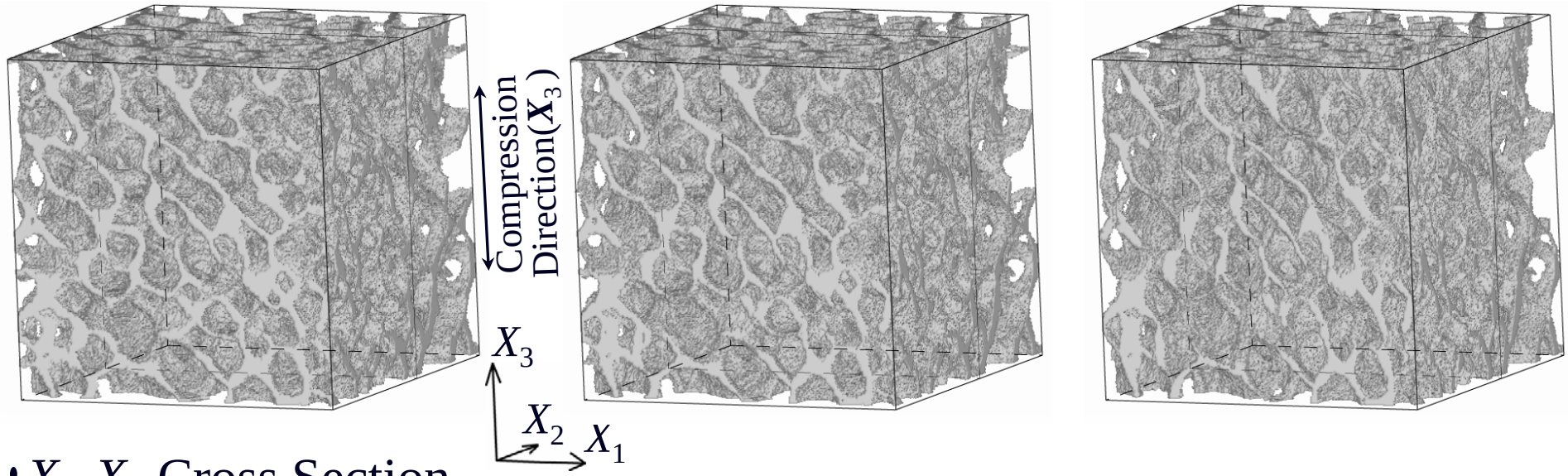
- Cubic Size: a = 5mm
- Compressive Loading:
  σ_3 = 1.24MPa
- Voxel Size: 25μm
- 200^3 = 800 Millions Elements

- Model Parameters
  l_L = 500μm
  Γ_u = 4.0, Γ_l = -5.0

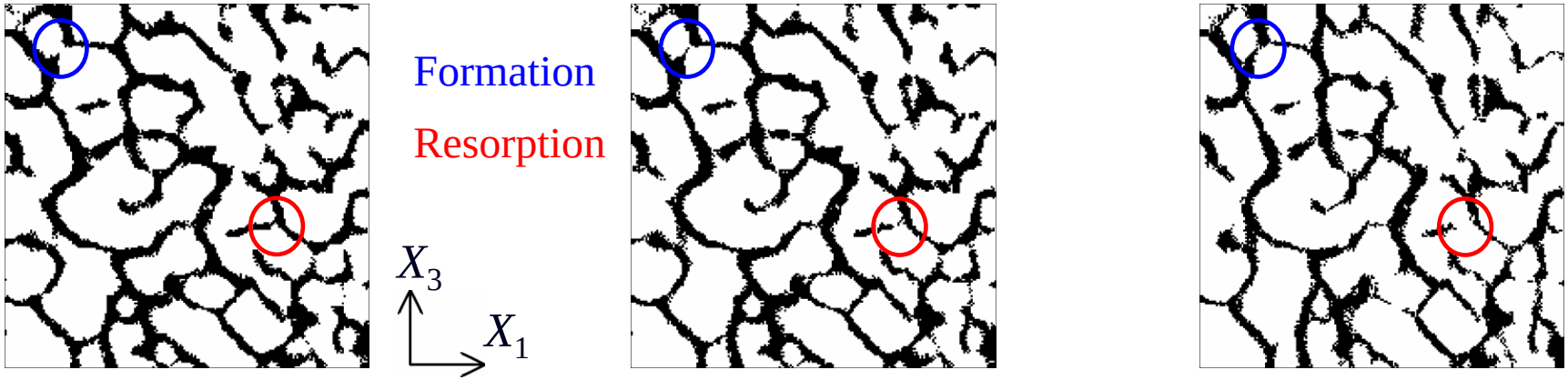
3. Results

3.1 Trabecular Remodeling Under Compressive Loading

- 3D Image

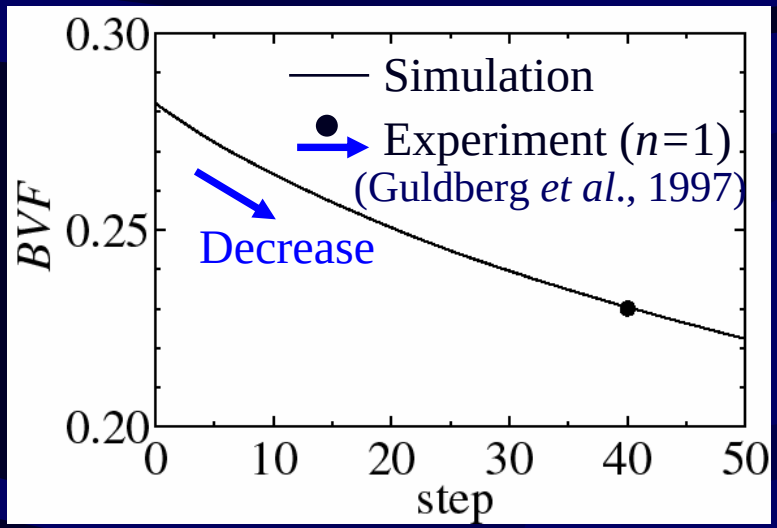


- X_1-X_3 Cross Section

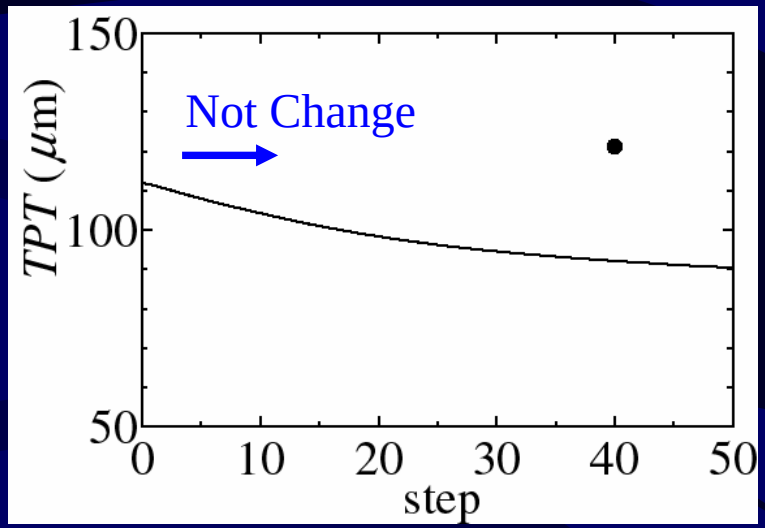


10th step　　20th step　　50th step

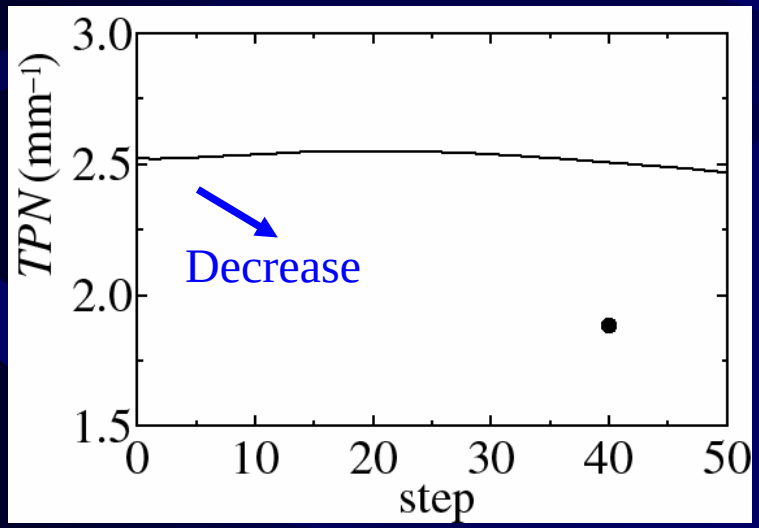
3.2 Change in Structural Indices



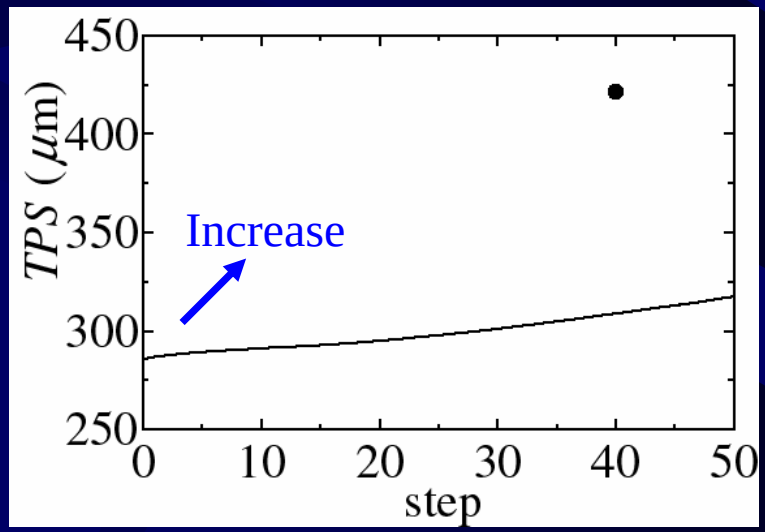
(a) Bone Volume Fraction



(b) Trabecular Plate Thickness



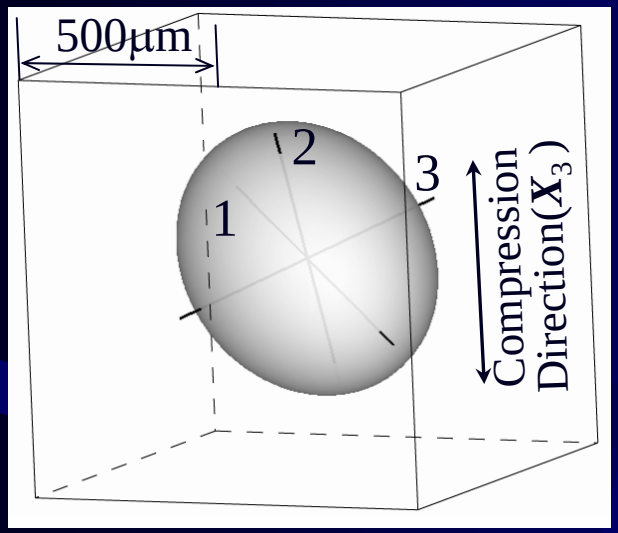
(c) Trabecular Plate Number



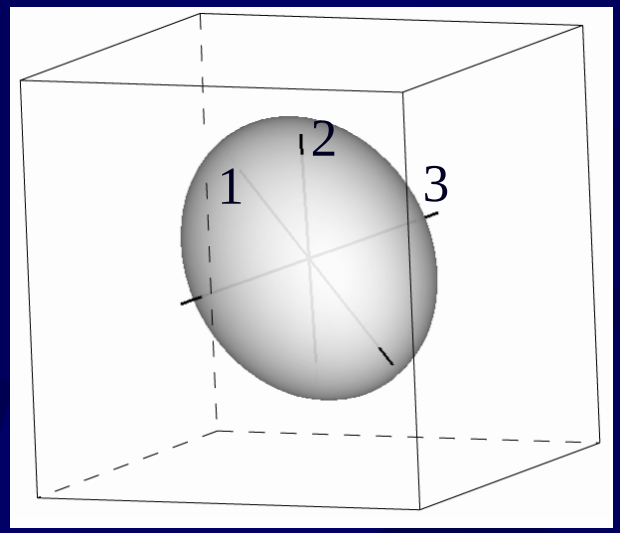
(d) Trabecular Plate Separation

3.3 Change in Structural Anisotropy

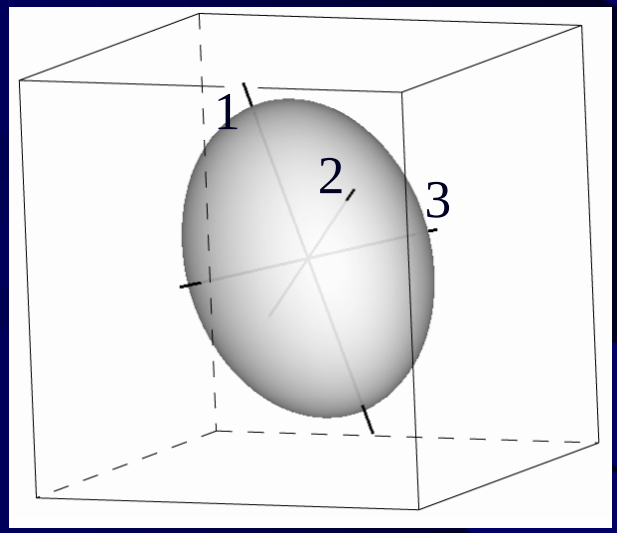
- Fabric Ellipsoid of Cancellous Bone



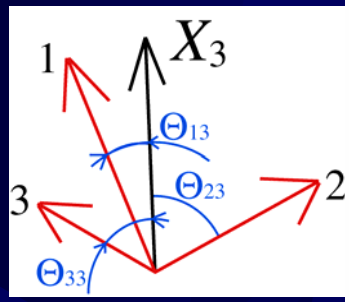
10th step

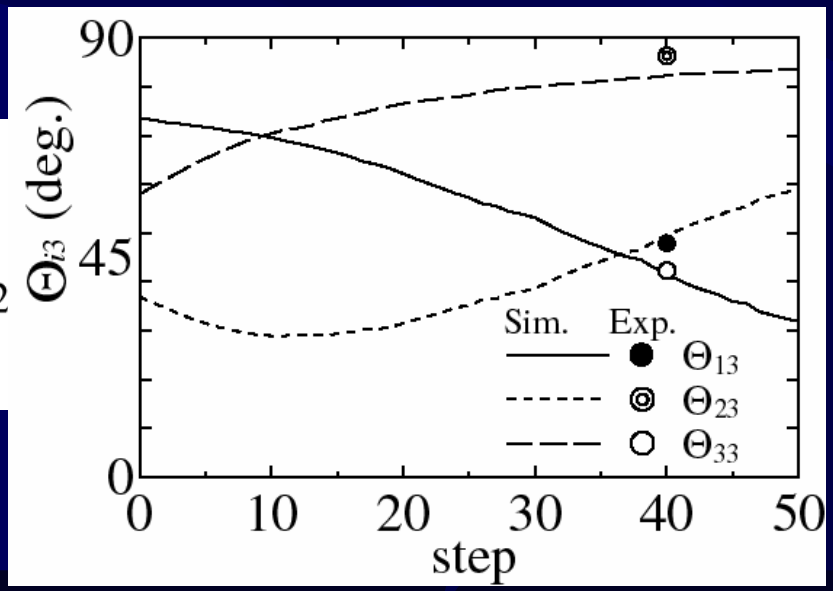


20th step



50th step

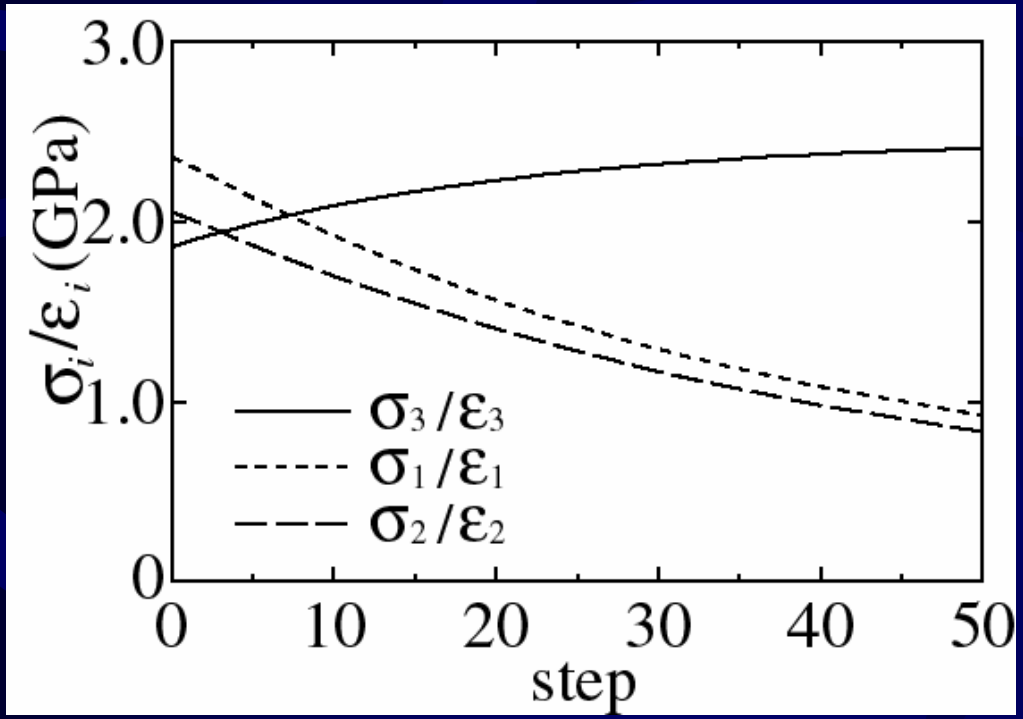


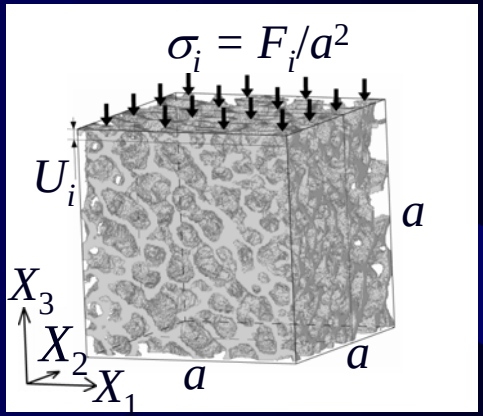


3.4 Functional Adaptation by Trabecular Reorientation

- Numerical Mechanical Testing to Obtain Structural Properties

(1) Central Region of 4*4*4mm^3 Cube Cancellous Bone
(2) Compressive Stress σ_i is applied for each direction (i = 1,2,3).
(3) Apparent Stiffness: σ_i/ε_i is Obtained ($\varepsilon_i = U_i/a$).





Conclusions

- Surface Remodeling Simulation for Trabecular Bone Using Digital Image-Based Model of Cancellous Bone

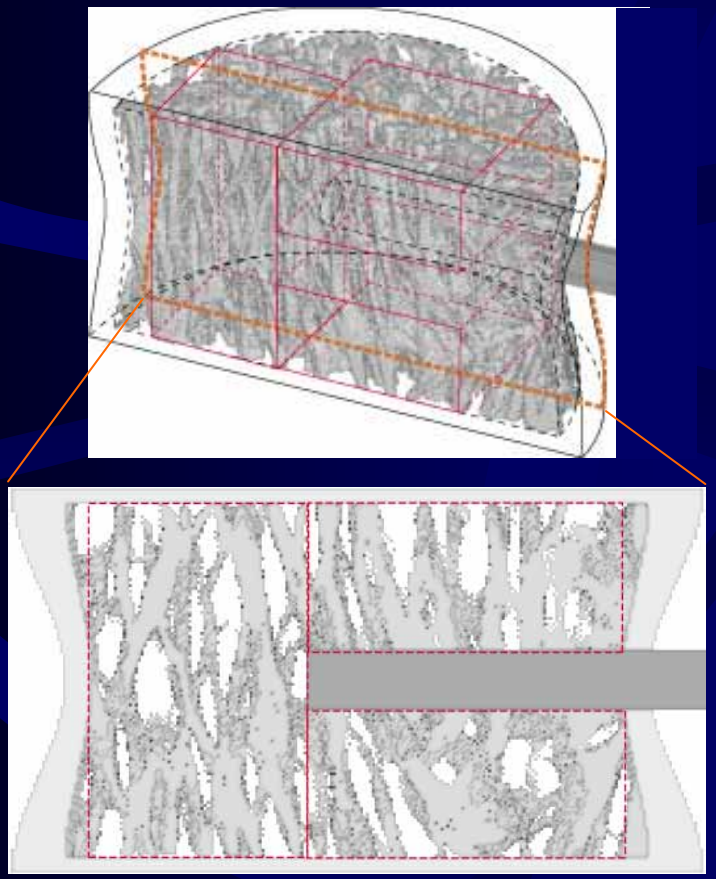
- Large-Scale Voxel Finite Element Model

- Remodeling for 3D & Complex Trabecular Structure

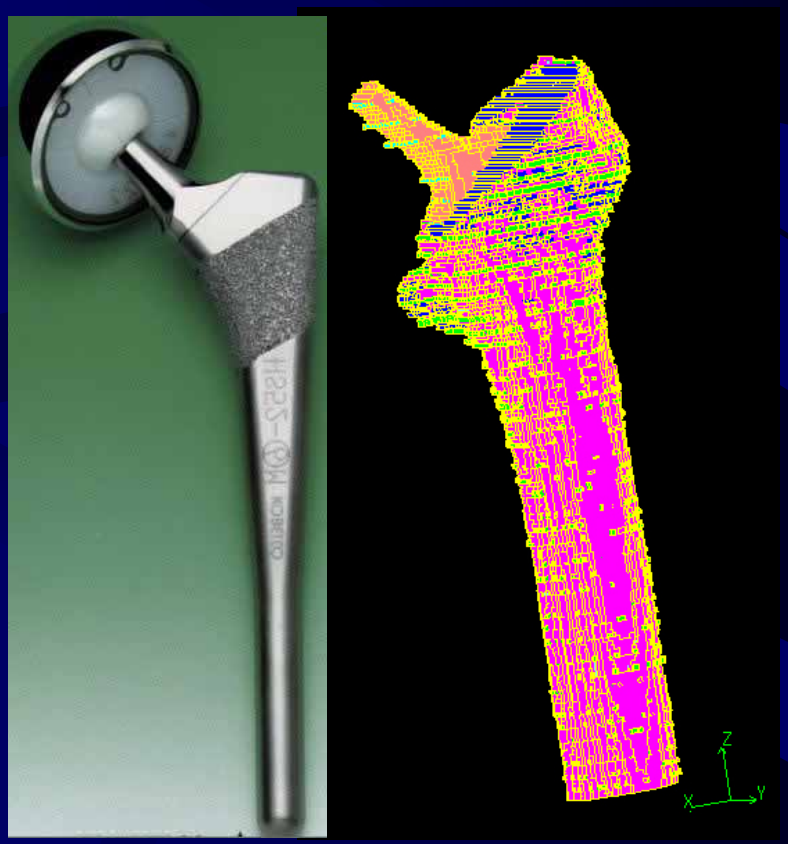
- Quantitative Comparison to Experimental Results

Future Work: Application to Design of Implant

- Quantitative Evaluation of Bone Structural Changes Due to Implantation
- Design of Implant Considering Bone Remodeling



Trabecular remodeling due to instrumentation of rod screw



Digital image-based model of THA stem implanted in proximal femur

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