RIKEN Symposium

– Computational Biomechanics –

Simulation Study on Mechanical Adaptation in Cancellous Bone by Trabecular Surface Remodeling

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Introduction

Bone Functional Adaptation by Remodeling

Mechanical Environment → **Bone Structure**

Hierarchical Structure of Bone

Mechanical Stimuli

↓

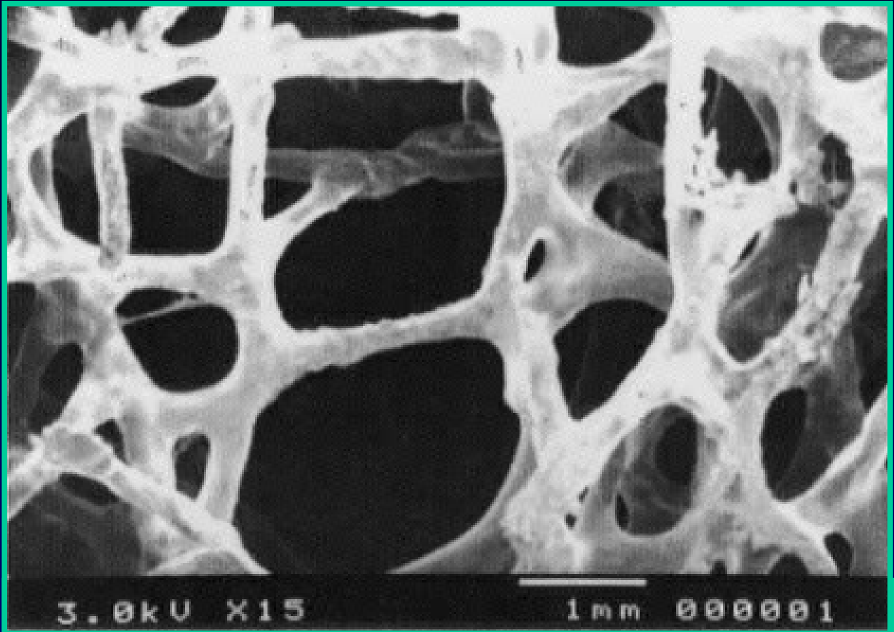
Cellular Activities

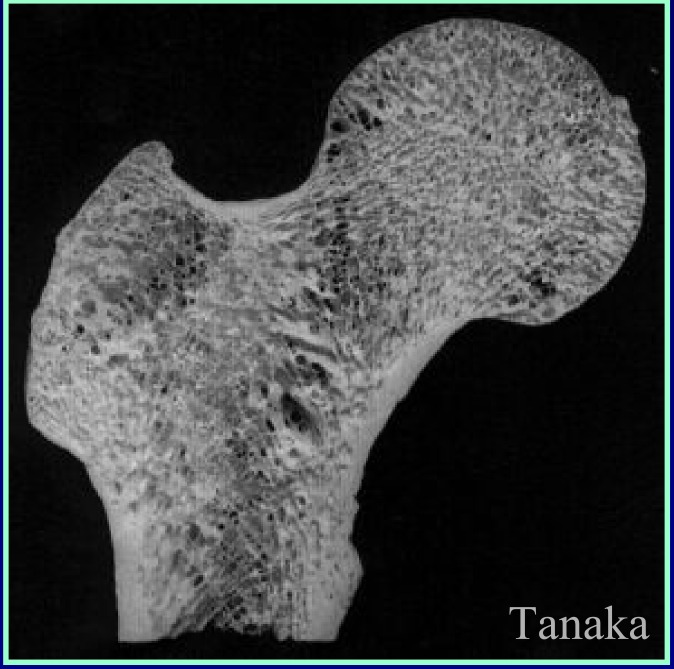
↓

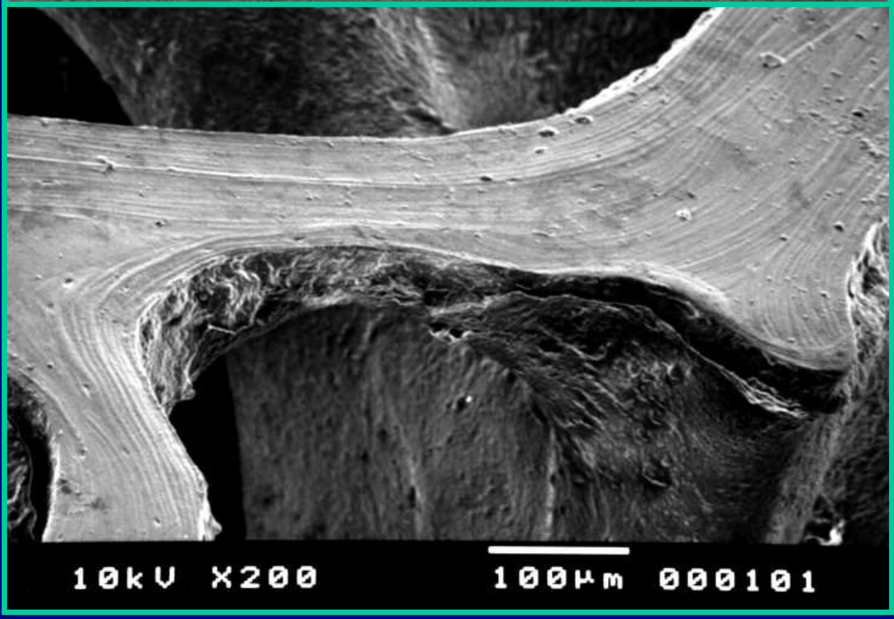
Formation / Resorption

↓

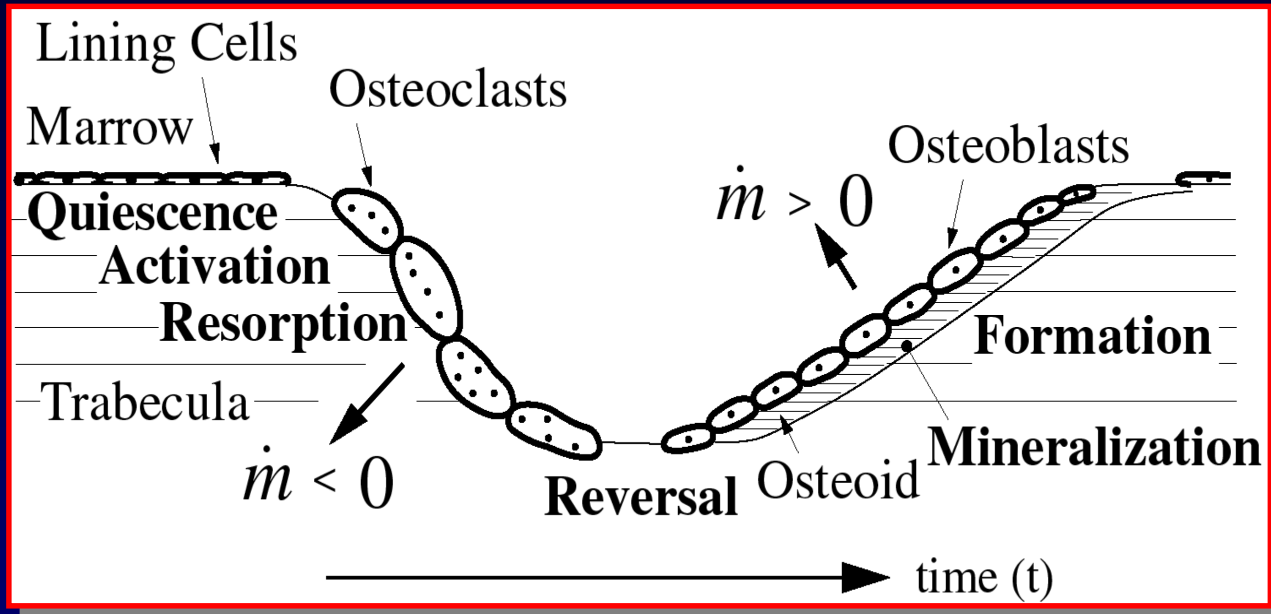
Structural Changes







Trabecular Surface Remodeling



(Parfitt94)

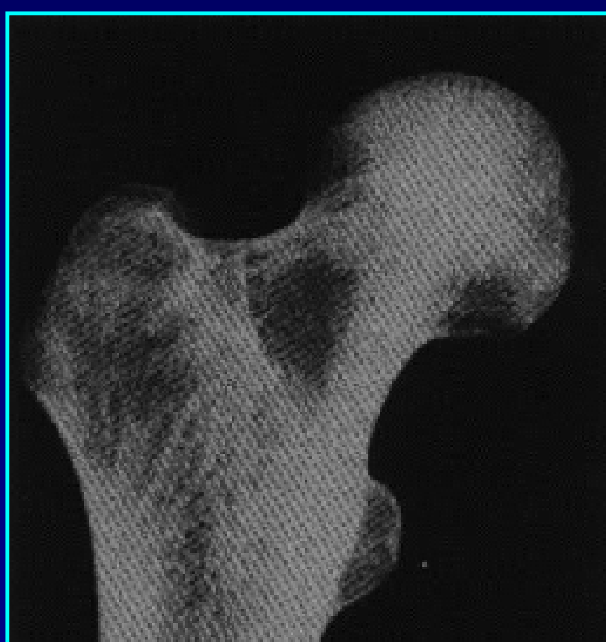
- **Trabecular microstructure of cancellous bone**
  - changing / maintained by remodeling under mech. influence
- **Adaptation to mechanical environment**
  - regulated by Oc / Ob activities on trabecular surface
- **Surface movement by cellular activities lead to**
  - macroscopic changes of trabecular architecture

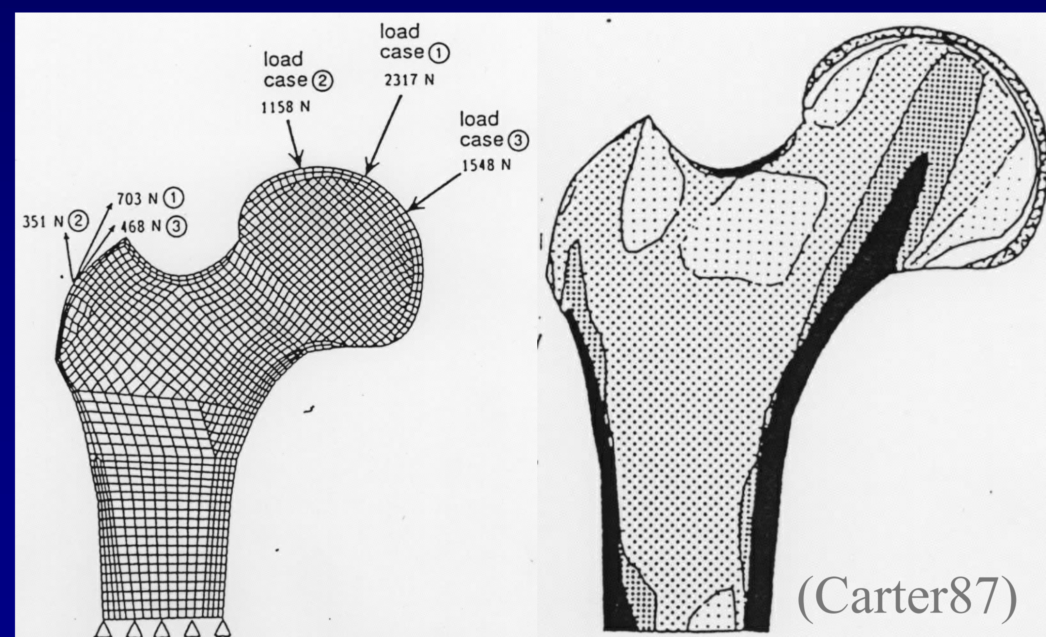
Computational Simulation for Bone Remodeling

Theoretical models & Computational simulations

Macroscopic Phenomena	**Microscopic Mechanism**
Cowin76, Carter87, Huiskes87, Beaupre90, Weinans92	Cowin92, Sadegh93, Mullender94

- **Adaptive Elasticity** (Cowin76)
- **Self Optimization Model** (Carter87)





(Carter87)

Trabecular Level Remodeling

Trabecular Remodeling

- **Microscopic resorption / formation by osteoclasts / osteoblasts on trabecular surface** (e. g. Parfitt84)
- **Local mechanical signals play an important role** (e.g. Guldberg97)
- **Trabecular level mechanical stimulus related to morphological changes of trabecular architecture**

Outline

Simulation for Trabecular Surface Remodeling

- **Remodeling Rate Equation**
- **Method of Pixel-based Simulation**
- **Computational Simulation for Proximal Femur**

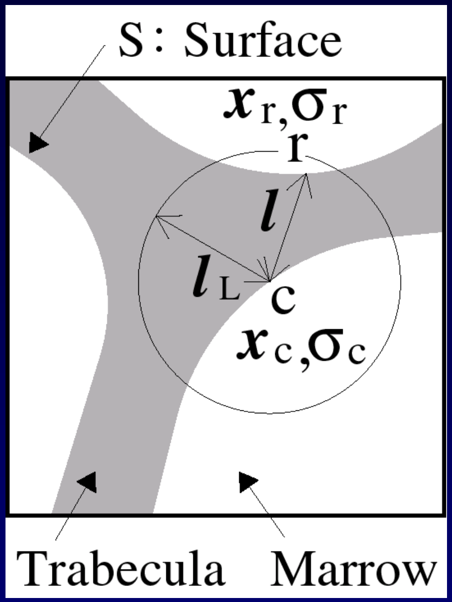
Uniform Stress Hypothesis

- **A Remodeling Rate Equation:**
  based on Uniform Stress Hypothesis
  as an optimality condition
  for remodeling equilibrium (Adachi98)

  - **Nonuniformity in local stress distribution on trabecular surface as driving force of remodeling**

  - **Related to local morphological changes of trabecular architecture**

A Remodeling Rate Equation



Stress nonuniformity

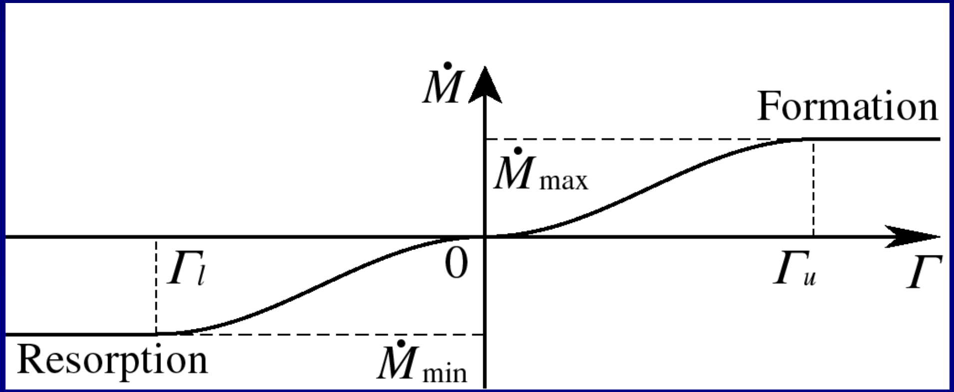
$$\Gamma = \ln(\sigma_c / \sigma_d)$$

Representative stress

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

→ **Driving force of remodeling**

A Remodeling Rate Equation



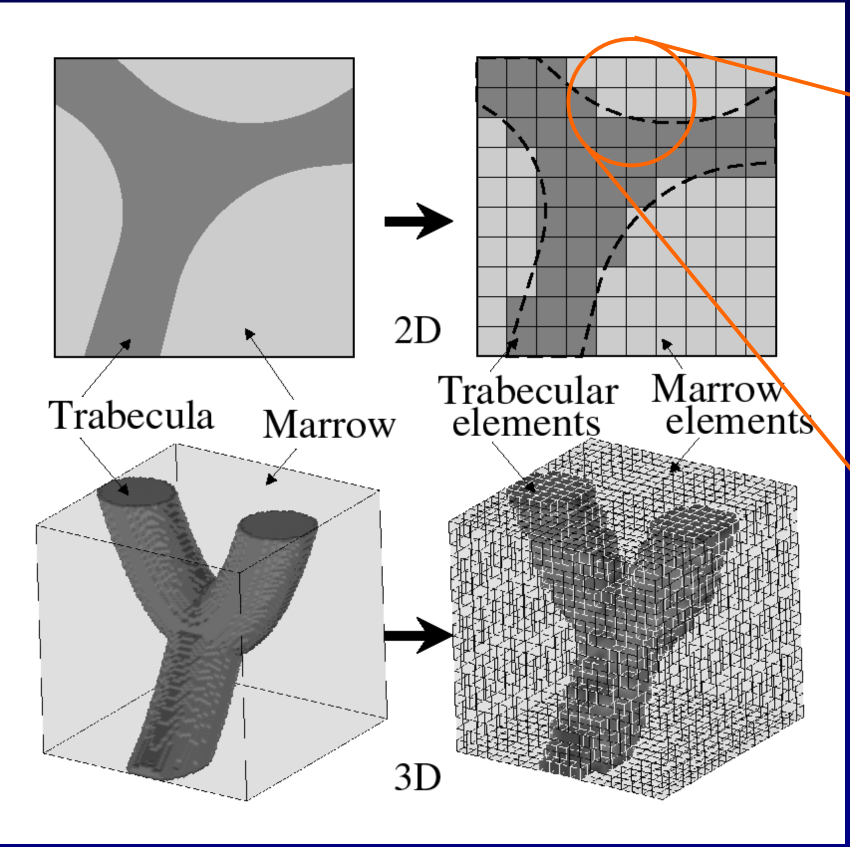
$$\dot{M} = F(\Gamma)$$

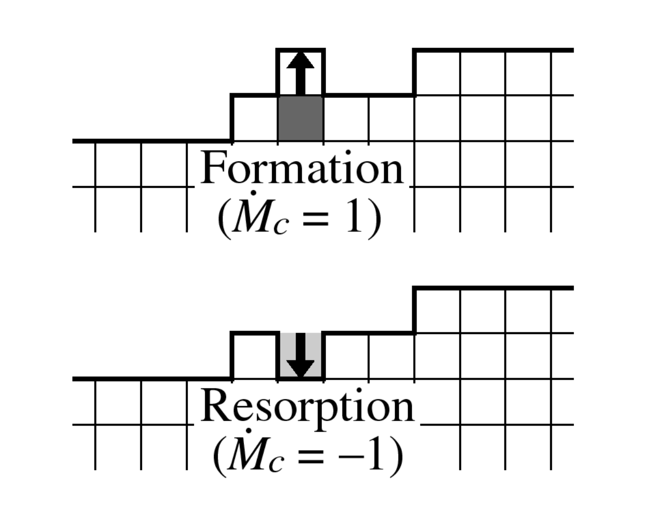
$$= \begin{cases} \Gamma > 0 : \text{Formation} \\ \Gamma < 0 : \text{Resorption} \end{cases}$$

Microstructural Finite Element Model

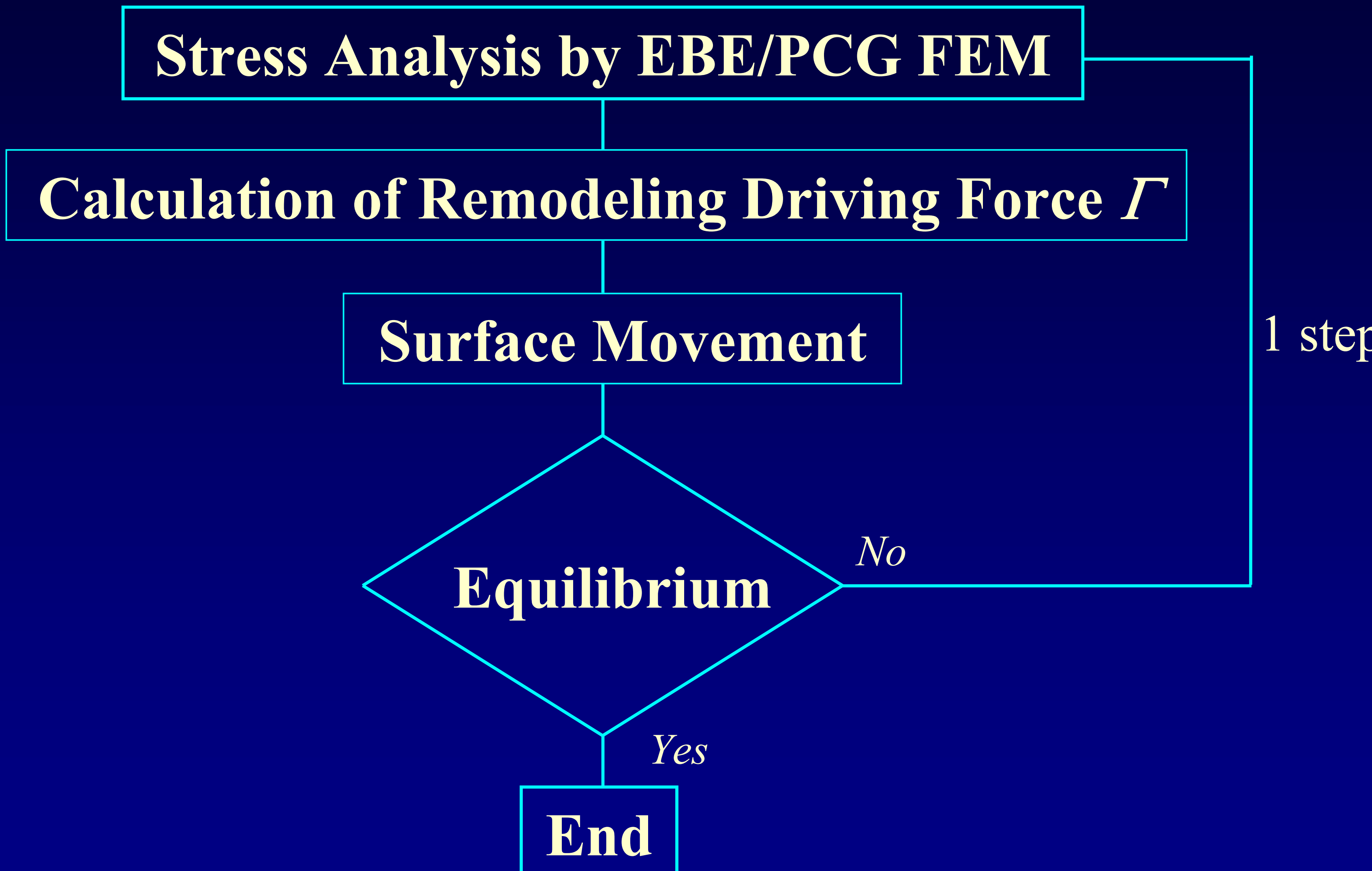
Trabecular Bone

- Microstructural voxel/pixel finite element models
- Resorption/formation by removing/adding elements
- Generated by using digital images, μCT

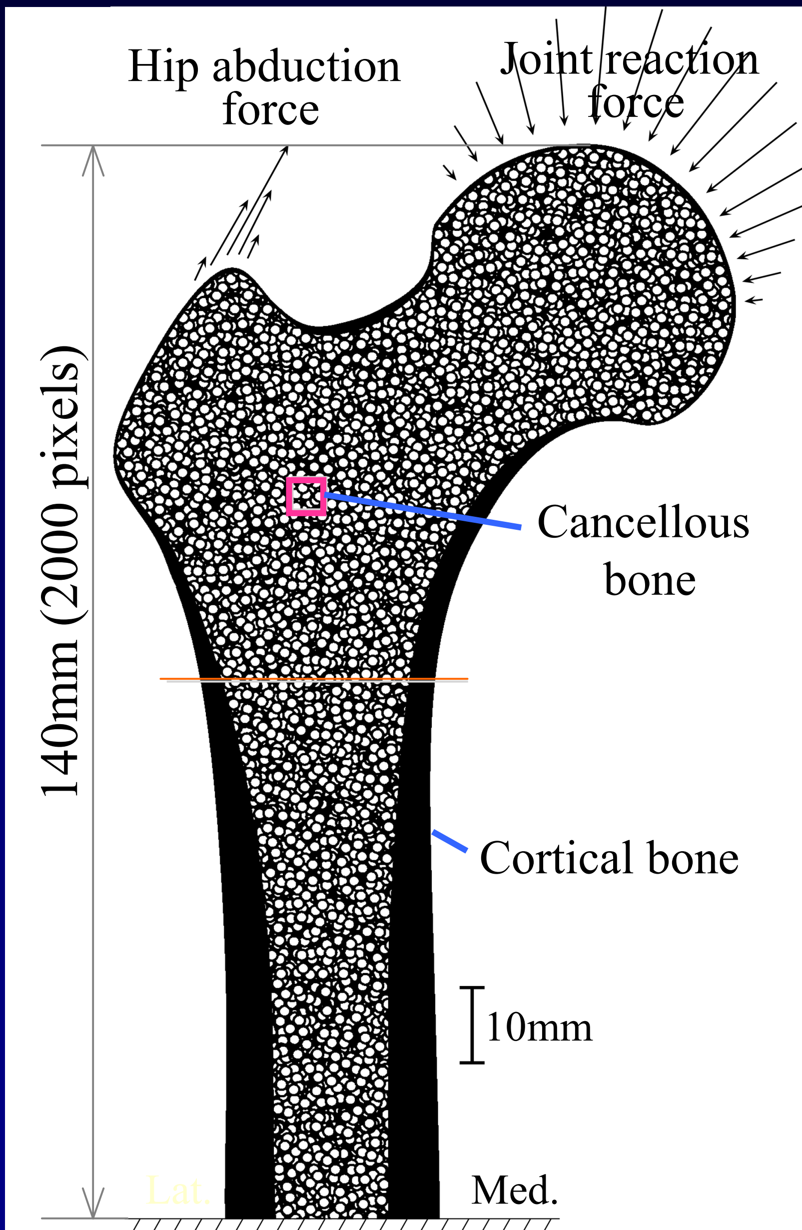




Remodeling Simulation



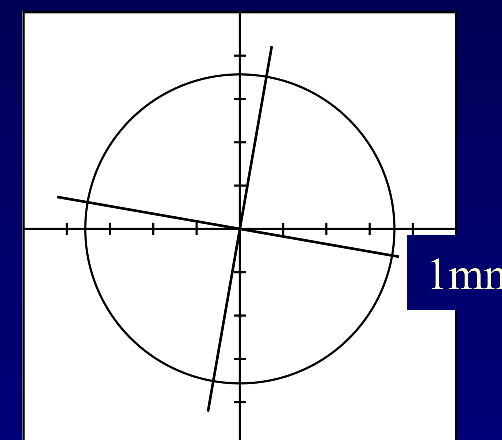
Large-Scale FE Pixel Model of Proximal Femur



- Bone part: 0.67 Million Elements
- Pixel size: 70μm

4mm × 4mm region

Fabric ellipse



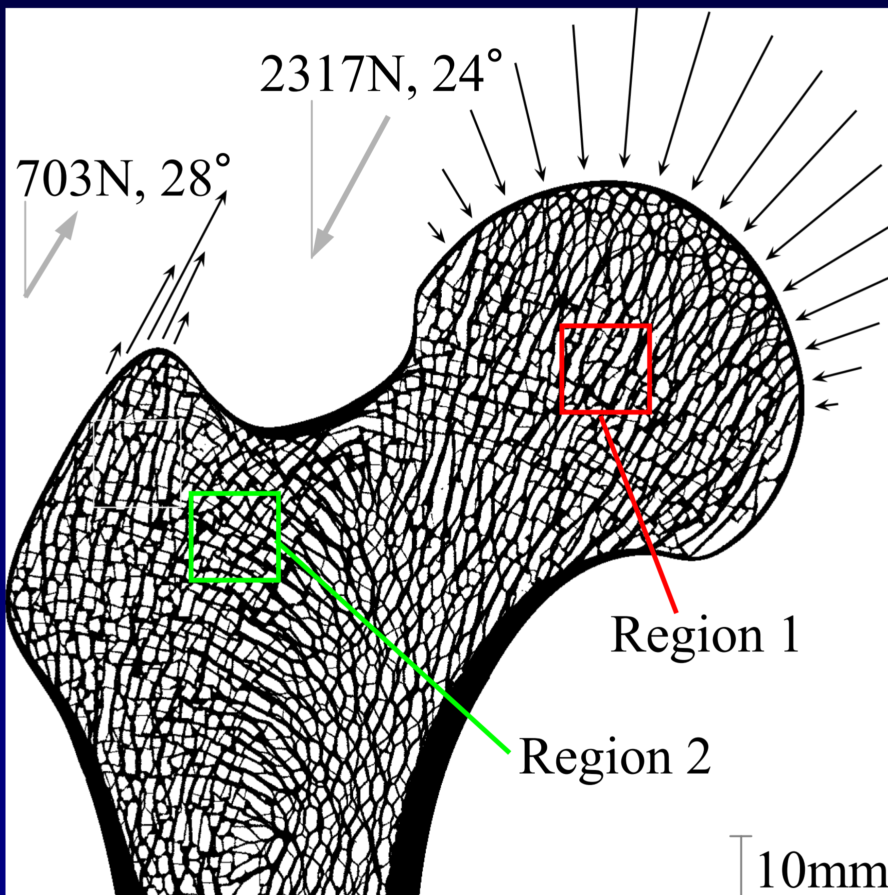
$H_1 = 714\mu m$, $H_2 = 713\mu m$
$H_1/H_2 = 1.00$

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

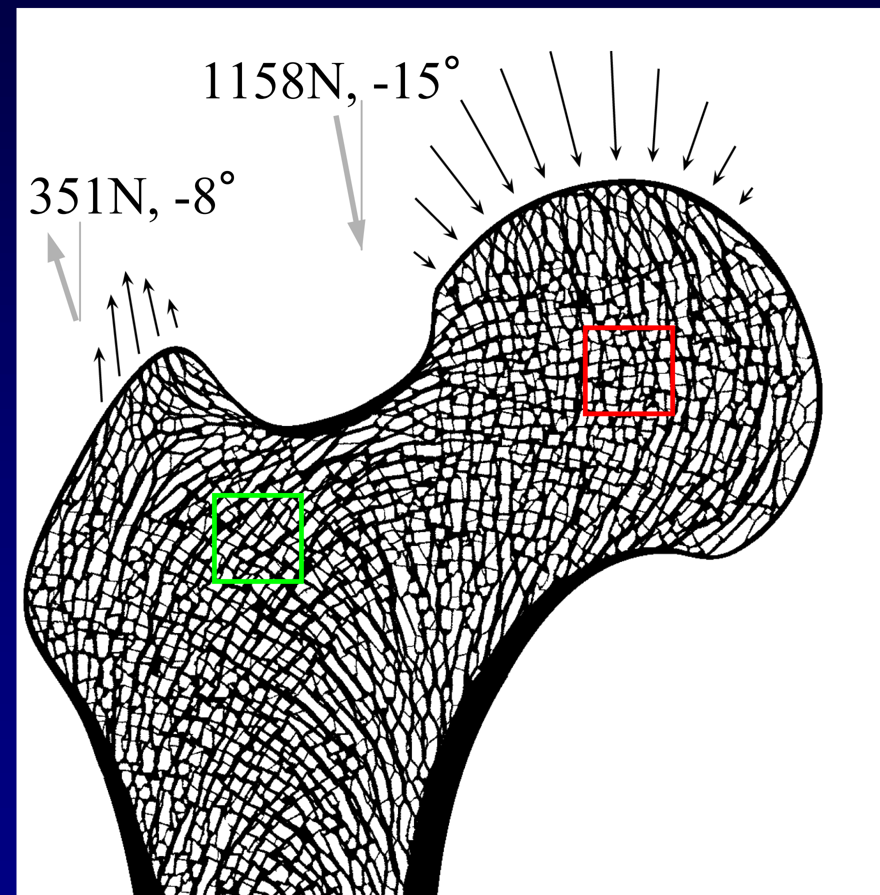
Trabecular Structural Changes

- Trabecular bone remodeling at 12th Step

One-legged stance



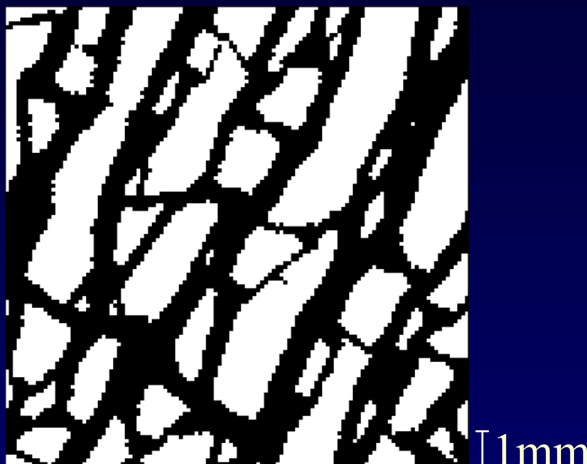
Abduction

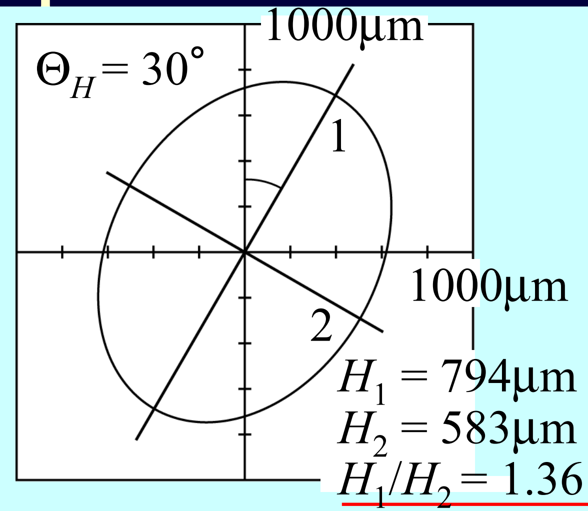


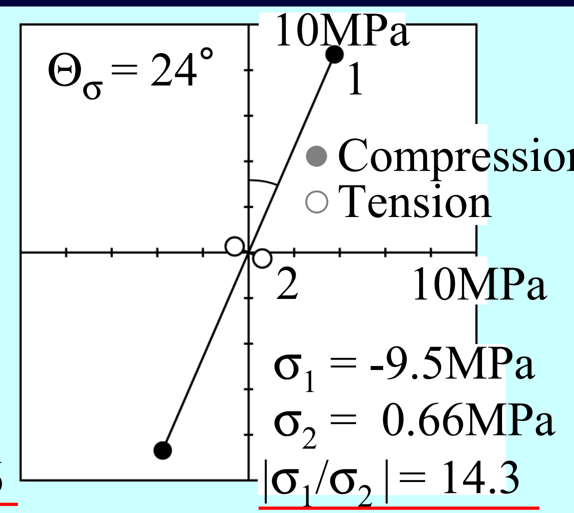
* Boundary condition (Beaupré90)

Trabecular Structure & Mechanical Environment

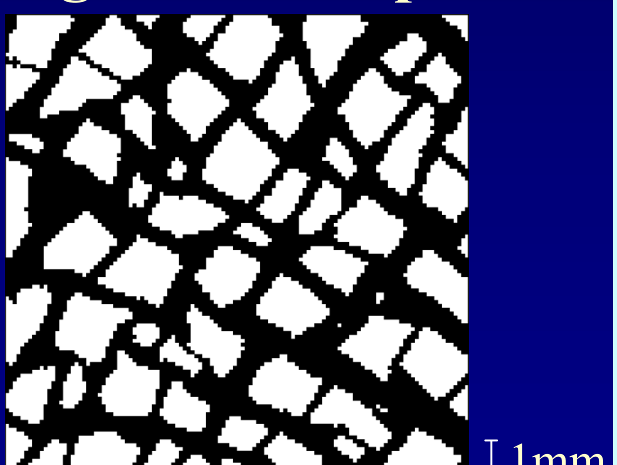
- Region 1: Uniaxial Compression

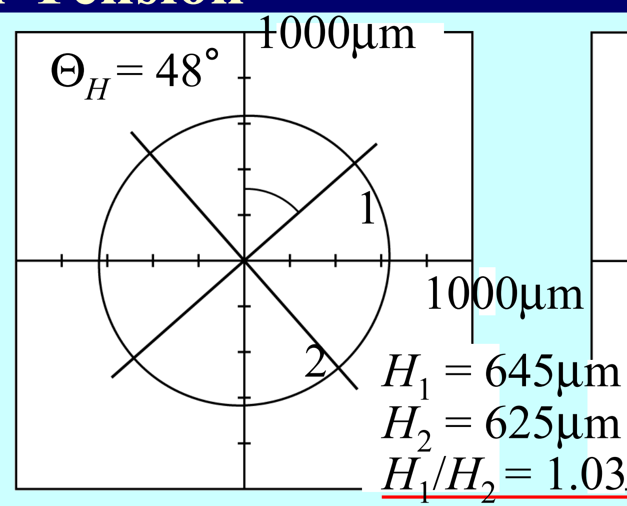


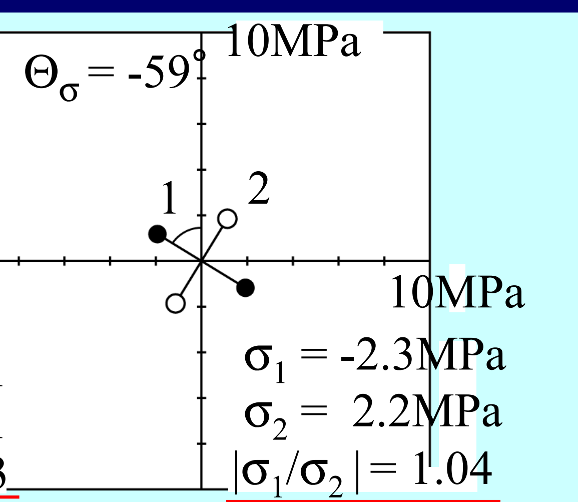




- Region 2: Compression-Tension

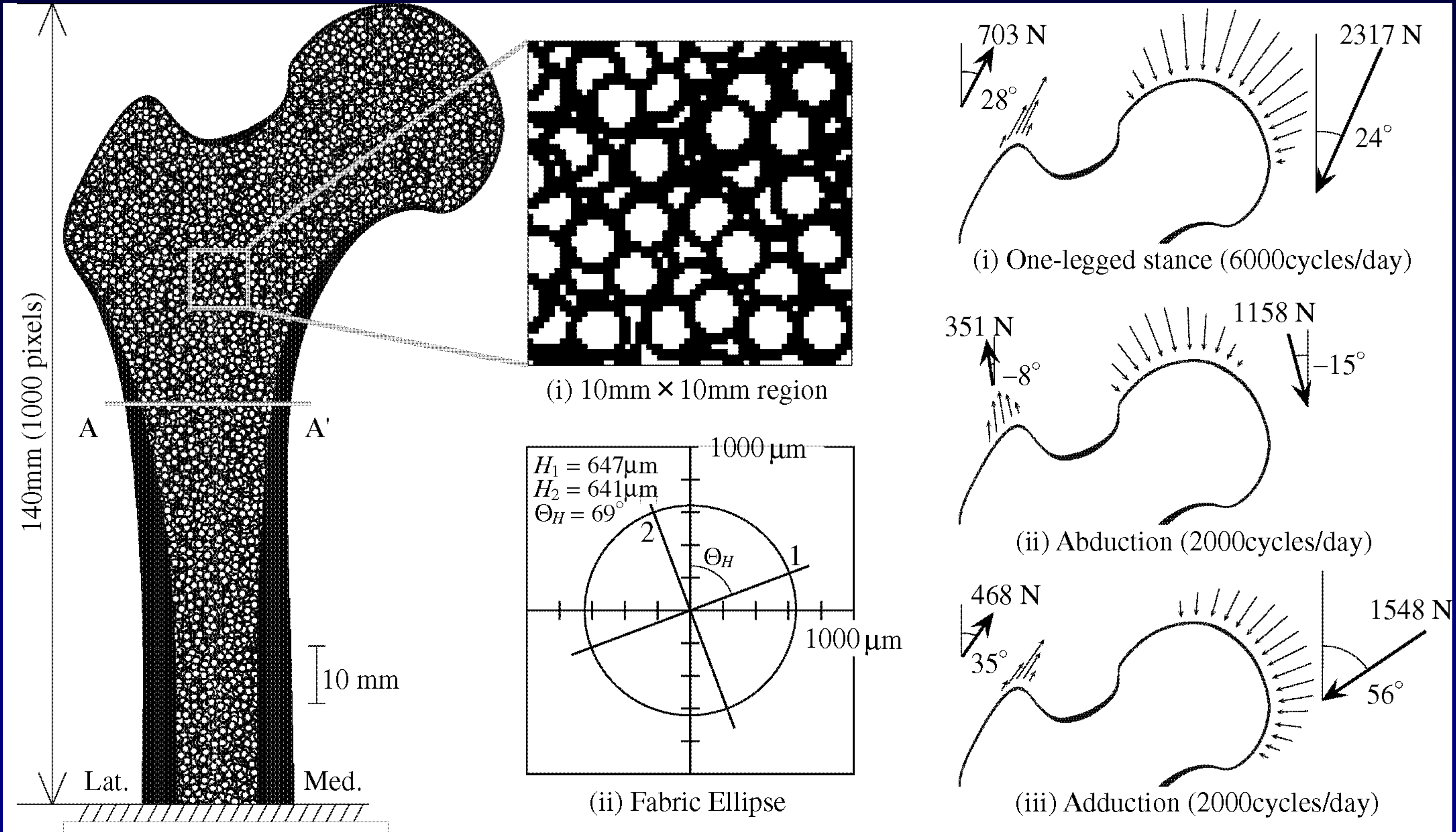






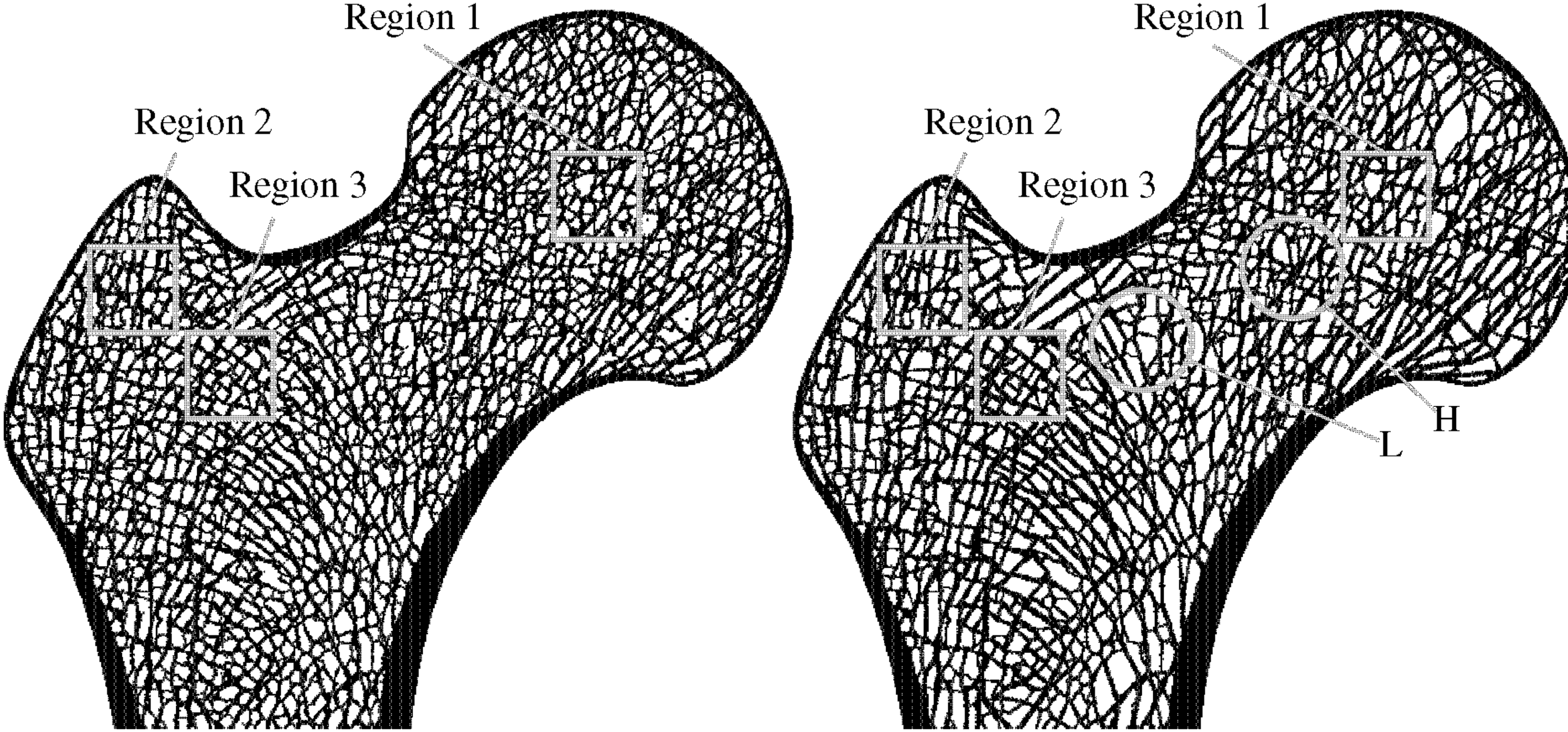
Trabecular microstructure **Fabric ellipse** **Apparent principal stress**

Remodeling under Multiple Loading



(a) Large scale pixel-based FE model (b) Initial morphology of cancellous bone (c) Boundary condition (Beaupré *et al.*, 1990)

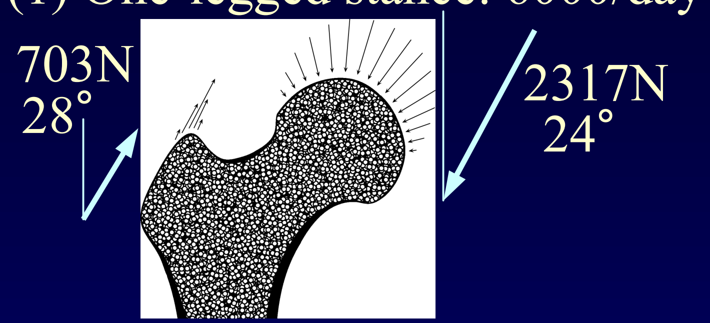
Structural Changes under Multiple Loading



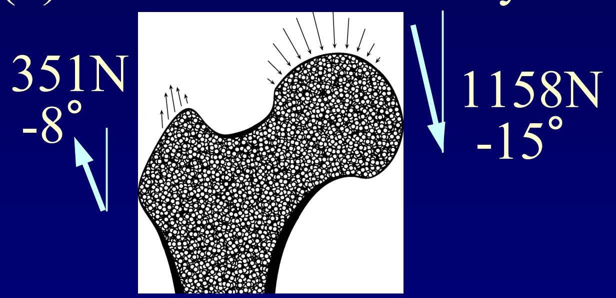
(a) 5th step (b) 15th step

Structural Changes under Multiple Loading

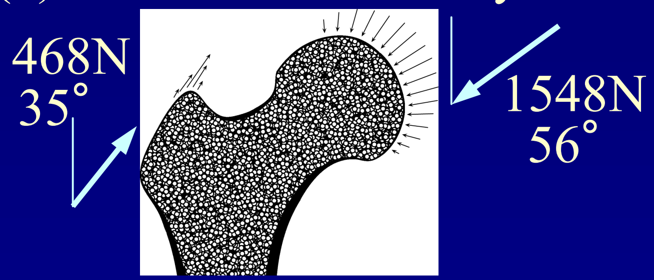
(1) One-legged stance: 6000/day



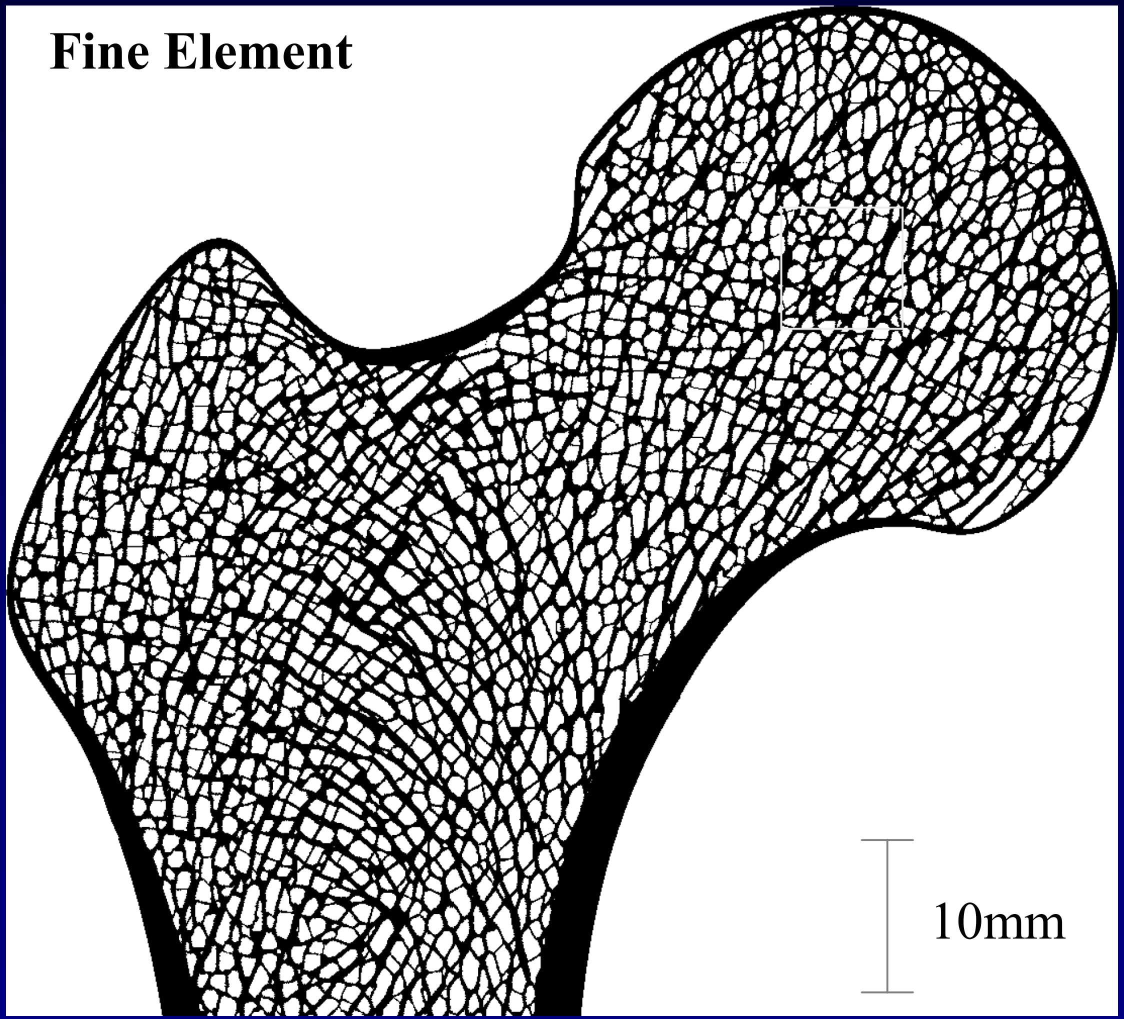
(2) Abduction: 2000/day



(3) Adduction: 2000/day

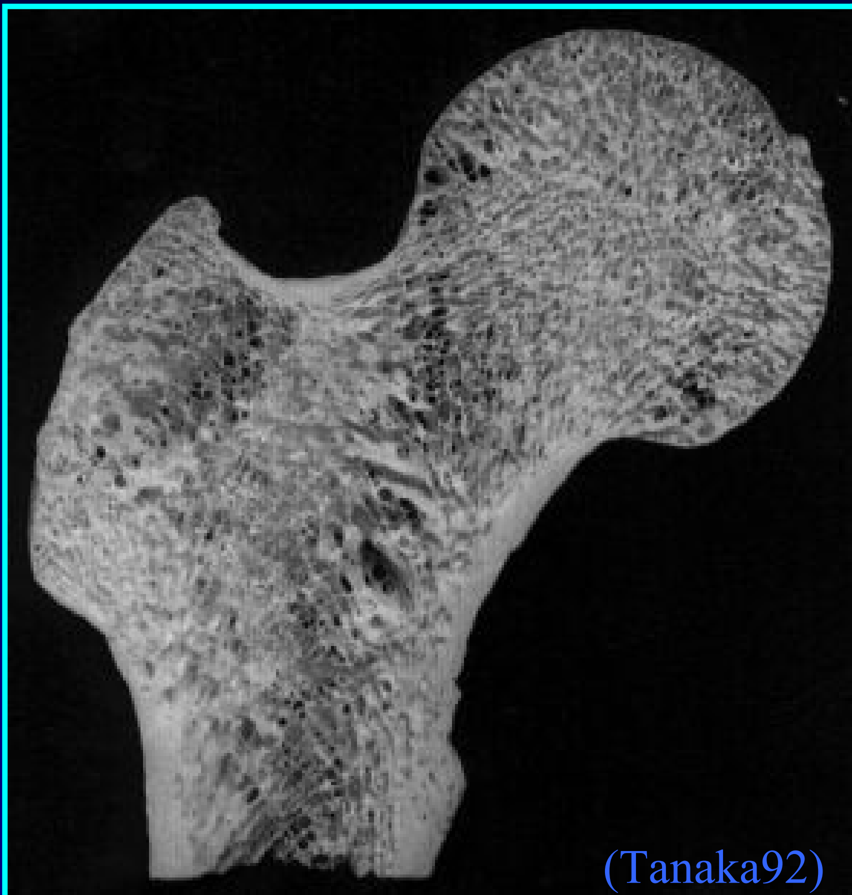


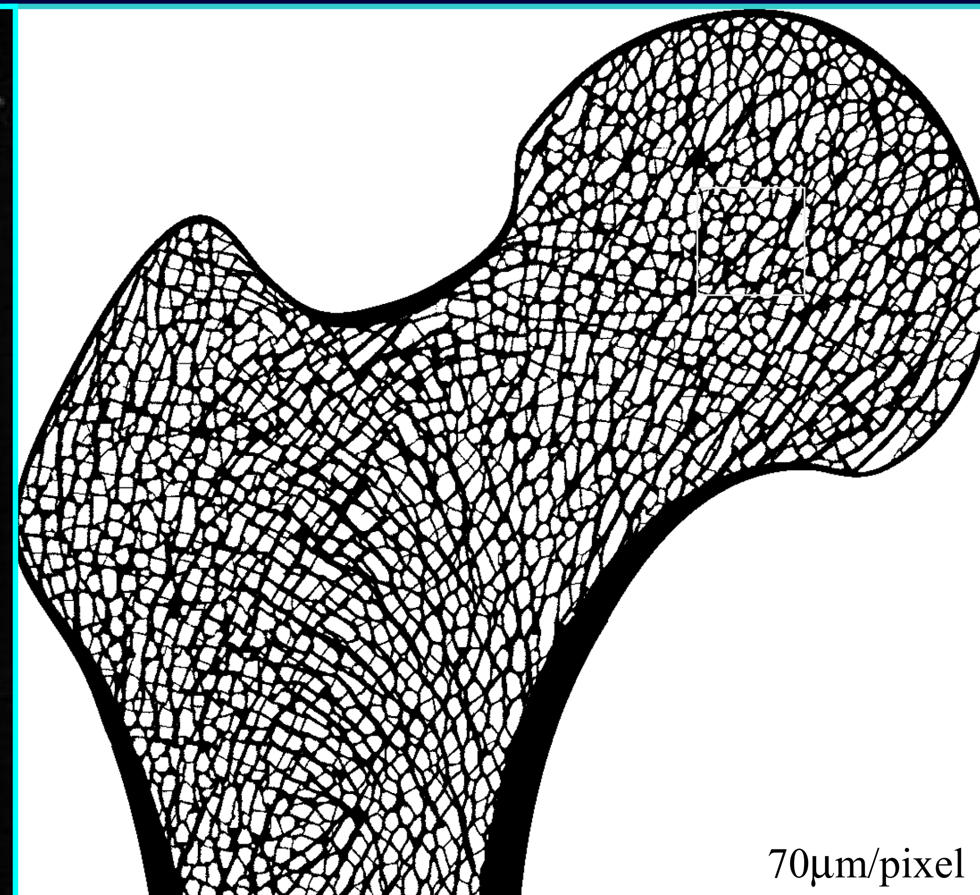
*** B.C.: Beaupré *et al.* (1990)**



Trabecular bone remodeling at 10th step

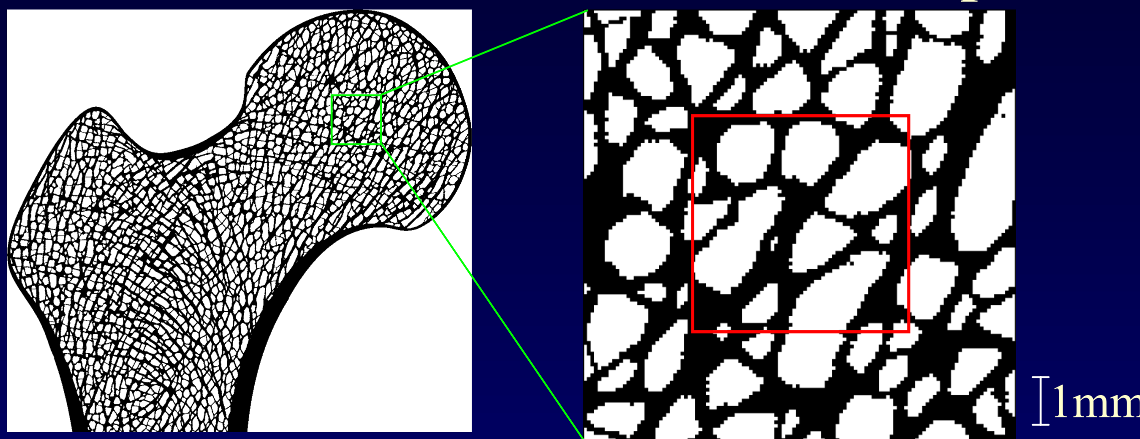
Comparison

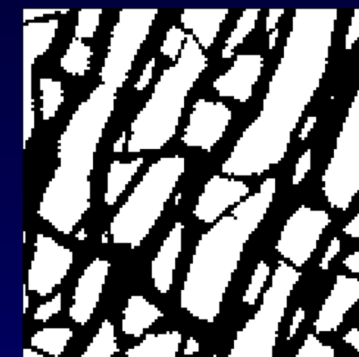




At Microstructural Level

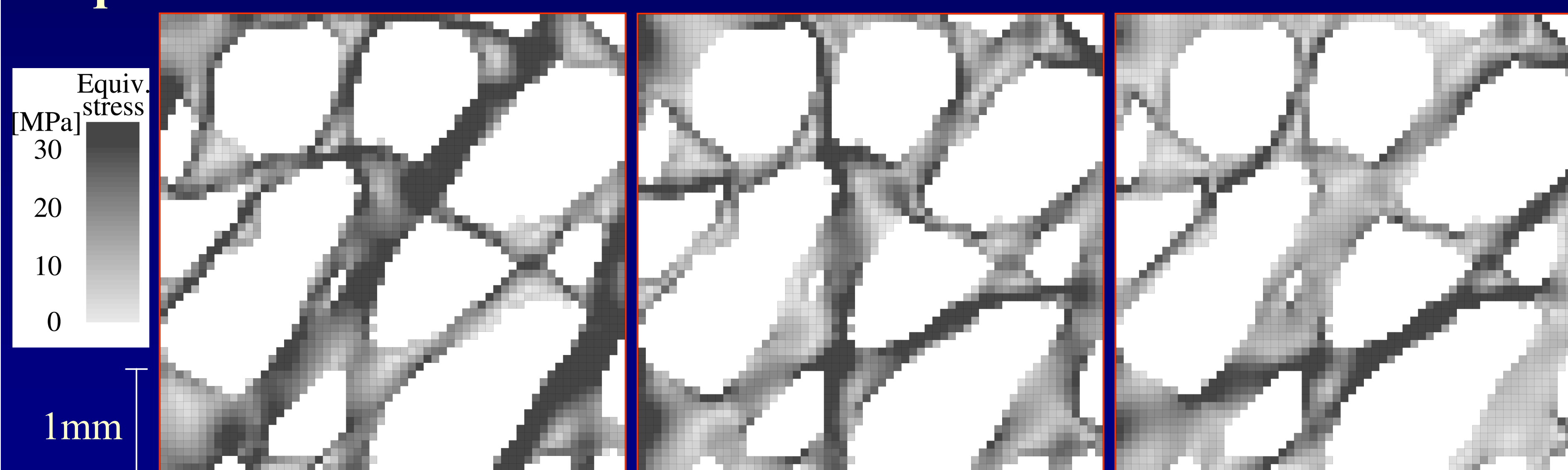
Trabecular microstructure for multiple loading condition





*Single loading condition:
One-legged stance

Equivalent stress distribution



One-legged stance   Abduction   Adduction

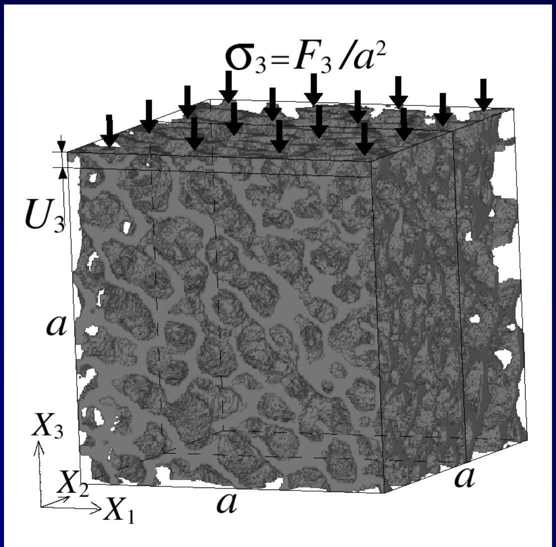
Discussion and Conclusion

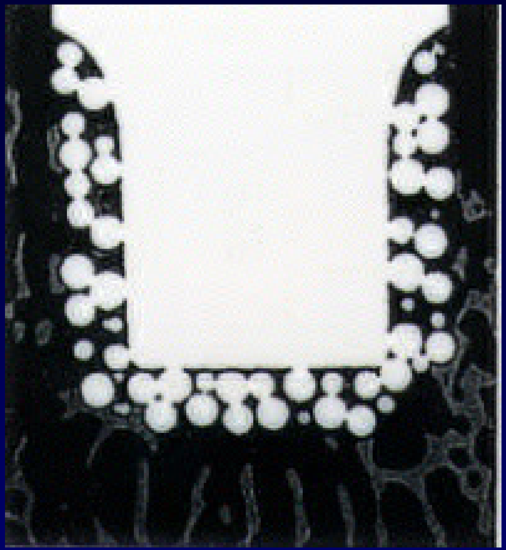
- Trabecular surface remodeling in cancellous bone
- Large-scale pixel FE model of proximal femur
- Trabeculae adapt to mechanical environment
- Direct evaluation of micro-macro relationships
- Insight into microscopic mechanism

Proposed simulation method using microstructural voxel FE models could be applicable to predict the trabecular remodeling

Future Works

3D remodeling simulation using digital-image based FE model (μCT)





Comparison with experiment

Application to orthopaedic research area: Remodeling at bone-implant interface