マイクロCTデジタルイメージを用いた骨梁構造の三次元モデルと再構築シミュレーション

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はじめに (1)

力学環境

再構築 { 微視的力学状態 ↓ 細胞活動 }

骨形態

図. 大腿骨海綿骨(田中,1992)

- 骨再構築シミュレーション: 現象の理解, 臨床への応用

(1) **巨視連続体レベル**: Cowin *et al.*(1985), Carter *et al.*(1989), Huiskes *et al.* (1987), Hart (1990)

(2) **微視構造レベル**: Cowin *et al.*(1992), Sadegh *et al.*(1993), Mullender *et al.* (1994), Tanaka & Adachi (1998)

⟶ **詳細なモデルの構築**: 三次元微視骨梁構造, 表面再構築

はじめに (2)

- **目的： 骨梁レベルの微視的な力学状態と形態変化とを直接関連づけた三次元シミュレーションモデルの構築**

- **手法： (1) 局所の応力一様化を仮定**

  (2) μCT**データを用いた海綿骨**Voxel**モデル**

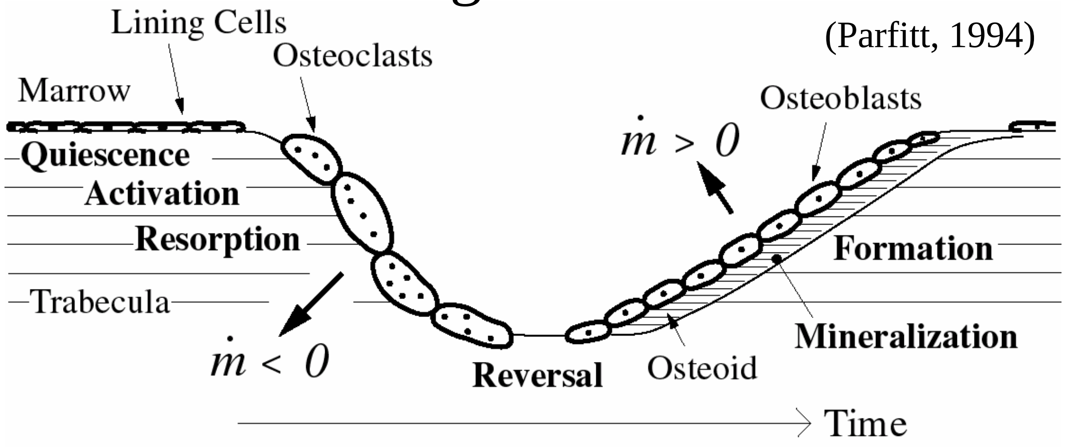
  (3) Large-Scale FEM **を用いた三次元表面再構築シミュレーション**

Trabecular Surface Remodeling Model

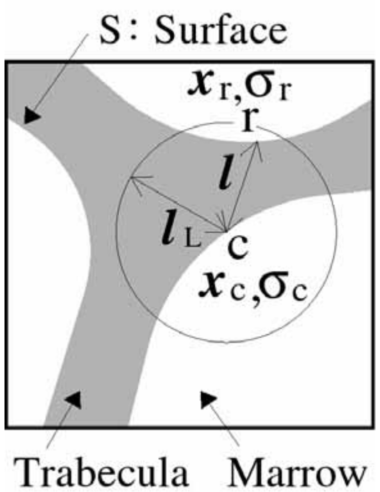
- Surface Movement Due to Remodeling

$\dot{m}$: Rate of Surface Movement

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



- Rate Equation Based on Uniform Stress Hypothesis (Adachi *et al*. 1998)

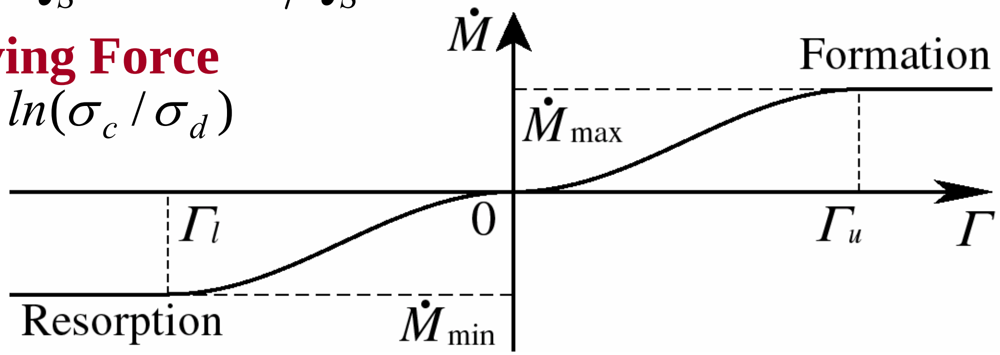


Representative Stress

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

Driving Force

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

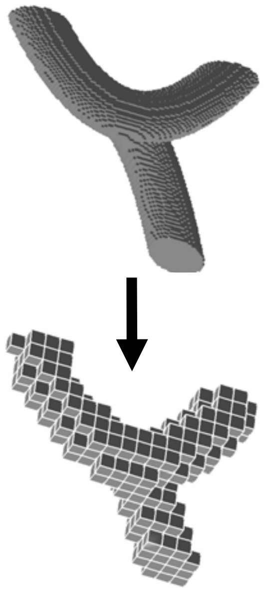


Microstructural FE Model of Cancellous Bone

- Direct Evaluation of Trabecular-Level Mechanical State (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 Method
→ Saving Both CPU Time and Memory Storage



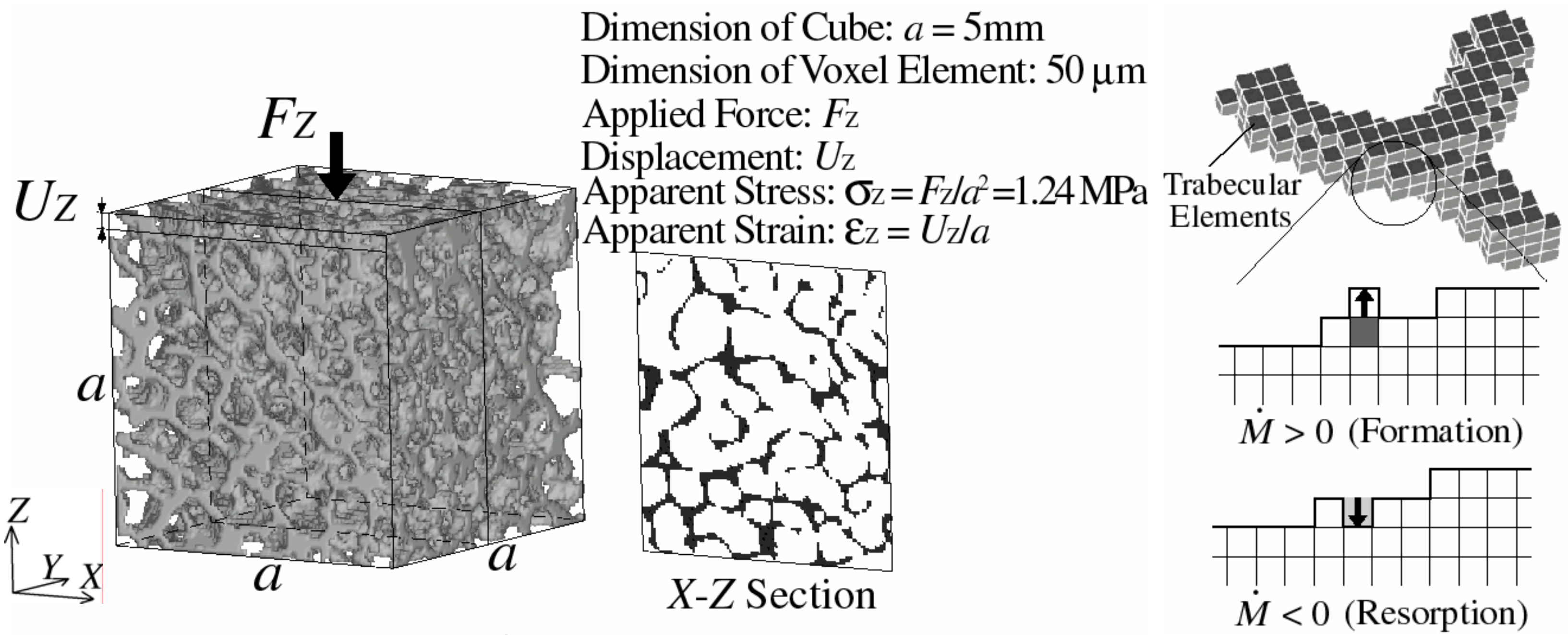
- Microstructural FE Model for Remodeling Simulation

Trabecular-Level

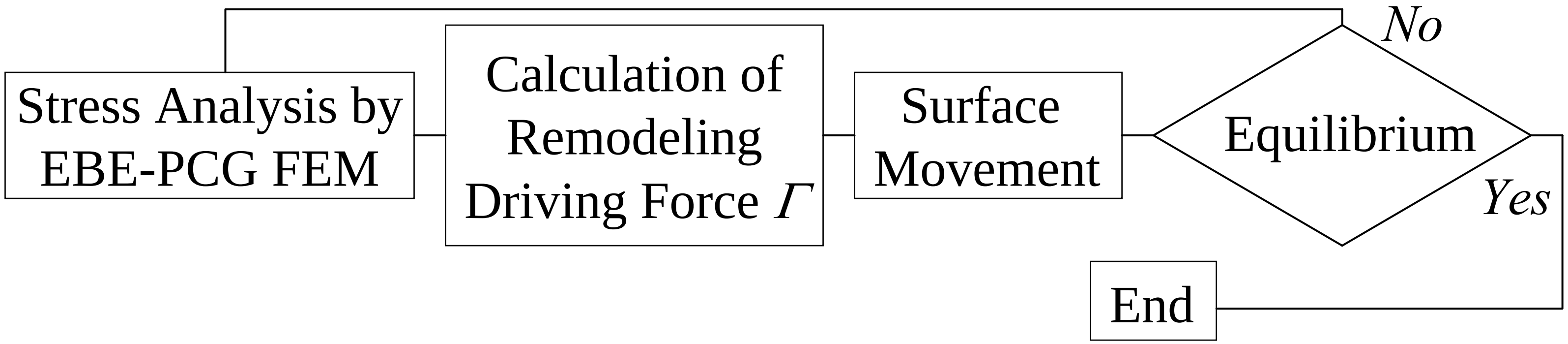
Mechanical Stimulus ↔ **Morphological Change**

Simulation Model for Trabecular Surface Remodeling

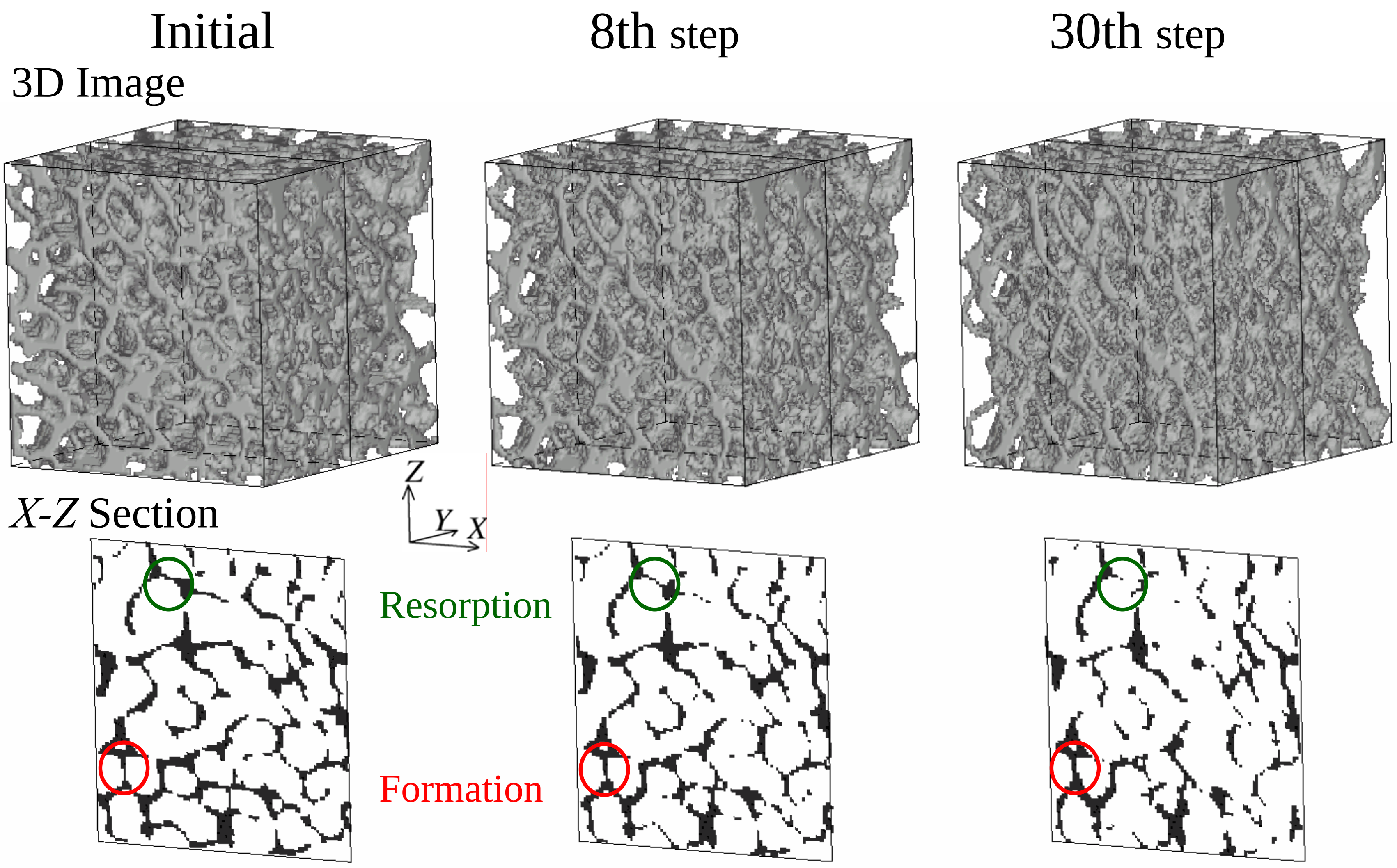
- μCT Image-Based Cancellous Bone Model



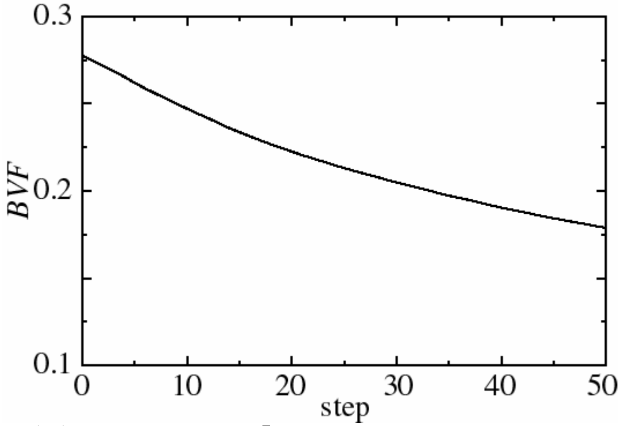
- Iterative Algorithm for Trabecular Bone Remodeling



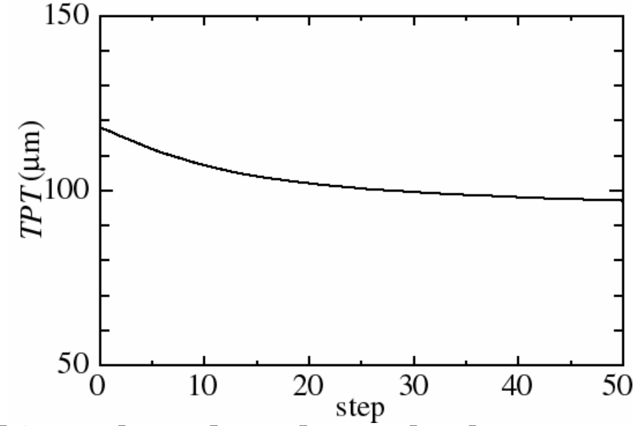
3D Trabecular Remodeling for Cancellous Bone



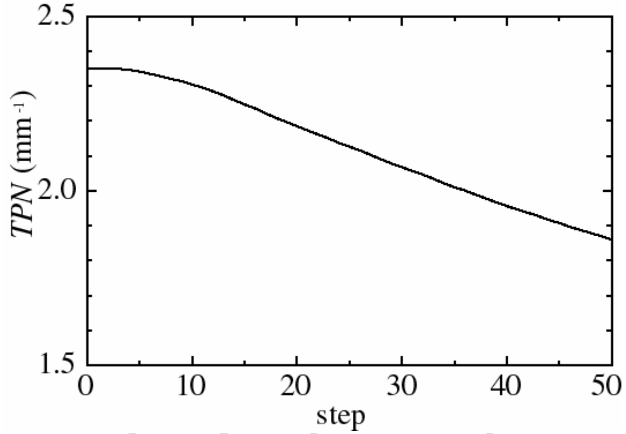
Changes in Structural & Mechanical Parameters



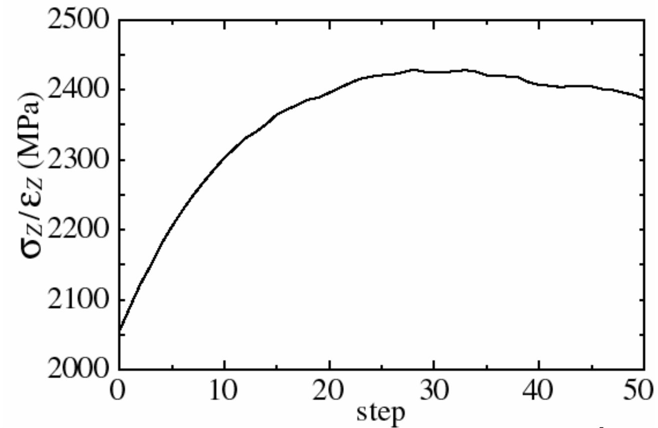
(a) Bone Volume Fraction: ***BVF***



(b) Trabecular Plate Thickness: ***TPT***



(c) Trabecular Plate Number: ***TPN***



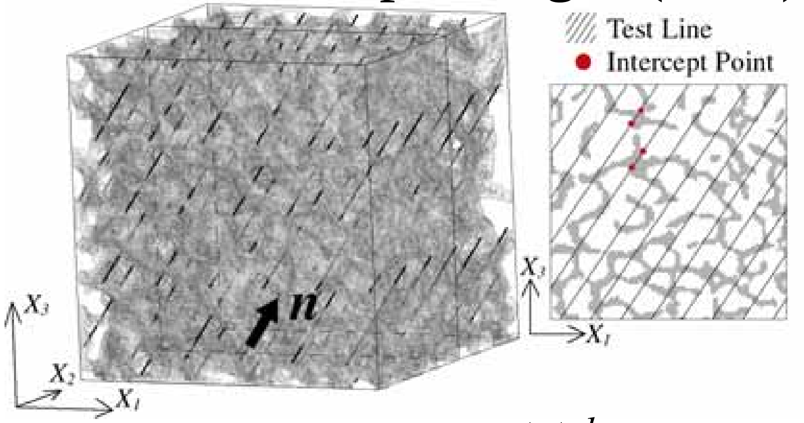
(d) Apparent Stiffness: $\boldsymbol{\sigma_z/\varepsilon_z}$

Volume Fraction: ***BVF*** ↘
Apparent Stiffness: $\boldsymbol{\sigma_z/\varepsilon_z}$ ↗

} Functional Adaptation

Structural Properties: Fabric Tensor (Cowin, 1986)

- Mean Intercept Length (MIL)



$$MIL : L(\boldsymbol{n}) = L^{total} / n$$

n: Number of Intercept Point,
L^{total}: Total Length of Test Line

- MIL Tensor $\boldsymbol{M}$

$$\frac{1}{L(\boldsymbol{n})} = M_{11}n_1^2 + M_{22}n_2^2 + M_{33}n_3^2 + 2(M_{12}n_1n_2 + M_{13}n_1n_3 + M_{23}n_2n_3$$

$$*\boldsymbol{n} = [n_1\ n_2\ n_3$$

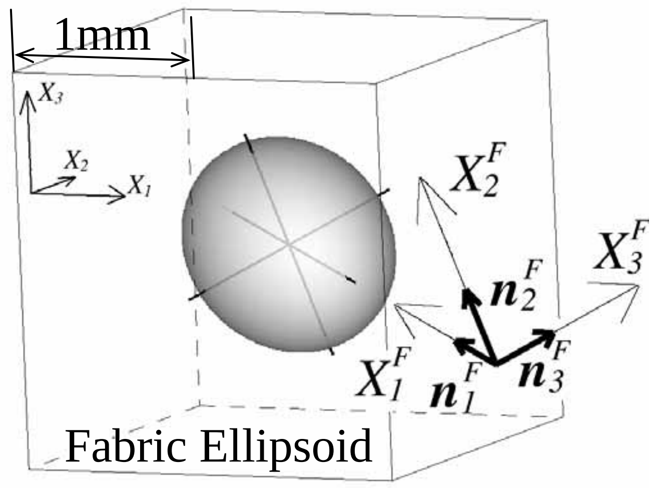
$$\boldsymbol{M} = \begin{bmatrix} M_{11} & M_{12} & M_{13} \\ M_{12} & M_{22} & M_{23} \\ M_{13} & M_{23} & M_{33} \end{bmatrix}$$

- Fabric Tensor $\boldsymbol{H}$

$$\boldsymbol{H} = \boldsymbol{M}^{-1/2}$$

Principal Value : $H_i \ (H_1 > H_2 > H_3)$
Principal Direction : $\boldsymbol{n}_i^F$

➡ Structural Anisotropy



Fabric Ellipsoid

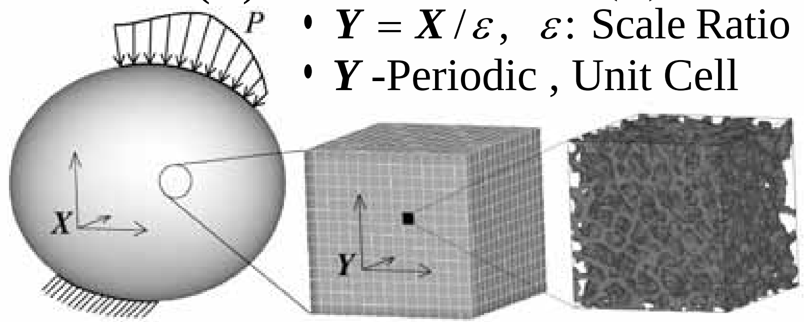
Mechanical Properties: Effective Stiffness Tensor

(van Rietbergen *et al.*, 1996)

- Homogenization Theory (Hollister & Kikuchi, 1992)

Macro($\boldsymbol{X}$) —— Micro($\boldsymbol{Y}$)

- $\boldsymbol{Y} = \boldsymbol{X}/\varepsilon$, ε: Scale Ratio
- $\boldsymbol{Y}$ -Periodic , Unit Cell



Effective Stiffness Tensor $\overline{\boldsymbol{C}}$

$$\overline{C}_{ijkl} = \frac{1}{V}\int_V C_{ijpm} L_{pmkl}\, dV,$$

$$L_{ijkl} = \frac{1}{2}(\delta_{ik}\delta_{jl} + \delta_{il}\delta_{jk}) - \varepsilon^{*kl}_{ij}$$

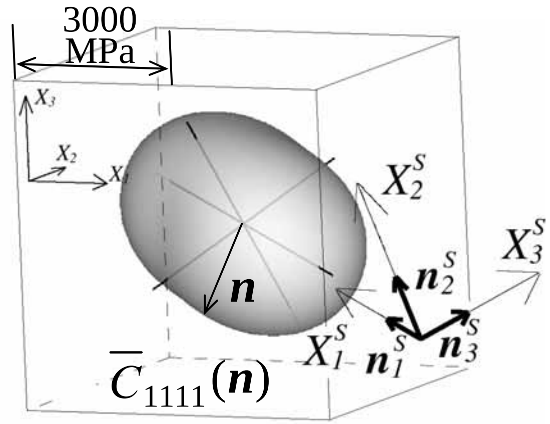
$$\int_V C_{ijpm}\varepsilon_{ij}(\boldsymbol{v})\varepsilon^{*kl}_{pm}(\boldsymbol{u})dV = \int_V \varepsilon_{ij}(\boldsymbol{v})\sigma^{*kl}_{ij}(\boldsymbol{u})dV$$

- Orthotropic Approximation

$$\overline{\boldsymbol{C}} = \begin{bmatrix} 2410.1 & 755.2 & 675.5 & 43.2 & -103.0 & -339.2 \\ 755.2 & 2123.0 & 697.2 & 35.3 & 16.7 & -289.2 \\ 675.5 & 697.2 & 1868.0 & -19.2 & -87.7 & 6.1 \\ 43.2 & 35.3 & -19.2 & 705.0 & -95.0 & -26.7 \\ -103.0 & 16.7 & -87.7 & -95.0 & 707.6 & 8.4 \\ -339.2 & -289.2 & 6.1 & -26.7 & 8.4 & 799.9 \end{bmatrix}$$

$$\boldsymbol{R} = \begin{bmatrix} 0.59 & 0.64 & 0.50 \\ -0.78 & 0.61 & 0.14 \\ -0.21 & 0.47 & 0.86 \end{bmatrix} \qquad \overline{C}^{ORT}_{ijkl} = R_{ip}R_{jq}R_{kr}R_{ls}\overline{C}_{pqrs}$$

$$\overline{\boldsymbol{C}}^{ORT} = \begin{bmatrix} 2988.1 & 666.6 & 715.9 & -5.9 & -19.5 & 0.1 \\ 666.6 & 1959.9 & 606.4 & 6.5 & -6.3 & -5.5 \\ 715.9 & 606.4 & 1730.9 & 29.8 & 39.1 & 10.4 \\ -5.9 & 6.5 & 29.8 & 524.3 & 3.4 & -5.5 \\ -19.5 & -6.3 & 39.1 & 3.4 & 732.6 & -0.7 \\ 0.1 & -5.5 & 10.4 & -5.5 & -0.7 & 816.7 \end{bmatrix}$$



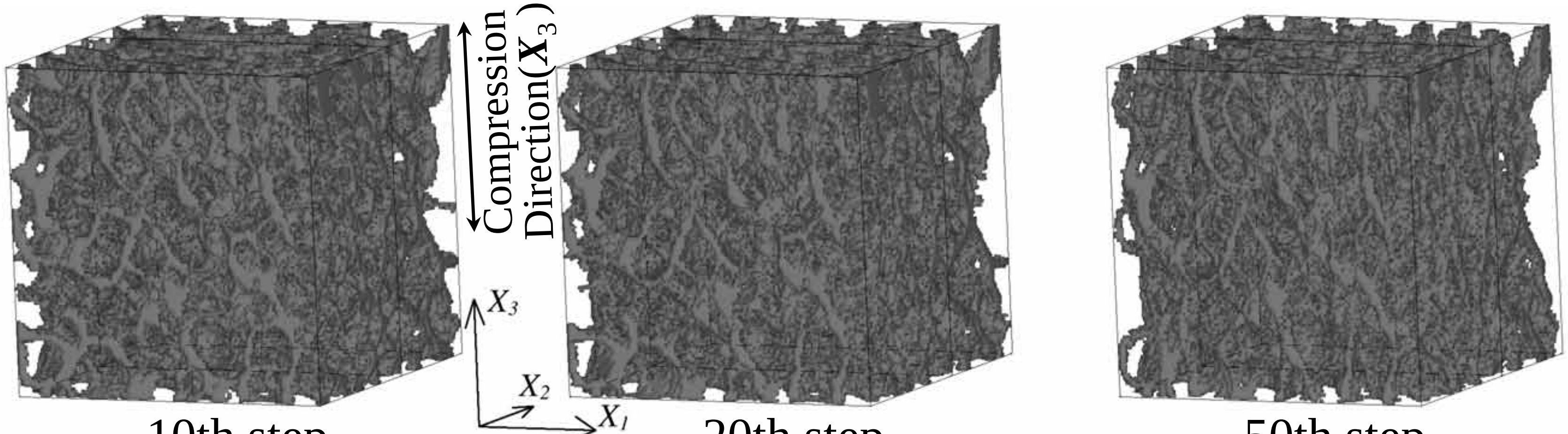
Coefficient: $\overline{C}^{ORT}_{iiii}$ $\left(\overline{C}^{ORT}_{1111} > \overline{C}^{ORT}_{2222} > \overline{C}^{ORT}_{3333}\right.$, i : not summed$\left.\right)$

Principal Direction : $\boldsymbol{n}^S_i$

➡ Mechanical Anisotropy

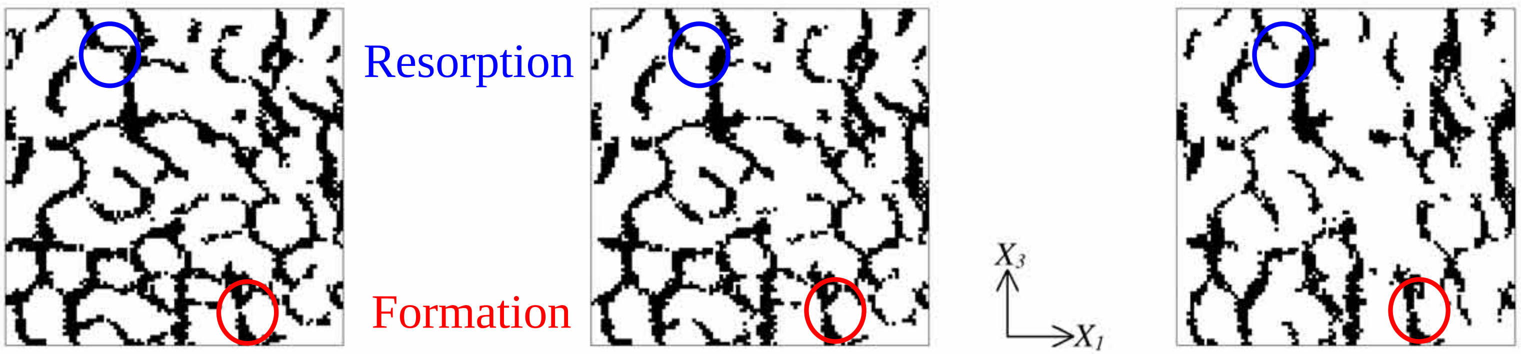
3D Trabecular Remodeling for Cancellous Bone

- 3D Image



10th step 20th step 50th step

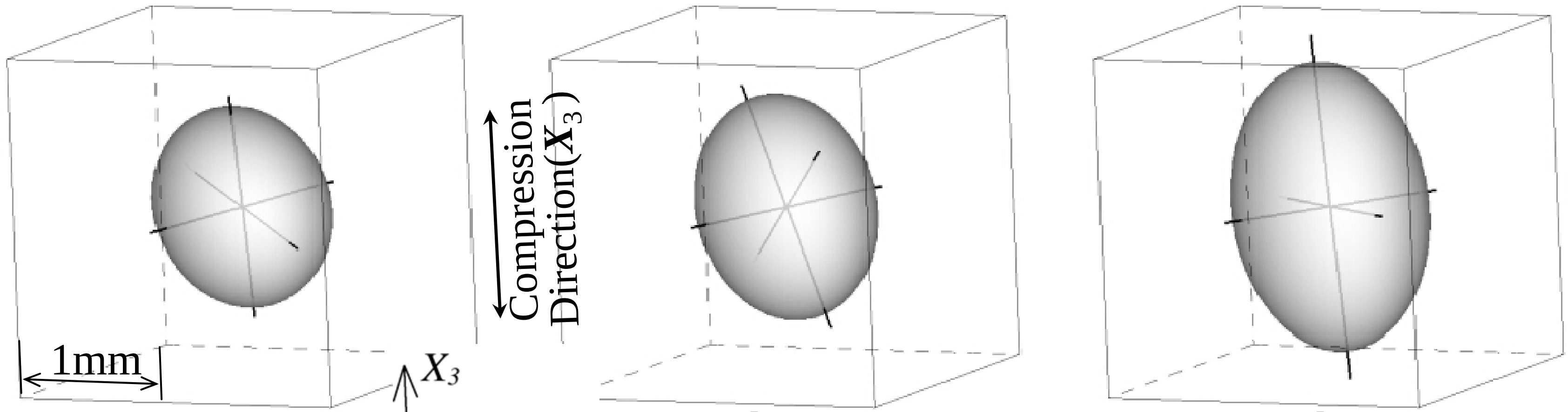
- X_1 -X_3 Section



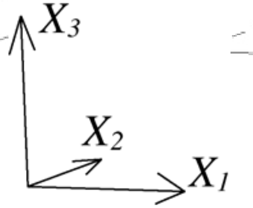
10th step 20th step 50th step

Changes of Structural & Mechanical Properties (1)

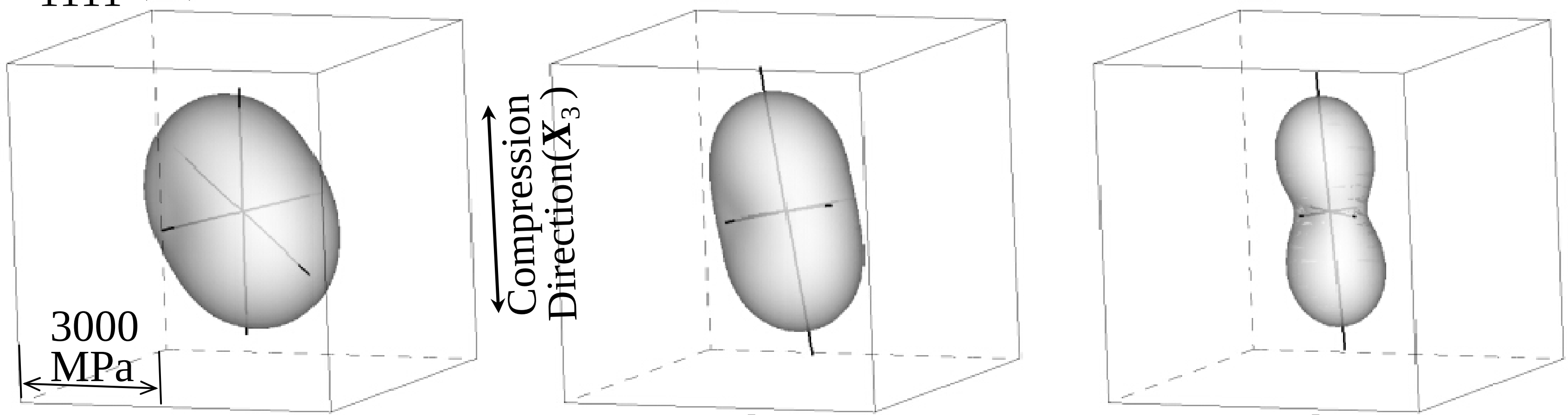
- Fabric Ellipsoid



10th step 20th step 50th step



- $\overline{C}_{1111}(\boldsymbol{n})$



10th step 20th step 50th step

本手法の利点と課題

- **利点**

(1) 規則メッシュ, EBE-PCG法を用いた大規模計算
(van Rietbergen *et al*. 1995)

(2) μCTで骨形態を評価する実験(Guldberg *et al*.1997)**との直接比較**

(3) シミュレーションモデルの構築が容易

- **課題**

(1) より細かい要素分割 ⟶ 計算手法の改良, 新たな開発

(2) 実験との比較による妥当性の確認

おわりに

まとめ

- Voxel Micro FE を用いた三次元再構築シミュレーション
- 外荷重に対する骨梁形態の機能的適応性
- 骨梁微視構造レベルにおける再構築現象を直接表現

今後の展望

- 整形外科領域におけるインプラントの設計
  - ⟶ 骨-インプラント界面の再構築現象の評価
- 骨代替物の設計
  - ⟶ 生体組織工学への応用