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The Importance of Geometric Nonlinearity in Finite Element Studies of Yielding in Trabecular Bone

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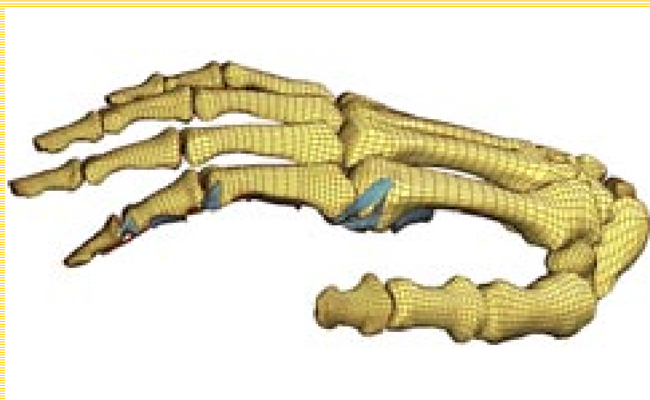
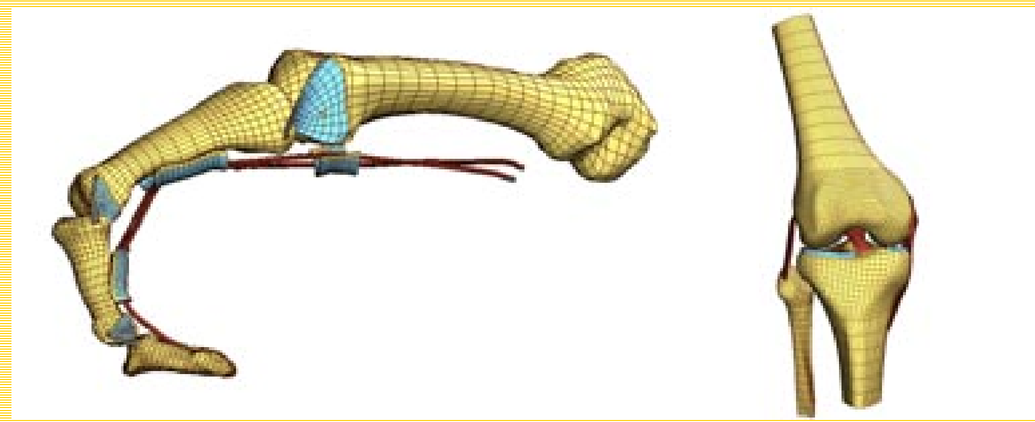
Background: Skeletal Finite Element (FE) Modeling





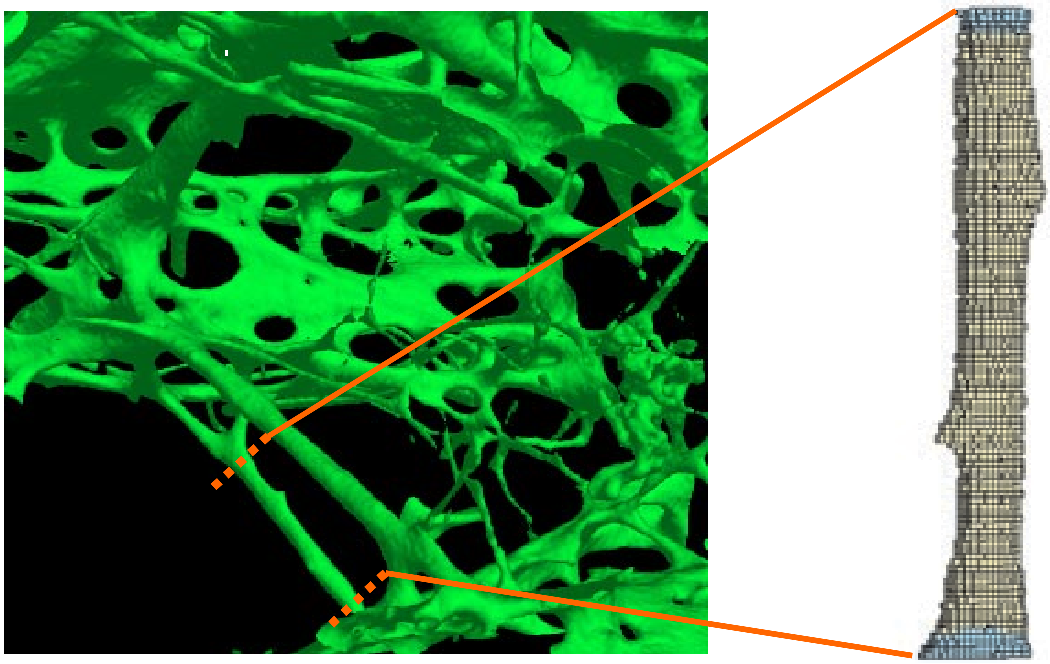
Scott Perfect (LLNL)

- Bone and connective tissues are given homogenized constitutive properties / nonlinear kinematics
- Useful for estimating loading patterns on long bones and joints
- Provide little predictive insight into how age or osteoporosis affect bone strength

Nonlinear Kinematics are Essential!

Background: Trabecular Bone FE Modeling

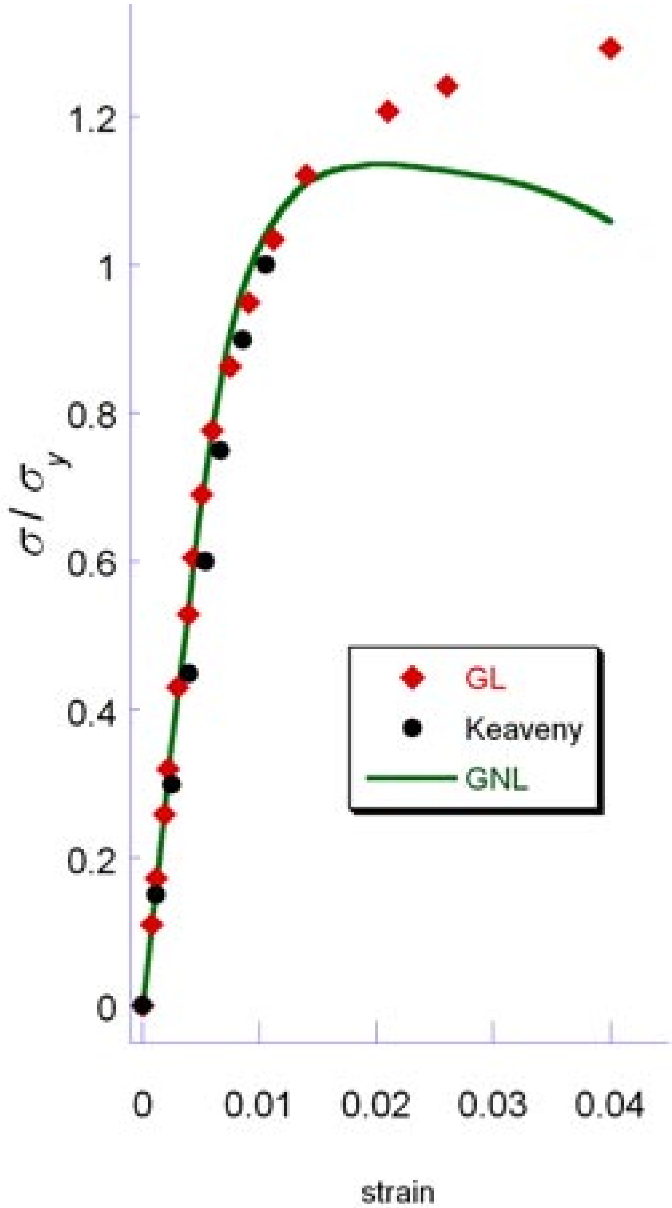
- Trabecular architectures are discretized: image voxels used as template for finite-element mesh
- Requires large number of elements – computationally intensive: typically assumes linear kinematics!
- Provides insights into how changes in trabecular architecture affect mechanical properties of the whole bone



Importance of Nonlinear Kinematics is Unclear!

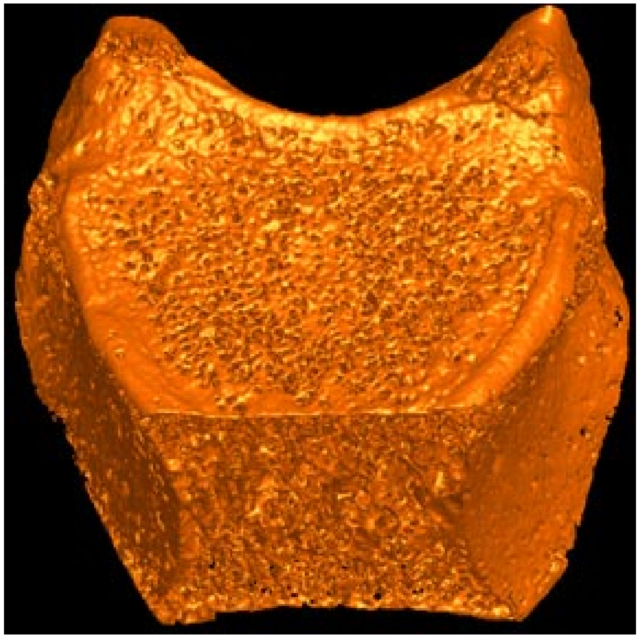
Hypothesis: Geometric Nonlinearity (GNL) can be Ignored for Simulation of Yield

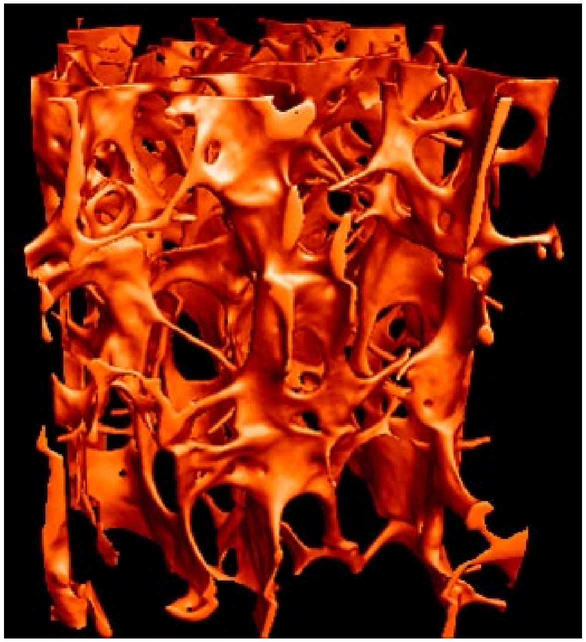
- Previous study demonstrated that nonlinear kinematics (GNL) was required to simulate post-yield behavior of trabecular bone *Bone,33:494-504(2004)*.
- Simplified analysis suggests that deformations up to yield could be simulated accurately with linear kinematic approximation.
- Hypothesis: GNL can be ignored for small deformations up to 0.2% apparent offset yield strain.



Methods: Imaging

- L1 vertebra from 63yr male imaged with 12μm voxels
- 4mm cube extracted from the centrum
- Cube meshed with 40μm elements





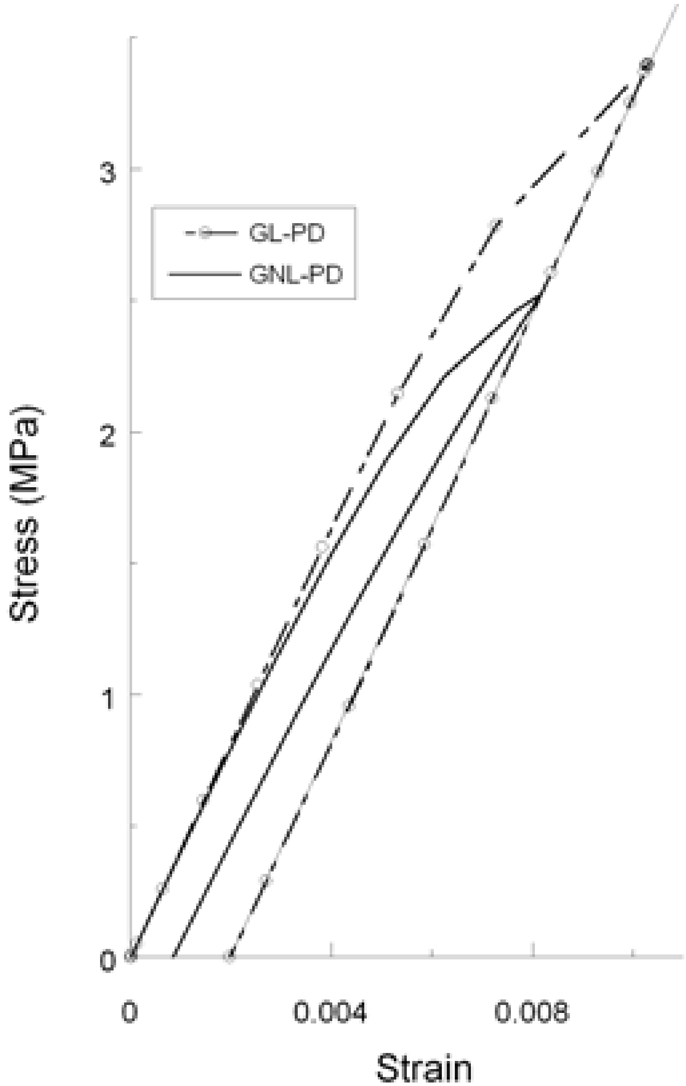
TBV ~ 6%

Low bone volume specimen chosen as a limiting case

Methods: Finite-Element Simulation

- Parallel Solver – NIKE3D Simulations
- Element Size: 40μm
- Element Type: 8-node "bricks" using 8-integration points/element
- Constitutive Model: Elastic-Perfectly Plastic
  - J_2 plasticity model, Yield stress 188.9MPa
  - Isotropic Young's modulus (18.7 GPa), Poisson's ratio 0.3
- Loading: Constant Platen Displacement Rate
  - Initial strain rate of $1 \times 10^{-4}\ s^{-1}$
  - Dynamic Calculation: inertial effects included to remove stiffness matrix singularity coincident with structural instability
- Mirror Boundary Conditions:
  - Nodes on cube surfaces are constrained to move with their respective planes
  - Upper cube surface is displaced downward at constant rate

Results: GNL is Important, Even at Low Strains!

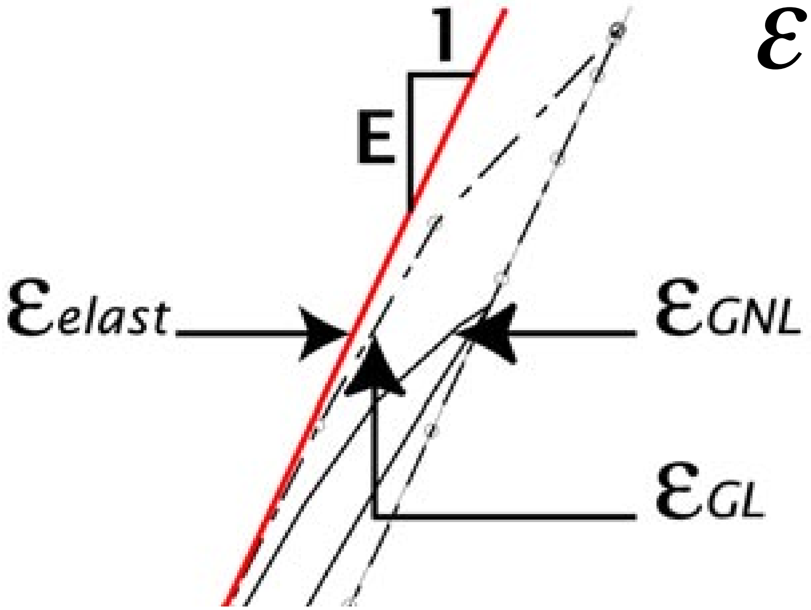


- Linear kinematics attributes all nonlinear behavior to material response (yield)
- Significant elastic energy is stored in finite elastic deformations
- Linear kinematics overestimates the amount of damage caused by loading
- At low bone volumes (< 6%), inclusion of geometric nonlinearities is required, even for small deformations

Inclusion of GNL alters apparent plastic strain by 60%!

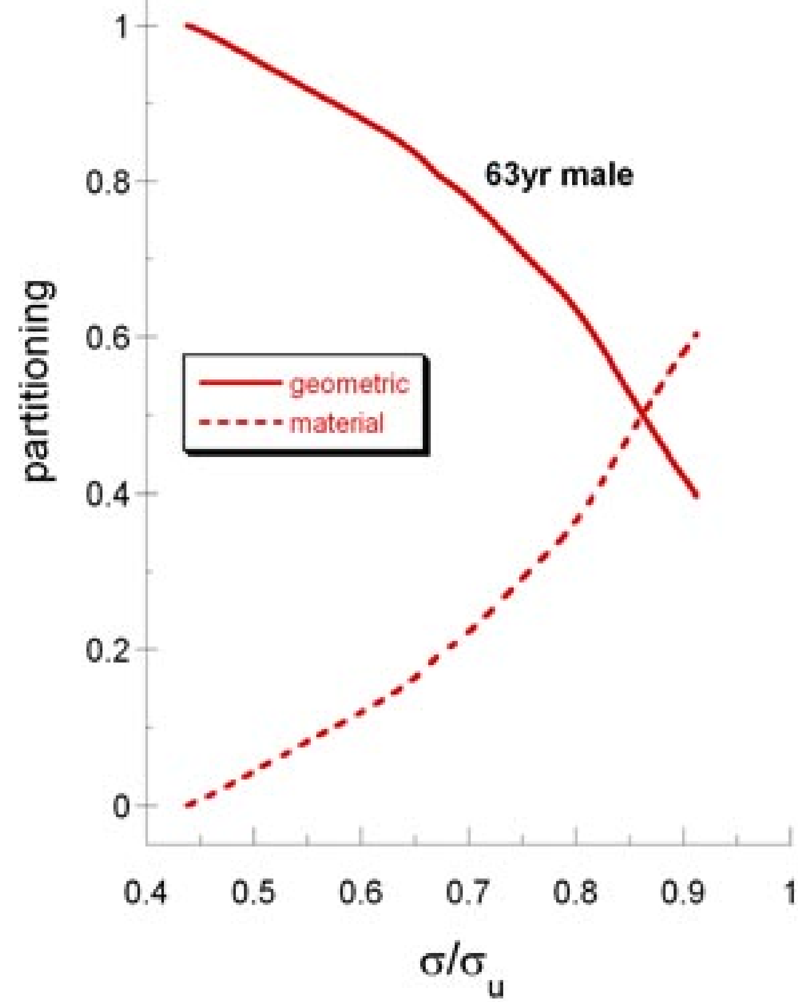
Conclusions: Non-Linear Strain Partitioning

$$\varepsilon_{tot} = \varepsilon_{elast} + \varepsilon_{mat} + \varepsilon_{GNL}$$



$$Mat = \frac{\varepsilon_{GL} - \varepsilon_{elast}}{\varepsilon_{GNL} - \varepsilon_{elast}}$$

$$Geo = \frac{\varepsilon_{GNL} - \varepsilon_{GL}}{\varepsilon_{GNL} - \varepsilon_{elast}}$$



GNL affect strain distribution at low stress!

Summary and Future Work

- Inclusion of finite deformation effects (finite displacements and rotations) is central to skeletal finite element modeling
- The influence of geometric nonlinearity (GNL) due to finite deformations in trabecular bone has only been recently investigated
- In finite element models of trabecular bone of low bone volume (osteopenic) , inclusion of GNL effects result in:
  - the presence of a “peak” in the apparent stress-strain curve at ultimate load and gradual unloading of the post-yield response
  - large differences in the apparent plastic strain at 0.02% offset
- As compared to GNL calculation, GL calculations tend to overestimate the level of damage at low bone volumes
- Deviations in unloading path suggest that large difference in residual stress state are predicted by GNL and GL models

Future Work: what is the influence of bone mass and architecture?