Finite Element Analysis of Human Bone Models

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Outline

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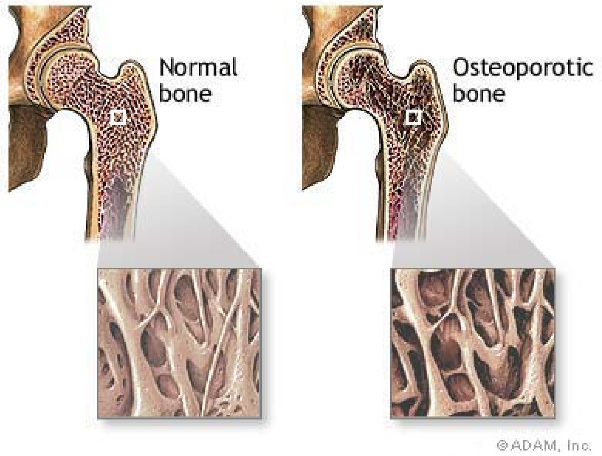
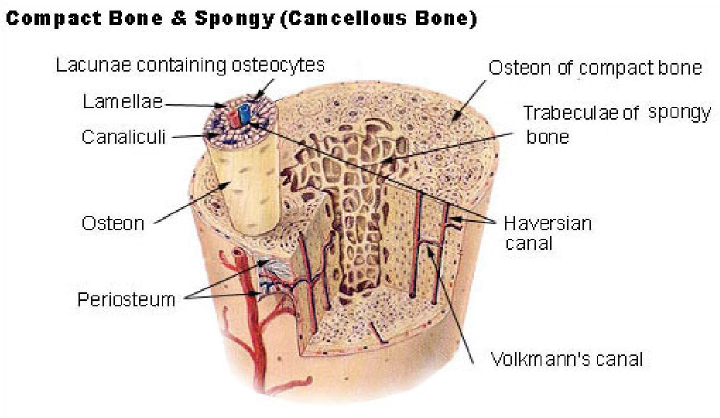
Why study bones?

- Osteoporosis: 44M Americans, $17B / year
- > 55% of over 50 have osteoporosis or low bone mass
- 350K hip fractures / year; over $10B / year
- A quarter of hip fracture patients die within a year
- ... and we're getting older

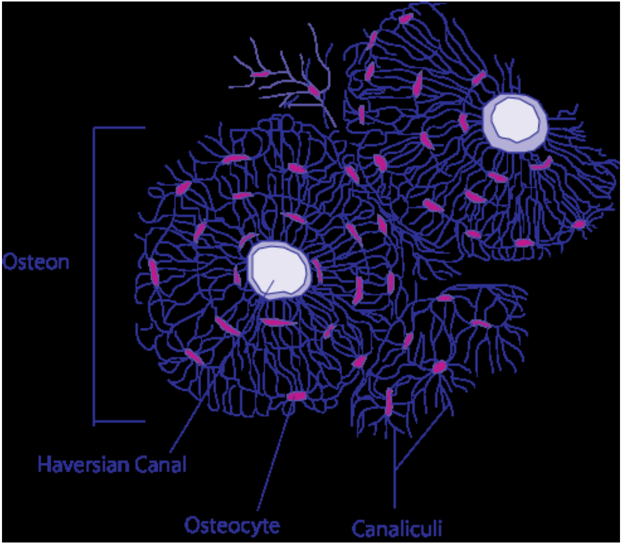
Bone basics: macrostructure



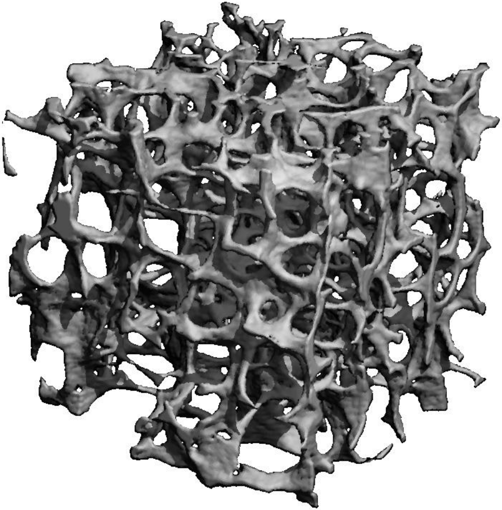
Bone basics: microstructure



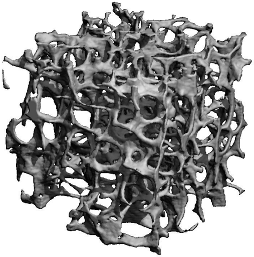
Bone basics: microstructure

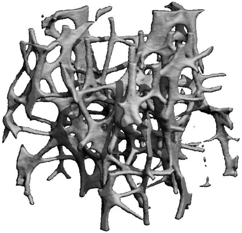


Bone basics: trabecular microstructure



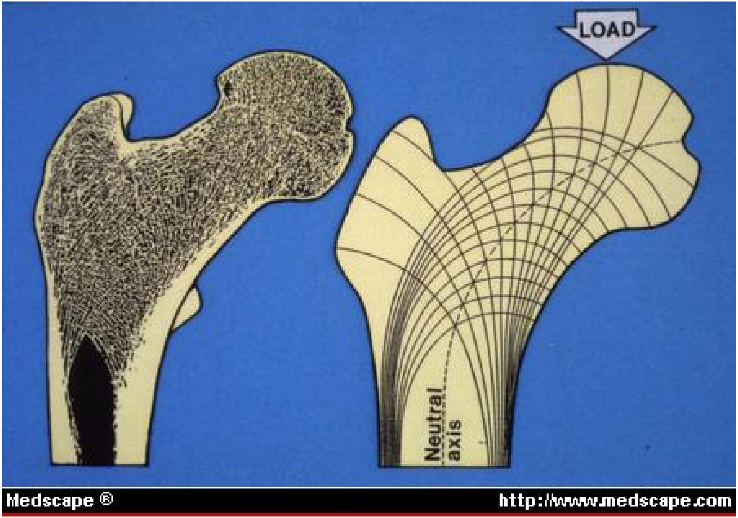
Bone basics: trabecular microstructure





(Scans from 23 and 85 year old females)

Bone basics: orientation and remodeling



Why study bones?

... because bone is a fascinating material!

- Structurally complicated across length scales
- Structure adapts to loads and changes over time
- inhomogeneous, anisotropic, asymmetric, often nonlinear

Outline

1 Bone basics

2 Bone measurement and modeling

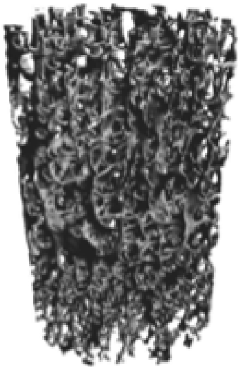
3 BoneFEA software

4 Conclusion

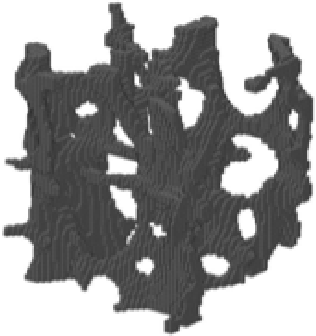
Bone measurement

- Diagnostic for osteoporosis: T-scores from DXA
- Ordinary microscopy on extracted cores
- QCT software: density profile, about 3 mm scale
- Micro-CT and micro-MRI: O(10 micron)

Micro-FE bone modeling



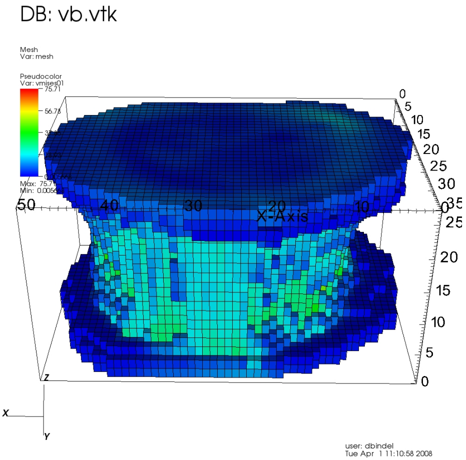
micro-CT @ 22 mm resolution
ϕ8.8 mm H:15 mm



micro-FE mesh
2.5 x 2.5 x 2.5 mm^3
44 μm hexahedral elements

One vertebrate = 57M+ elements at 40 microns

Whole bone modeling



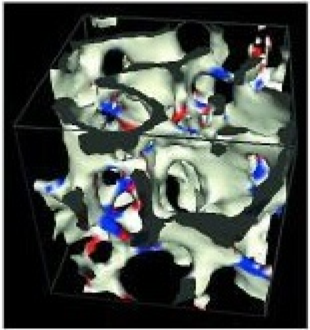
- Density only weakly predicts strength
- Wanted: Good effective constitutive relation

Difficulties

Bone is:

- Variable over time and between individuals
- Inhomogeneous and anisotropic
- Different in tension and compression

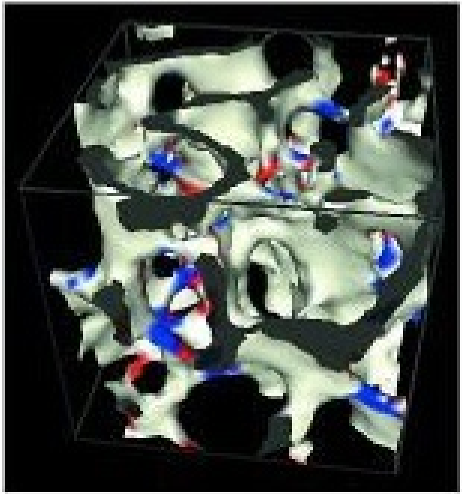
Yielding and nonlinearity



Example difficulty:

- Trabecular network has beam and plate elements
- Small macro strains yield much larger micro strains
- Small-scale geometric nonlinearity a significant effect

Yielding and nonlinearity



An approach

- Micro-CT structure scans for orientation
- Use orientation indices + density to approximate material parameters
- Proceed phenomenologically

Outline

Diagnostic toolchain

- Micro-CT scan data from patient
- Inference of material properties
- Construction of coarse FE model (voxels)
- Simulation under loading
- Output of stress fields, displacements, etc.

BoneFEA

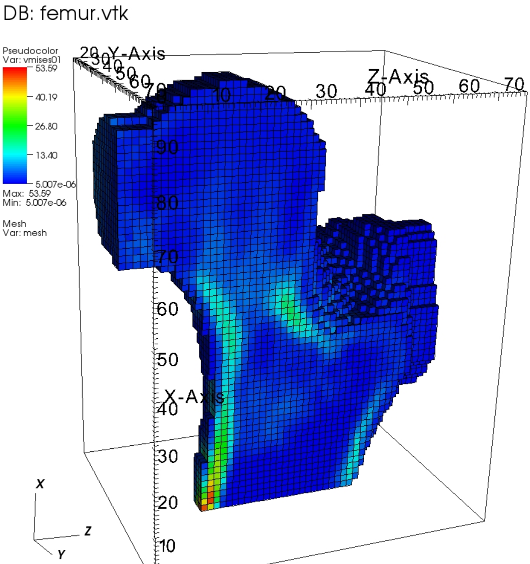
- Standard displacement-based finite element code
- Elastic and plastic material models (including anisotropy and asymmetric yield surfaces)
- High-level: incremental load control loop, Newton-Krylov solvers with line search for nonlinear systems
- Library of (fairly simple) preconditioners; default is a two-level geometric multigrid preconditioner

Example analysis loop

```
mesh:rigid(mesh:numnp()-1, {z='min'},
  function()
    return 'uuuuuu', 0, 0, bound_disp
  end)

pc = simple_msm_pc(mesh,20)
mesh:set_cg{M=pc, tol=1e-6, max_iter=1000}
for j=1,n do
  bound_disp = 0.2*j
  mesh:step()
  mesh:newton{max_iter=6, Rtol=1e-4}
end
```

Example analyses



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Conclusion

- Bones are interesting as well as important!
- Initial BoneFEA work done, in use by ON Diagnostics
- Possible follow-up work for diagnostic tool
- Plenty of interesting research directions