Finite Element Analysis of Human Bone Models

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Outline

1. Bone basics
2. Bone measurement and modeling
3. BoneFEA software
4. Conclusion
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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

Compact Bone & Spongy (Cancellous Bone)

- Lacunae containing osteocytes
- Lamellae
- Canaliculi
- Osteon
- Periosteum
- Osteon of compact bone
- Trabeculae of spongy bone
- Haversian canal
- Volkmann's canal
Bone basics: microstructure

- Osteon
- Haversian Canal
- Osteocyte
- Canaliculi
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
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

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
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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

```plaintext
mesh:rigid(mesh:numnp()-1, {z='min'},
    function()
    return 'uuuuuuu', 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