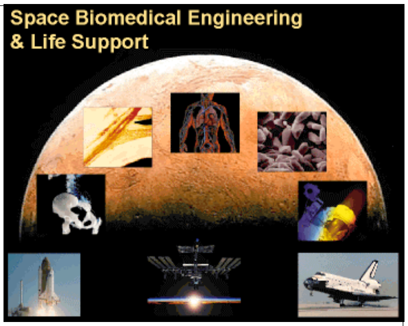
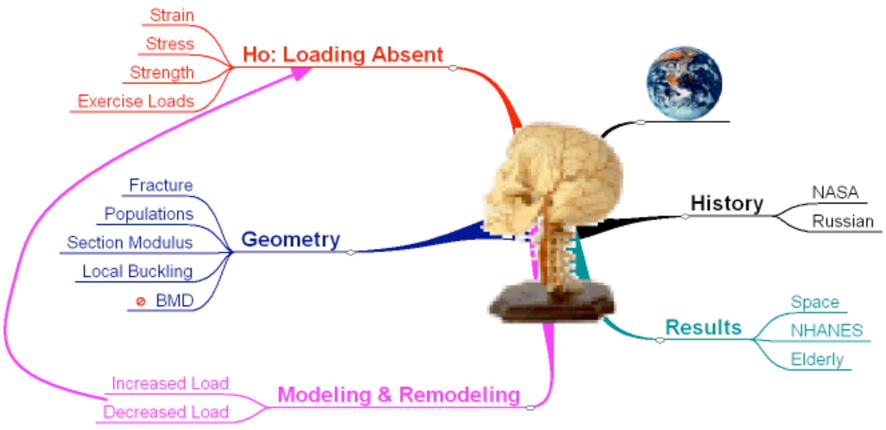
Space Biomedical Engineering
& Life Support



Skeletal Consequences of Spaceflight

Prof. Dava Newman
February, 2006

Bone - Summary



Ho: Loading Absent
- Strain
- Stress
- Strength
- Exercise Loads

Geometry
- Fracture
- Populations
- Section Modulus
- Local Buckling
- ⊘ BMD

Modeling & Remodeling
- Increased Load
- Decreased Load

History
- NASA
- Russian

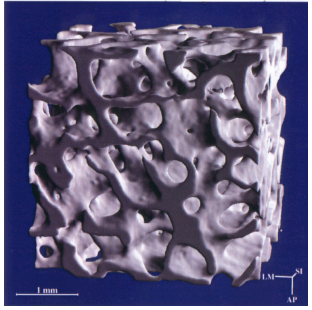
Results
- Space
- NHANES
- Elderly

Physiological Challenges

Astronauts suffer from physiological deconditioning

- 20–30% muscle atrophy
- 10–40% muscle strength loss
- 1–2% bone density loss/month, data from over 20 cosmonauts
- What's the relation to aging?

Male (37 years)



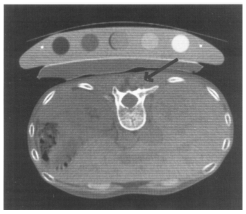
Male (84 years)

Skeletal Consequences of Spaceflight

Background

- Early flights: very little idea of physiological changes to expect
  - big concerns: respiration, cardiovascular
  - bone probably wasn't a serious consideration
- What has been learned in the past 4 decades of human spaceflight?
- DXA

QCT



Spaceflight Bone Loss in Humans

Flight / Study	Finding	References
Gemini 4, 5, and 7	4-14 days; Calcaneus and metacarpal bone density losses of 2-4% for 5 astronauts, and 9% for sixth	Vose, 1974
Soyuz 9	18 days; 8-10% decrease in calcaneus density for both cosmonauts	Birykov and Krasnykh, 1970
Apollo 17	12.6 days; mean Ca loss of 0.2% of total body and mean Phosphorus loss of 0.7% of total body through increased urinary and fecal excretion	Rambaut, et al., 1975
Skylab 2 Mission	No significant bone mineral content changes in arm; calcaneus loss returned to normal by 87th day postfl.	Vogel & Whittle, 1976
Long Term Follow-Up of Skylab Bone Demin.	Statistically significant loss of os calcis mineral in nine Skylab crewmembers, 5 years after flight	Tilton, et al., 1980
Combined U.S. / U.S.S.R. Study of Long Term Flight	QCT of spine; Up to 8 months; No loss in vertebral bodies, but 8% loss in posterior elements (4% loss in volume of attached muscles); exercise countermeasures only partially successful	Oganov, et al., 1990
Mir 366-Day Mission	One cosmonaut averaged 10% loss of trabecular bone from L1, L2, L3; measured by QCT	Grigoriev, et al., 1991
Mir 4.5-6 Month Flights	QDR assessment of BMD; total body mineral losses averaged 0.4%; most marked local loss was in ***femoral neck and greater trochanter -- up to 14%***	Oganov, et al., 1992
Mir 1 and 6 Month Flights	pQCT; noticeable loss of trabecular and cortical bone in tibia after 6 months	Collet, et al., 1997
NASDA Study of 2 NASA Astronauts	42 y.o. female and 32 y.o. male; short flight; negative calcium balance; 3.0% loss of BMD in L2-4	Miyamoto, et al., 1998

Bedrest / Hypokinesia Studies

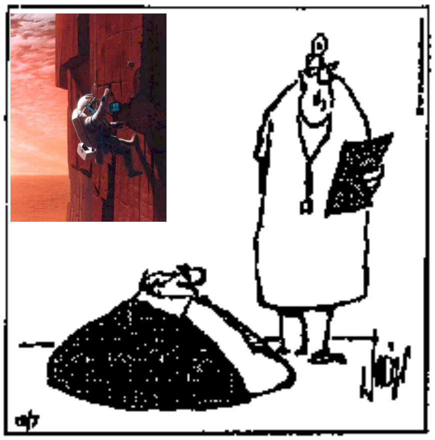
Models for Weightlessness of Spaceflight

Study	Finding	References
5-36 Weeks Bedrest	90 healthy young men; 5% loss of calcaneal minerla each month; mechanical and biochemical countermeasures not successful	Schneider and McDonald, 1984
120-day Bedrest	Mineralization rate slowed; contradictory results demonstrate difficulties of bedrest as space analog	Vico, et al., 1987
17-week Bedrest	6 healthy young males; 6 months of reambulation; ***BMD % change (p < .05): femoral neck (FN) -3.6, trochanter (T) -4.6; % / week (p < .05): FN -.21 +/- .05, T -.27 +/- .05; Reambulation % recovery: FN 0.00 +/- .06, T 0.05 +/- .05 (prox. femur did not recover well)***	LeBlanc, et al., 1990
370-day Antiorthostatic Hypokinesia Test	Highest losses in foot bones; remedial measures delay osteoporosis but do not completely exclude it; results obtained by different methods often conflicting	Zaichick and Morukov, 1998

Spaceflight Bone Loss in Animals

Flight / Study	Finding	References
Cosmos 605	Rats; Bone formation reduced in metaphyses of long bones	Yagodovsky, et al., 1976
Cosmos 782	Rats; 40% reduction in length of primary spongiosa due to reduced formation and increased resorption	Asling, 1978
Cosmos 782?	Rats; Osteoblast differentiation in *non-weight-bearing site* suppressed during weightlessness	Roberts, 1981
Cosmos 936	Rats; 30% decrease in femoral breaking strength of femora with recovery of normal properties after 25d	Spector, et al., 1983
Cosmos 782 & 936	Rats; Arrest line separating bone formed during and post-spaceflight; defective and hypomineralized bone	Turner, et al., 1985
Rat Tail Suspension, 1984	Up to 15 days; Calcium content: tibia = 86.2 +/- 2.5%, vertebra = 75.5 +/- 3.5% of control	Globus, et al., 1984
Cosmos 1514	Primates; 5 days; resorption increased during flight	Cann, et al., 1986
Cosmos 1667, 1887, 2044	Primates; 13 days; lower mineralization rate and less bone mineralized; longitudinal growth slowed	Cann, et al., 1990
Cosmos 1667	Rats; 7d spaceflight vs 7d tail-suspension; loss of trabecular bone in prox tibial metaph more extensive in flight rats	Vico, et al., 1991
Cosmos 2044	Rats; Fracture repair process impaired during flight	Kaplansky, et al., 1991
Cosmos 2229	Primates; 11.5 days; tendency toward decreased BMC during flight; only partial recovey 1 month after	Zerath, et al., 1996
Rat Tail Suspension, 1998	Unloaded bones display reduced osteoblast number, growth, and mineralization rate in trabecular bone	Morey-Holton and Globus, 1998

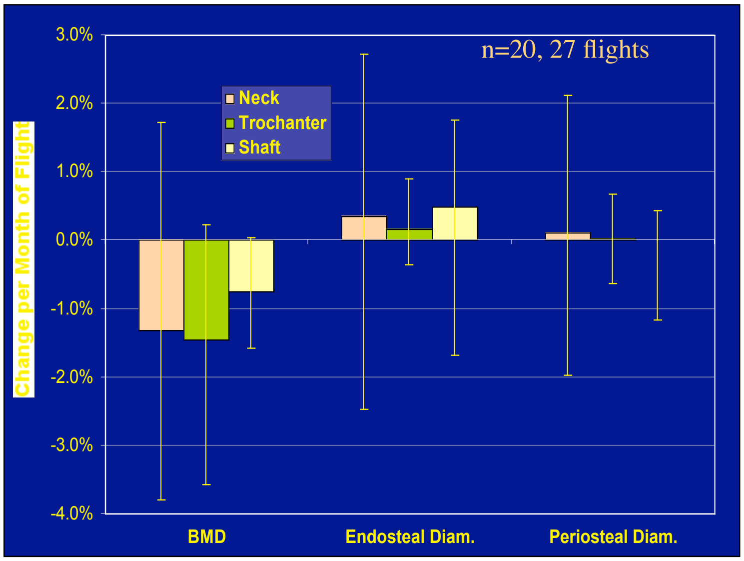
Physiological Deconditioning?

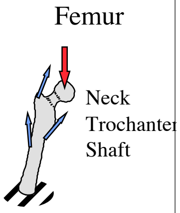


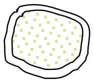
Cardiovascular:CV

"Your CV, neurovestibular, and musculoskeletal systems can't support you anymore."

Motivation: Recent Results







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Source: Beck TJ, Ruff, C, Newman, DJ, Oden, ZM; Nat'l. Space Biomedical Research Institute Bone Team Project

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Institute for Biomedical Problems
"Results of studies of the effects of space flight factors on human physiological systems and psychological status, and between the NSBRI and the IBMP", Section 4. BONE. May 2000.
NSBRI. V.S. Oganov, A. Bakulin, V. Novikov, L. Murashko, O. Kabitskaya.

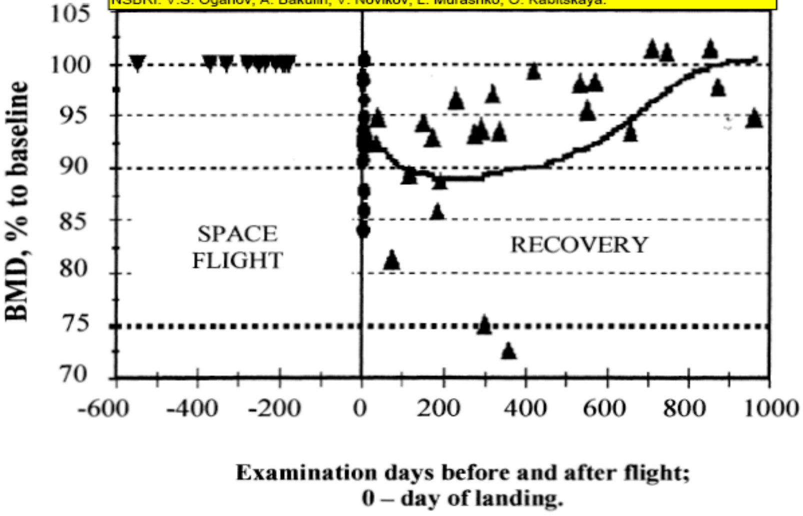

Fig 3.9 The bone loss values and time curve of BMD recovery after space missions lasting 5 to 7 months.

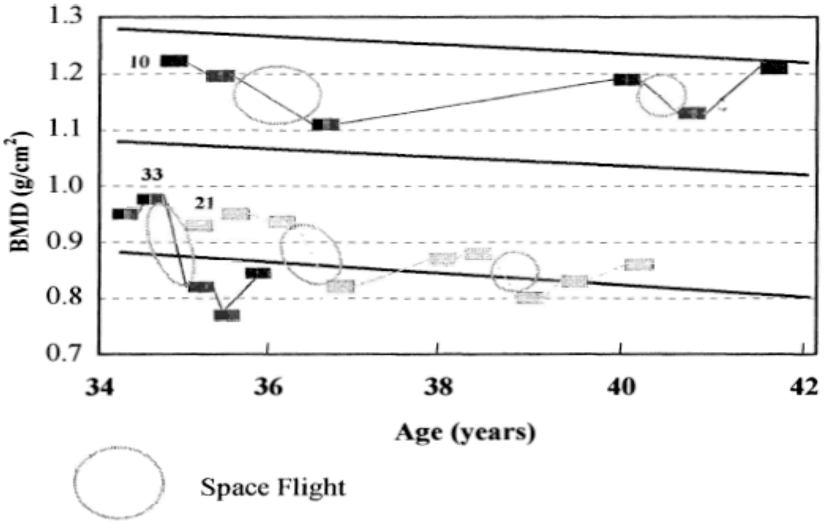

Fig. 4.4 Individual lumbar spine BMD changes after space flight and bone loss recovery.

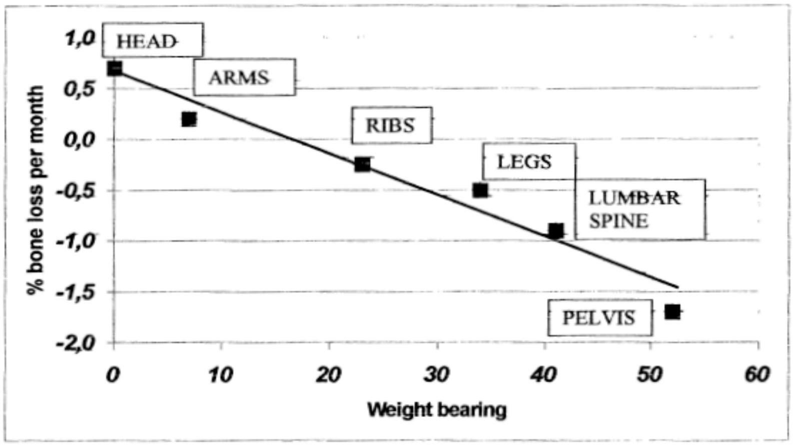

Fig.5.1. Bone mineral density: Correlation between regional bone changes after space flight and weight bearing of the region (DEXA, HOLOGIC QDR-1000/W).

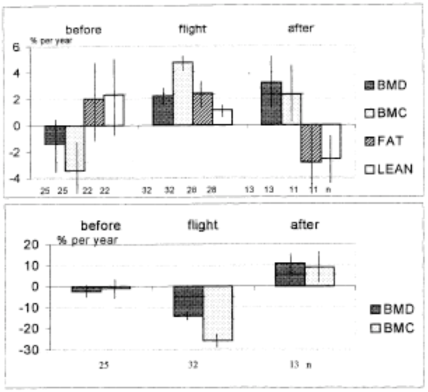

Fig. 3.4. Time curve of the scull/cervical spine (top) and pelvis (bottom) BMD, BMC and tissue composition changes in cosmonauts in space missions lasting 5 to 7 months.

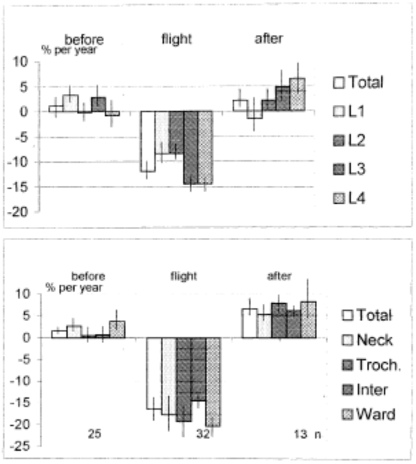

Fig.3.6. Time curve of the lumbar spine and proximal femur BMD changes in cosmonauts in space missions lasting 5 to 7 months.

Summary of Findings

- Significant bone loss in weightlessness
- Calcium excretion increases– negative balance
- Bone mineral density decreases
  - weight bearing areas: 1-2% per month
- Osteoblast (builders) proliferation and activity reduced, while osteoclasts (consumers) appear to be unaffected
- Bone growth is slowed
- Fracture repair may be impaired
- Bone strength is reduced

Significance/Conclusions

- Astronauts (> 1 month) loss of bone strength, increase in fracture risk (Earth, µG, moon, Mars)
  - Walking, running, or falls
  - IVA and EVA in reduced gravity
- Fracture on Mars? Serious consequences:
  - Remoteness
  - Inhibition of repair & immune response
  - Loss of function

Research Questions

- What is the rate of bone loss in critical areas?
- How does this affect bone strength?
- What is the risk of fracture?
  - duration of spaceflight
  - activity, gravity level
  - bone habitus: body weight, etc.
- What countermeasures are possible and how effective are they?

Current Research

Justification

- Focus on critical weight bearing areas and regions of rapid bone loss (related due to remodeling)
  - lumbar spine
  - proximal femur (hip)
- Presently, bone strength estimated from DXA BMD (or BMC) correlation with failure load

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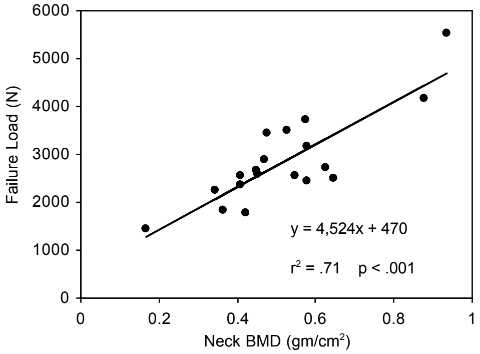
Current Research



- Neglects: specific loading condition, body habitus, bone geometry, 3-D density distribution (DXA is 2-D)
- Does not exploit engineering theory

Other Research Efforts

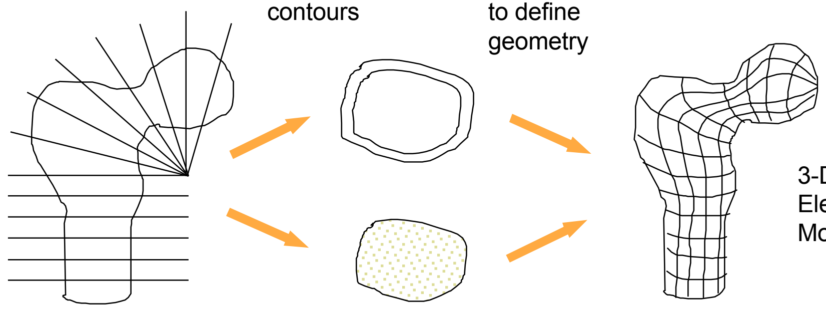
Curved Beam Model from DXA (Beck & Ruff, 1996)

- Use algorithm to get section properties (A, I) from DXA scan
- Develop curved beam model with stress concentration due to curvature
- Apply loads and assess stress on medial and lateral edges to determine failure load
- Limitations: 2-D, beam theory

Finite Element Analysis Approach

Collaboration with Orthopaedic Biomechanics Lab

(Oden & Selvitelli)



QCT scans and NIH Image

Extract contours

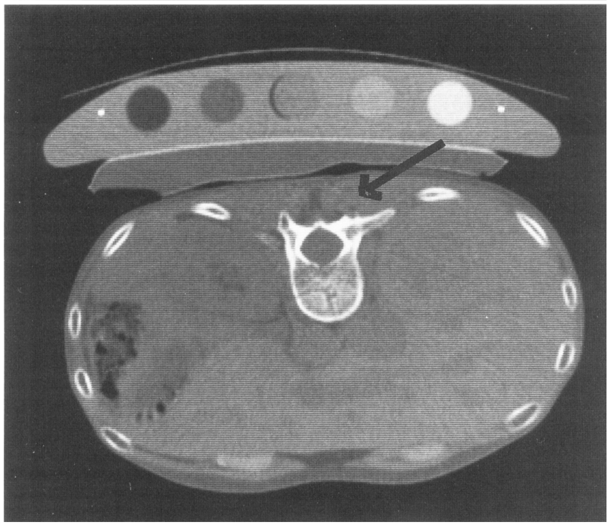
Stack contours to define geometry

3-D Finite Element Model

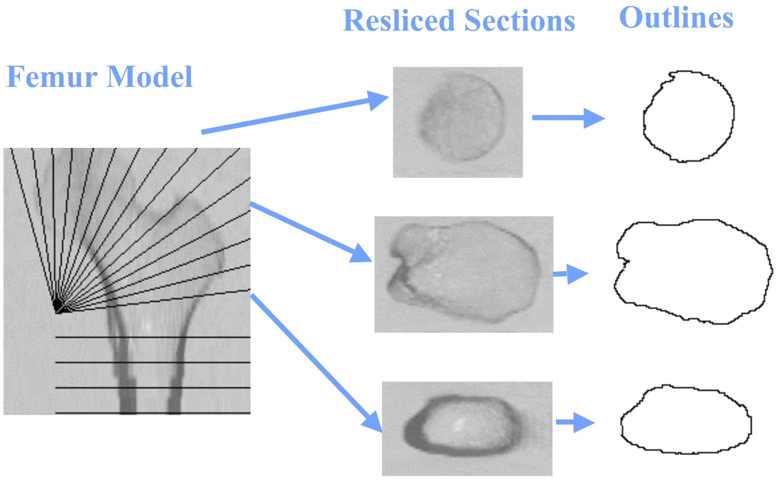
Extract density distribution (trabecular area)

Define element material properties

QCT Slice



Methods: NIH Image



Resliced Sections

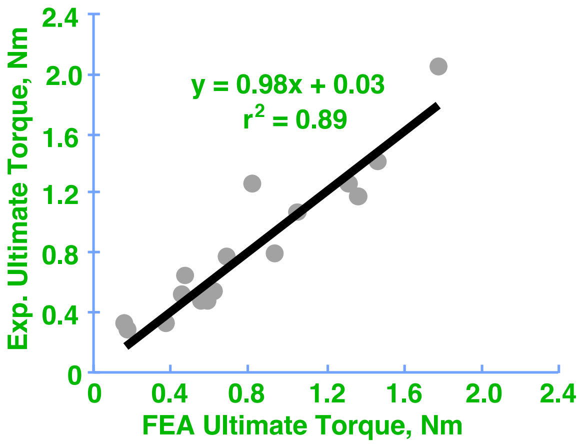
Outlines

Femur Model

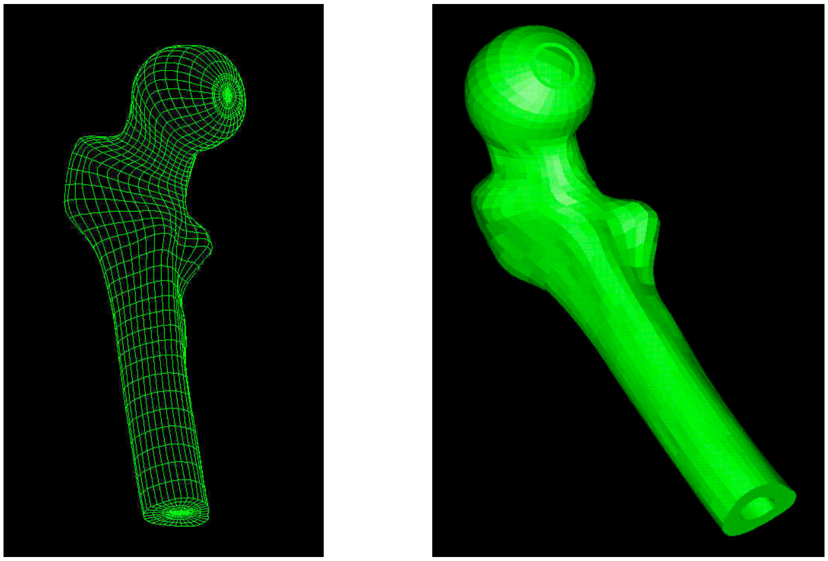
Results: Failure Analysis Validation

Trabecular bone specimens in torsion

Similar results, r^2=0.86 in bending

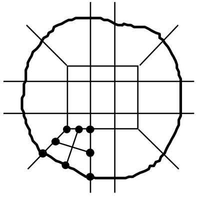


Skeletal Representations

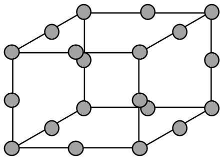


Meshing

- Cut selected contours into subsections to guide meshing so that warped elements are avoided and mesh pattern aligns with density distribution



- Quadrilateral elements with 27 nodes per element



Assign Element Material Properties

- Use empirical modulus relationships to assign values based on density
- Human trabecular and cortical bone assumed to be transversely isotropic – assign elastic constants for each element: E, E’, ν, ν', G, G’. Poisson’s ratio assumed constant ($\nu = \nu' = 0.3$).

Cancellous elements [Ashman et al., 1989]:

$$E = (2.84 \times 10^3)\rho^{1.07}$$

Cortical elements [Snyder and Schneider, 1991]:

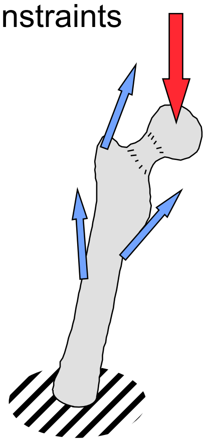
$$E = 21{,}910\rho - 23{,}500$$

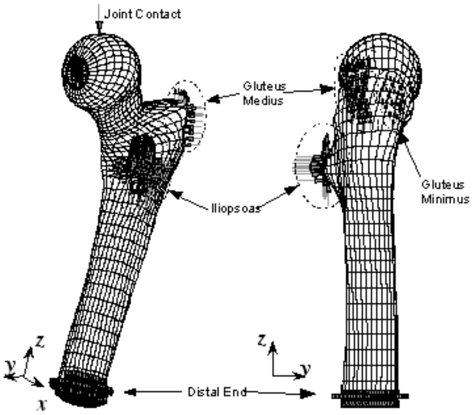
Poisson’s ratio: $\nu = 0.3$ for all elements

Source: Selvitelli, 1997

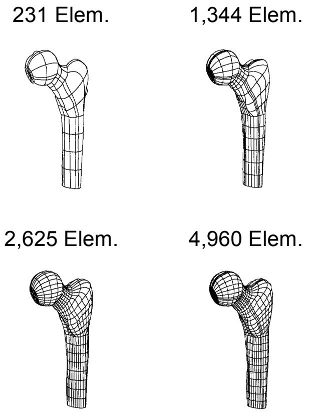
Apply Boundary Conditions

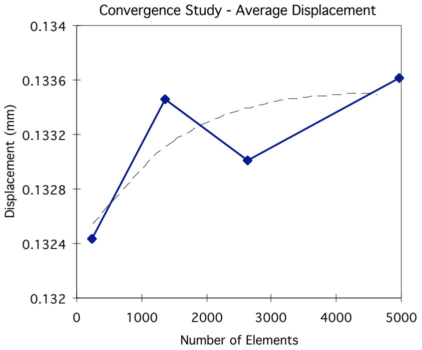
- Loads
  - joint contact
  - muscle forces?
- Constraints





Convergence Study

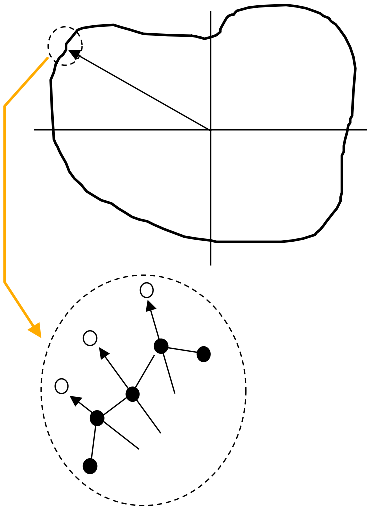




Method of Increasing Endosteal Diameter

For each curve defining endosteal boundary:

- Determine centroid
- Calculate average radius
- Calculate magnitude of point displacement (JHU results)
- Direction of displacement found by bisecting angle defined by adjacent points



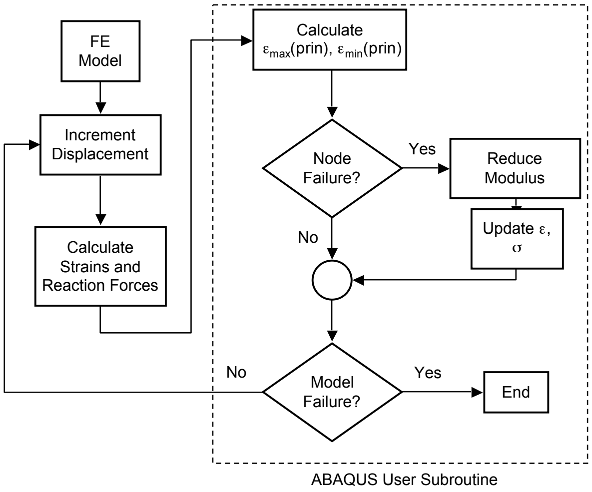
Muscle Strength Loss in Spaceflight

- Start with Earth-normal muscle magnitudes and directions: for mid-stance [Cheal et al.,1992] :

	Mag (BW)	X (med-lat)	Y (post-ant)	Z (dist-prox)
Gluteus medius	0.80	-0.67	0.18	0.72
Gluteus minimus	0.30	-0.78	0.21	0.59
Iliopsoas	1.30	-0.10	0.73	0.68

- Reduce muscle strength with duration of weightlessness:
  - 40% lower at 6 months, 60% lower at 12 months, based on lit.
    - 21% lower peak activated force 17 day flight [Widrick et al., 1999]
    - 120 days of HDT bed rest [Koryak, 1999] :
      - 44% / 33% (M/F) decline in isometric max. voluntary contraction (MVC)
      - 36% / 11% (M/F) decline in isometric twitch contraction (Pt)
      - 34% / 24% (M/F) decline in tetanic contraction force (Po)
    - Maximal explosive power (MEP) reduced to 67% after 31 days, and to 45% after 180 days of space flight [Antonutto et al., 1999]

Failure Analysis Algorithm



FE Model

Increment Displacement

Calculate Strains and Reaction Forces

Calculate ε_{max}(prin), ε_{min}(prin)

Node Failure?

Yes

Reduce Modulus

Update ε, σ

No

Model Failure?

No

Yes

End

ABAQUS User Subroutine

Node Failure:

Maximum Principle Strain
> 0.8% (tension)

Minimum Principle Strain
< -1.1% (compression)

Model Failure:

Reaction Force undergoes two successive decrements with increasing displacement

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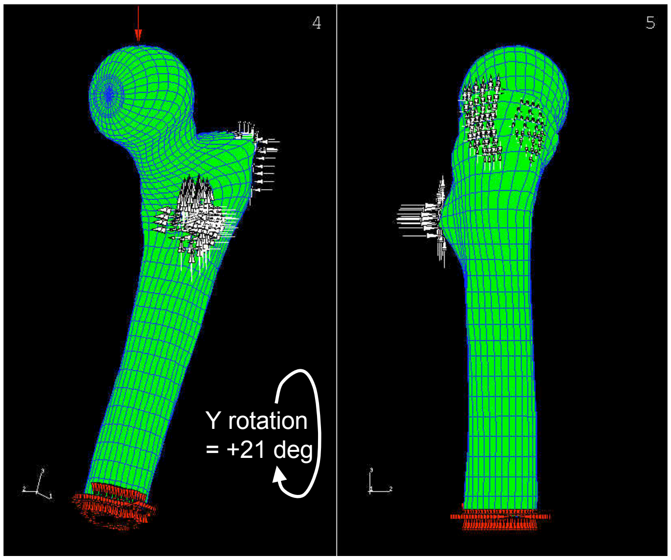
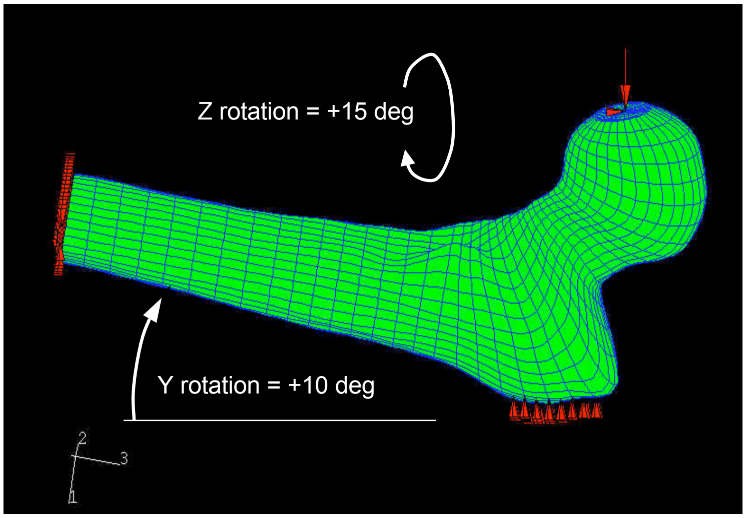
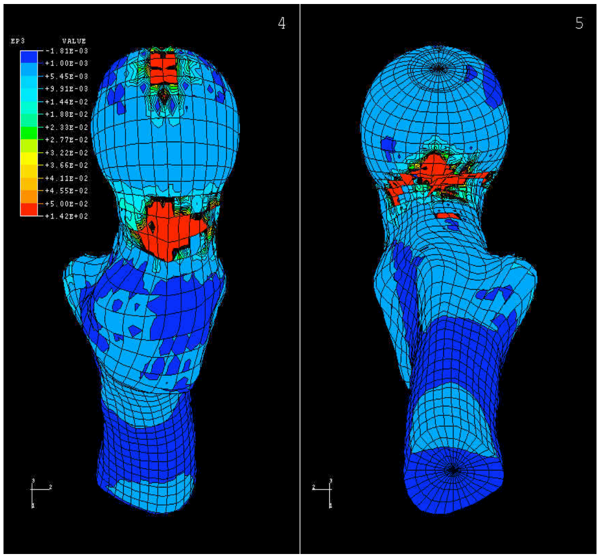
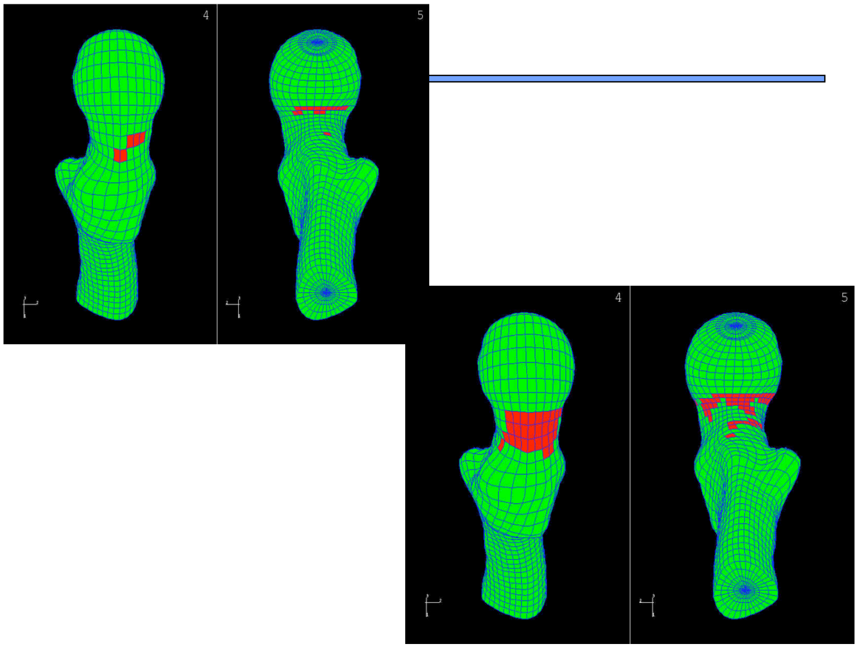
Back to Musculoskeletal Considerations

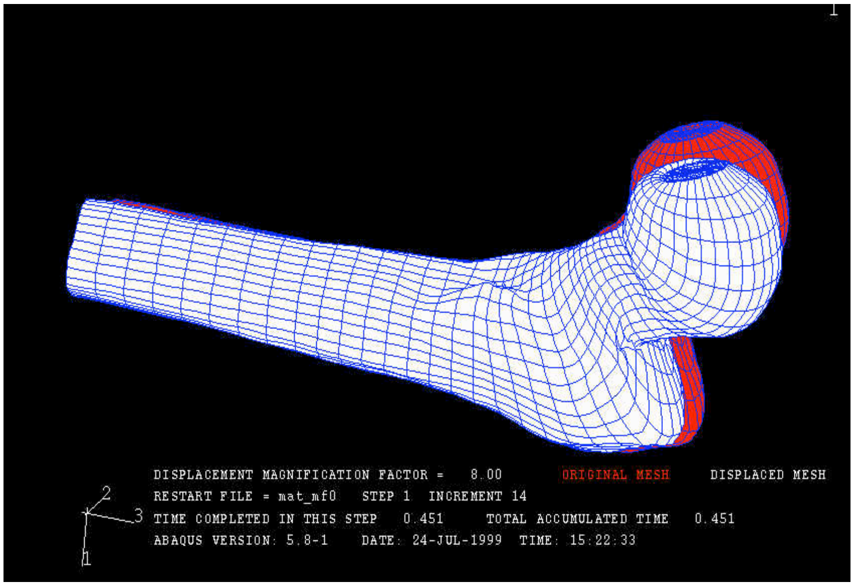


Fall on Hip: Fracture?









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RESTART FILE = mat_mf0   STEP 1  INCREMENT 14
TIME COMPLETED IN THIS STEP    0.451      TOTAL ACCUMULATED TIME    0.451
ABAQUS VERSION: 5.8-1    DATE: 24-JUL-1999  TIME: 15:22:33
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Astronaut Skeletal Modeling

I Dynamic Model of Fall on Hip

II Structural Analysis of Femur