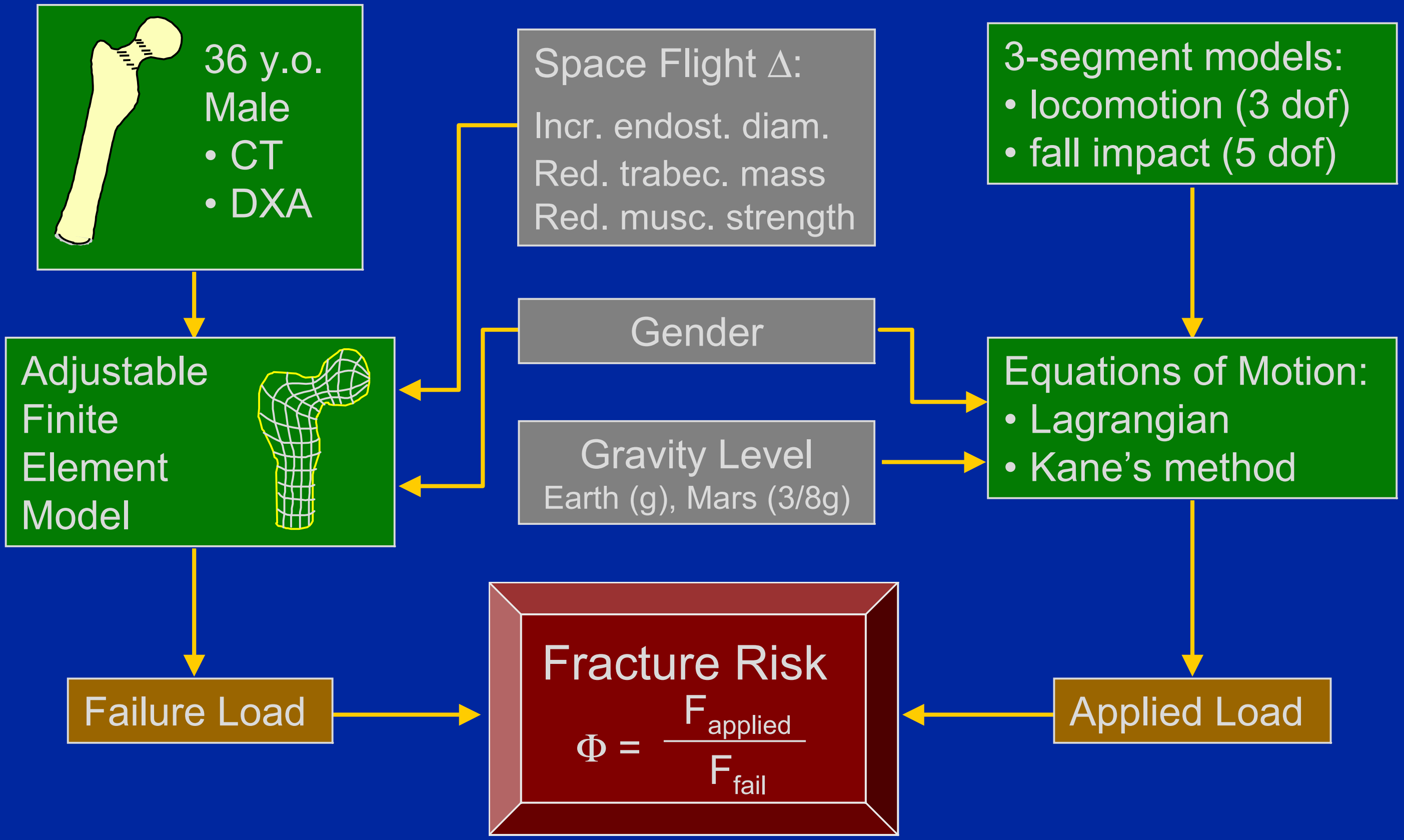
Principal Aim

To assess the strength changes, and associated change in fracture risk, due to structural alterations in the proximal femora of astronauts experiencing long-term weightlessness.

- 3-D FEA has not yet applied to bone loss in astronauts
  - Greatly increased risk of fracture upon return to Earth and possibly even under strenuous loading in space or on the moon or Mars.
- Calculate change in factor of risk (Φ)
  - Φ = actual load / predicted failure load
  - hypothesis: $\Phi_{pre} < \Phi_{post}$
  - relationship between Φ and duration of weightlessness

Research Plan



36 y.o.
Male
- CT
- DXA

Adjustable Finite Element Model

Space Flight Δ:

Incr. endost. diam.
Red. trabec. mass
Red. musc. strength

Gender

Gravity Level
Earth (g), Mars (3/8g)

3-segment models:
- locomotion (3 dof)
- fall impact (5 dof)

Equations of Motion:
- Lagrangian
- Kane's method

Failure Load

Applied Load

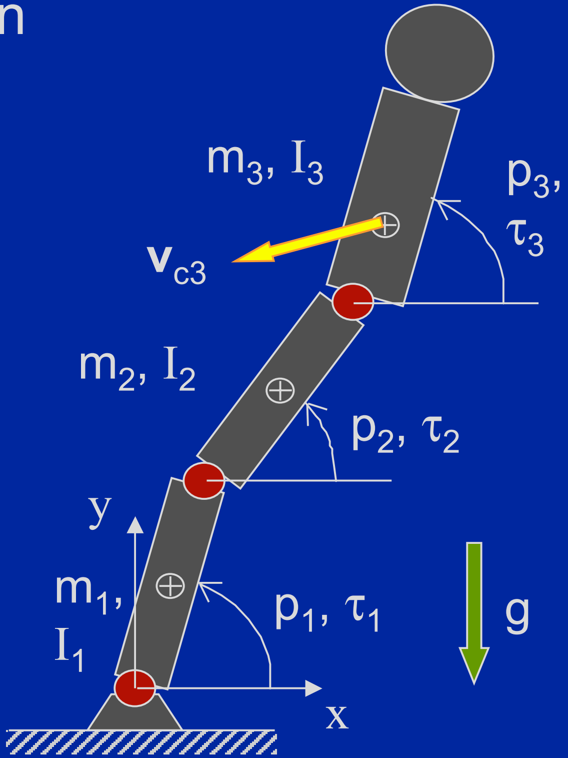
Fracture Risk

$$\Phi = \frac{F_{applied}}{F_{fail}}$$

Aim 1: Hip Loading During Locomotion

3-segment model for locomotion

- Lagrangian formulation



Solution of Equations for Locomotion

Initial joint velocity from hip/seg. 3

Calc. joint acceleration at each time step

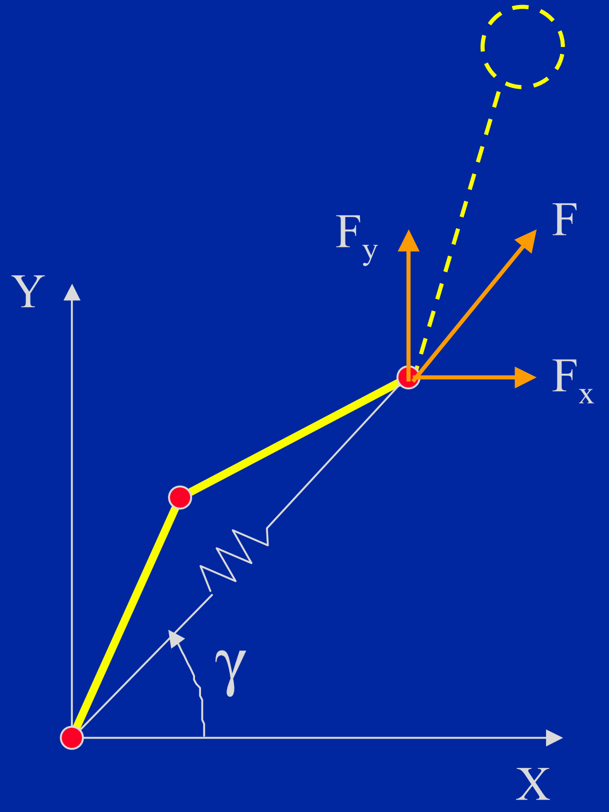
Integrate to get velocity and position values

Hip force from c.m. acceleration via Jacobian

Control Scheme (locomotion)

Hip torque:
PPD control

Ankle & knee torque:
Impedance control



Variation of Parameters (Locomotion)

- Body Mass Properties (m, I) and Anthropometrics:

  Male and female, 5%, 50%, 95%

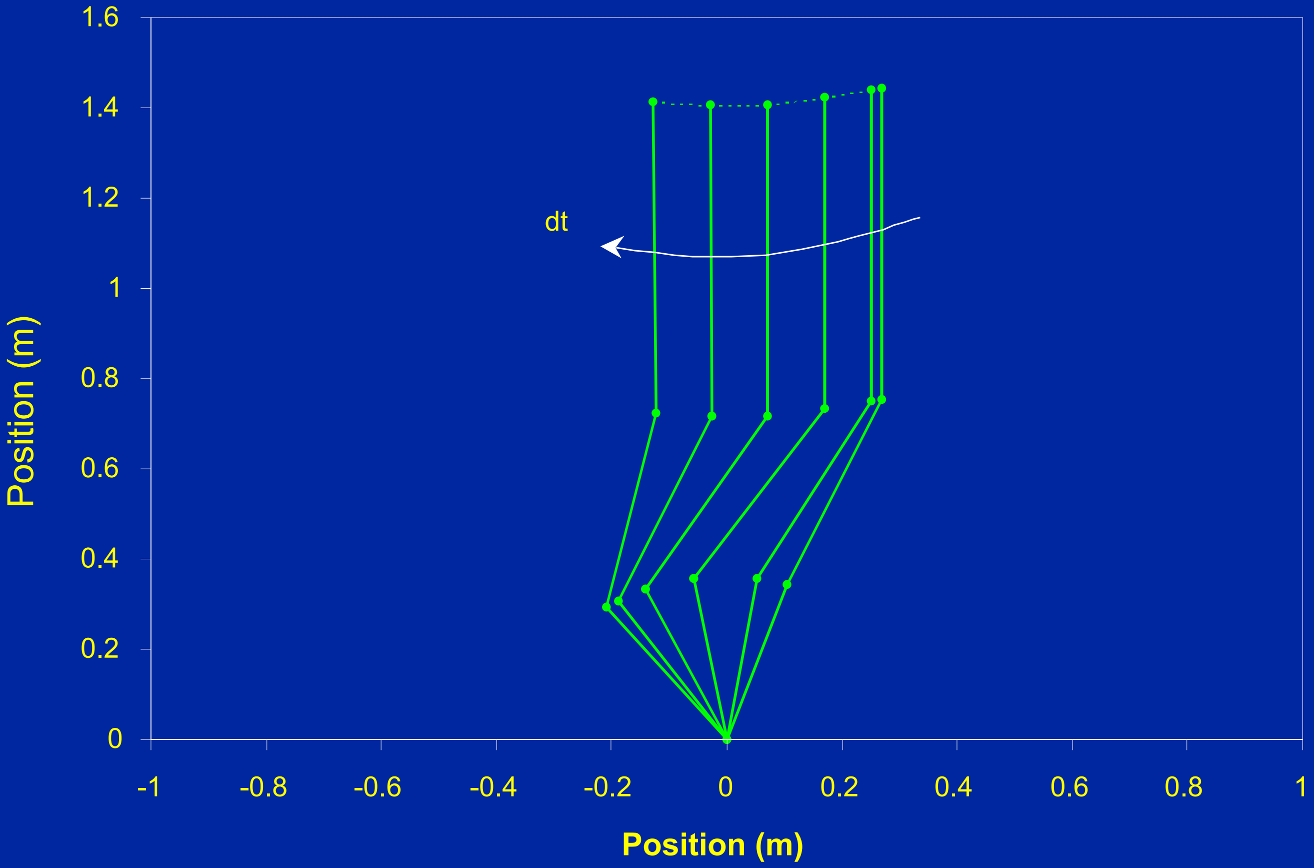
  Values derived using GEBOD
- Horizontal velocity:

  u_{Earth} = 2 - 6 m/s (He et al., 1991)

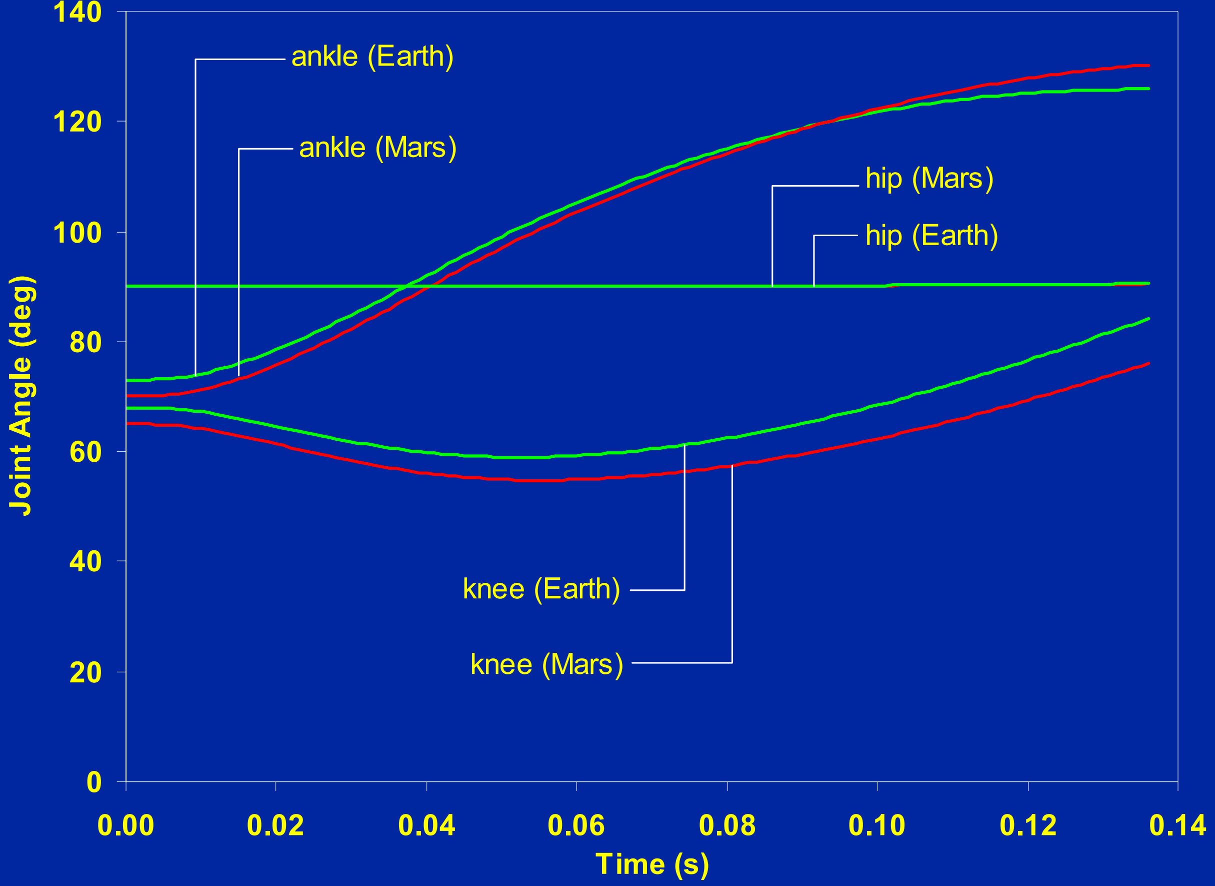
  u_{Mars} = 2 - 4 m/s (Newman et al., 1994; Wickman & Luna, 1996)
- Leg stiffness:

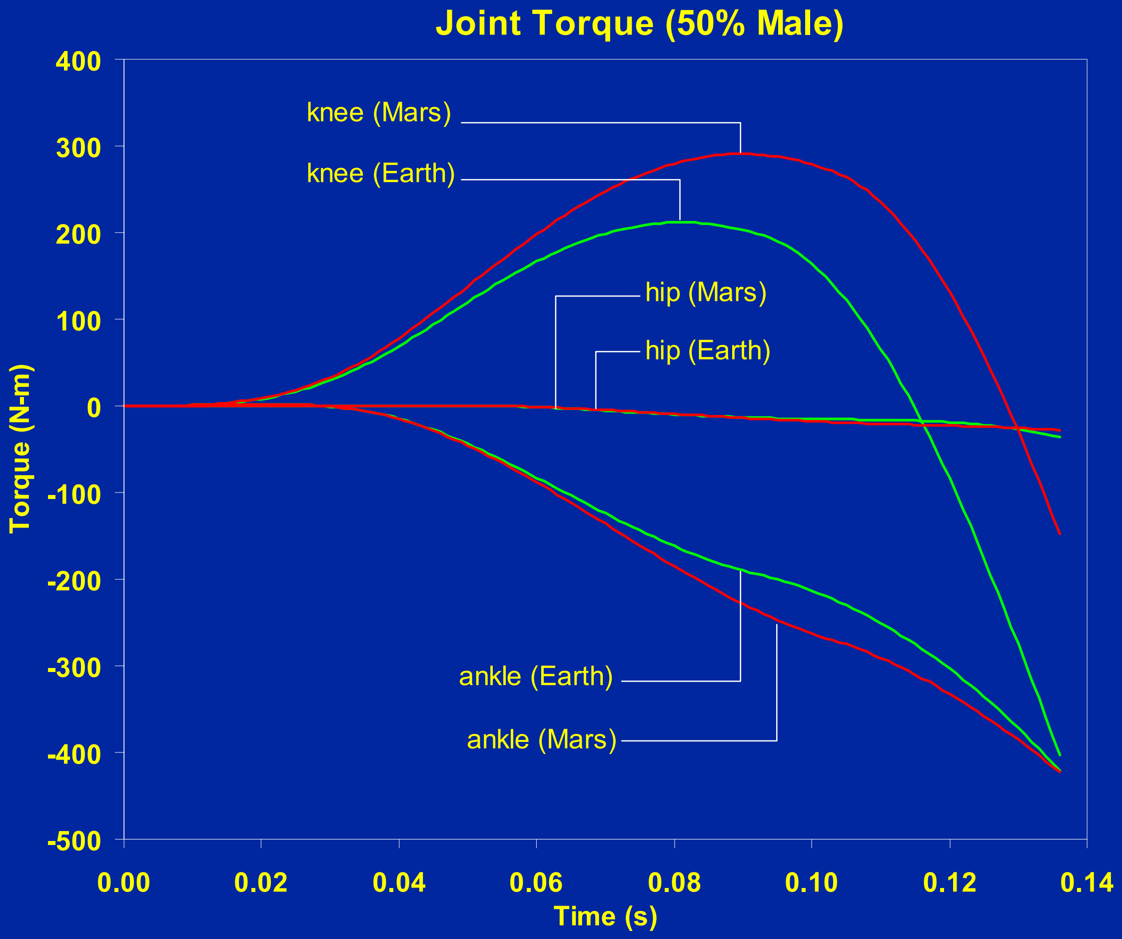
  K_{leg} = 9 - 15 kN/m (He et al., 1991; Farley & Gonzalez, 1996; Viale et al., 1998)
- Gravity:

  Earth G = g, Mars G = 3/8 g   ($g = 9.807\ m/s^2$)
- Initial ankle angle: iteration until lowest point of hip trajectory occurs at x=0 (initial knee angle set to 5 deg)

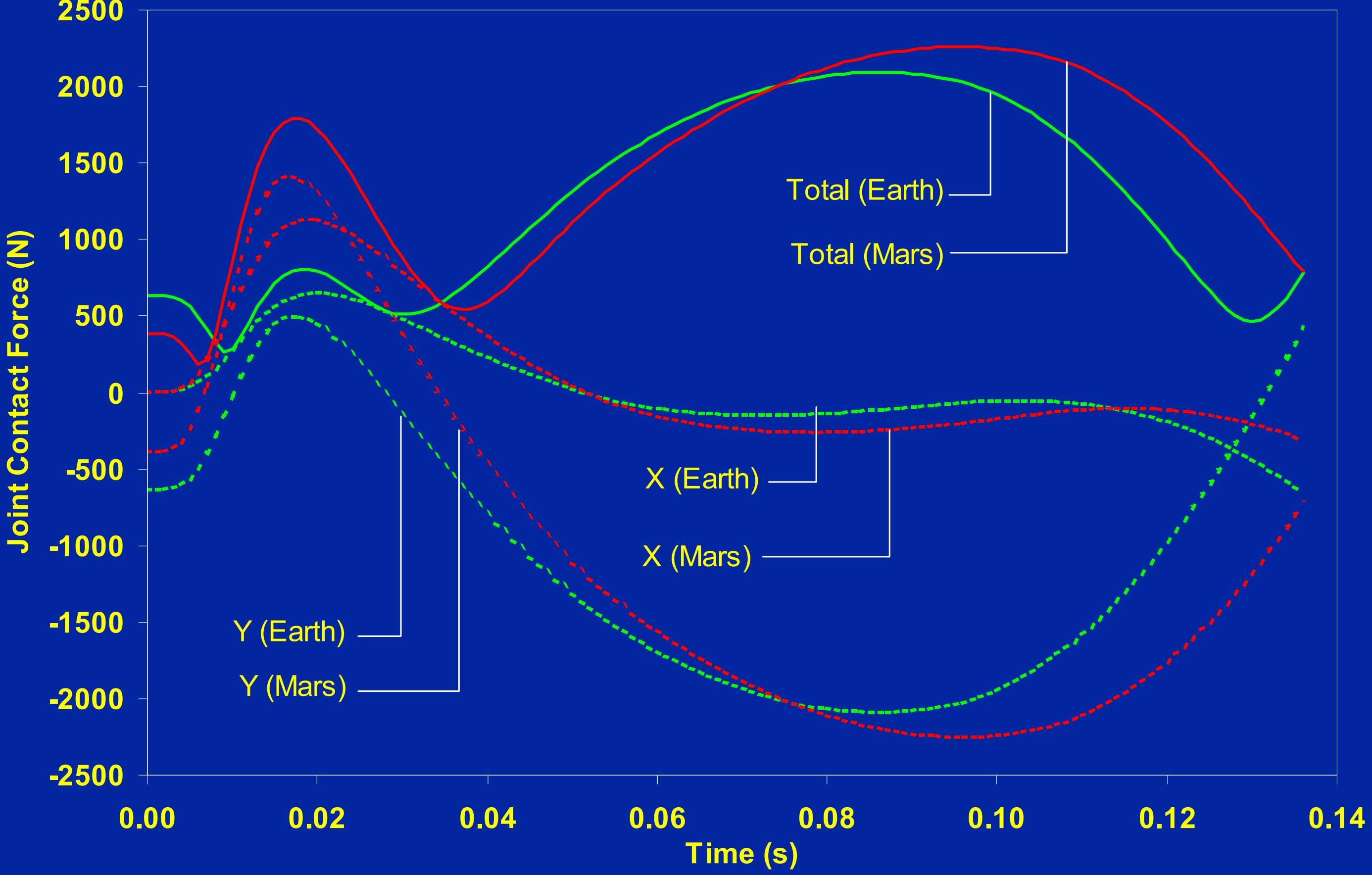

1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
Position (m)
dt
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1
Position (m)

Joint Position (50% Male)

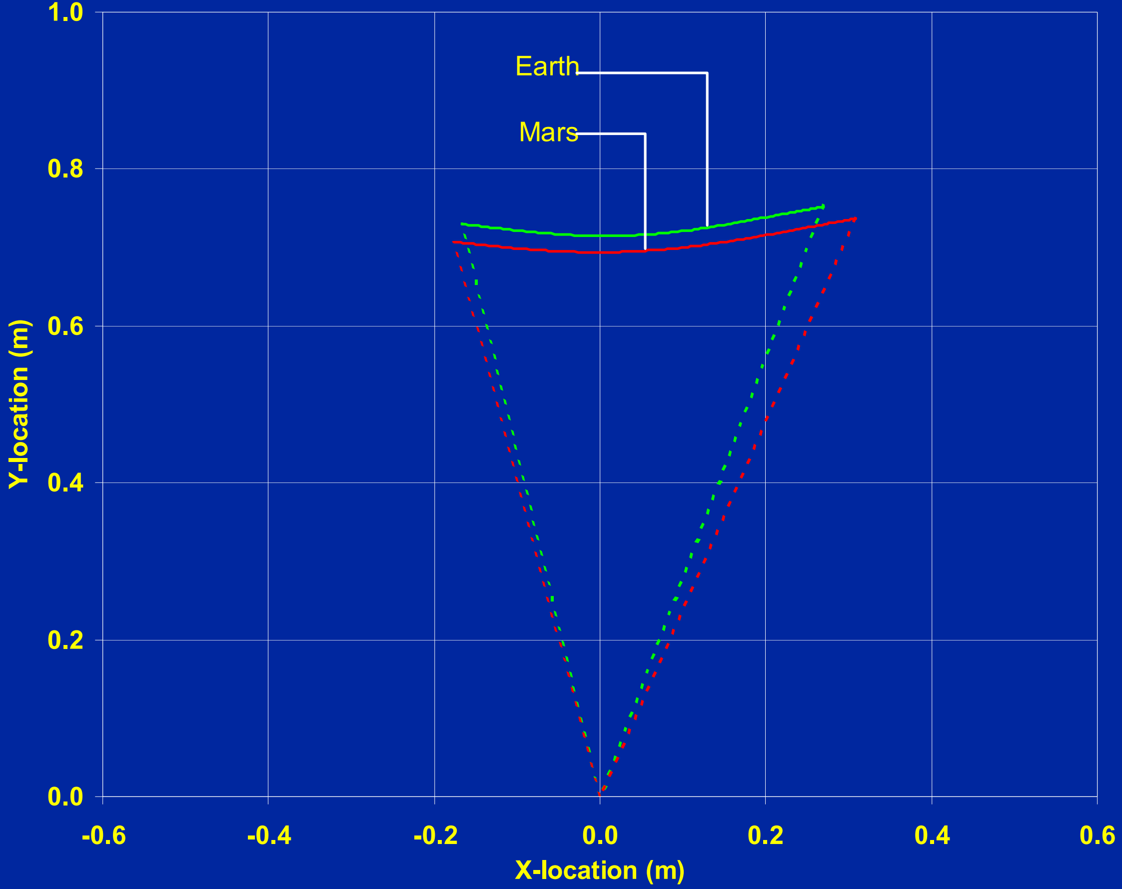



Joint Torque (50% Male)
Torque (N-m)
400
300
200
100
0
-100
-200
-300
-400
-500
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.14
Time (s)
knee (Mars)
knee (Earth)
hip (Mars)
hip (Earth)
ankle (Earth)
ankle (Mars)

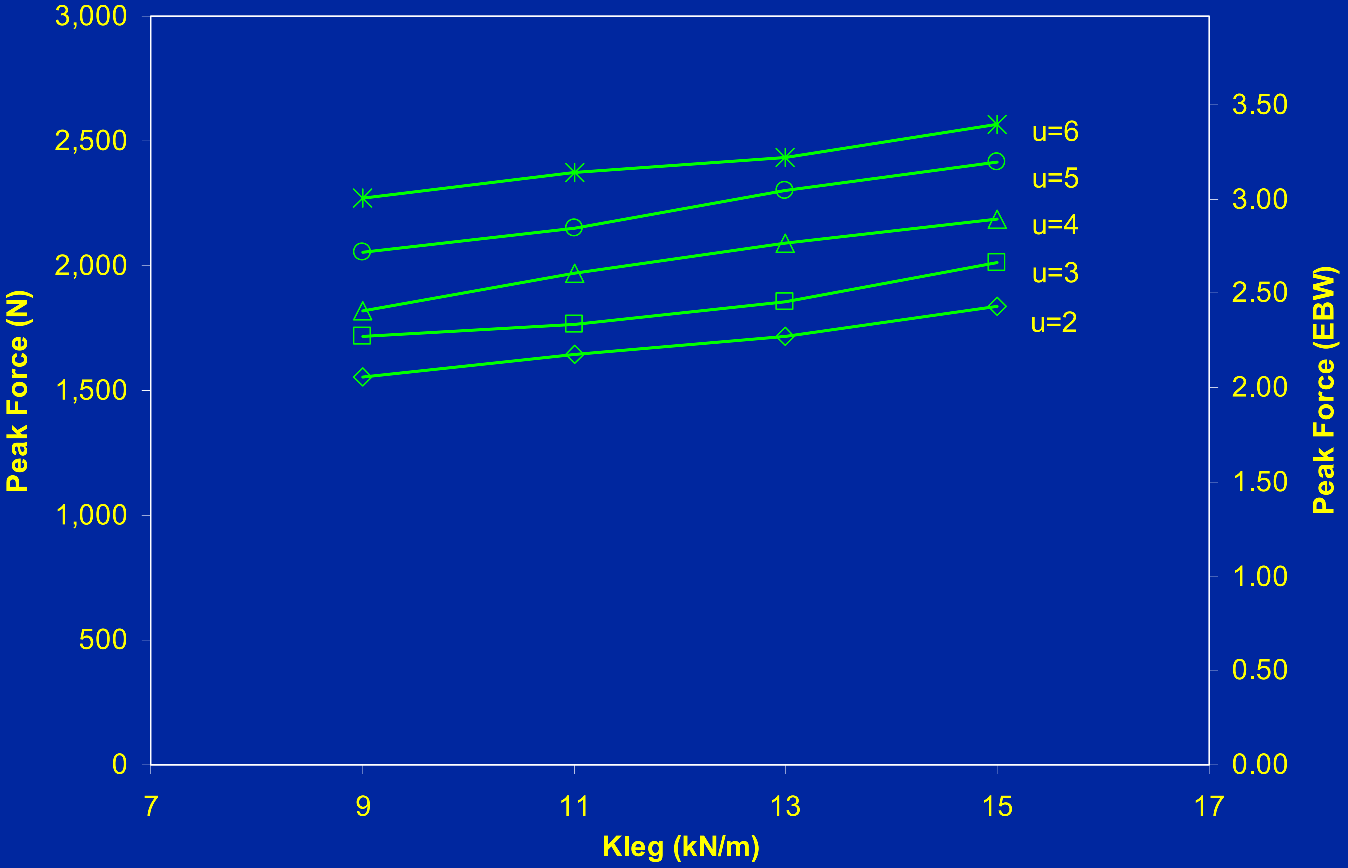
Hip Force (50% Male)



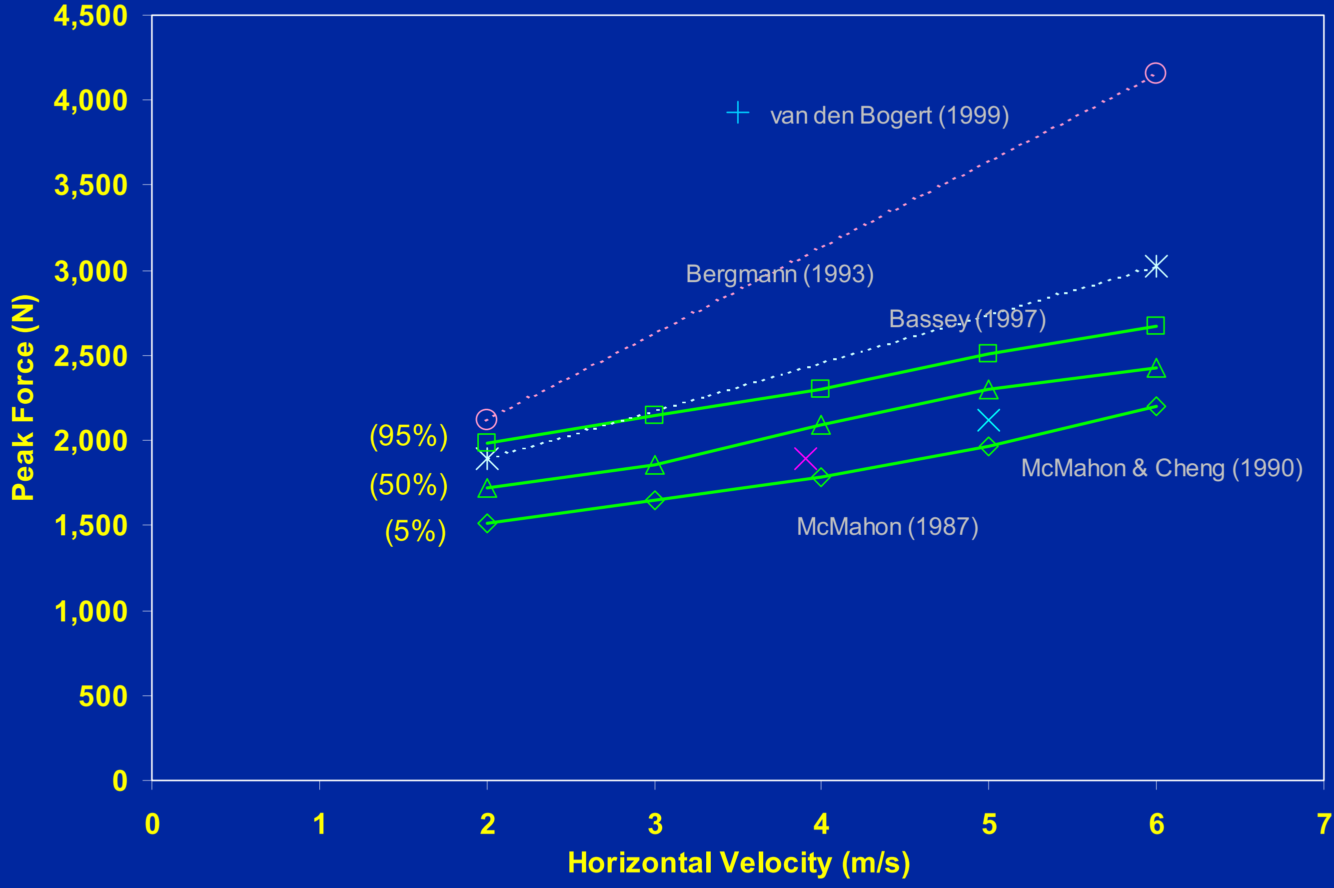
Hip Locus (50% Male)



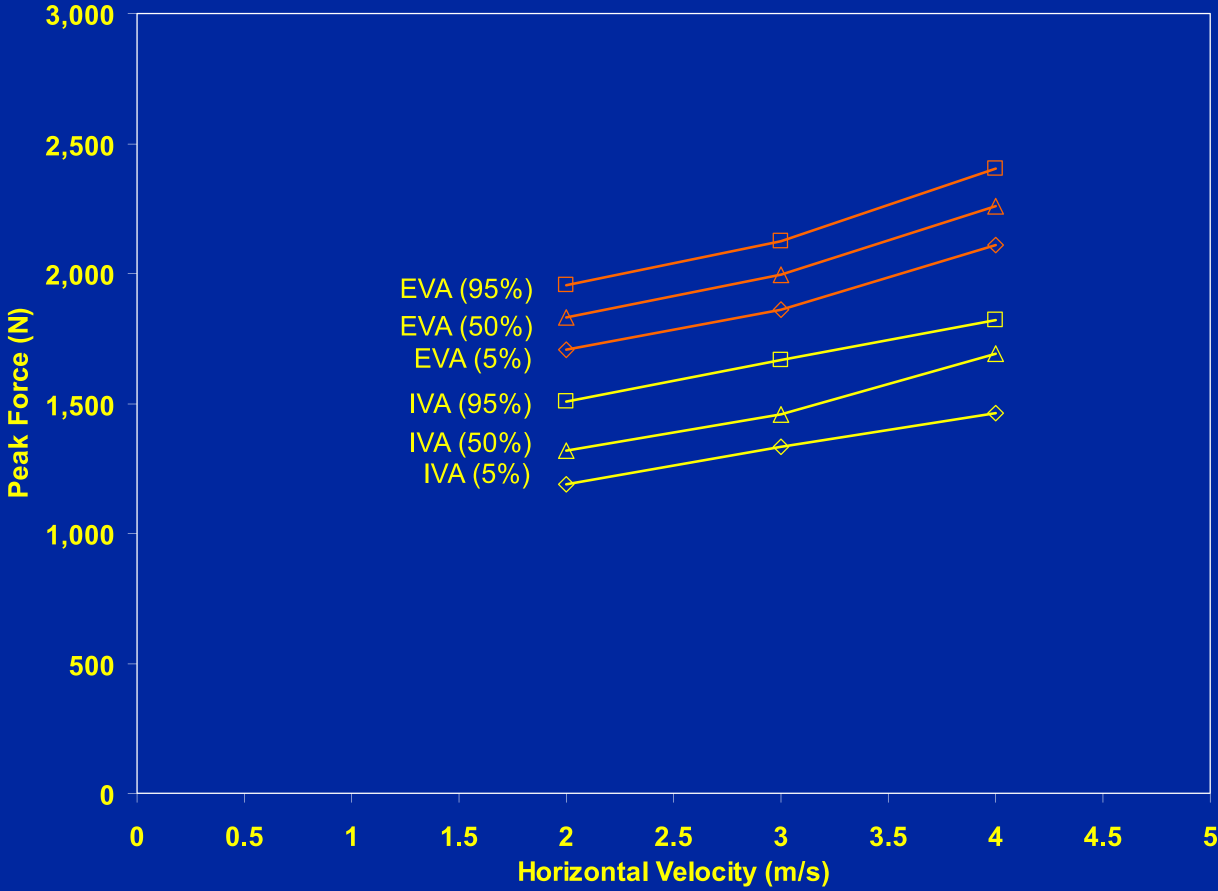
50th Percentile Male (Earth)



Male (Earth)

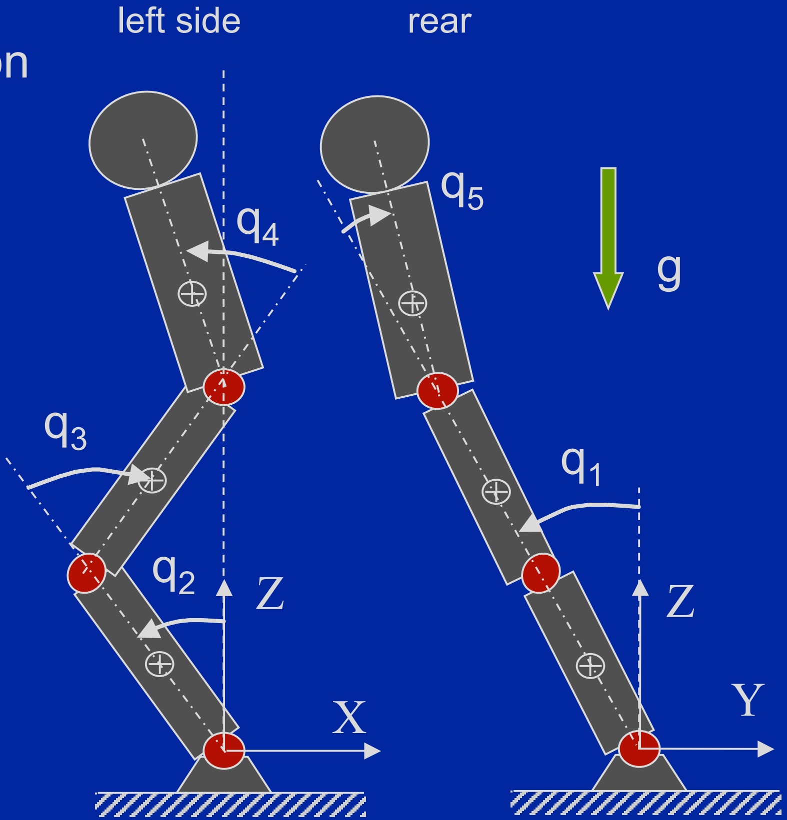

4,500
4,000
3,500
3,000
2,500
2,000
1,500
1,000
500
0
Peak Force (N)
0
1
2
3
4
5
6
7
Horizontal Velocity (m/s)
van den Bogert (1999)
Bergmann (1993)
Bassey (1997)
McMahon & Cheng (1990)
McMahon (1987)
(95%)
(50%)
(5%)

Male (Mars)


3,000
2,500
2,000
1,500
1,000
500
0
Peak Force (N)
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Horizontal Velocity (m/s)
EVA (95%)
EVA (50%)
EVA (5%)
IVA (95%)
IVA (50%)
IVA (5%)

Aim 1: Hip Loading During Falls

- 3-segment model based on that derived by van den Kroonenberg (1995)
- 5 degrees-of-freedom



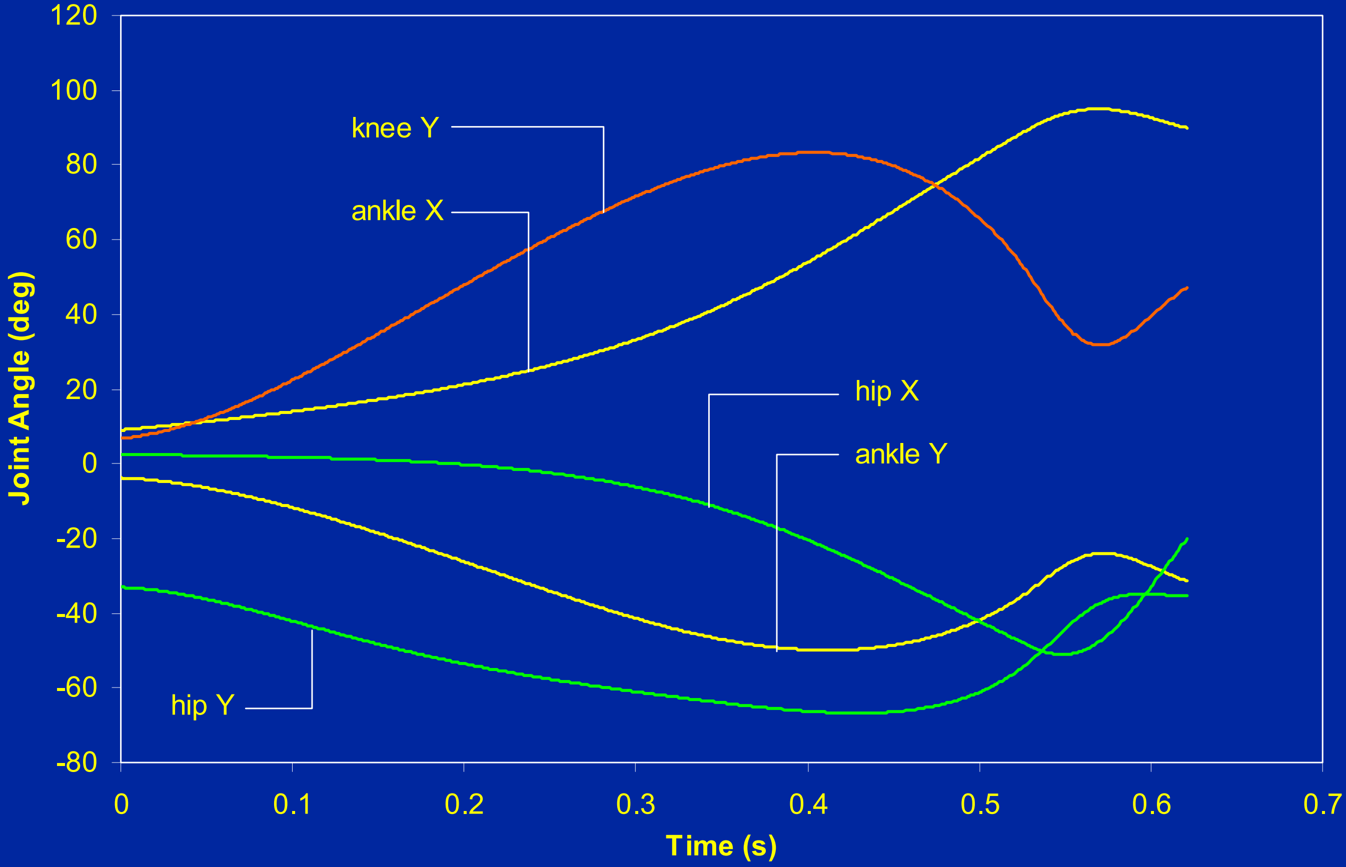
Control Scheme

- Ankle and knee: Impedance Control
  - Adjust $(K_p)_x$ and $(K_d)_x$ so that hip stays close to Y-Z plane
  - Adjust $(K_p)_z$ and $(K_d)_z$ so that body configuration at impact is close to that reported by van den Kroonenberg from kinematic studies
- Hip joints: PPD
  - Adjust control parameters to obtain appropriate trunk orientation at impact

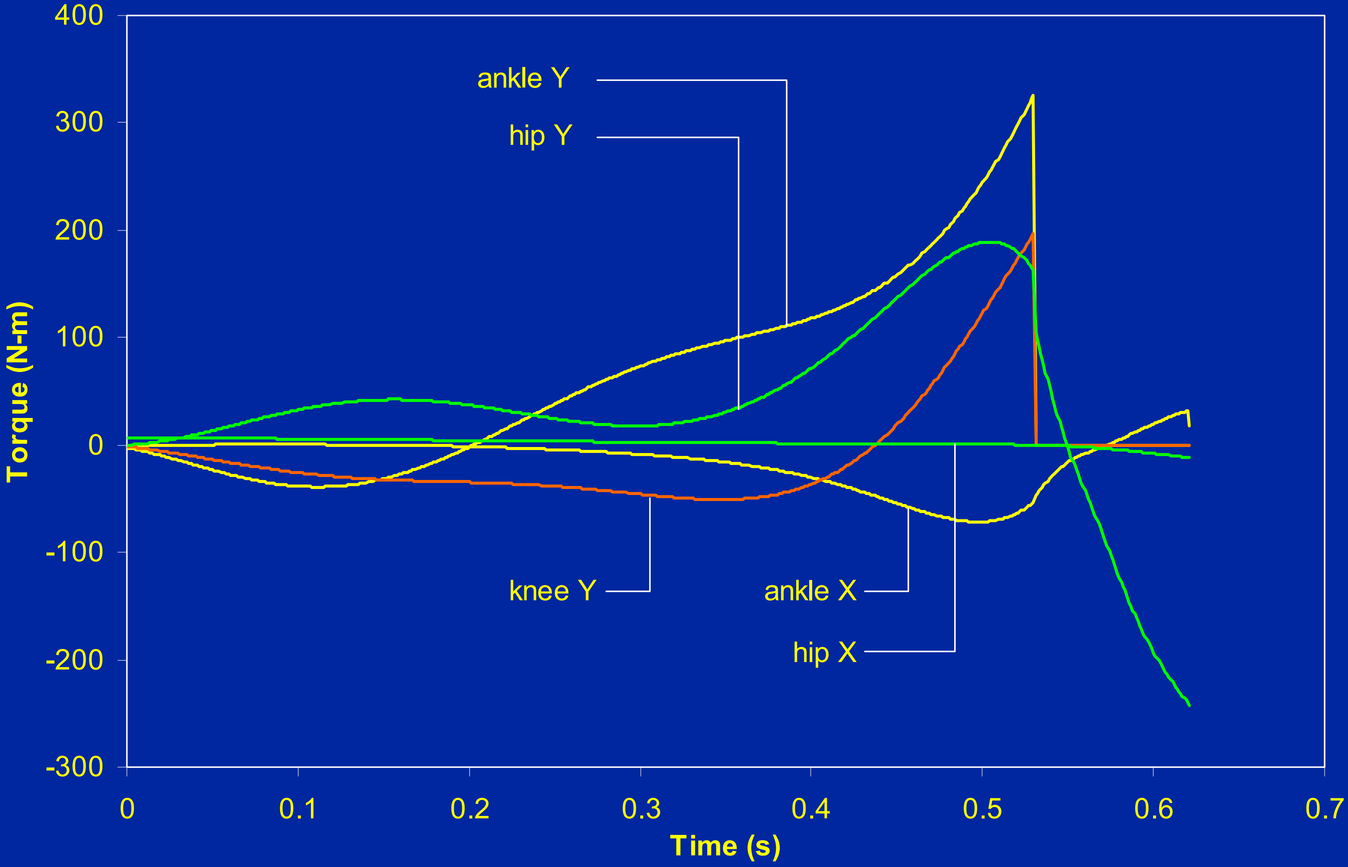
Variation of Parameters (Fall)

- Body Mass Properties (m, I) and Anthropometry:
  - Male and female, 5%, 50%, 95%
  - Values derived using GEBOD
- Gravity: Earth G = g, Mars G = 3/8 g (g = 9.807 m/s^2)
- Initial joint position and velocity values set to correspond with van den Kroonenberg (interpolated to get 50% values)
- Impact model
  - Stiffness: KEarth = 71 kN/m (Robinovitch, et al., 1991)
    KMars = 57 kN/m (20% less for space suit padding)
  - Damping: B = 923 N/m-s (damping ratio = 0.2, Robinovitch, et al., 1991)

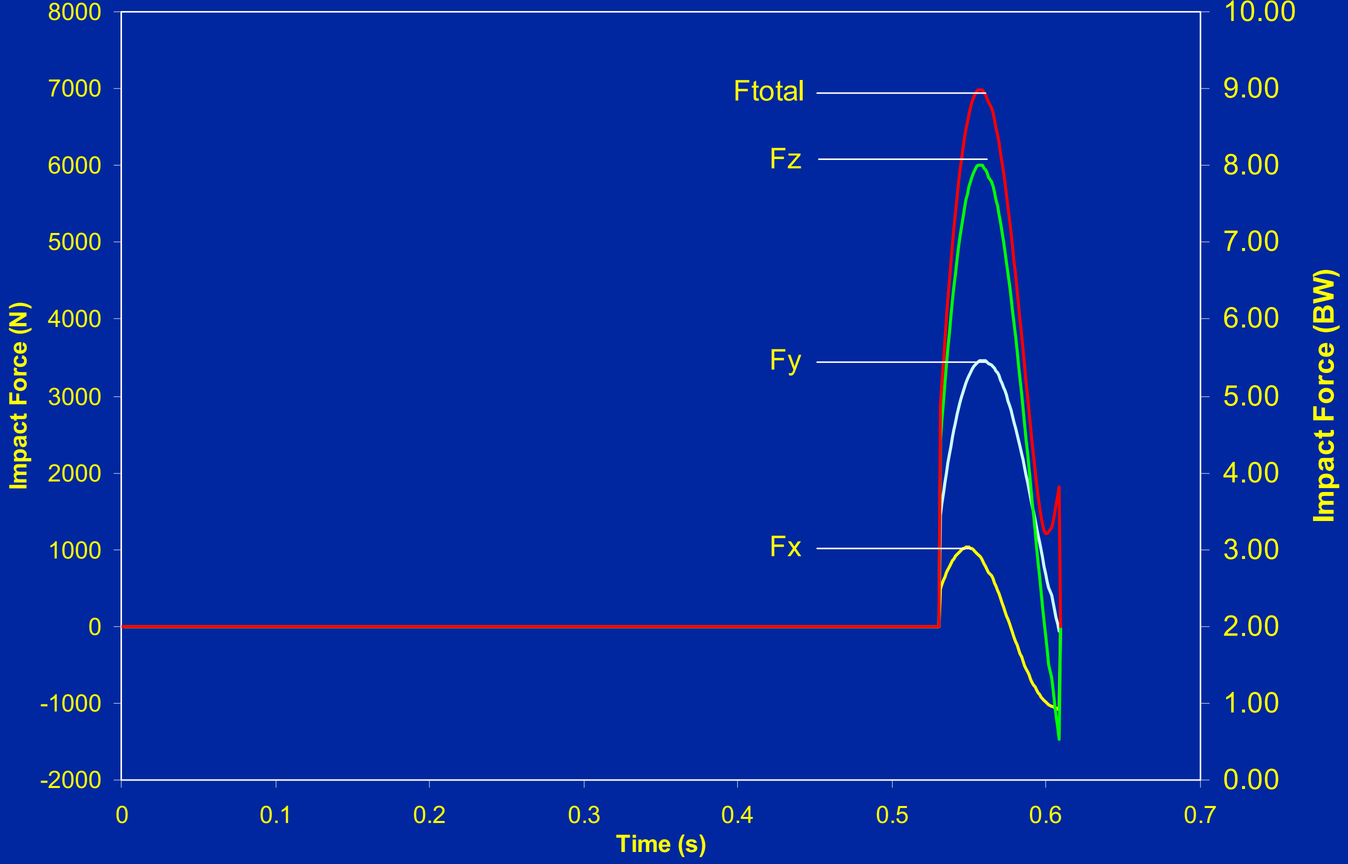
Joint Angle (50% Male — Earth)



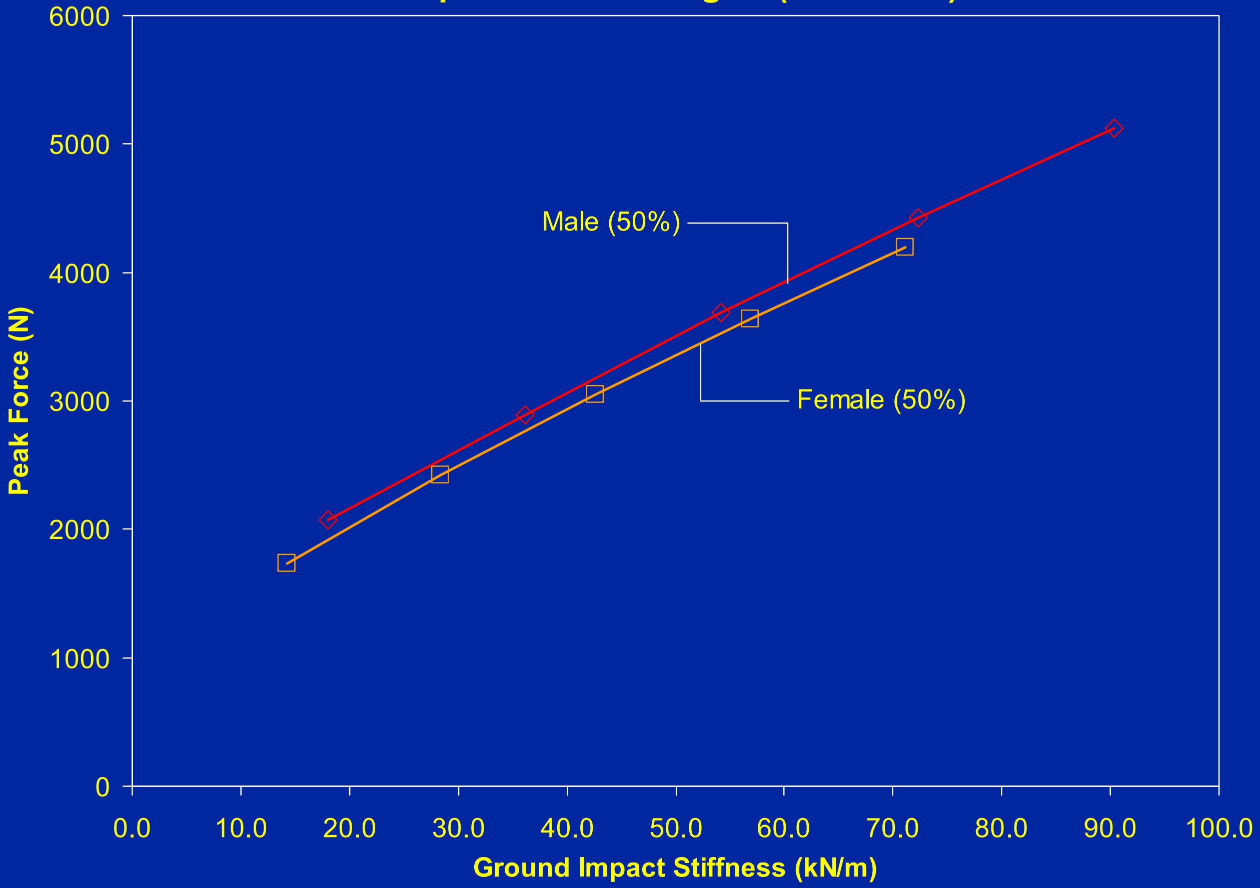
Joint Torque (50% Male — Earth)



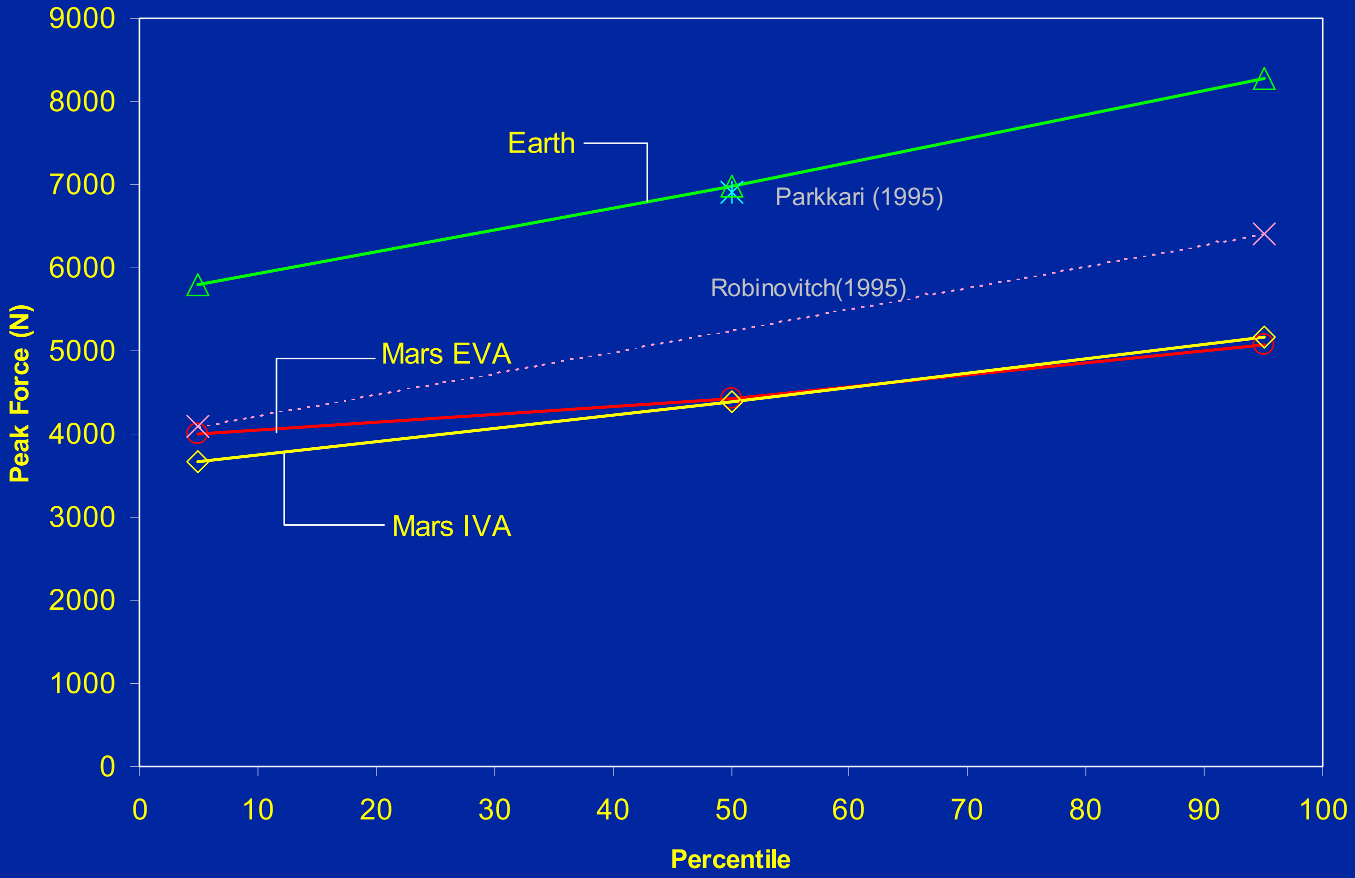
Hip Force (50% Male — Earth)



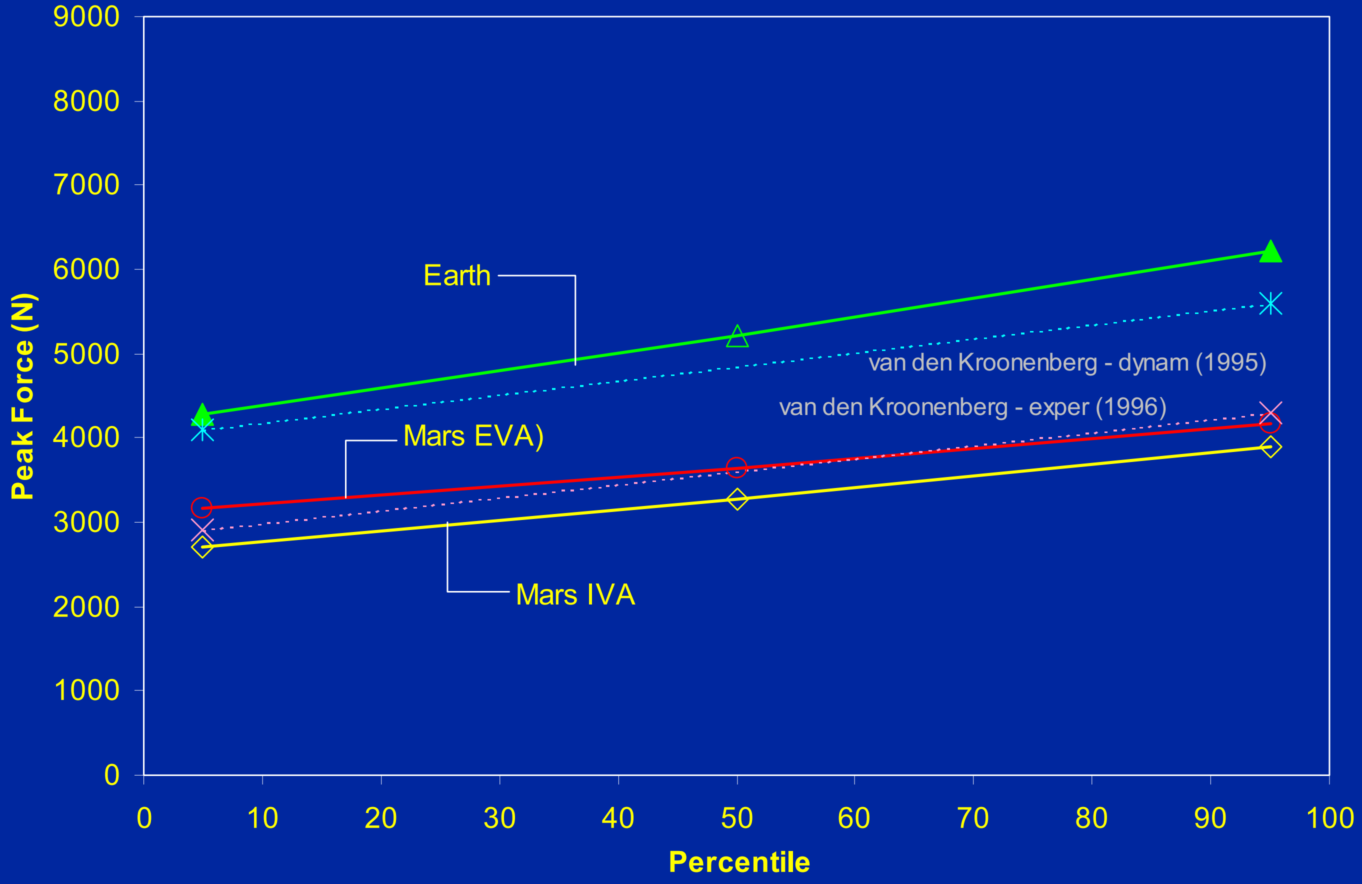
Peak Impact Force vs Kgnd (Mars EVA)



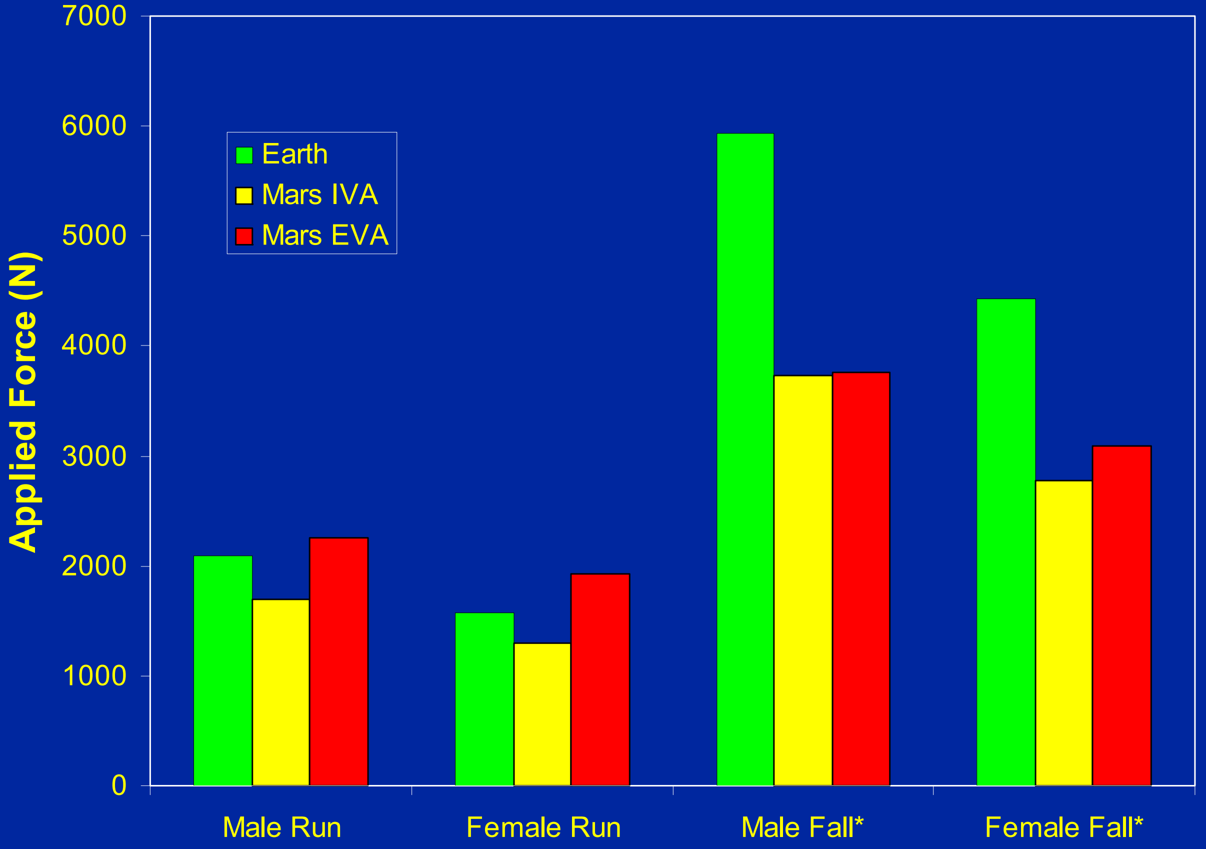
Hip Force during Impact (Male)



Hip Force during Impact (Female)

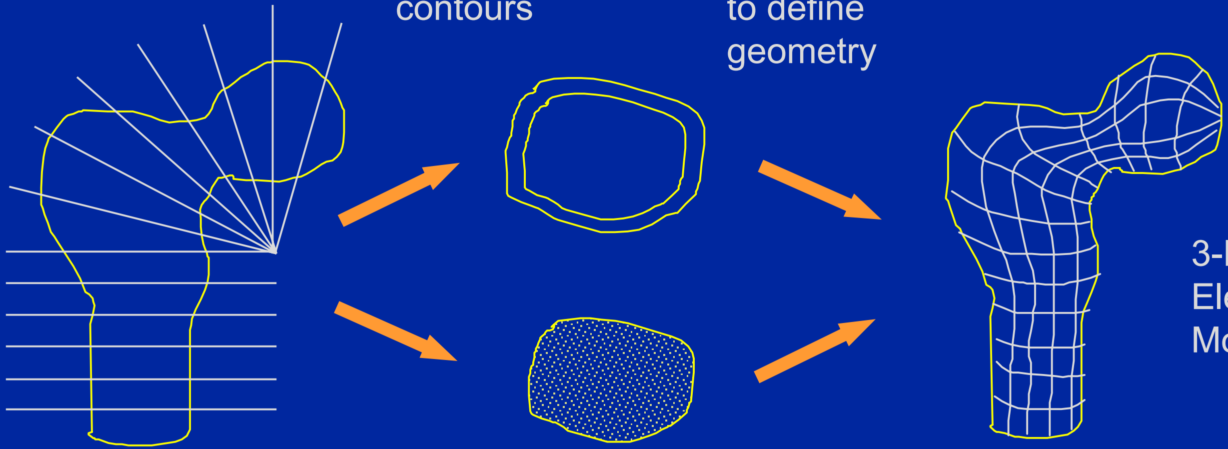


Applied Force Summary (Male & Female 50%)



* Fall impact forces reduced by 15% to account for soft tissue attenuation (Robinovitch et al., 1997)

Finite Element Analysis



QCT scans and
NIH Image

Extract
contours

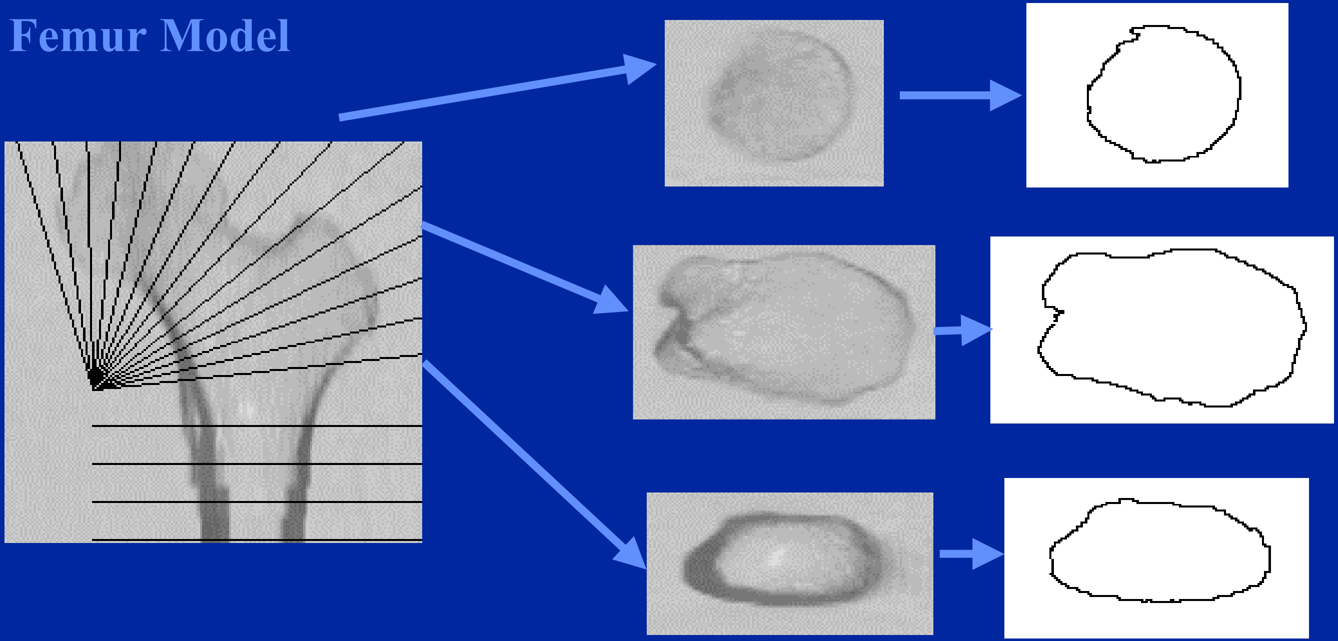
Stack
contours
to define
geometry

3-D Finite
Element
Model

Extract density
distribution
(trabecular area)

Define element
material properties

Methods: NIH Image



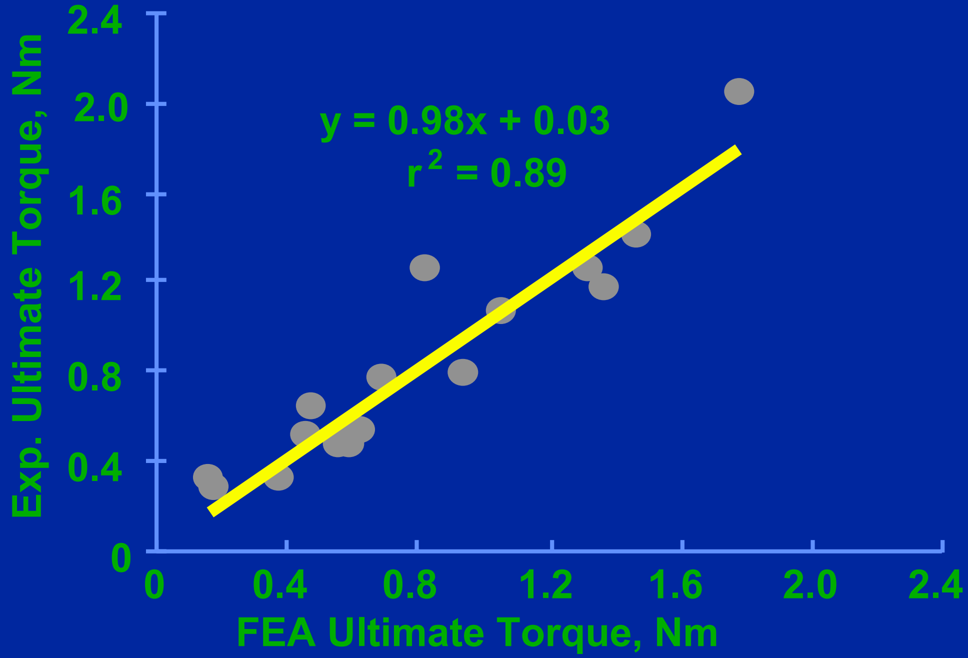
Femur Model

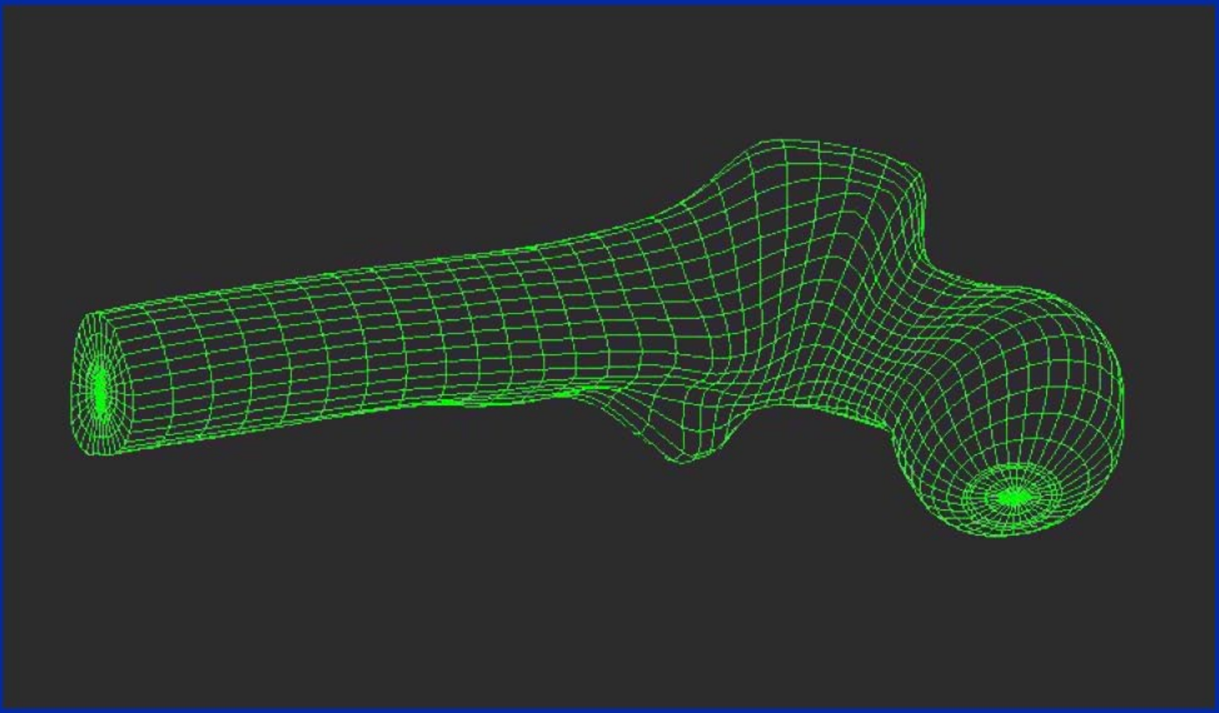
Resliced Sections

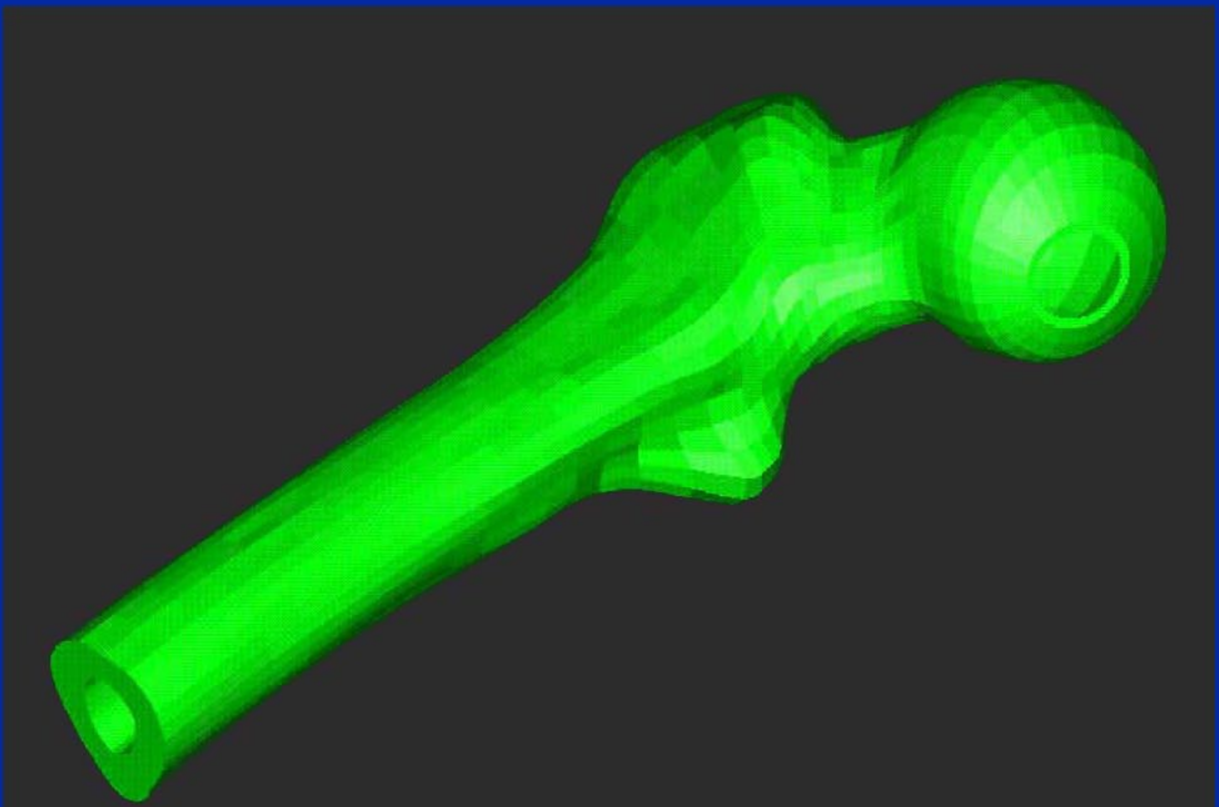
Outlines

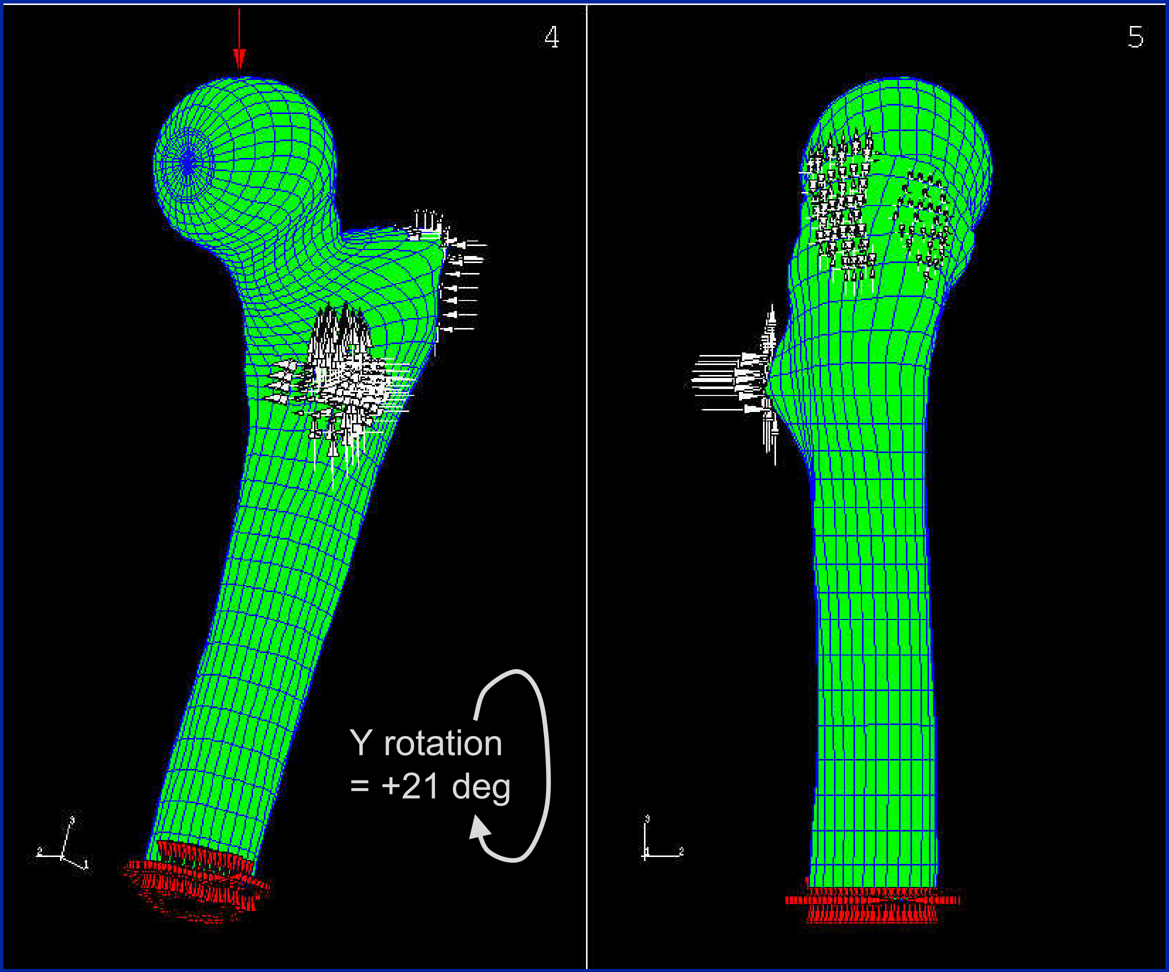
Results: Failure Analysis Validation

- Trabecular bone specimens in torsion
- Similar results, r^2=0.86 in bending

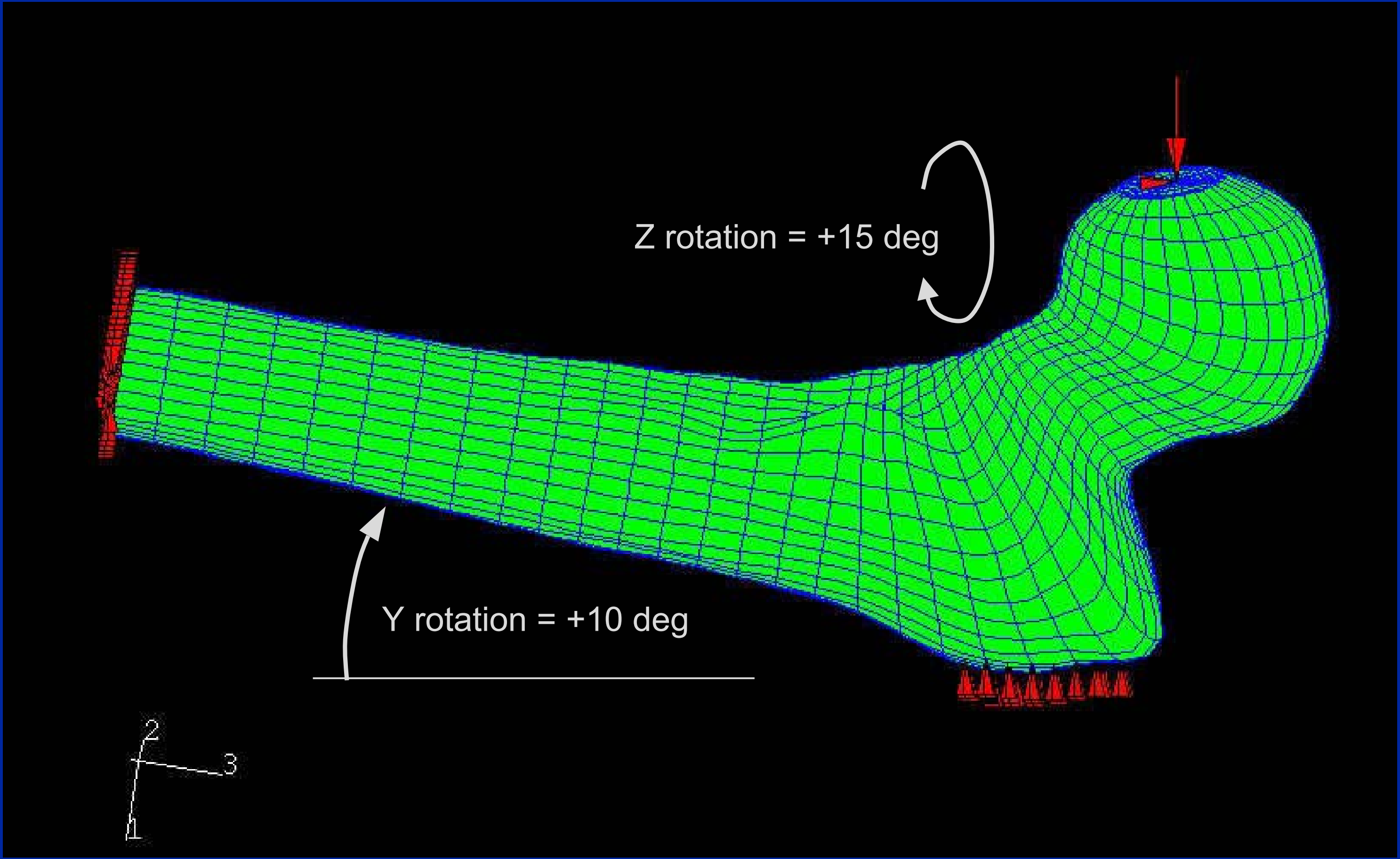








Y rotation
= +21 deg


Z rotation = +15 deg
Y rotation = +10 deg
2
3
1

Element Material Properties

Cancellous elements [Ashman et al., 1989]:

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

Cortical elements [Snyder and Schneider, 1991]:

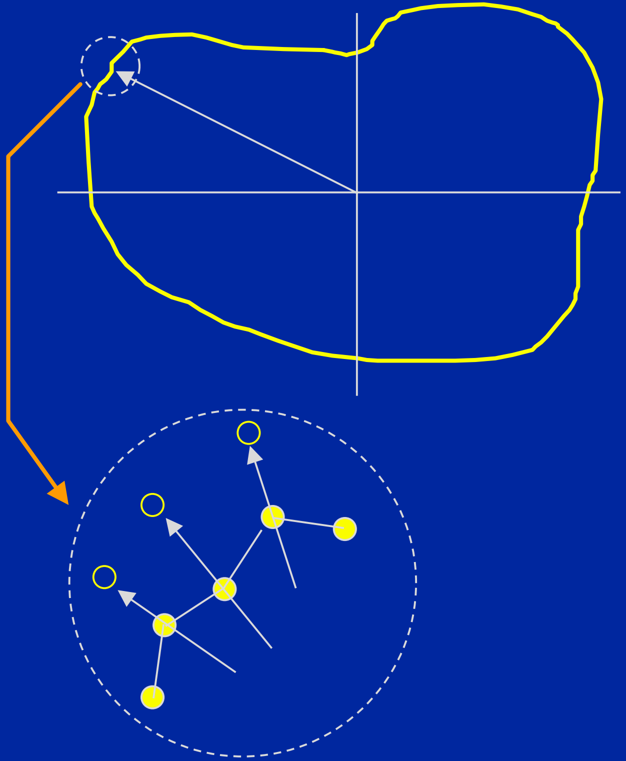
$$E = 21{,}910\rho - 23{,}500$$

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

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



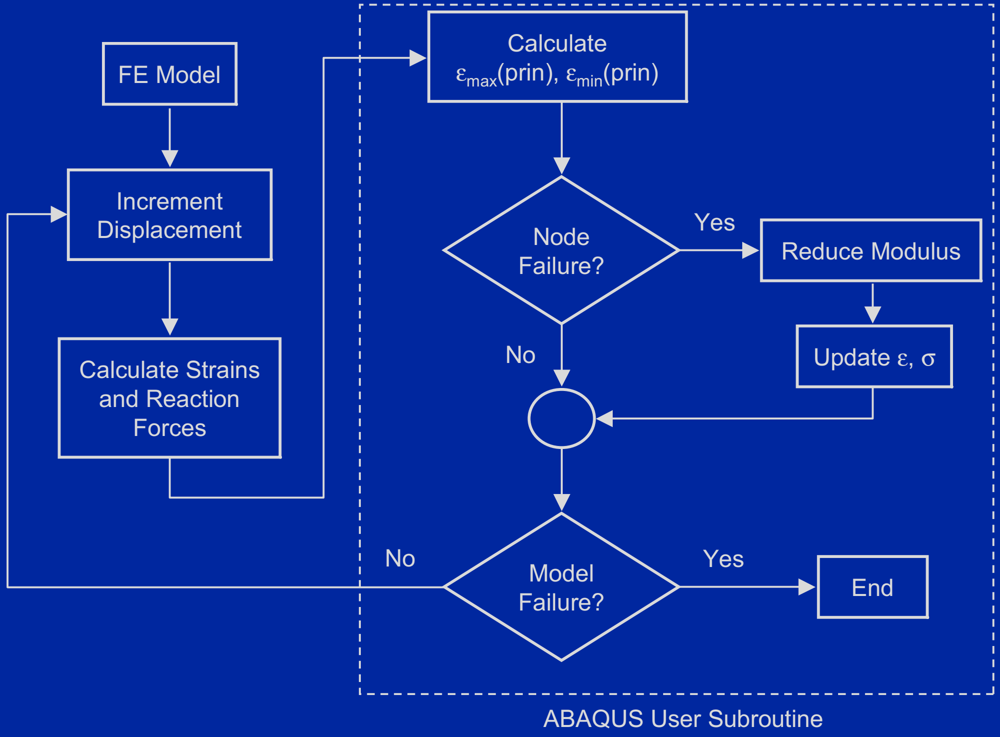
Muscle Strength Loss in Spaceflight

- 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

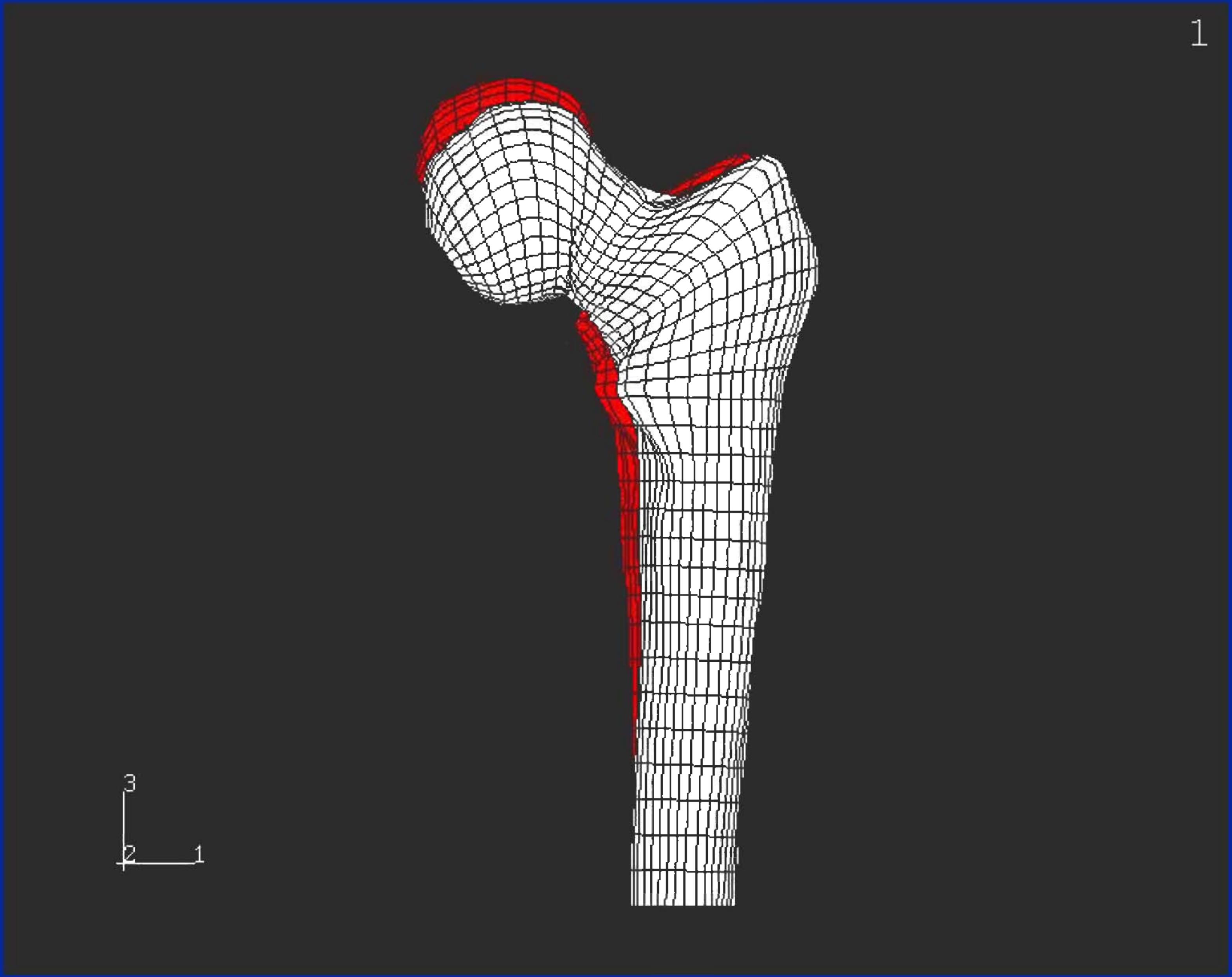
Yes

End

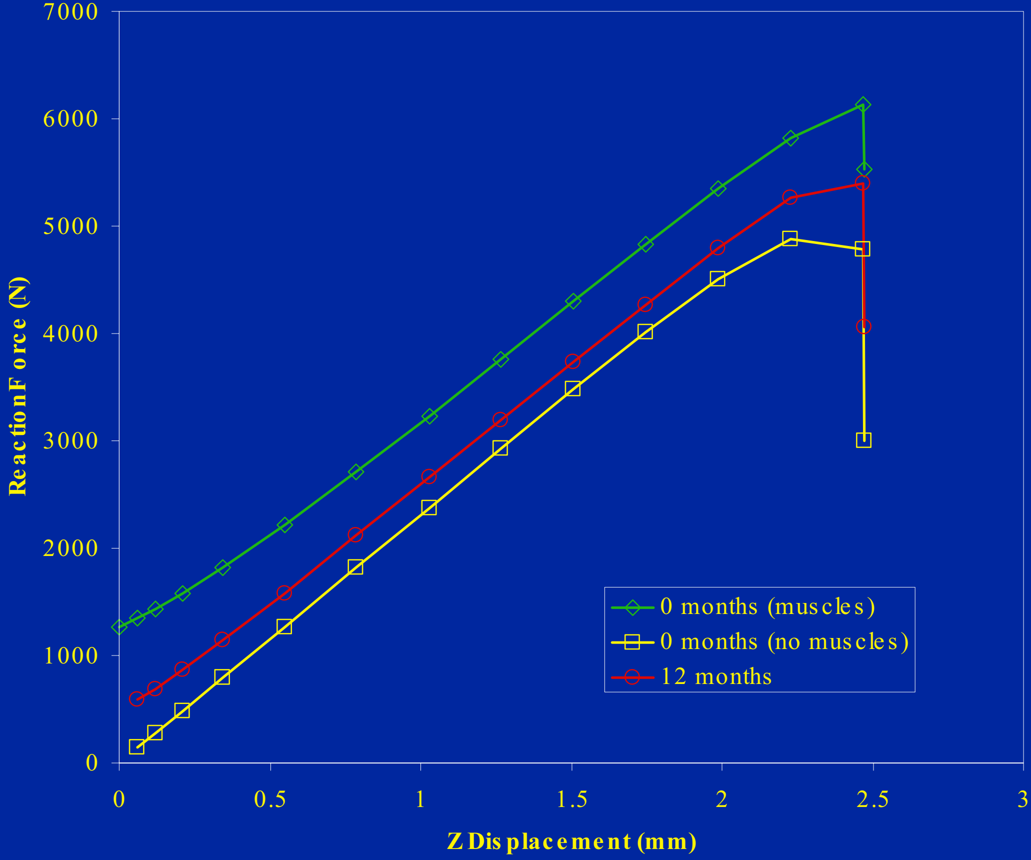
ABAQUS User Subroutine

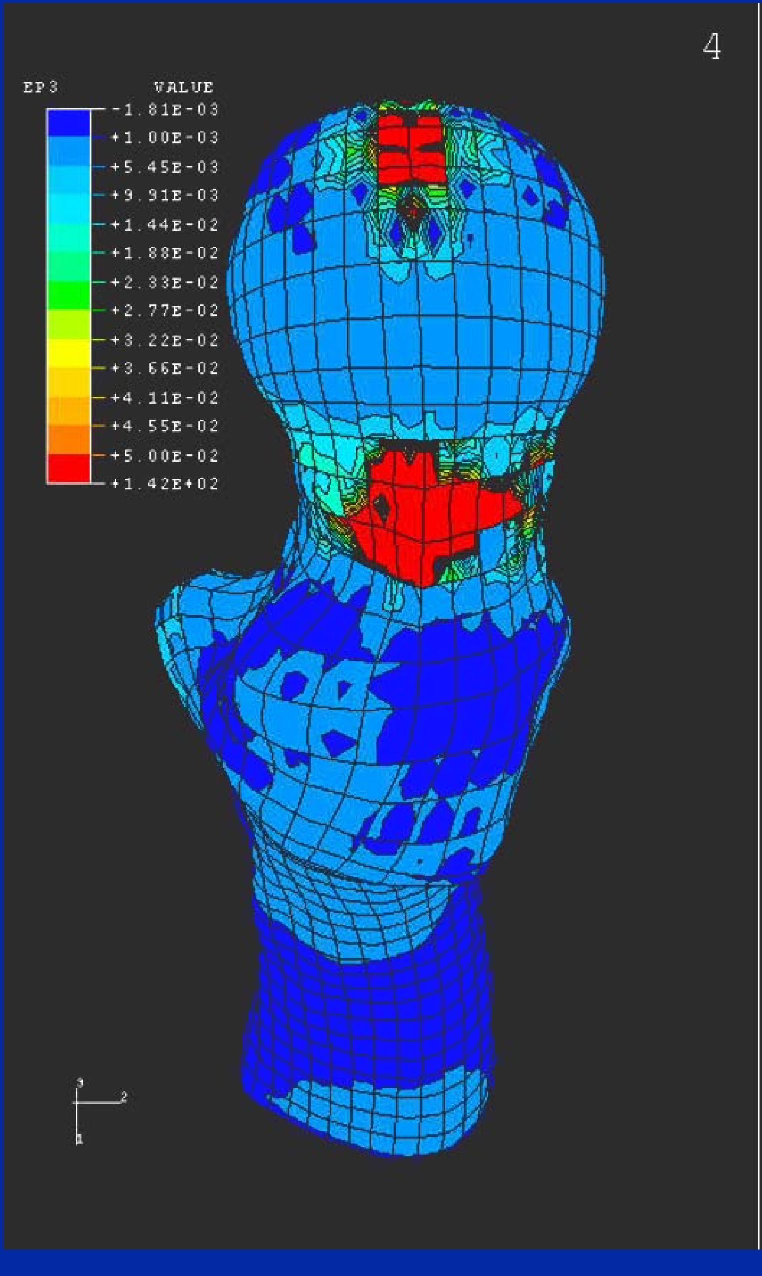
Node Failure:
Maximum Principle Strain
> 0.8% (tension)
Minimum Principle Strain
< -1.1% (compression)

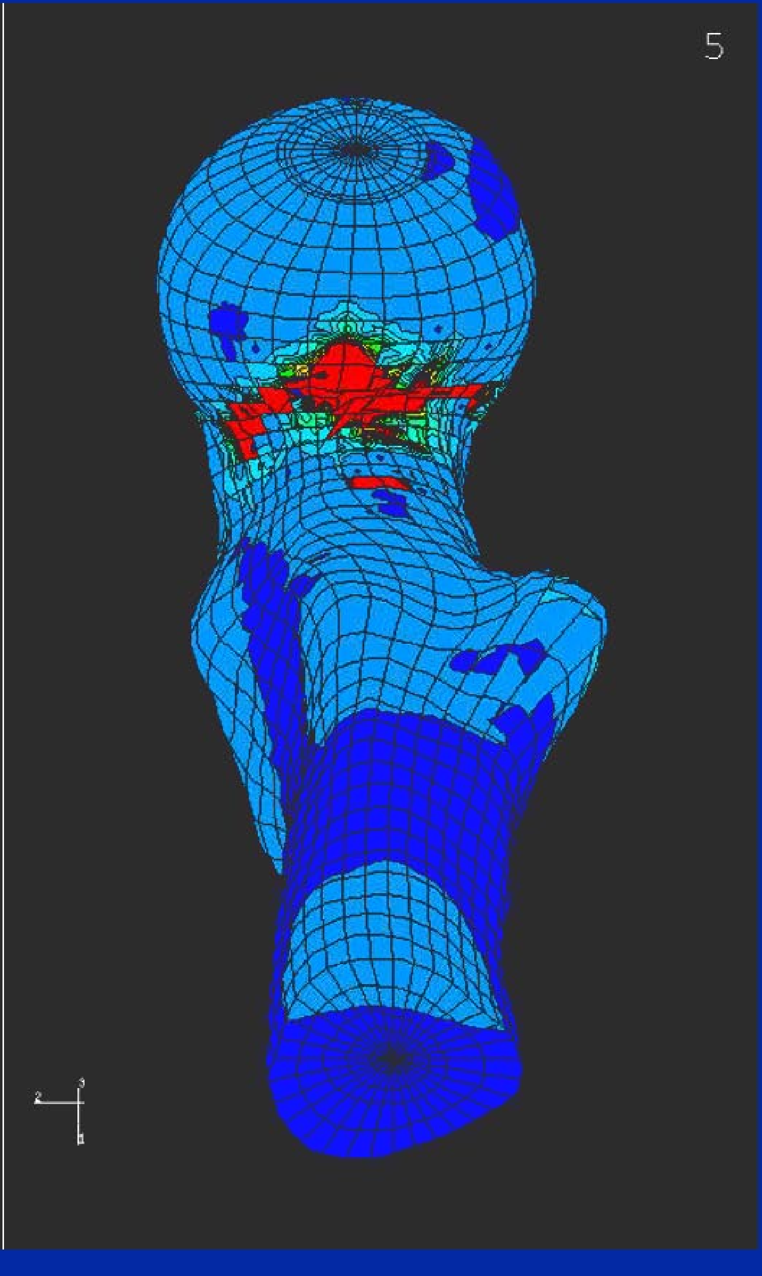
Model Failure:
Reaction Force undergoes two successive decrements with increasing displacement

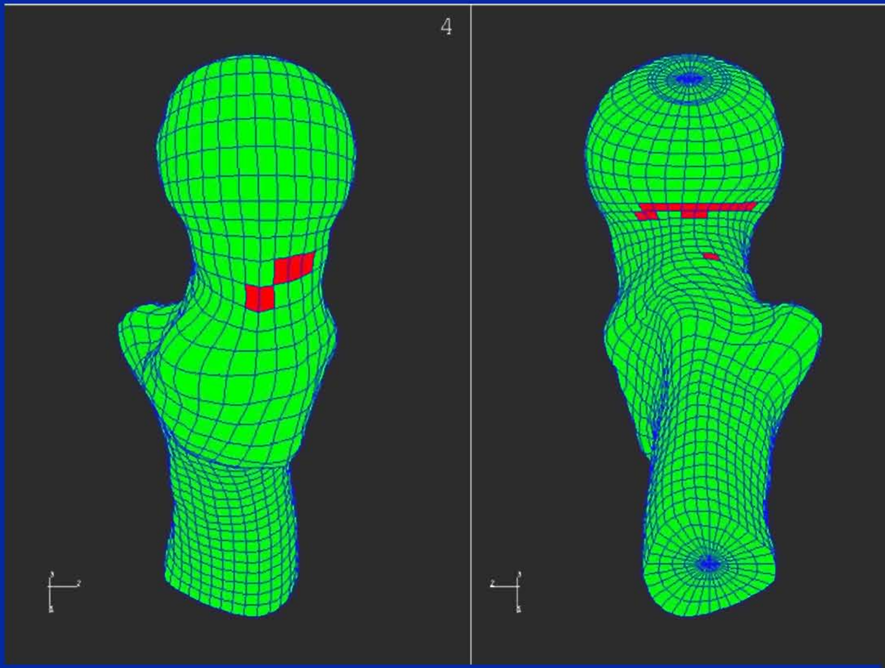

1
3
2
1

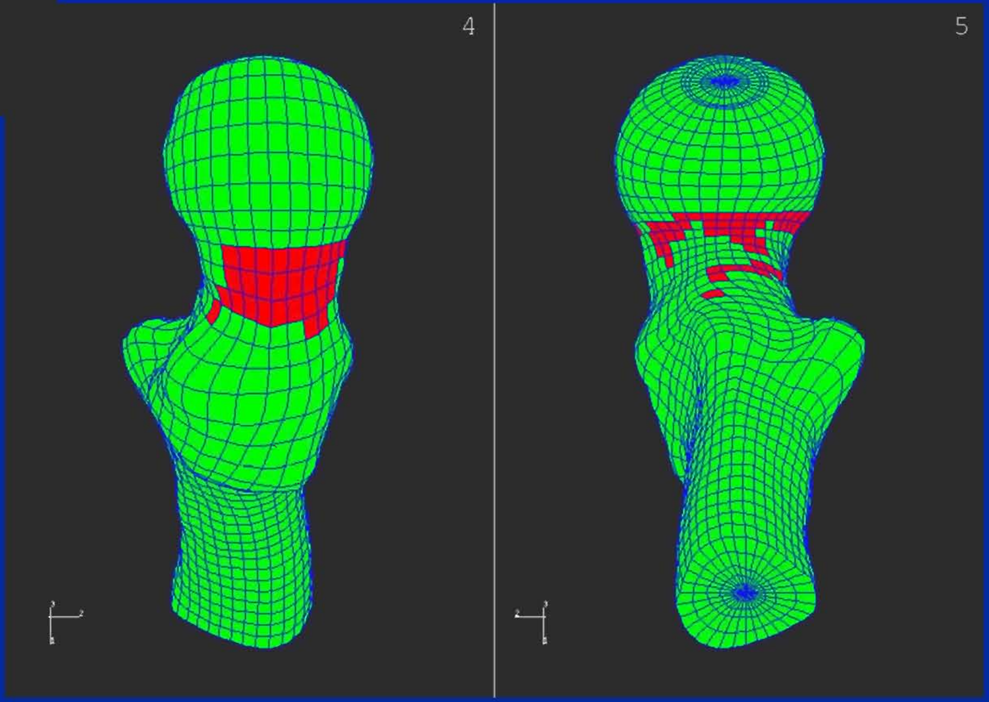
Mid-stance Loading (Pre- and Post-Flight)

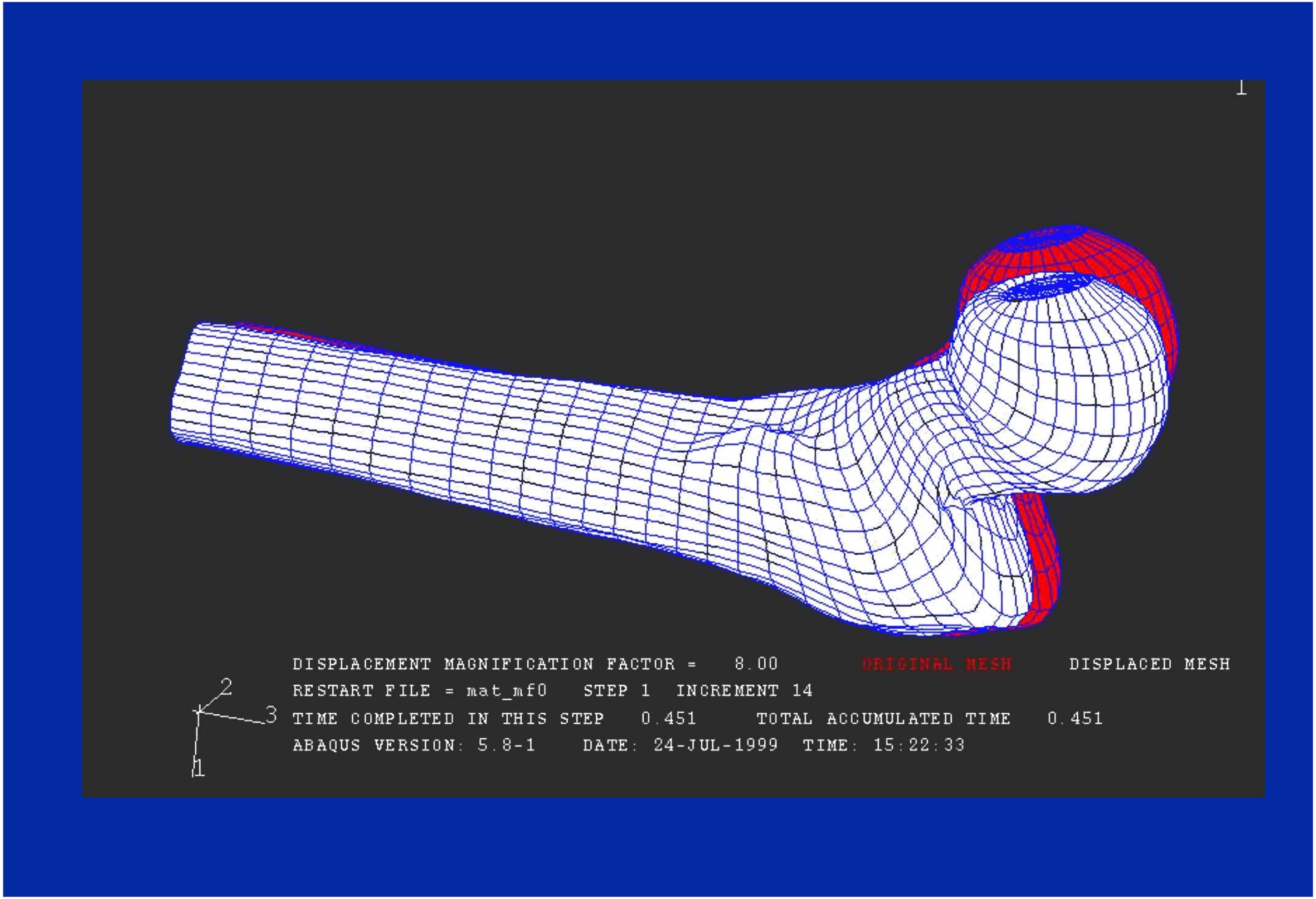



4
EP3
VALUE
-1.81E-03
+1.00E-03
+5.45E-03
+9.91E-03
+1.44E-02
+1.88E-02
+2.33E-02
+2.77E-02
+3.22E-02
+3.66E-02
+4.11E-02
+4.55E-02
+5.00E-02
+1.42E+02
3
2
1


5
2
3
1

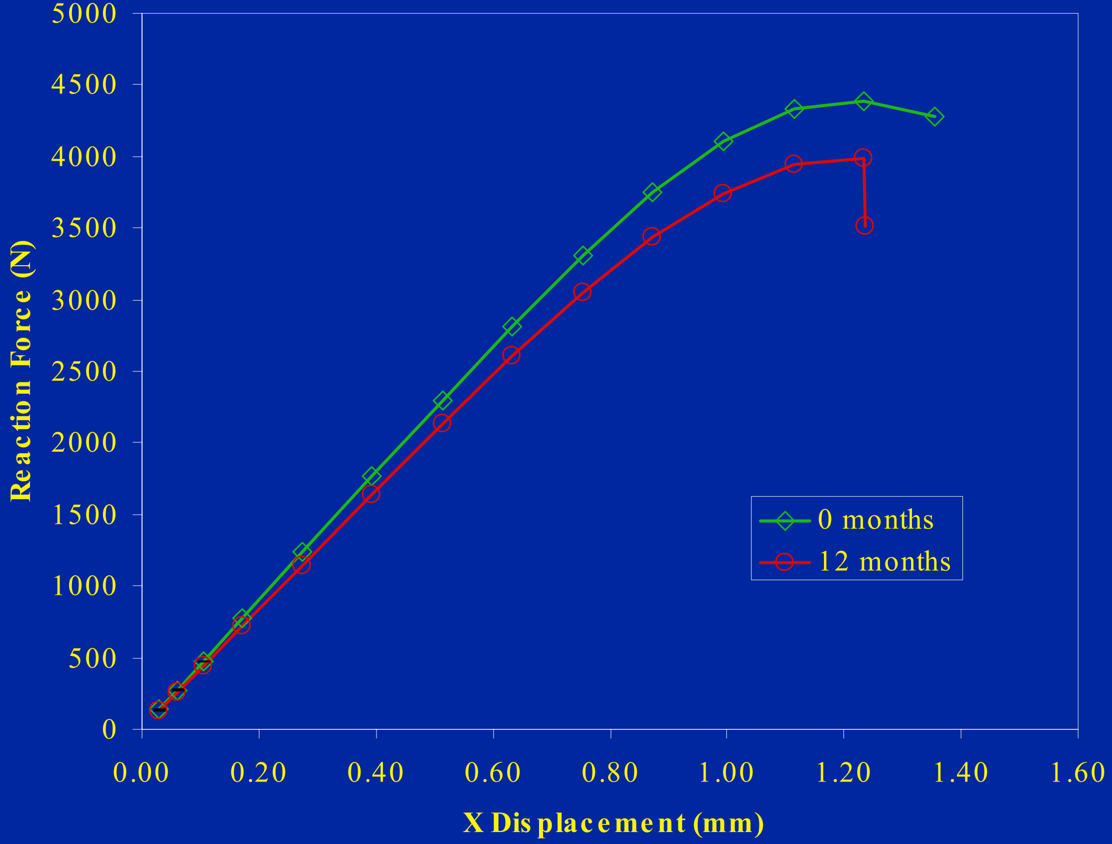

4
5

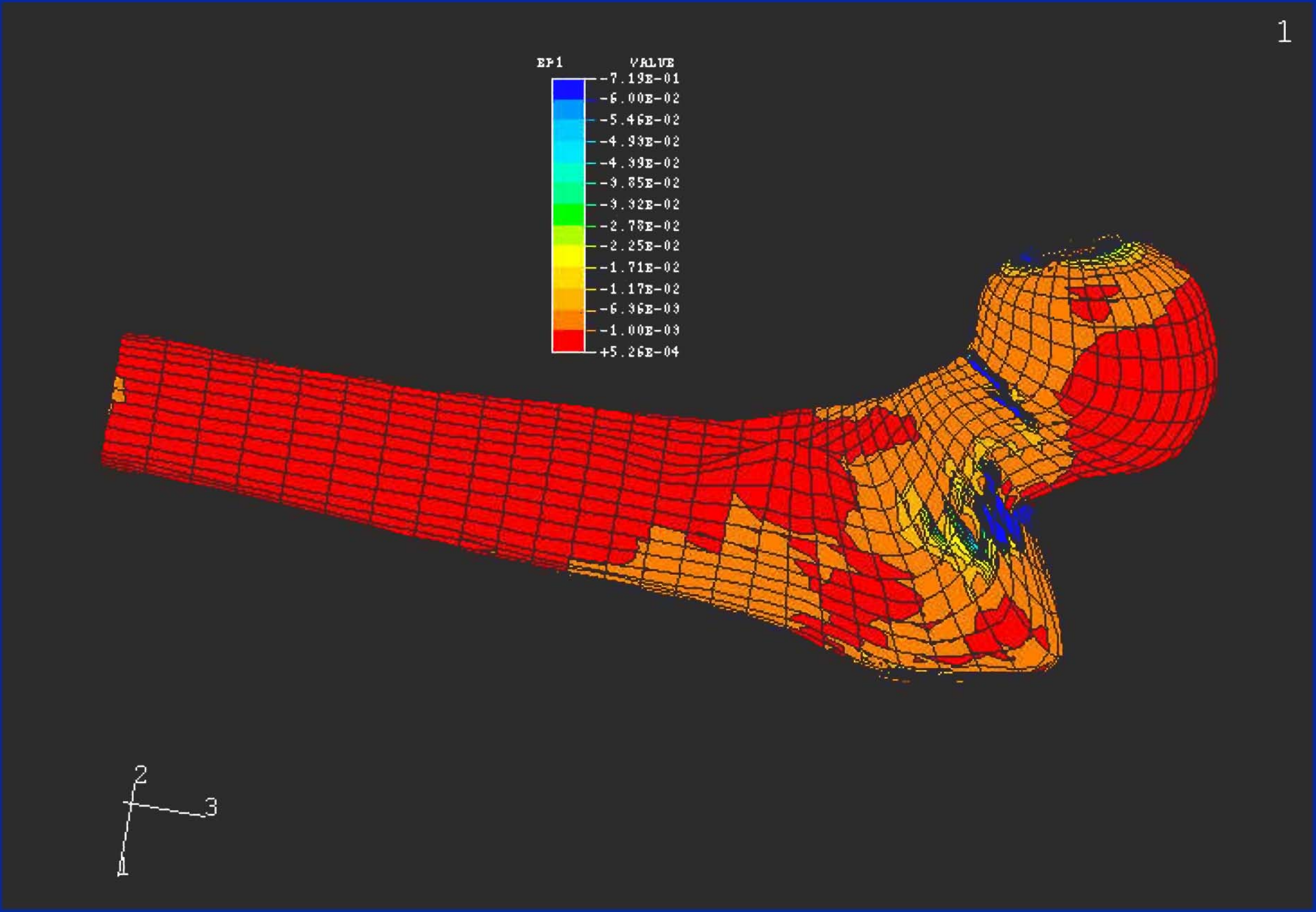

4
5

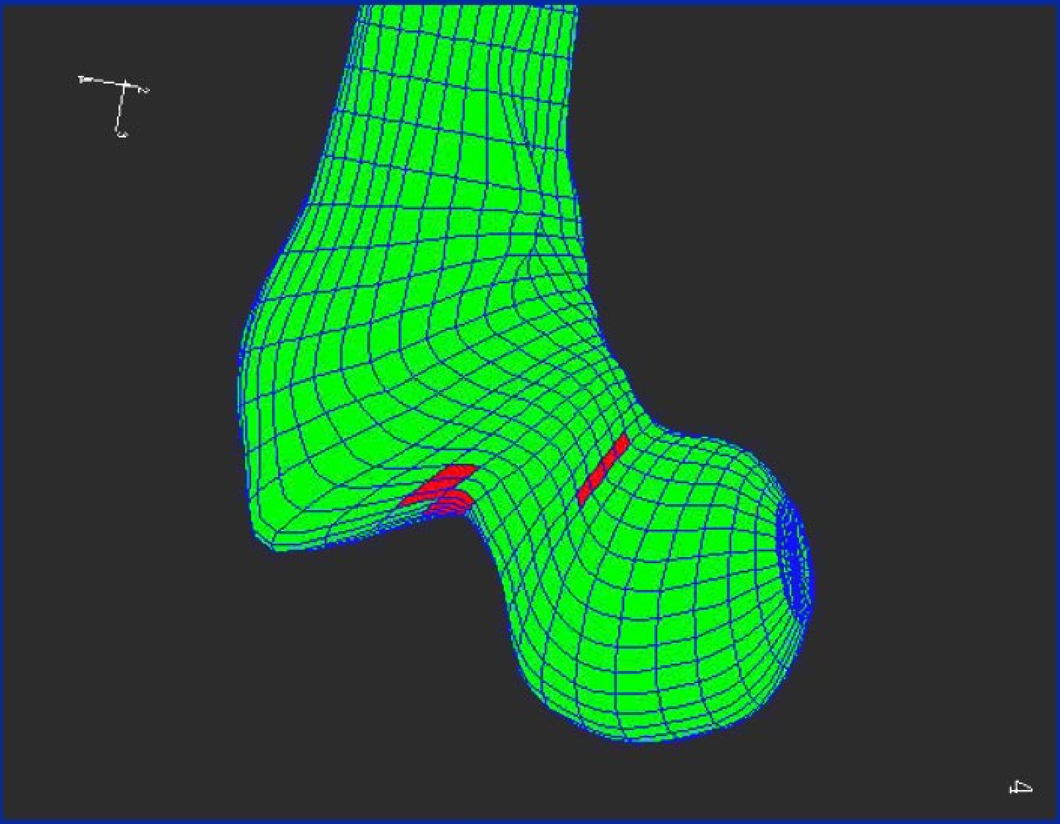


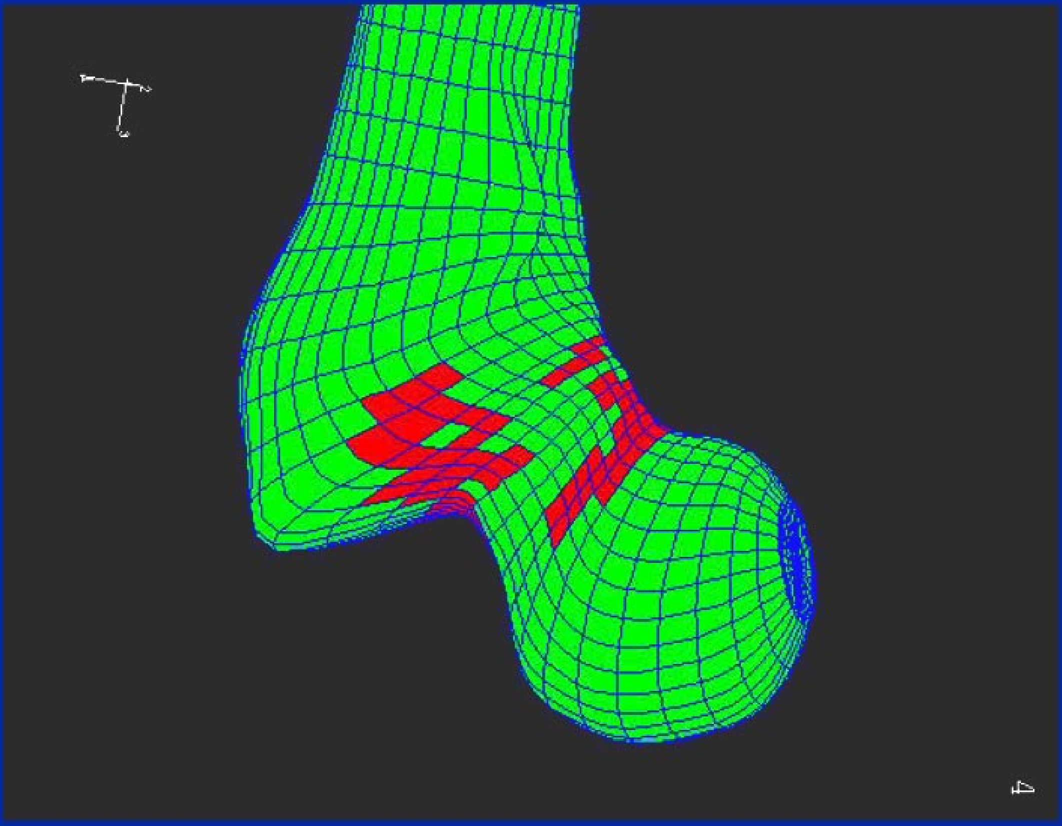
```
DISPLACEMENT MAGNIFICATION FACTOR =    8.00        ORIGINAL MESH     DISPLACED MESH
RESTART FILE = mat_mf0   STEP 1  INCREMENT 14
TIME COMPLETED IN THIS STEP   0.451      TOTAL ACCUMULATED TIME   0.451
ABAQUS VERSION: 5.8-1    DATE: 24-JUL-1999  TIME: 15:22:33
```

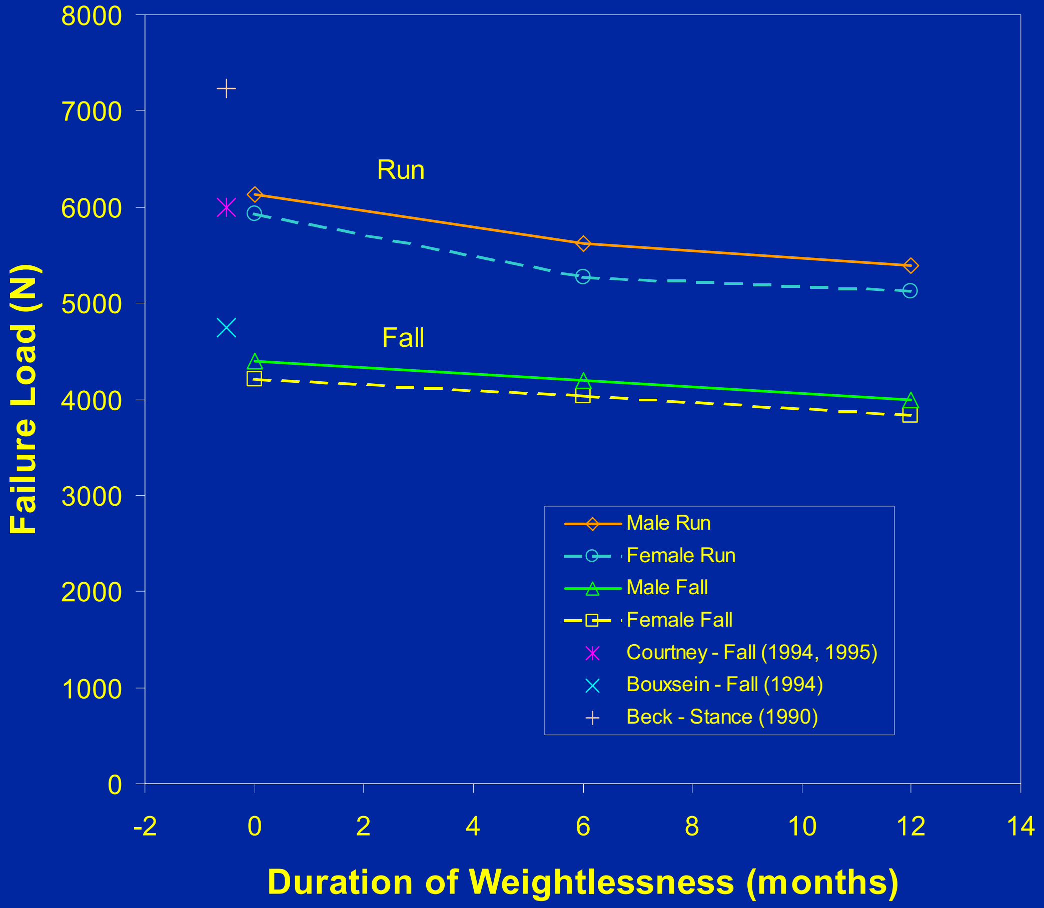
Fall Configuration Loading (Pre- and Post-flight)

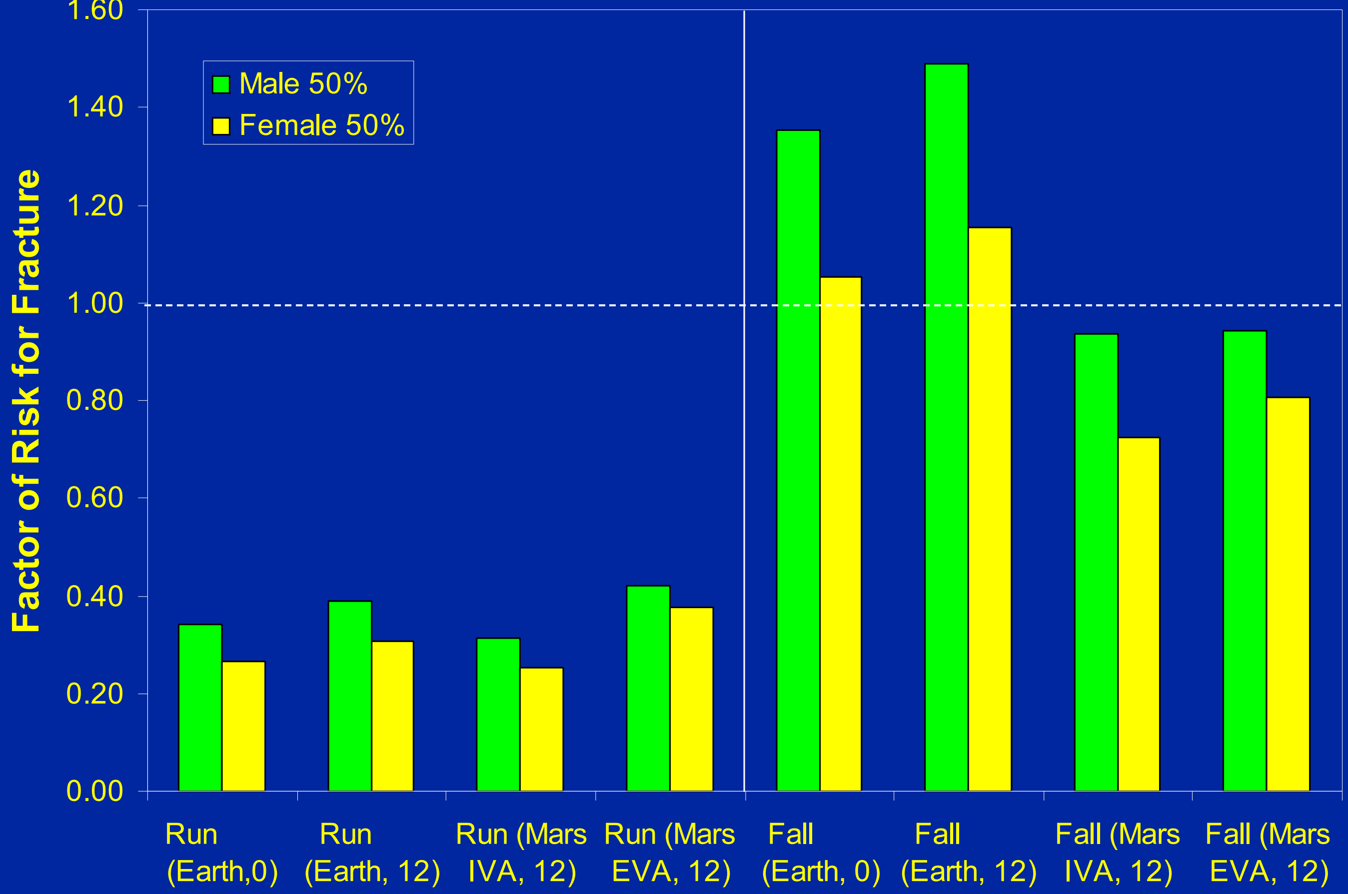



1
EP1
VALUE
-7.19E-01
-6.00E-02
-5.46E-02
-4.93E-02
-4.39E-02
-3.85E-02
-3.32E-02
-2.78E-02
-2.25E-02
-1.71E-02
-1.17E-02
-6.36E-03
-1.00E-03
+5.26E-04
2
3
1


4


4


Failure Load (N)
8000
7000
6000
5000
4000
3000
2000
1000
0
-2
0
2
4
6
8
10
12
14
Duration of Weightlessness (months)
Run
Fall
Male Run
Female Run
Male Fall
Female Fall
Courtney - Fall (1994, 1995)
Bouxsein - Fall (1994)
Beck - Stance (1990)



Factor of Risk for Fracture
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
🟩 Male 50%
🟨 Female 50%
Run (Earth,0)
Run (Earth, 12)
Run (Mars IVA, 12)
Run (Mars EVA, 12)
Fall (Earth, 0)
Fall (Earth, 12)
Fall (Mars IVA, 12)
Fall (Mars EVA, 12)

Conclusions

- Fall impact carries higher risk of fracture under all circumstances.
- Risk of fracture during locomotion is significantly greater for Mars EVA compared to Earth-normal and Earth-return. Reducing space suit mass is important.
- Muscles contribution during mid-stance is critical.
- Contrary to popular belief, risk of fracture during a fall on Mars (both IVA and EVA) is decreased compared to Earth-normal (lower gravity, spacesuit padding for EVA). FOR values are still close to 1.0, though, especially for males.
- Greatest risk to astronauts is from a fall occurring right after return from a long-duration mission. Use hip pads temporarily?