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 ($\Phi$)
  – $\Phi = \text{actual load} / \text{predicted failure load}$
  – hypothesis: $\Phi_{\text{pre}} < \Phi_{\text{post}}$
  – relationship between $\Phi$ and duration of weightlessness
Research Plan

Adjustable Finite Element Model

36 y.o. Male
- CT
- DXA

Gender

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

Space Flight $\Delta$:
- Incr. endost. diam.
- Red. trabec. mass
- Red. musc. strength

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

Equations of Motion:
- Lagrangian
- Kane’s method

Failure Load

Fracture Risk
$$\Phi = \frac{F_{\text{applied}}}{F_{\text{fail}}}$$

Applied Load
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:
  \( u_{\text{Earth}} = 2 - 6 \text{ m/s} \) (He et al., 1991)
  \( u_{\text{Mars}} = 2 - 4 \text{ m/s} \) (Newman et al., 1994; Wickman & Luna, 1996)

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

• Gravity:
  Earth \( G = g \), Mars \( G = 3/8 \text{ g} \) (\( g = 9.807 \text{ m/s}^2 \))

• Initial ankle angle: iteration until lowest point of hip trajectory occurs at \( x=0 \) (initial knee angle set to 5 deg)
Hip Locus (50% Male)

X-location (m)

Y-location (m)

Earth
Mars
Male (Earth)

Horizontal Velocity (m/s)

Peak Force (N)

(95%)
(50%)
(5%)

van den Bogert (1999)
Bergmann (1993)
Bassey (1997)
McMahon & Cheng (1990)
McMahon (1987)

McMahon (1987)
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: $K_{\text{Earth}} = 71 \ kN/m$ (Robinovitch, et al., 1991)
    $K_{\text{Mars}} = 57 \ kN/m$ (20% less for space suit padding)
  – Damping: $B = 923 \ N/m\cdot s$ (damping ratio = 0.2, Robinovitch, et al., 1991)
Joint Angle (50% Male — Earth)

-80
-60
-40
-20
0
20
40
60
80
100
120

0 0.1 0.2 0.3 0.4 0.5 0.6 0.7

Time (s)

Joint Angle (deg)

ankle X
knee Y
hip X
ankle Y
hip Y
Hip Force (50% Male — Earth)

Impact Force (N)

Ftotal

Fz

Fy

Fx

Time (s)
Peak Impact Force vs Kgnd (Mars EVA)

- Male (50%)
- Female (50%)
Hip Force during Impact (Male)

Peak Force (N)

Percentile

Earth
Parkkari (1995)
Robinovitch (1995)
Mars EVA
Mars IVA
Hip Force during Impact (Female)

- Peak Force (N)
- Percentile
- Earth
- Mars EVA
- Mars IVA
- van den Kroonenberg - dynam (1995)
- van den Kroonenberg - exper (1996)
Fall impact forces reduced by 15% to account for soft tissue attenuation (Robinovitch et al., 1997)

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

Extract density distribution (trabecular area)
Define element material properties

3-D Finite Element Model
**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
Z rotation = +15 deg

Y rotation = +10 deg
Element Material Properties

**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
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] :

<table>
<thead>
<tr>
<th></th>
<th>Mag (BW)</th>
<th>X (med-lat)</th>
<th>Y (post-ant)</th>
<th>Z (dist-prox)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gluteus medius</td>
<td>0.80</td>
<td>-0.67</td>
<td>0.18</td>
<td>0.72</td>
</tr>
<tr>
<td>Gluteus minimus</td>
<td>0.30</td>
<td>-0.78</td>
<td>0.21</td>
<td>0.59</td>
</tr>
<tr>
<td>Iliopsoas</td>
<td>1.30</td>
<td>-0.10</td>
<td>0.73</td>
<td>0.68</td>
</tr>
</tbody>
</table>

• 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

ABAQUS User Subroutine

Calculate $\varepsilon_{\text{max}}(\text{prin}), \varepsilon_{\text{min}}(\text{prin})$

Node Failure?

Yes
Reduce Modulus

No
Update $\varepsilon, \sigma$

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

Model Failure?

Yes
End

No

FE Model

Increment Displacement

Calculate Strains and Reaction Forces

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

Reaction Force (N) vs. Z Displacement (mm)

- 0 months (muscles)
- 0 months (no muscles)
- 12 months
Duration of Weightlessness (months)

Failure Load (N)

Run

Fall

Male Run
Female Run
Male Fall
Female Fall
Courtney - Fall (1994, 1995)
Bouxsein - Fall (1994)
Beck - Stance (1990)
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)

Factor of Risk for Fracture

Male 50%
Female 50%
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?