RISK ASSESSMENT OF BONE FRACTURE DURING SPACE EXPLORATION MISSIONS TO THE MOON AND MARS

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Abstract

The possibility of a traumatic bone fracture in space is a concern due to the observed decrease in astronaut bone mineral density (BMD) during spaceflight and because of the physical demands of the mission. The Bone Fracture Risk Module (BFxRM) was developed to quantify the probability of fracture at the femoral neck and lumbar spine during space exploration missions. The BFxRM is scenario-based, providing predictions for specific activities or events during a particular space mission. The key elements of the BFxRM are the mission parameters, the biomechanical loading models, the bone loss and fracture models and the incidence rate of the activity or event. Uncertainties in the model parameters arise due to variations within the population and unknowns associated with the effects of the space environment. Consequently, parameter distributions were used in Monte Carlo simulations to obtain an estimate of fracture probability under real mission scenarios. The model predicts an increase in the probability of fracture as the mission length increases and fracture is more likely in the higher gravitational field of Mars than on the moon. The resulting probability predictions and sensitivity analyses of the BFxRM can be used as an engineering tool for mission operation and resource planning in order to mitigate the risk of bone fracture in space.
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Exploration Medicine Capabilities Project
Human Research Program

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Topics to cover

• Overview of Integrated Medical Model (IMM) and Bone Fracture Risk Module (BFxRM)
• Definition of Fracture Risk Index (FRI)
• Library of biomechanical models used to estimate load on bones during activities and events
• Decrease of Bone Mineral Density (BMD) in space and relationship between BMD and ultimate strength of bone
• Model uncertainty
• Earth based validations of models
• Sample results – probability of fracture on moon and Mars missions
• Conclusions
The Integrated Medical Model (IMM) is a tool for quantifying the probability and consequences of medical risks. It integrates best evidence in a quantifiable assessment of risk and identifies medical resources such as skills, equipment, and supplies necessary to optimize mitigation strategies.
Bone Fracture Risk Module (BFxRM)

Biomechanics and Mission Operations

Bone Loss in Space

Estimate of Fracture Probability

Clinical and Engineering Characteristics of Bone Strength

- Probability of Fracture
- Probability bone will fail to support load
- Probability of event
Fracture Risk Index (FRI)

• The ratio of the load experienced by the bone during an activity to the ultimate strength of the bone.
  – An FRI of less than one indicates that the bone should be strong enough to support the load
  – An FRI of greater than one indicates that there is a significant risk of bone fracture.

Loads experienced by the bone are estimated with biomechanical models.

The ultimate strength of bone is found from testing the strength of cadaver bone.


Library of biomechanical loading models

Femoral Neck – Fall to the side

Hip mass

Stiffness and damping of hip pad and ground


Lumbar Spine – Fall, landing on two feet

Upper body mass

Stiffness and damping of lumbar spine

Pelvis and leg mass

Stiffness of leg

Foot mass

Stiffness and damping of ground


Lumbar Spine – Trunk flexed, holding a load

Load on Spine

CoM

Load

BMD Loss in space over time

\[ \text{BMD}_{\text{DoE}} = \text{BMD}_{\text{Start}} \left(1 - \frac{\text{BMD}_{\text{Loss}}}{\text{BMD}_{\text{Start}}} \right) \]

- \( \text{BMD}_{\text{DoE}} = \text{BMD value on the day of the event} \)
- \( \text{BMD}_{\text{Start}} = \text{BMD at the beginning of the mission} \)
- \( \text{BMD}_{\text{Loss}} = \text{The amount of BMD loss prior to the day of the event} \)

Data used to determine slope includes LSHA Data and Published Data and takes into consideration uncertainty.
Relationship between BMD and Ultimate Load of bone for different loading conditions


BFxRM uncertainty

- Monte Carlo and Latin Hypercube simulations performed to determine most likely probability since:
  - The system parameters (i.e. astronaut mass, reference BMD level, BMD loss per day, ultimate strength/BMD, anthropometric values, physiological stiffness and damping constants, angle of trunk flexion, load lifted, etc.) are defined as distributions over a range of values.
  - The event could happen on any day during the mission
Earth based validations—Static lumbar spine model

Comparison of lumbar spine loading calculations

Comparison of FRI calculations


Earth based validations – Static lumbar spine model

Comparison of Ultimate Load vs. Age

Comparison of % FRI above 1 vs. Age


Earth based validations – Dynamic lumbar spine model

Comparison of Ground Reaction Force calculations

Earth based validations – Dynamic lumbar spine model

Comparison of fracture prediction for a fall height distribution

Our simulations predicted an FRI above 1 for 34.2% of the trials. Goonetilleke found 29.7% of falls in his study resulted in fracture.

Example results

Probability of fracture of the lumbar spine by a male or female astronaut due to lifting a load with the trunk flexed during an EVA during a long duration, Lunar mission.

<table>
<thead>
<tr>
<th>Gender</th>
<th>Mean Probability</th>
<th>Standard Deviation</th>
<th>5%</th>
<th>95%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Male</td>
<td>3.19e-4</td>
<td>1.17e-4</td>
<td>1.84e-4</td>
<td>5.36e-4</td>
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<tr>
<td>Female</td>
<td>3.28e-4</td>
<td>1.36e-4</td>
<td>1.8e-4</td>
<td>5.85e-4</td>
</tr>
</tbody>
</table>
Example results

Probability of fracture of the lumbar spine by a male or female astronaut due to a 1m fall during an EVA during a long duration, Martian mission.

<table>
<thead>
<tr>
<th>Gender</th>
<th>Mean Probability</th>
<th>Standard Deviation</th>
<th>5%</th>
<th>95%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Male</td>
<td>2.64e-3</td>
<td>5.36e-3</td>
<td>5.54e-5</td>
<td>1.19e-2</td>
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<tr>
<td>Female</td>
<td>3.02e-3</td>
<td>6.00e-3</td>
<td>5.97e-5</td>
<td>1.39e-2</td>
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</tbody>
</table>
Conclusions

• A model has been developed that bounds the uncertainty associated with the risk of bone fracture in space.
  – Integrative approach accounting for extenuating factors
    • Equipment and Vehicle
    • Bone Health
    • Training and Operations

• The model can be used to predict the most likely probability of bone fracture in space.
  – “what if” scenarios
    • What if reduced gravity is osteo-protective?
    • What if the FFD is reduced to t-score of -1.25?

• The model can be used as a useful engineering tool during mission planning.
Future Work

• Wrist fracture risk assessment

• Renal stone formation risk assessment

• Insomnia and circadian rhythm upset risk assessment
Acknowledgements

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  – Joyce Keyak and Tom Lang - NSBRI
  – John Charles – Acting Chief Scientist HRP Program NASA-JSC
  – ExMC and IMM development teams
Extra Slides
Calculating Bone Ultimate Structural Strength

**Posteriorateral fall:**
UL Reduced up to 0.8% per Degree

- **State of Bone at 1g**
- **Pre-Flight DEXA-BMD**

**Estimate Time Course to and Degree Of Bone Loss at Skeletal Location**
On day of loading

**Use BMD correlations to Estimate UL**

- **NHANES DATA** - Represents Pre-Flight Bone Health, FFD Standards And Reference Max BMD Condition
- **Based on appropriate ex vivo test data**

**Apply UL attenuation for load direction**

**Ultimate Structural Load Capacity for Loading Conditions**

- **Maximum Loss Est. With Pop. Variability**
- **Linear or Exponential Model**

**Graph:**
- **Male:** UL = 11249*BMD - 3510
  - R^2 = 0.88, SEE = 613
- **Female:** UL = 9231*BMD - 2546
  - R^2 = 0.83, SEE = 515

**Table:**
- **Female**
  - Average CF - female
- **Male**
  - Average CF - Male

<table>
<thead>
<tr>
<th>BMD (g/cm²)</th>
<th>Male UL</th>
<th>Female UL</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.35</td>
<td>0.45</td>
<td>0.55</td>
</tr>
<tr>
<td>1000</td>
<td>11249</td>
<td>9231</td>
</tr>
<tr>
<td>2000</td>
<td>-3510</td>
<td>-2546</td>
</tr>
<tr>
<td>3000</td>
<td></td>
<td></td>
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</tbody>
</table>

- **Linear Loss Model With Pop. Variability**
- **Maximum Loss Est. With Pop. Variability**

www.nasa.gov 20
Calculating Loading in Reduced Gravity Environment

Loading Event Occurs From Specified Activity or Incident

EVA Suit Mass & Padding

Active Response

Estimate of Load w/ 1g Biomechanics

Scale Load to Gravity Level Using Appropriate Methods

Determine Load Additive or Attenuation Factors

Resultant Skeletal Load

\[ F = \frac{m \sqrt{2gh}}{\Delta t} \]

\[ F_n = F_n \cdot \left( \frac{\Delta t_n}{\Delta t} \right)^{-1} \cdot \left( \frac{g_m}{g_e} \right)^{\frac{1}{2}} \cdot \left( \frac{h_m}{h_e} \right) \]

Uses the change in momentum
Includes additional mass

UPDATE: Newest models use simulations based on Robinovitch type loading simulations

Represents a perceived loading state during on surface activities
Tying It All Together: Falls to the Side Impacting Proximal Femur

Probability of FN Fracture

Probability bone will fail to support load

Probability of 1 or more Falls

Probability fall is posteriorlateral

FRI Estimates From BFRM
- Bone Loss
- Bone Strength / Quality
- Loading Levels in Hypo-g
- Mission Characteristics
- Equipment / Suit Characteristics

Published Data Relating FRI and Fracture Probability

Estimated upper and lower bounds: FRI To Probability of Fracture

Fall Rate: 0.35/hr and \( \sigma = 0.066 \)
Pr(Postlat): 0.0517 and \( \sigma = 0.0404 \)

Published Data Relating FRI and Fracture Probability

mu = 0.58, theta = 7.7
mu = 0.95, theta = 15
mu = 0.58, theta = 15
mu = 0.95, theta = 7.7
“Smell” Test Validation

Pre-flight estimate of FRI for Unhindered Posteriolateral Fall
i.e. a fall to the side and slightly backward
Male in 1g with ~1m fall heights

IMM-BFRM
Mean = 1.98
SD = 0.90

Lang et al 2006
Mean +/- 2 SD
M = 2.1
SD = 0.47

Schaffner
Results
Probability of Fracture Due to Side Falls Male on Extra Vehicular Activity

Data Shown for Mars: 540D Surface Mission

<table>
<thead>
<tr>
<th>Mission</th>
<th>Fracture Probability</th>
<th>Std</th>
<th>5th Percentile</th>
<th>95th Percentile</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lunar: 8D Surface</td>
<td>1.50E-4</td>
<td>1.15E-3</td>
<td>3.30E-07</td>
<td>5.36E-04</td>
</tr>
<tr>
<td>Lunar: 170D Surface</td>
<td>1.94E-4</td>
<td>1.54E-3</td>
<td>3.47E-07</td>
<td>6.15E-04</td>
</tr>
<tr>
<td>Mars: 40D Surface</td>
<td>1.44E-3</td>
<td>7.66E-3</td>
<td>1.15E-06</td>
<td>4.85E-03</td>
</tr>
<tr>
<td>Mars: 540D Surface</td>
<td>2.47E-3</td>
<td>9.95E-3</td>
<td>1.68E-06</td>
<td>1.15E-02</td>
</tr>
</tbody>
</table>

Lateral/Posteriolateral Fall heights range from .25m to ~1m
Bone loss not attenuated by partial gravity
The suit attenuation characteristics and the impulse scaling factors produce the most sensitivity.

Interesting to note that:
- Successful reaction to the fall is the next most driving factor.
- Bone loss rates are not as significant for lunar missions.
- Reference BMD produces more sensitivity to the calculation than rate of bone loss in both scenarios.