Sensitivity Analysis of the Bone Fracture Risk Model

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Introduction

• The probability of astronaut bone fracture before, during and after spaceflight is quantified with the NASA Bone Fracture Risk Module (BFxRM)*

• The BFxRM uses a probabilistic modeling approach with distributions of model parameters which introduce uncertainty into the probability results

• This uncertainty masks the ability to quantify the effect of countermeasures on fracture probability

Introduction

• We hypothesize that the large uncertainty is due to the inability to measure key contributors to bone strength with areal bone mineral density (aBMD) techniques*

• This presentation reports the results of a sensitivity analysis of the BFxRM in order to identify the parameters which contribute the most to the uncertainty

BFxRM Model Components

- A biomechanical model to estimate applied loads from a loading event
- An algorithm for spaceflight bone mineral density (BMD) loss and a mathematical relationship between BMD and bone strength
- The fracture risk index (FRI) which is the ratio of applied load to bone strength
- An algorithm to convert FRI to bone fracture probability

Monte Carlo Simulation

- Probability and magnitude of loading event
- Estimate relative skeletal strength
- Est. fx probability by load to strength ratio
- Most likely probability of fracture for event + uncertainty
BFxRM Model Parameters

- Environmental factors
  - Gravity level
  - EVA suit/no EVA suit
- Factors associated with the fall event
  - Fall height
  - Translational velocity
  - Attenuation
- Mass and anthropometric values of the astronaut
  - Body mass
  - Effective hip mass
  - Hip spring and damping characteristics
- BMD characteristics
  - Preflight BMD value
  - Rate of BMD loss during spaceflight
  - Maximum BMD loss
  - Recovery half-life
- Characteristics of the relationship between BMD and bone strength
  - Slope of the relationship
  - Intercept of the relationship
- Bone fracture characteristics
  - Parameters associated with the conversion between FRI and fracture probability
Sensitivity Analysis

• Performed to determine which parameters cause the most variation in model results

• Fracture probability for pre-flight, 0 days post-flight and 365 days post-flight is calculated 100,000 times as the parameter distributions are sampled

• A correlation coefficient is found between the sample set of each model parameter and the calculated fracture probabilities

• Each parameter’s contribution to the variance is found by:
  – Squaring the correlation coefficients
  – Dividing by the sum of the squared correlation coefficients
  – Multiplying by 100%
Results

- The top five most sensitive parameters:

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Preflight % Variance</th>
<th>0 days Post-flight % Variance</th>
<th>365 days Post-flight % Variance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hip Spring Constant ($k_H$)</td>
<td>36.7</td>
<td>37.7</td>
<td>37.4</td>
</tr>
<tr>
<td>Probability Equation Midpoint FRI Value ($\mu$)</td>
<td>35.5</td>
<td>29.0</td>
<td>33.4</td>
</tr>
<tr>
<td>Preflight Trochanter BMD ($BMD_{\text{Pre}}$)</td>
<td>19.9</td>
<td>21.7</td>
<td>20.6</td>
</tr>
<tr>
<td>Trochanter Bone Strength Equation Intercept ($B_{BSE}$)</td>
<td>4.56</td>
<td>5.16</td>
<td>4.7</td>
</tr>
<tr>
<td>Effective Hip Mass Multiplier ($h_m$)</td>
<td>1.65</td>
<td>1.50</td>
<td>1.58</td>
</tr>
</tbody>
</table>
Future Work

• Updates to the BFxRM are planned
  – Update the applied load model with any additional hip spring and damping constant information from new journal articles
  – Perform a Bayesian update to the BMD to bone strength relationship using FEM bone strength data
  – Update the relationship between FRI and fracture probability with data sets that include fracture outcomes
  – Identify additional validation tests that can be performed and update the NASA-STD-7009A compliance matrix for the BFxRM
Thank you

Questions?