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

1. Probability and magnitude of loading event
2. Estimate relative skeletal strength
3. Est. fx probability by load to strength ratio
4. 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 ($BMD_{pre}$)</td>
<td>19.9</td>
<td>21.7</td>
<td>20.6</td>
</tr>
<tr>
<td>Trochanter Bone Strength Equation Intercept ($B_{PC}$)</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?