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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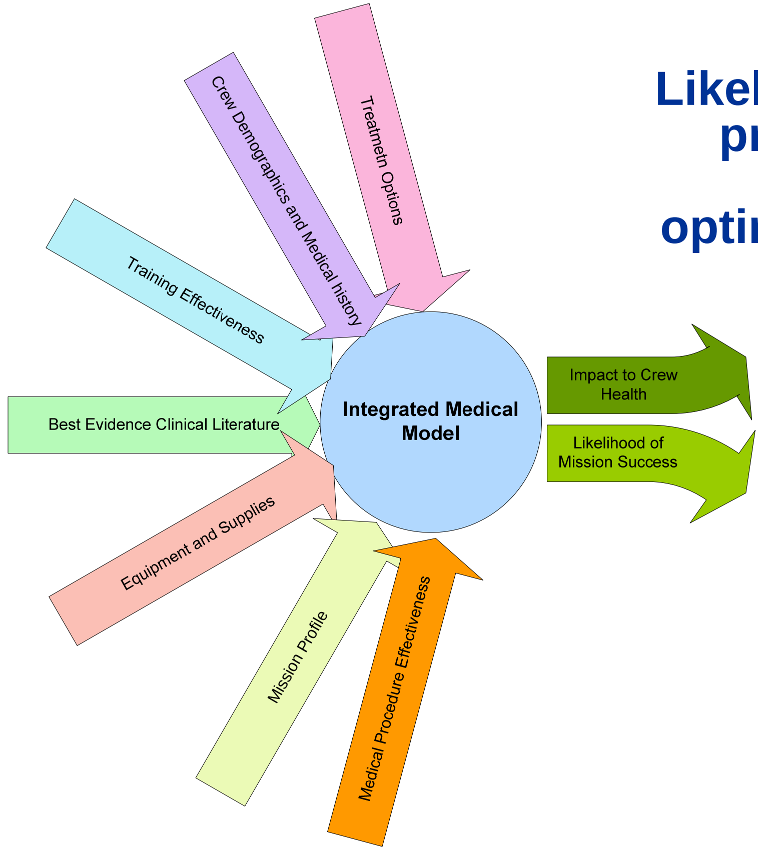
Topics to cover

- 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

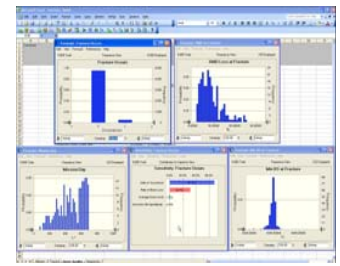
Integrated Medical Model (IMM)

Potential Medical Condition

Evaluate with IMM



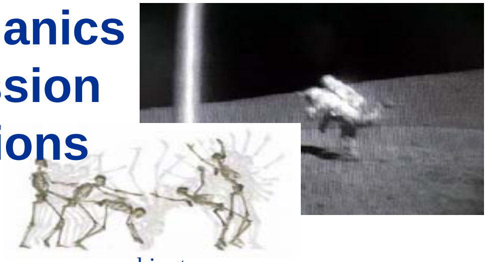
Likelihood of occurrence, probable severity of occurrence, and optimization of treatment and resources.



- The Integrated Medical Model (IMM) is a tool for quantifying the probability and consequences of medical risks
- Integrate best evidence in a quantifiable assessment of risk
- Identify medical resources such as skills, equipment, and supplies necessary to optimize mitigation strategies.

Bone Fracture Risk Module (BFxRM)

Biomechanics and Mission Operations



courses.washington.edu/me598rc

Bone Loss in Space

Estimate of Fracture Probability

Probability of Fracture

Probability of event

Probability bone will fail to support load

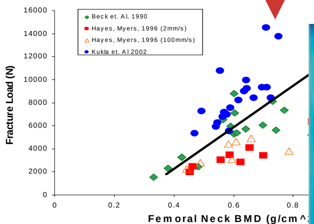


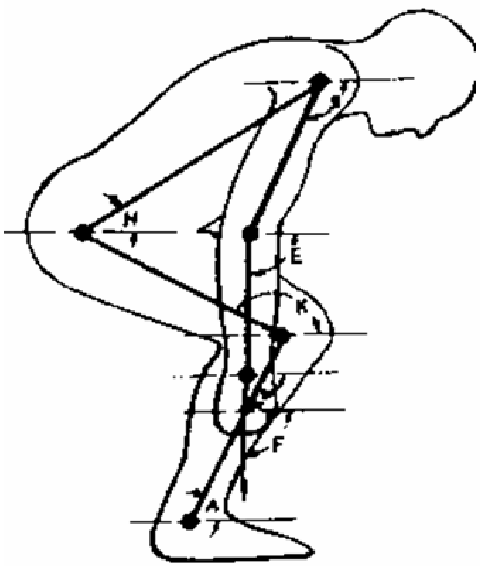
Figure 2. Summary of literature survey on fracture load as a neck BMD

Clinical and Engineering Characteristics of Bone Strength

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.

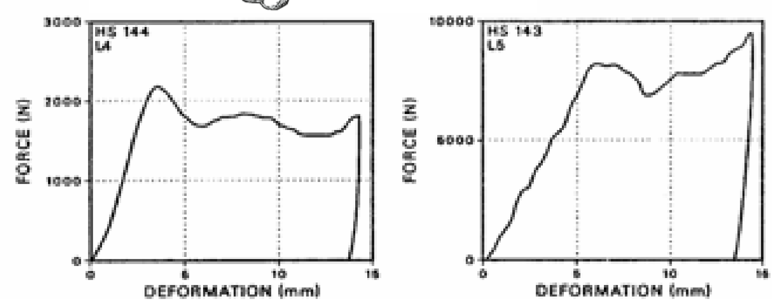
Loads experienced by the bone are estimated with biomechanical models



Chaffin DB, Baker WH, A biomechanical model for analysis of symmetric sagittal plane lifting, *AIIE Transactions*, 2(1), March 1970, pp. 16-27

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

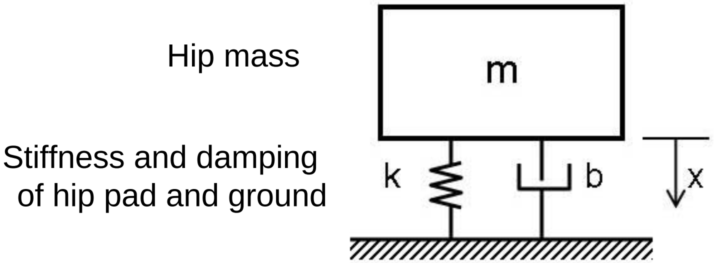
http://www.bartleby.com



Yoganandan N, Pintar F, Sances A, Maiman D, Mykelbust J, Biomechanical investigations of the human thoracolumbar spine, *In Biomechanics of Impact Injuries and Injury Tolerances of the Abdomen, Lumbar Spine and Pelvis Complex*, Edited by SH Backaitis, Society of Automotive Engineers, Inc., 1995, pp. 97 – 114.

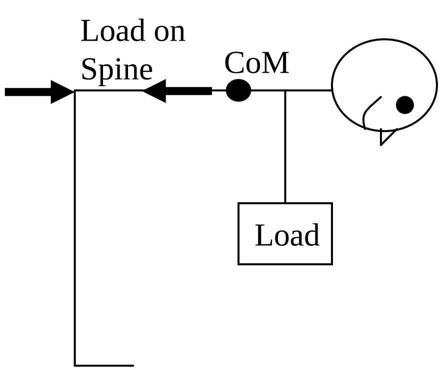
Library of biomechanical loading models

Femoral Neck – Fall to the side



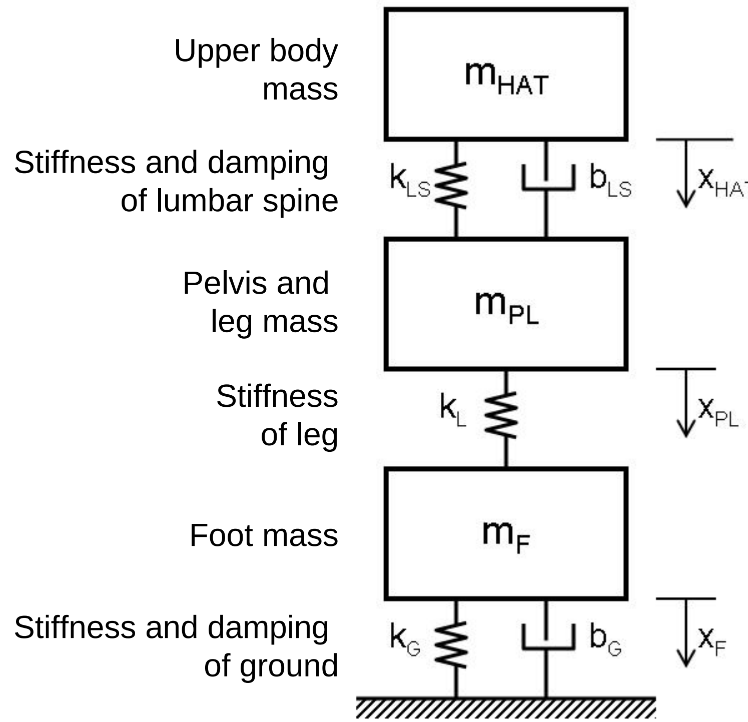
S. N. Robinovitch, W. C. Hayes, and T. A. McMahon, "Prediction of femoral impact forces in falls on the hip," *J. Biomech. Eng, vol. 113, no. 4, pp. 366-374, Nov.1991.*

Lumbar Spine – Trunk flexed, holding a load



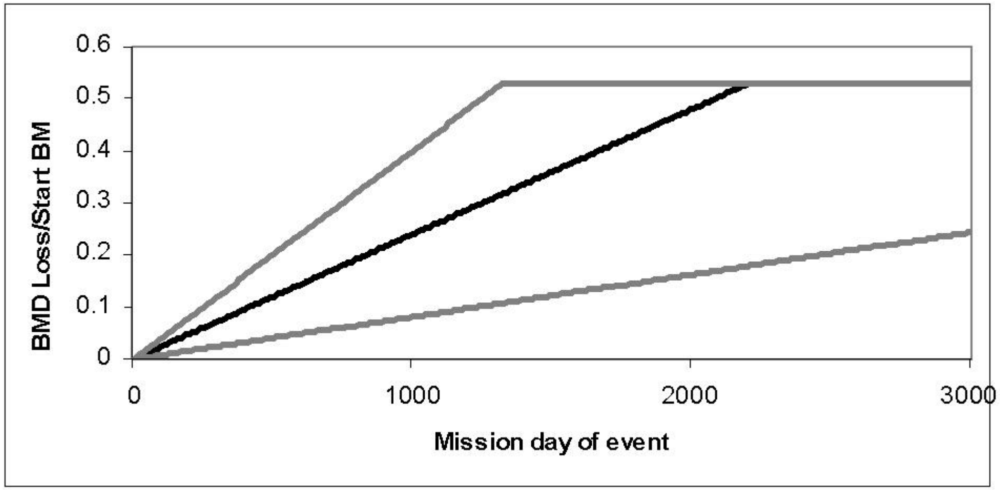
A. Schultz, G. B. Andersson, R. Ortengren, R. Bjork, and M. Nordin, "Analysis and quantitative myoelectric measurements of loads on the lumbar spine when holding weights in standing postures," *Spine, vol. 7, no. 4, pp. 390-397, July1982.*

Lumbar Spine – Fall, landing on two feet



K. J. Chi and D. Schmitt, "Mechanical energy and effective foot mass during impact loading of walking and running," *J. Biomech., vol. 38, no. 7, pp. 1387-1395, July2005.*

BMD Loss in space over time



$$BMD_{DoE} = BMD_{Start}\left(1 - \frac{BMD_{Loss}}{BMD_{Start}}\right)$$

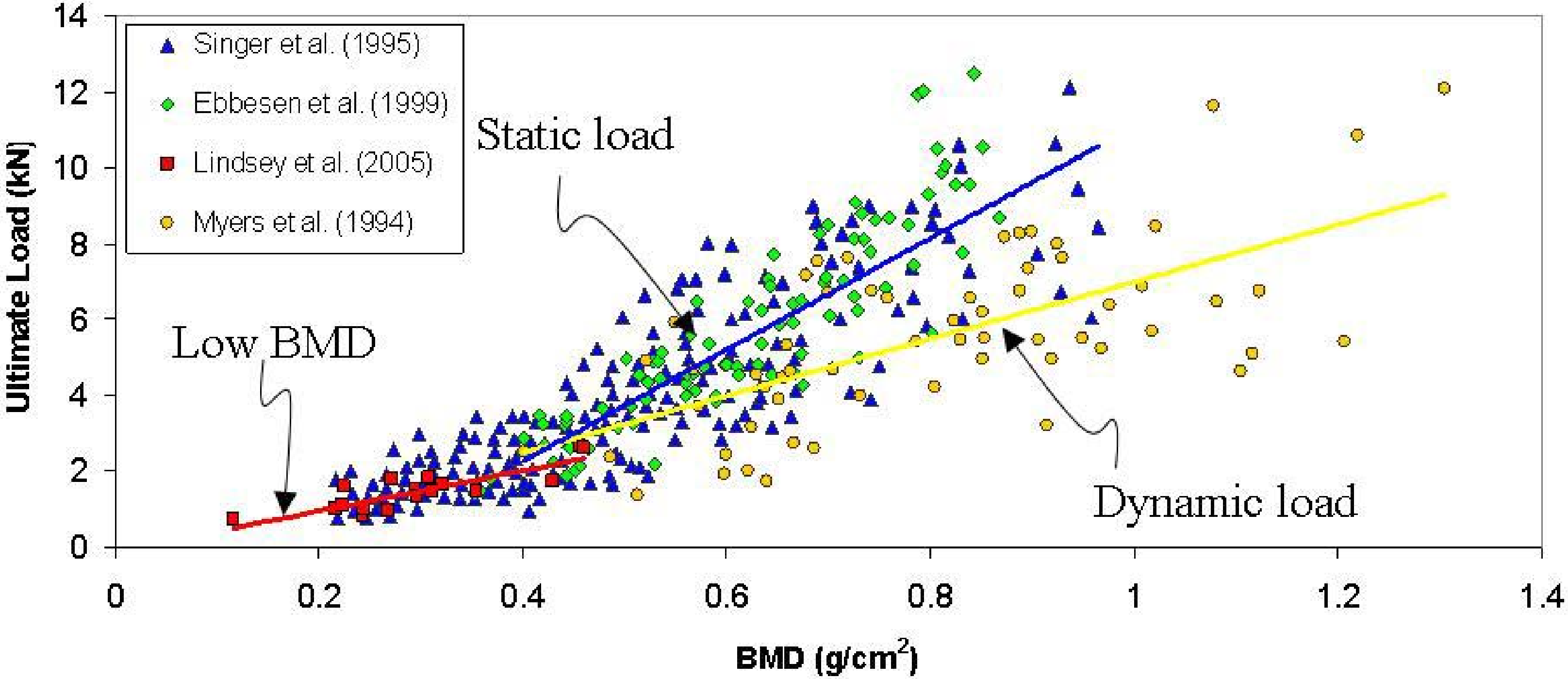
BMD_{DoE} = *BMD value on the day of the event*

BMD_{Start} = *BMD at the beginning of the mission*

BMD_{Loss} = *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



K. Singer, S. Edmondston, R. Day, P. Breidahl, and R. Price, "Prediction of thoracic and lumbar vertebral body compressive strength - Correlations with Bone Mineral Density and vertebral region," *Bone, vol. 17, no. 2, pp. 167-174, 1995.*

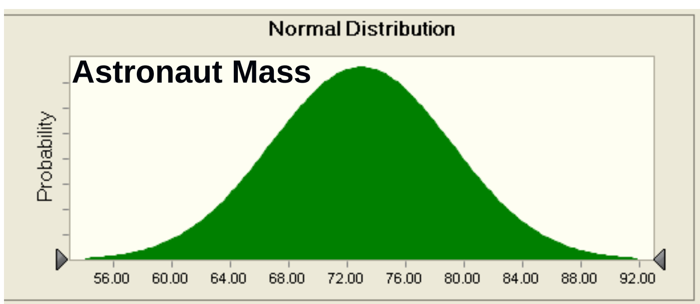
E. N. Ebbesen, J. S. Thomsen, H. Beck-Nielsen, H. J. Nepper-Rasmussen, and L. Mosekilde, "Lumbar vertebral body compressive strength evaluated by dual-energy X-ray absorptiometry, quantitative computed tomography, and ashing," *Bone, vol. 25, no. 6, pp. 713-724, Dec.1999.*

D. P. Lindsey, M. J. Kim, M. Hannibal, and T. F. Alamin, "The monotonic and fatigue properties of osteoporotic thoracic vertebral bodies," Spine, vol. 30, no. 6, pp. 645-649, Mar.2005.

B. S. Myers, K. B. Arbogast, B. Lobaugh, K. D. Harper, W. J. Richardson, and M. K. Drezner, "Improved assessment of lumbar vertebral body strength using supine lateral dual-energy x-ray absorptiometry," *J. Bone Miner. Res., vol. 9, no. 5, pp. 687-693, May1994.*

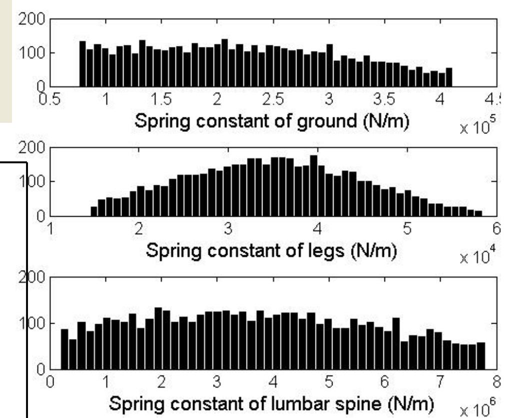
BFxRM uncertainty

- 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

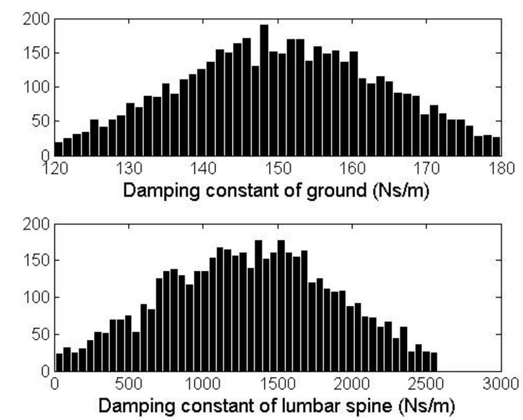


Mission day of event

Stiffness constants

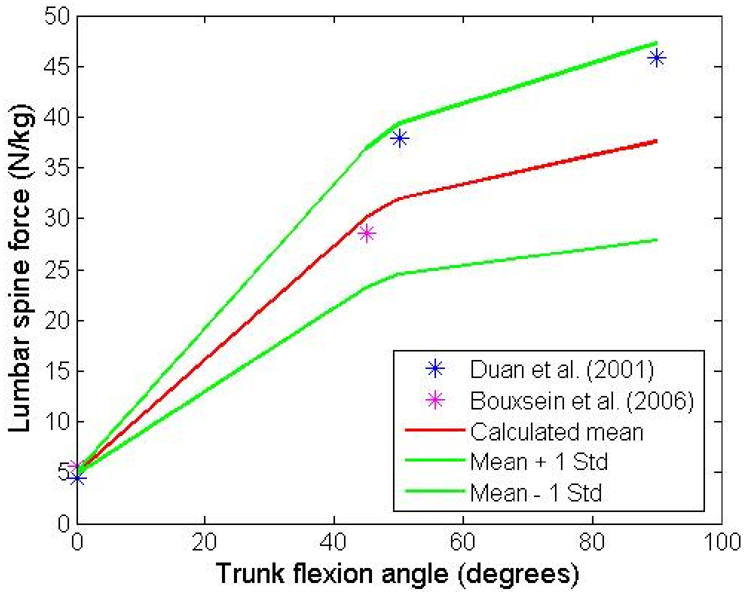


Damping constants

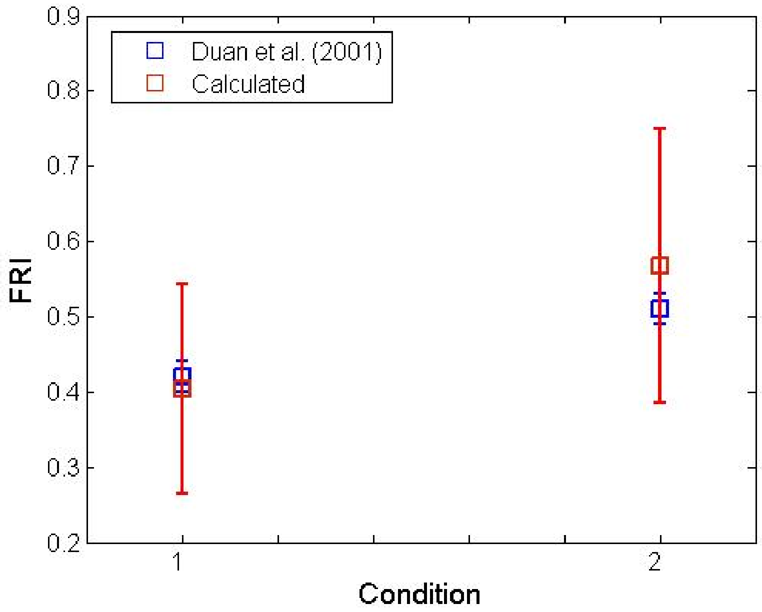


Earth based validations– Static lumbar spine model

Comparison of lumbar spine loading calculations



Comparison of FRI calculations



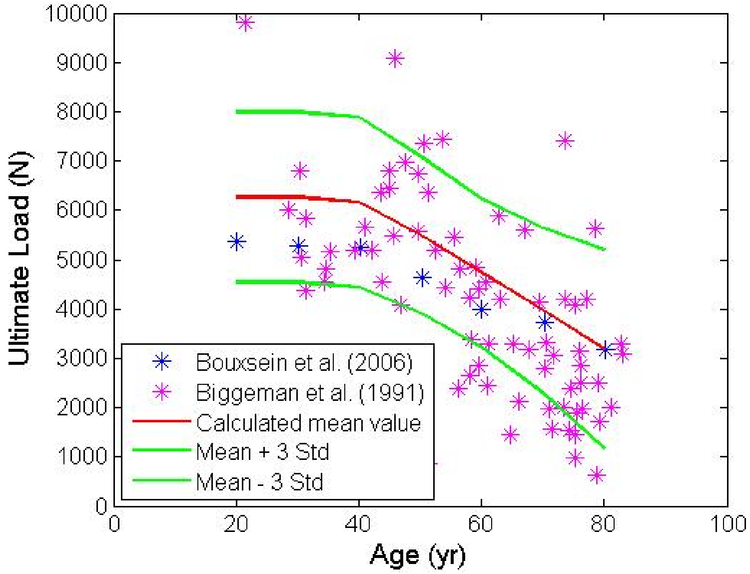
Condition 1 are young subjects
Condition 2 are elderly subjects

Y. Duan, E. Seeman, and C. H. Turner, "The biomechanical basis of vertebral body fragility in men and women," *J. Bone Miner. Res., vol. 16, no. 12, pp. 2276-2283, Dec.2001.*

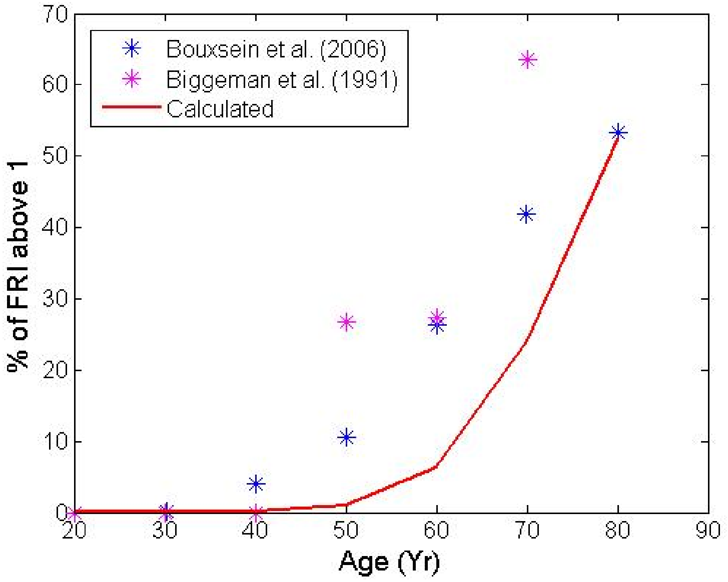
M. L. Bouxsein, L. J. Melton, III, B. L. Riggs, J. Muller, E. J. Atkinson, A. L. Oberg, R. A. Robb, J. J. Camp, P. A. Rouleau, C. H. McCollough, and S. Khosla, "Age- and sex-specific differences in the factor of risk for vertebral fracture: a population-based study using QCT," J. Bone Miner. Res., vol. 21, no. 9, pp. 1475-1482, Sept.2006.

Earth based validations– Static lumbar spine model

Comparison of Ultimate Load vs. Age



Comparison of % FRI above 1 vs. Age

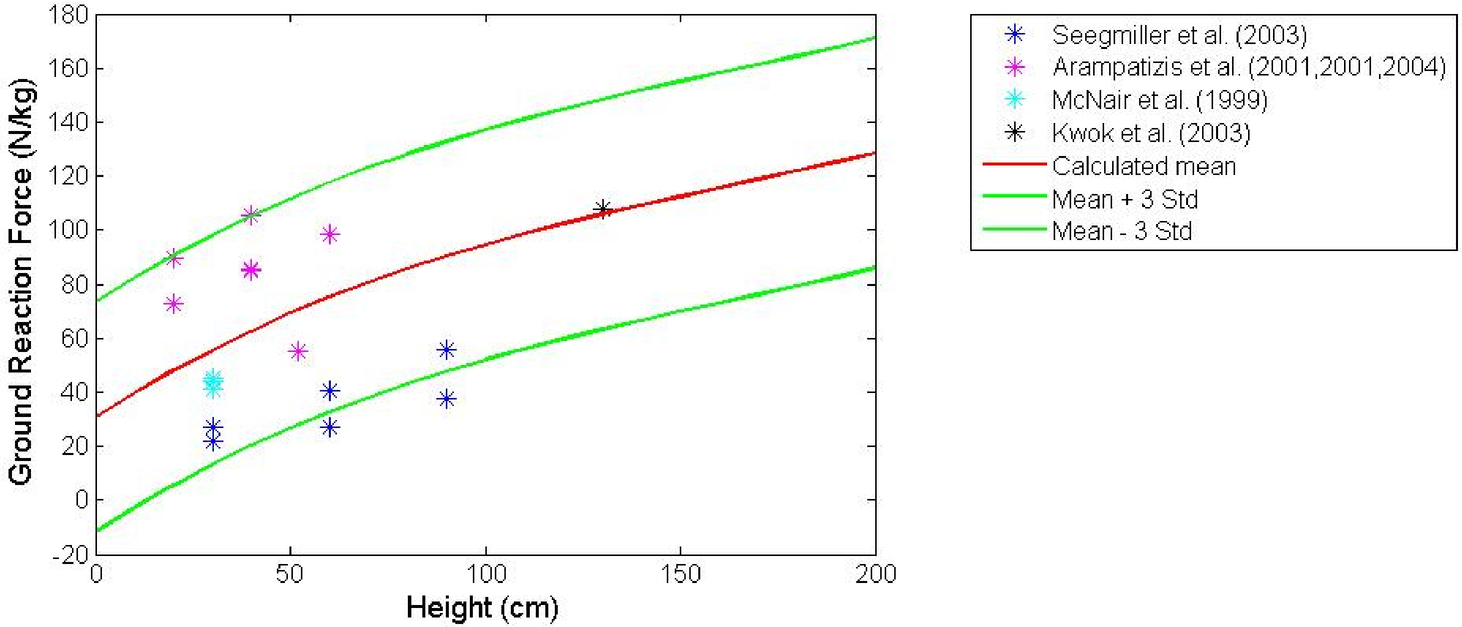


M. L. Bouxsein, L. J. Melton, III, B. L. Riggs, J. Muller, E. J. Atkinson, A. L. Oberg, R. A. Robb, J. J. Camp, P. A. Rouleau, C. H. McCollough, and S. Khosla, "Age- and sex-specific differences in the factor of risk for vertebral fracture: a population-based study using QCT," J. Bone Miner. Res., vol. 21, no. 9, pp. 1475-1482, Sept.2006.

M. Biggeman, D. Hilweg, S. Seidel, M. Horst, and P. Brinckmann, "Risk of vertebral insufficiency fractures in relation to compressive strength predicted by quantitative computed tomography, "Euro J Rad, vol. 13, pp. 6-10, 1991.

Earth based validations – Dynamic lumbar spine model

Comparison of Ground Reaction Force calculations



J. G. Seegmiller and S. T. McCaw, "Ground Reaction Forces Among Gymnasts and Recreational Athletes in Drop Landings," *J. Athl. Train., vol. 38, no. 4, pp. 311-314, Dec.2003.*

A. Arampatzis, G. P. Bruggemann, and G. M. Klapsing, "Leg stiffness and mechanical energetic processes during jumping on a sprung surface," *Med. Sci. Sports Exerc., vol. 33, no. 6, pp. 923-931, June2001.*

A. Arampatzis, F. Schade, M. Walsh, and G. P. Bruggemann, "Influence of leg stiffness and its effect on myodynamic jumping performance," *J. Electromyogr. Kinesiol., vol. 11, no. 5, pp. 355-364, Oct.2001.*

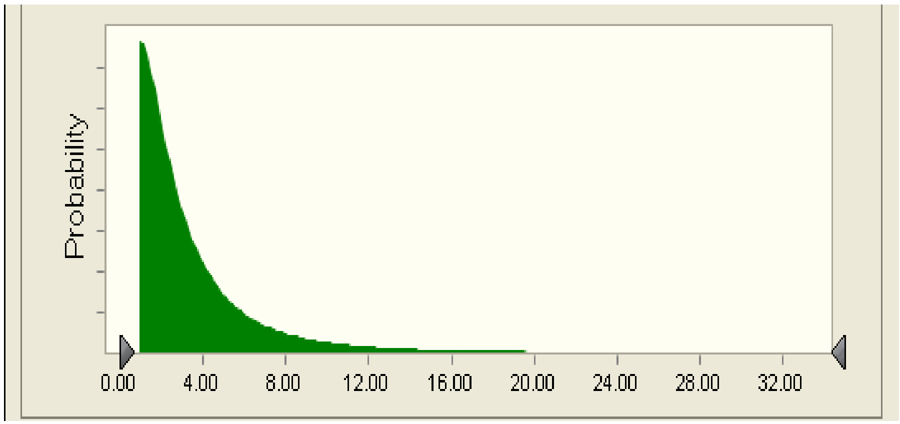
A. Arampatzis, S. Stafilidis, G. Morey-Klapsing, and G. P. Bruggemann, "Interaction of the human body and surfaces of different stiffness during drop jumps," *Med. Sci. Sports Exerc., vol. 36, no. 3, pp. 451-459, Mar.2004.*

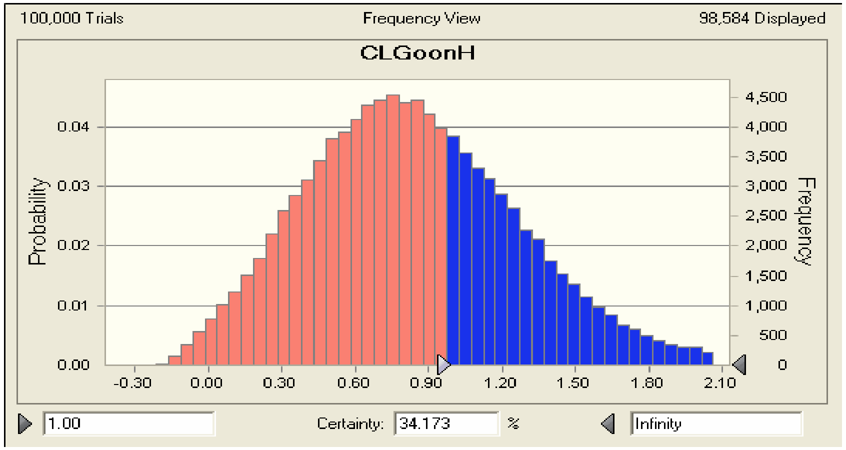
P. J. McNair and H. Prapavessis, "Normative data of vertical ground reaction forces during landing from a jump," *J. Sci. Med. Sport, vol. 2, no. 1, pp. 86-88, Mar.1999.*

P. Kwok, W. Kong, K. Kasturi, C. Lee, J. Hamill, "A biomechanical study on the parachute landing fall," 17th AIAA Aerodynamic Decelerator Systems Technology Conference and Seminar, 19-22 May 2003, Monterey, CA., AIAA 2003-2149.

Earth based validations – Dynamic lumbar spine model

Comparison of fracture prediction for a fall height distribution





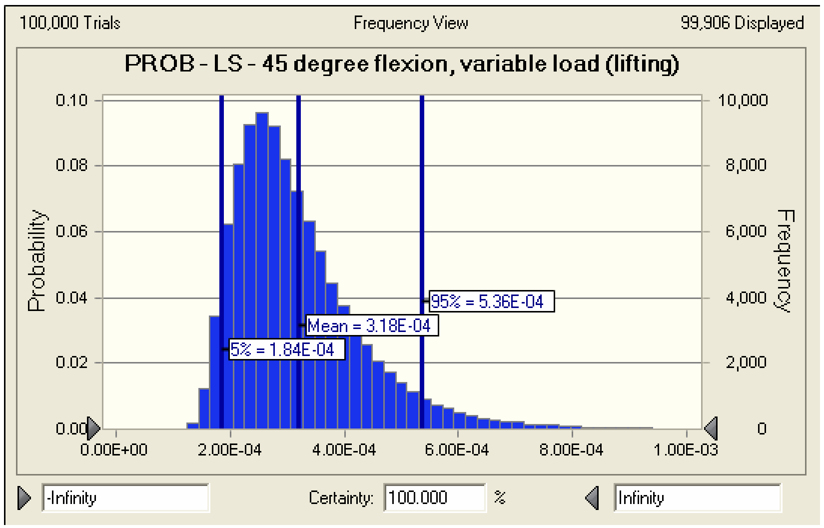
Our simulations predicted an FRI above 1 for 34.2% of the trials. Goonetilleke found 29.7% of falls in his study resulted in fracture.

U. K. Goonetilleke, "Injuries caused by falls from heights," *Med. Sci. Law, vol. 20, no. 4, pp. 262-275, Oct.1980.*

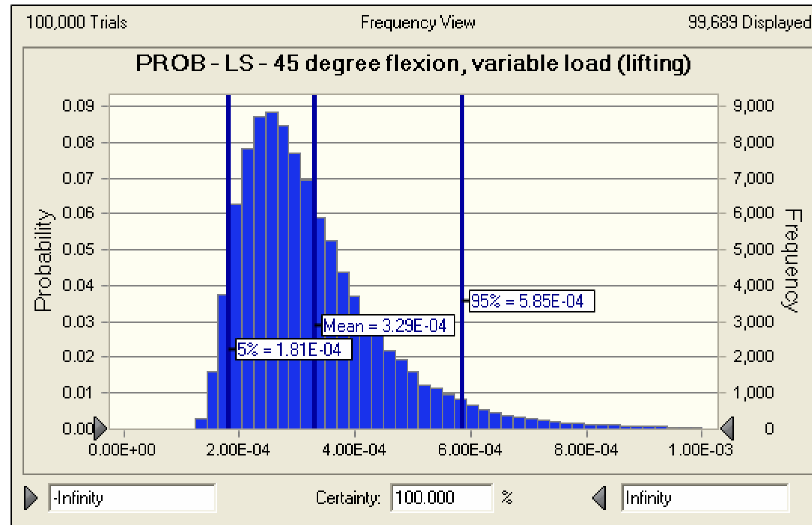
Example results

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.

Male



Female

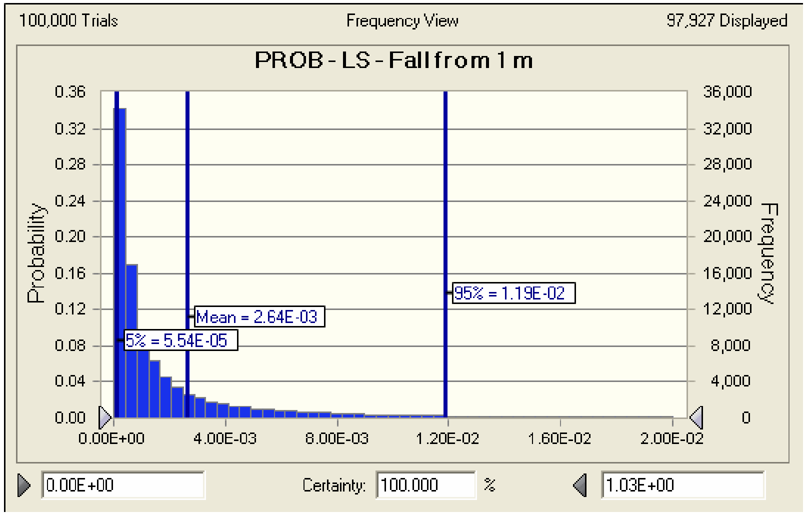


Gender	Mean Probability	Standard Deviation	5%	95%
Male	3.19e-4	1.17e-4	1.84e-4	5.36e-4
Female	3.28e-4	1.36e-4	1.8e-4	5.85e-4

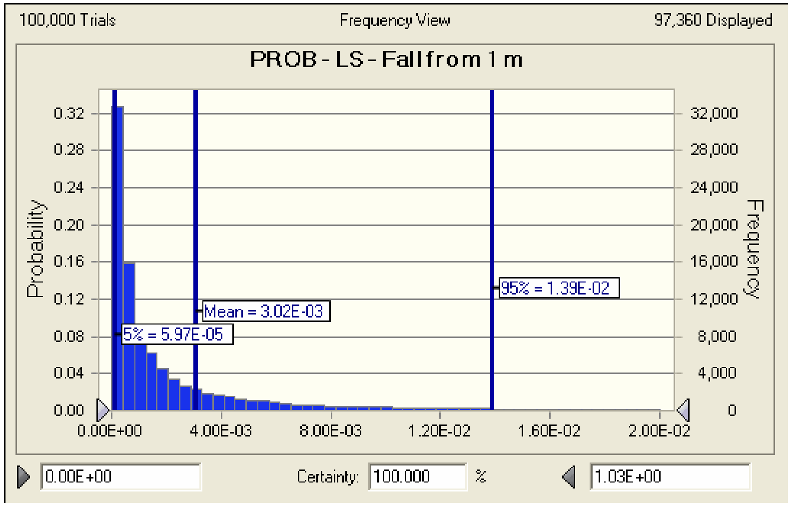
Example results

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.

Male



Female



Gender	Mean Probability	Standard Deviation	5%	95%
Male	2.64e-3	5.36e-3	5.54e-5	1.19e-2
Female	3.02e-3	6.00e-3	5.97e-5	1.39e-2

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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- Contributors
  - Tina Sulkowski, Student, University of Akron
  - Kelley Ruehl, Student, Rose-Hulman Institute of Technology

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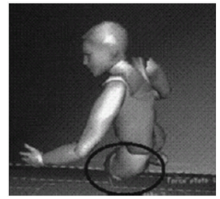
  - Peter Cavanagh – CCF/NSBRI
  - Joyce Keyak and Tom Lang - NSBRI
  - John Charles – Acting Chief Scientist HRP Program NASA-JSC
  - ExMC and IMM development teams

Extra Slides

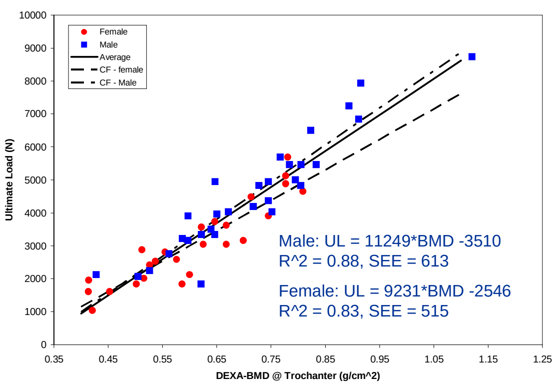
Calculating Bone Ultimate Structural Strength

Posterolateral fall:
UL Reduced up to
0.8% per Degree



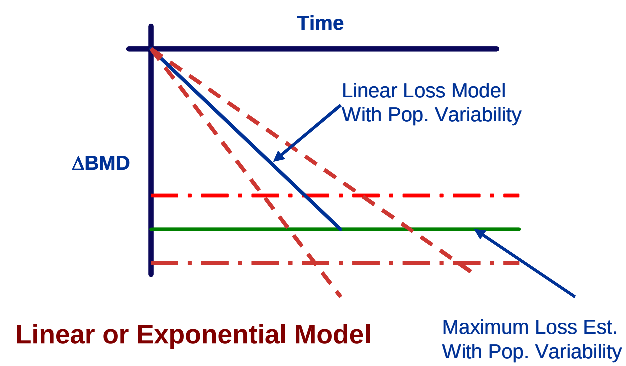
Ultimate Structural Load
Capacity for Loading Conditions

Apply UL attenuation for
load direction



Use BMD correlations to
Estimate UL

Based on appropriate
ex vivo test data



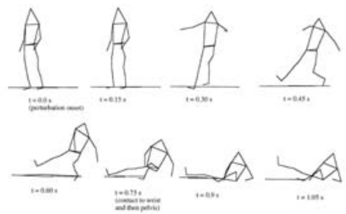
Estimate Time Course to and Degree
Of Bone Loss at Skeletal Location
On day of loading

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

NHANES DATA - Represents Pre-
Flight Bone Health, FFD Standards
And Reference Max BMD Condition

Calculating Loading in Reduced Gravity Environment

EVA Suit
Mass & Padding



Active Response

Resultant Skeletal Load

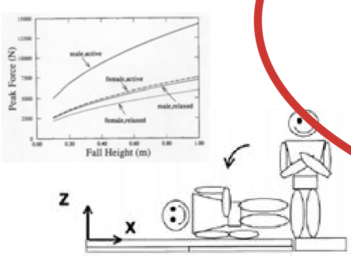
Determine Load Additive or Attenuation Factors

Scale Load to Gravity Level Using Appropriate Methods

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

$$F_m = F_e \frac{m_m}{m_e} \cdot \left(\frac{\Delta t_m}{\Delta t_e}\right)^{-1} \cdot \left(\frac{g_m}{g_e}\right)^{1/2} \cdot \left(\frac{h_m}{h_e}\right)$$

Uses the change in momentum
Includes additional mass



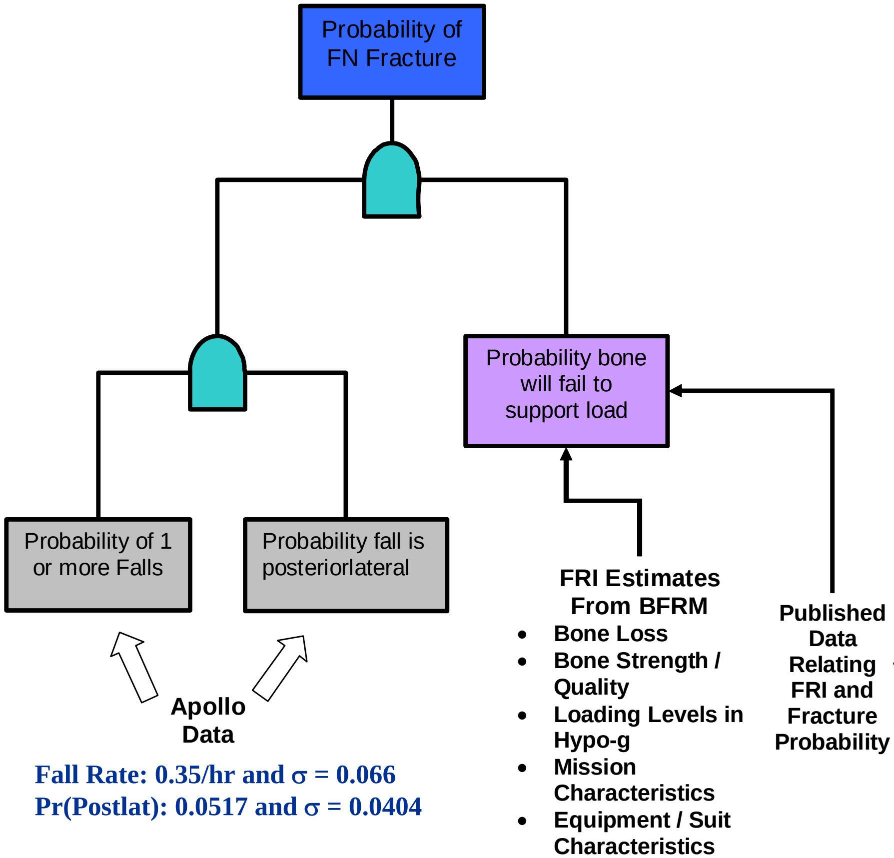
Estimate of Load w/ 1g Biomechanics

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

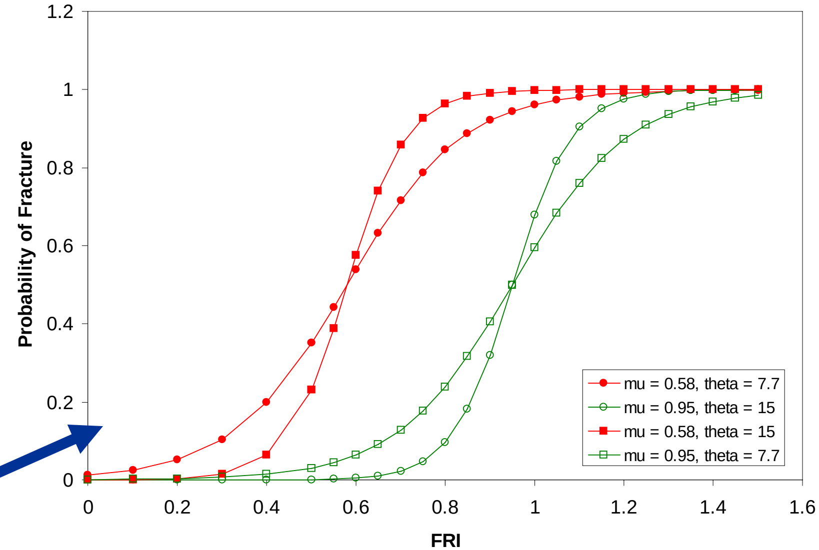
Loading Event Occurs From Specified Activity or Incident

Represents a perceived loading state during on surface activities

Tying It All Together: Falls to the Side Impacting Proximal Femur

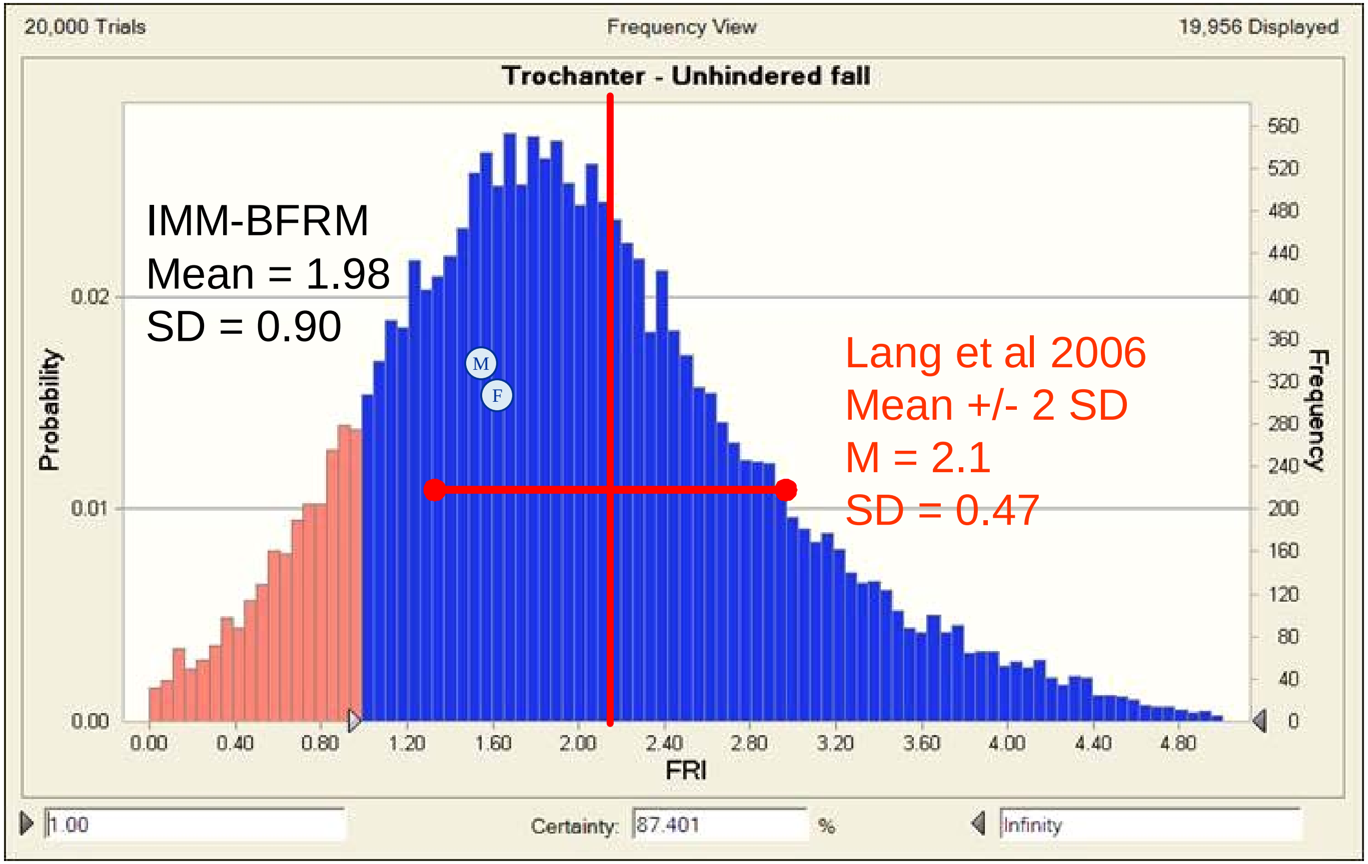


Fall Rate: 0.35/hr and σ = 0.066
Pr(Postlat): 0.0517 and σ = 0.0404



Estimated upper and lower bounds: FRI To Probability of Fracture

"Smell" Test Validation

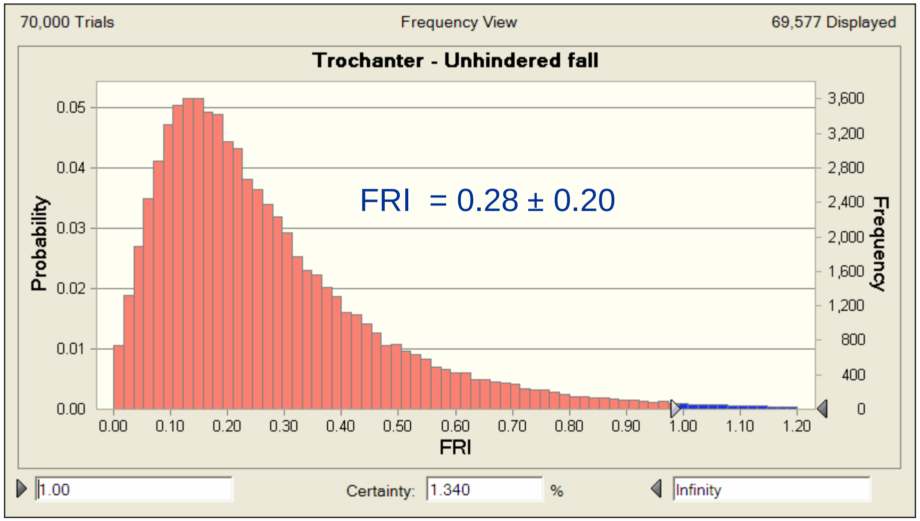


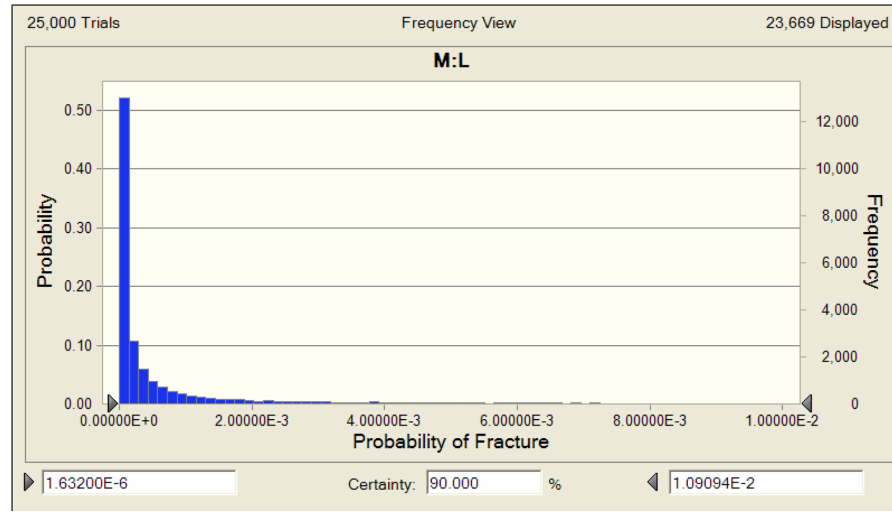
Pre-flight estimate of FRI for Unhindered Posteriolateral Fall
i.e. a fall to the side and slightly backward
Male in 1g with ~1m fall heights

M Schaffner
F Results

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

Data Shown for Mars: 540D Surface Mission



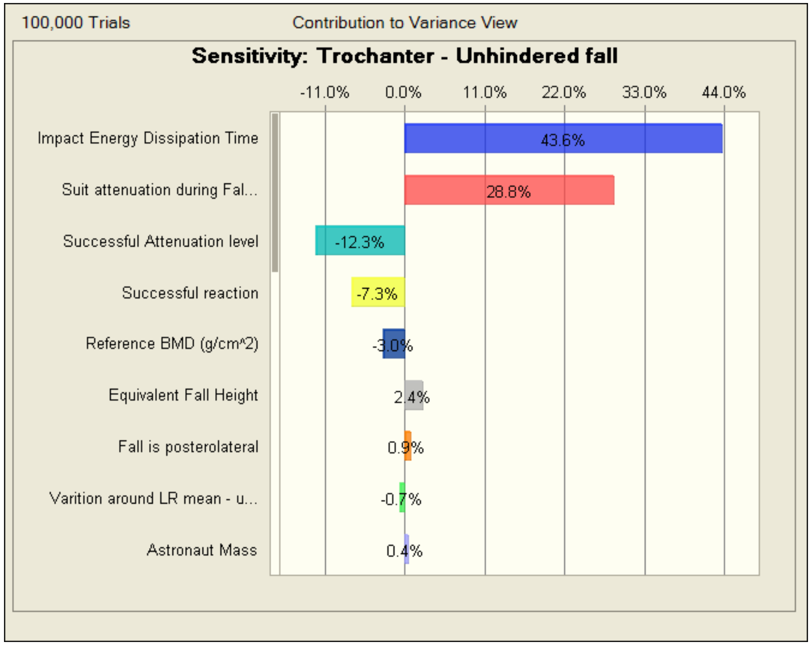


Mission	Fracture Probability	Std	5th Percentile	95th Percentile
Lunar: 8D Surface	1.50E-4	1.15E-3	3.30E-07	5.36E-04
Lunar: 170D Surface	1.94E-4	1.54E-3	3.47E-07	6.15E-04
Mars: 40D Surface	1.44E-3	7.66E-3	1.15E-06	4.85E-03
Mars: 540D Surface	2.47E-3	9.95E-3	1.68E-06	1.15E-02

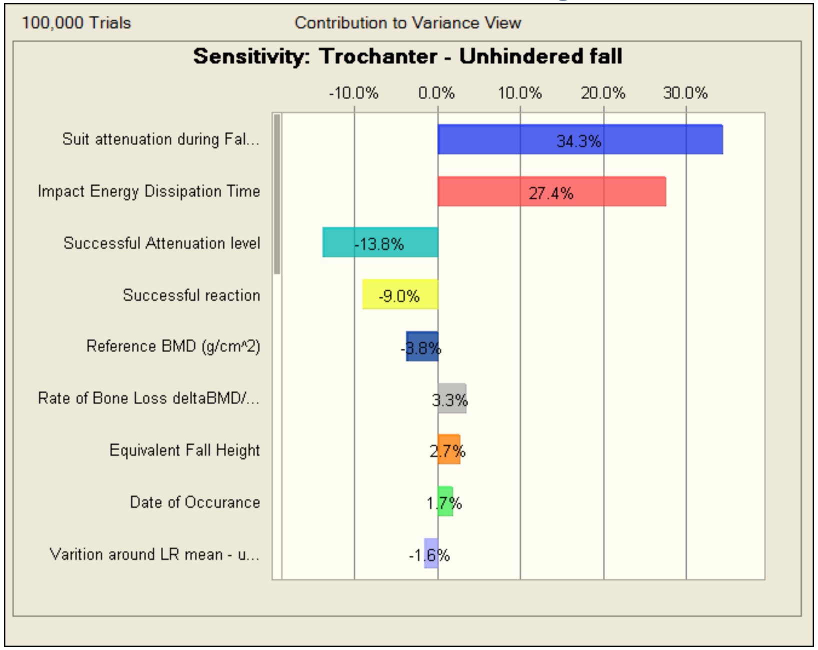
Lateral/Posteriolateral Fall heights range from .25m to ~1m
Bone loss not attenuated by partial gravity

Model Sensitivity

Lunar: Long



Mars: Long



- 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