Glenn Research Center
Human Research Program

Probabilistic Risk Assessment for Astronaut Post Flight Bone Fracture

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Overview

- Why the Bone Fracture Risk Module (BFxRM) was developed
- The probabilistic methods used for making fracture likelihood estimates
- Application of the BFxRM in estimating mission fracture risk
- BFxRM estimates of post-flight fracture risk
- Areas for future improvement and application of the BFxRM

Why the Bone Fracture Risk Module (BFxRM) was developed

- Historically, fracture probability calculations have been used for preventative treatment planning in specific clinical populations

- The DXA/T-score system has been used
  - To assess risk of fragility fractures
  - Typically applied to an elderly, female, postmenopausal, Caucasian population with a high prevalence of osteoporosis

- This reference population is not analogous to the astronaut corps
  - Those at high risk have T-scores $\leq$ -2.5 (2.5 standard deviations less than the population mean)
  - Astronauts are young, healthy, physically fit, work in a unique environment and are engaged in unique activities

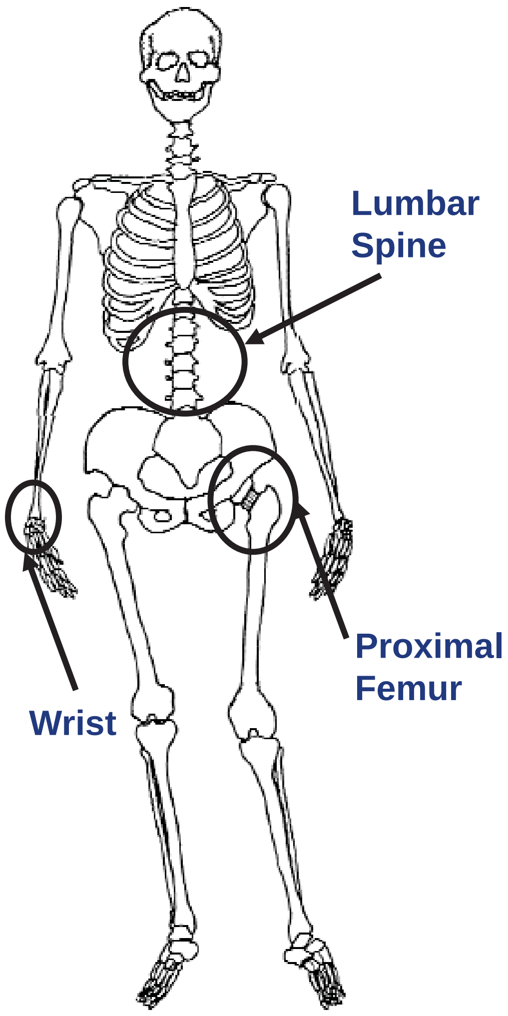
The BFxRM was developed for assessing fracture likelihood during missions

- Skeletal fracture is a concern for astronauts due to:
  - The loss of bone mineral density experienced
  - The unique loading states experienced

- The calculation of fracture likelihood was desired for:
  - In-flight activities (on space station and in new crew capsules)
  - During planetary activities (on Earth, Moon and Mars)

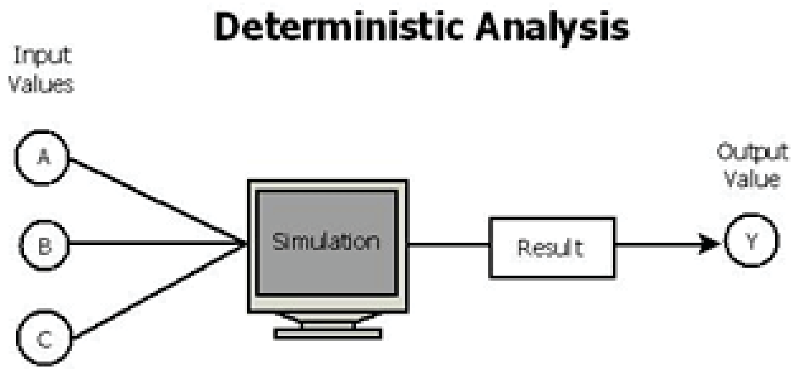
- Prediction capabilities were limited due to the lack of historical injuries

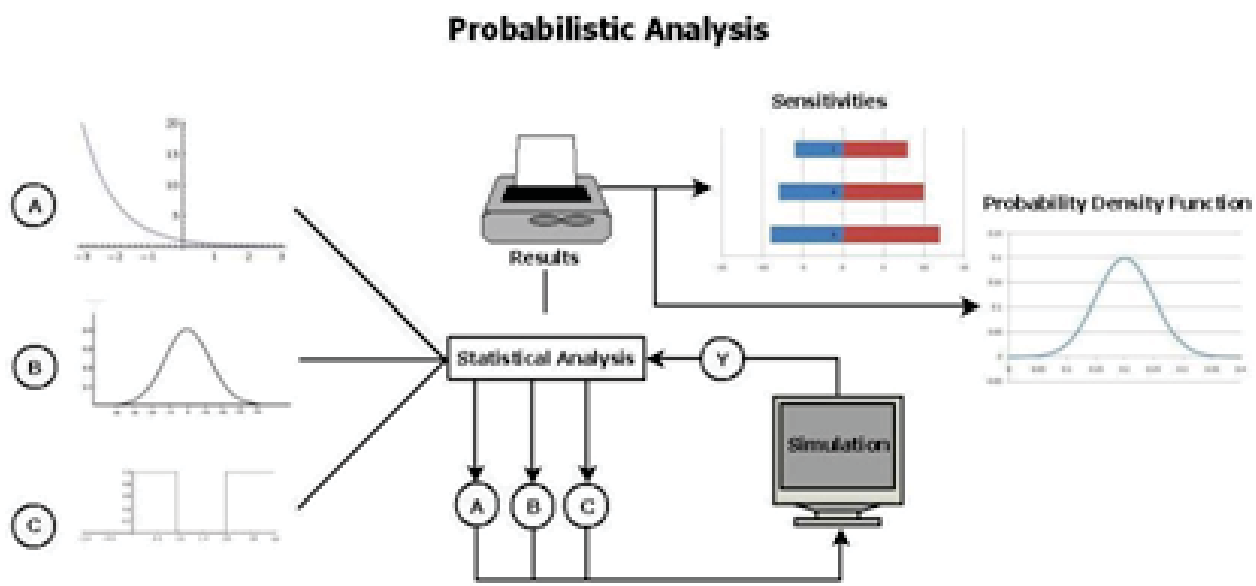
- The goals of the BFxRM were to:
  - Capture the state of knowledge and uncertainty of the likelihood of fracture
  - Incorporate mission related factors, environmental influences, and the best available clinical and biomedical knowledge in a probabilistic risk analysis



Probabilistic risk assessment (PRA) simulation models

- Include physical models, physiological data and probabilistic simulations
- Acts as integrator for the interacting contributing conditions
- Integration obtained with Monte Carlo simulations

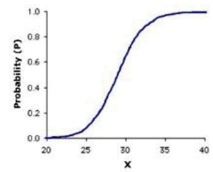


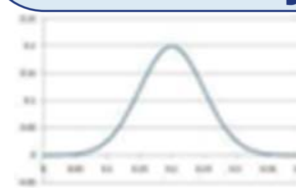


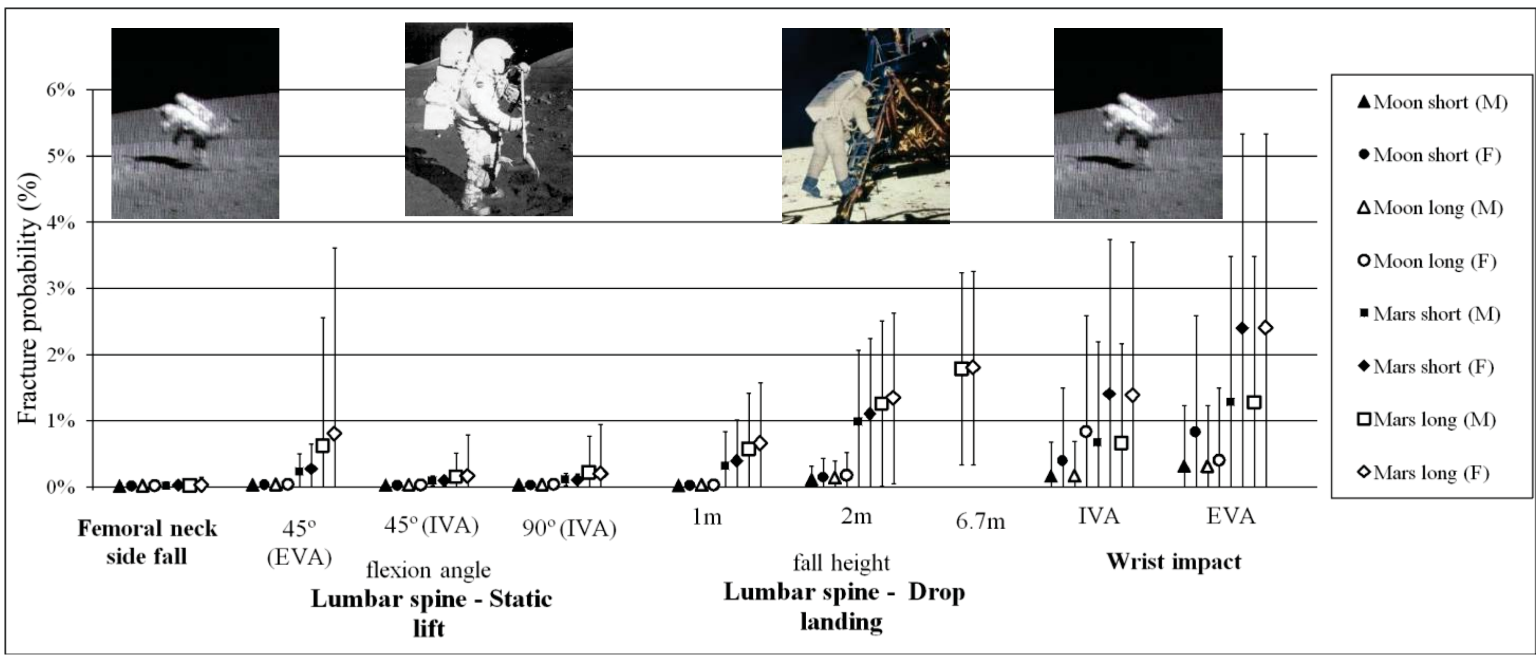
The BFxRM for mission likelihood estimates

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**







Nelson et al., ***Development and Validation of a Predictive Bone Fracture Risk Model for Astronauts***, Annals of Biomedical Engineering, 2009, Vol. 37, Number 11, 2337-2359.

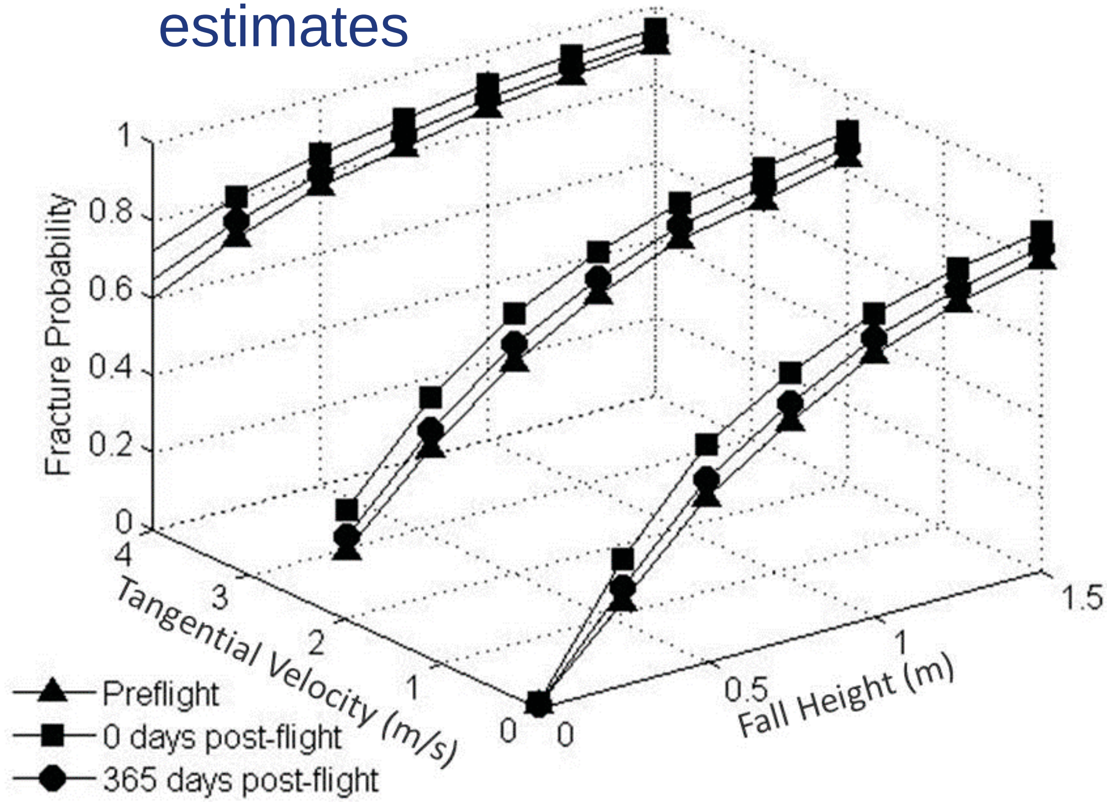
Post-flight fracture risk

- Quantification of the increased likelihood of fracture during post-flight activities
  - Specific loading scenarios were modeled:
    - Elevated, unprotected falls
    - Impacts that included a translational velocity

- Informed injury criteria definition
  - Injury loading threshold for off-nominal Orion landings
  - Developed a deconditioning factor to help guide risk decisions

Post-flight fracture risk – Unprotected lateral fall

- Loading conditions:
  - Lateral falls from 0-1.5 m heights
  - Translational velocity 0-4 m/s
  - No protective action or equipment
- BMD loss:
  - LeBlanc BMD loss rate
  - Deconditioning during a 6 month flight
- BMD recovery:
  - Sibonga recovery rate
  - Estimates at 0 and 365 days post-flight
- Mean fracture probability:
  - 12% greater than preflight on day 0
  - 5% greater than preflight on day 365
- Parameter uncertainty drives the large variance in fracture probability estimates



Post-flight fracture risk – Off-nominal landing

- Estimated deconditioned vs. preflight bone strength

- Loading conditions:
  - Loading at the femoral neck
  - Similar to lateral fall loading
  - No protective equipment considered
  - Landing surface is land rather than water

- BMD loss:
  - LeBlanc BMD loss rate
  - Deconditioning during a 6 month flight
  - No recovery time

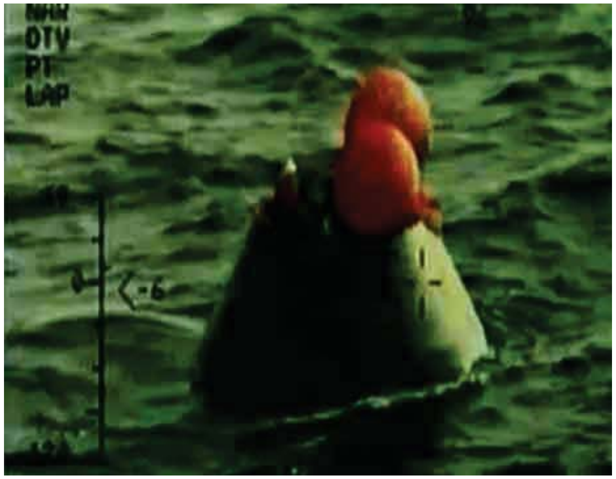
$$FRI_{Pre} = \beta FRI_{Post}$$

$$\beta = \frac{BS_{Post}}{BS_{Pre}}$$

$$\Phi = \beta_M - 2\sigma_\beta$$

$$\Phi \sim 0.80$$

- The deconditioning factor was defined as the 5th percentile value of β



BFxRM results summary

- The BFxRM provides fracture risk estimates specifically for the astronaut population and for the activities they perform
  - Spaceflight mission scenarios (in-flight activities and EVAs)
  - Return and post-flight scenarios (off-nominal landings, post-flight activities)
- Astronaut fracture resistance after 6 months in space decreases to
  - A mean value of 12% less than pre-flight values at return, with a 5^{th} percentile of 20% less
  - A mean value of 5% less than pre-flight values at one year after return for active lifestyle, off-nominal loading conditions
- The uncertainty associated with the fracture risk estimates can be significant
- The source of the uncertainty is due to significant uncertainty in the sensitive parameters
  - Using the change in BMD as the only factor that contributes to changes in bone strength during spaceflight
  - Using simplifying assumptions within the biomechanical loading calculations

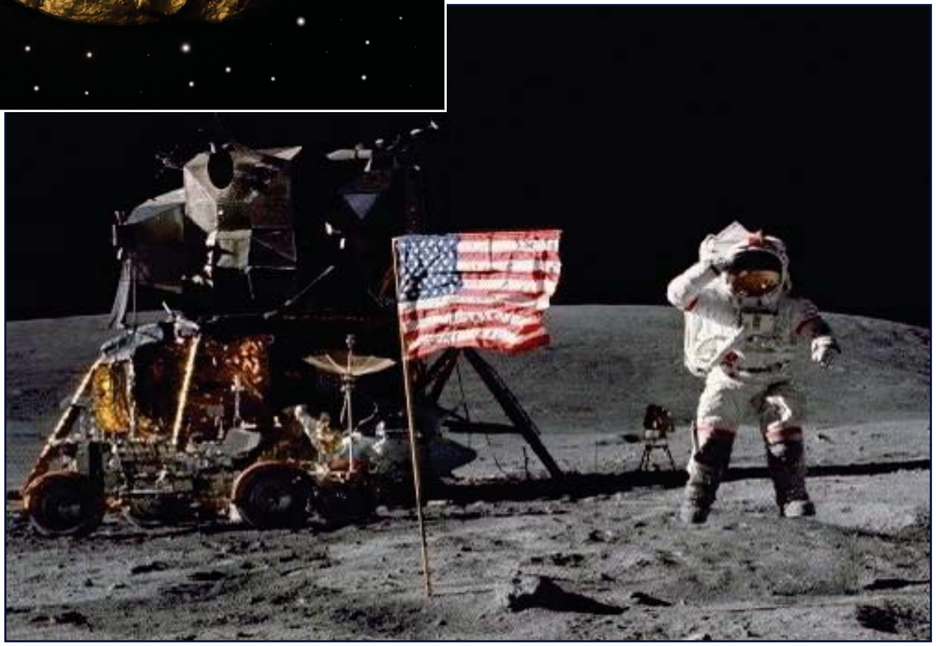
Areas for future improvement and application of the BFxRM

- Improved representation of bone and fracture conditions
  - Use biomechanical information about real fracture events to improve the function that translates the load to ultimate strength ratio to fracture probability
  - Integrate FEM and other "bone quality parameters" to increase the fidelity of the bone strength estimate

- Perform additional validation and credibility testing

- Address the impacts of other space flight adaptations and countermeasure use
  - Considering micro-architecture in addition to BMD to predict ultimate strength
  - Bisphosphonates, diet and (ARED, AEC) exercise

- Influence mission planning and operational environment
  - Spacecraft, spacesuit and habitat designs
  - Operational processes and specific training



QUESTIONS?