

# Quantitative CT and MRI-based Modeling Assessment of Spine Injury Risk Following Long-Duration Spaceflight



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## INTRODUCTION

- Standard mission to the International Space Station (ISS) is  $\geq 6$  months
- Past ISS missions resulted in 0.9% monthly bone losses in the spine [1]
- Global Human Body Models Consortium (GHBMC) percentile computational Human Body Models (HBMs) are used to study astronaut biomechanical loading under spaceflight-relevant multidirectional conditions [2], [3].
  - No variation in geometry, biomechanics, or deconditioning effects

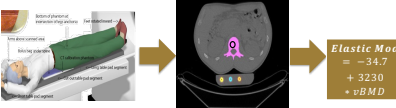
**Objective:** Evaluate how injury risk varies between individualized models

## METHODS

### Image Analysis

- 9 crewmembers who completed ISS missions  $\geq 6$  months
- Volumetric bone mineral density (vBMD) via a calibration phantom in a quantitative computed tomography (qCT) scan of C3, T3, L1 vertebrae
  - Elastic modulus for each spinal region was calculated from vBMD
- MRI of entire spine and musculature
  - Cross-sectional area (CSA) of 19 spinal muscles and vertebral geometry
  - Physiological cross-sectional area (PCSA) calculated from CSA or scaled by mass

### Quantitative Computed Tomography (qCT) [4]



### Magnetic Resonance Imaging (MRI) [5]

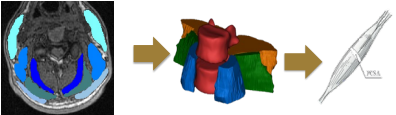


Fig 1. Depiction of vBMD and CSA measurement

### Individualization Process

- Anthropometric measurements from:
  - Direct body measurements
  - MRI based measurements
  - Regression based measurements
- Thin plate spline morph to individualize GHBMC M50-OS+DeformSpine model (Fig 2)
  - Morph and target lengths  $<5\%$
- Measurements from qCT and MRI implemented into each subject model to create a pre-flight and post-flight model
- To capture a range of typical landing scenarios, 6 directions, 3 pulse magnitudes and 2 rise times were evaluated (Fig 3)

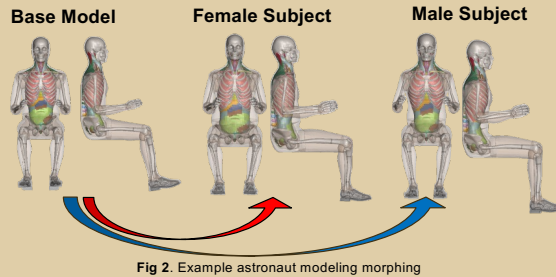


Fig 2. Example astronaut modeling morphing

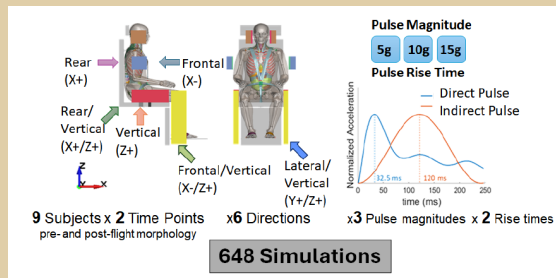


Fig 3. Dynamic simulation setup for subject-specific full-body human finite element (FE) models in a design of experiments

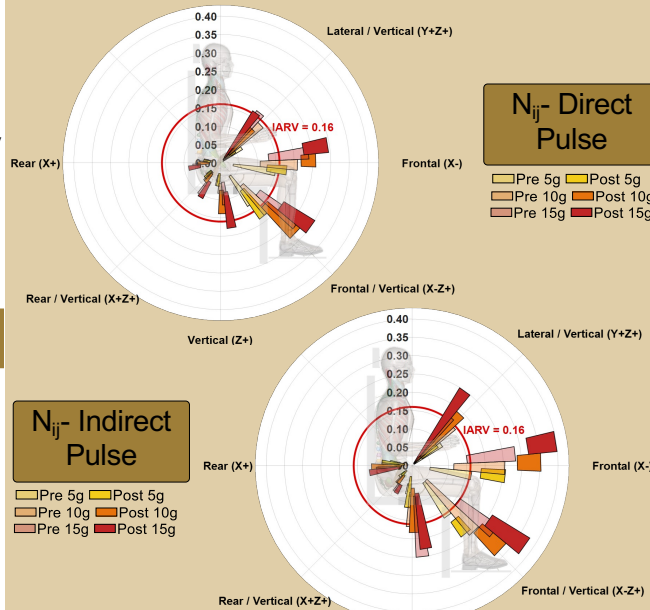


Fig 4. Minimum to maximum neck injury criterion (Nij) in pre- vs. post-flight simulations by loading direction and pulse severity (5, 10, 15 g) under direct vs. indirect pulse conditions. The red ring indicates the IARV for the injury metric.

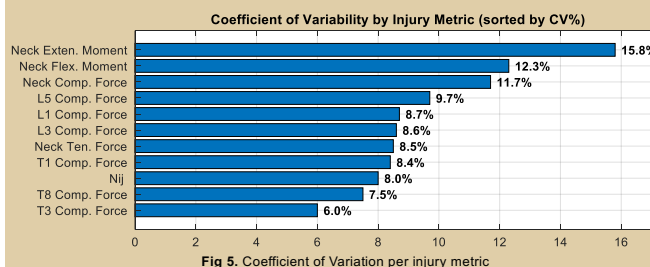


Fig 5. Coefficient of Variation per injury metric

## RESULTS

- Subject-specific force and moment responses compared against 50th percentile male spaceflight injury assessment reference values (IARVs) (Table 1) [6]

Table 1	Injury Metric	Injury tolerance limit for spaceflight applications
Neck injury	Neck Compression Force	1100 N
	Neck Tension Force	1097 N
	Neck Flexion Moment	96 Nm
	Neck Extension Moment	39 Nm
	Neck Injury Criterion, Nij	0.16
Thoracic-lumbar spine injury	Spinal Compression Force	5300 N

### Neck tension force:

- 2% (n=13) of the simulations exceeded the 1097 N IARV
- Exceedances: (X-), (X-/Z+), and (Y+/Z+) directions at 15g severity for the indirect pulse

### Neck Injury Criterion (Nij)

- 5g: 12.9%, 10g: 29.6%, 15g: 36.6%
- Max: 0.40 (Fig 4.)

- All other injury metrics remained below respective IARV values

$$CV\% = \frac{SD \text{ across subjects of their maximum values}}{\text{Group mean of subject maxima}} \times 100$$

Eq 1. Coefficient of Variation (CV) equation

- Coefficient of variability calculated with Eq 1.
  - Injury metrics with greatest inter-subject variability indicated higher CV (Fig 5)
  - Neck extension moment had highest CV (15.8%), implying injury response is more sensitive to individual variation than other metrics

## CONCLUSIONS

- Spine injury risk low across all injury metrics but increases with severity
- Sensitivity to anatomical variations across injury metrics shows importance of utilizing subject-specific FE models
- Future work should further individualize these models to increase injury risk prediction accuracy

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## REFERENCES

- [1] R. Carpenter et al. 2010. [2] J. P. Gaewsky et al. 2019. [3] X. Ye et al. 2020. [4] Kopperdahl et al. 2002. [5] Ohta et al. 2014. [6] M. Lalwala et al. 2023.