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

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Introduction: Long-duration exposure to microgravity compromises musculoskeletal integrity, elevating the risk of tissue failure when subjected to dynamic mechanical loads. The objective of this study was to assess astronaut musculoskeletal health from pre- and post-flight imaging and to construct subject-specific finite element (FE) models to evaluate changes in vertebral strength under different loading scenarios.

Objective: The objectives of this study were to: (1) Analyze how injury risk varies between pre- and post-flight and (2) Evaluate how injury risk varies between individualized models.

Methodology: Quantitative computed tomography (qCT) and magnetic resonance imaging (MRI) scans were collected from nine International Space Station (ISS) crewmembers before and after spaceflight. Bone mineral density (BMD) was measured at the C3, T3/4 and L1 vertebrae using a calibration phantom in qCT. MRI scans were examined to quantify pre- and post-flight neck and thoracolumbar muscle cross-sectional areas and vertebral geometry. Anthropometric measures were inputs to a thin plate spline framework to morph the Global Human Body Models Consortium 50th percentile male simplified occupant FE model with a deformable spine (GHBMC M50-OS+DeformSpine) to generate pre- and post-flight subject-specific FE geometries. Subject-specific material properties for the vertebral elastic moduli were defined from the qCT BMD; physiological cross-sectional areas (PCSAs) were calculated for muscles seen in MRI, while PCSA for non-visualized muscles were scaled by subject body mass. The pre- and post-flight subject-specific FE models were then used to simulate landing scenarios across 6 directions (rear, frontal, vertical, rear/vertical, frontal/vertical/, lateral/vertical), 3 magnitudes (5, 10, 15g), and 2 pulse shapes (direct, indirect).

Results: Force and moment responses at the neck and thoracolumbar spine were compared against 50th percentile male spaceflight injury assessment reference values (IARVs). Neck compressive force did not exceed the 1100N IARV in any simulations, while neck tension forces exceeded the 1097N IARV in 10 simulations, all occurring at 15g severity, primarily under indirect pulses in the frontal, frontal/vertical, and lateral/vertical directions. Overall, 32% of simulations exceeded the neck injury criterion (Nij) IARV of 0.16, with a maximum Nij of 0.40 observed during frontal/vertical loading under a 15g indirect pulse, shown in **Figure 1**. Frontal and frontal/vertical loading at 15g had the highest proportion of simulations exceeding the Nij IARV (94%). The largest N_{IJ} value was observed in the frontal/vertical (X-/Z+) direction, under an indirect 15g pulse for subject 4 (post-flight). Across the thoracolumbar vertebrae, compressive forces remained below the 5300N IARV, except in the L5 vertebra where the maximum force reached was 5319 N under 15g direct frontal loading for subject 8 (post-flight). Peak thoracolumbar compression was generally associated with 15g indirect pulses, with the highest forces produced with frontal loading at the T1–T8, L2, L4, and L5 vertebrae, and vertical loading at the T9–L1 and L3 vertebrae.

Conclusions: The simulation results indicated low injury risk in most loading conditions, however displayed elevated risk under 15g indirect pulse loading in the frontal, vertical, and frontal/vertical directions. These results highlight the importance of loading direction and pulse characteristics in predicting astronaut injury risk.

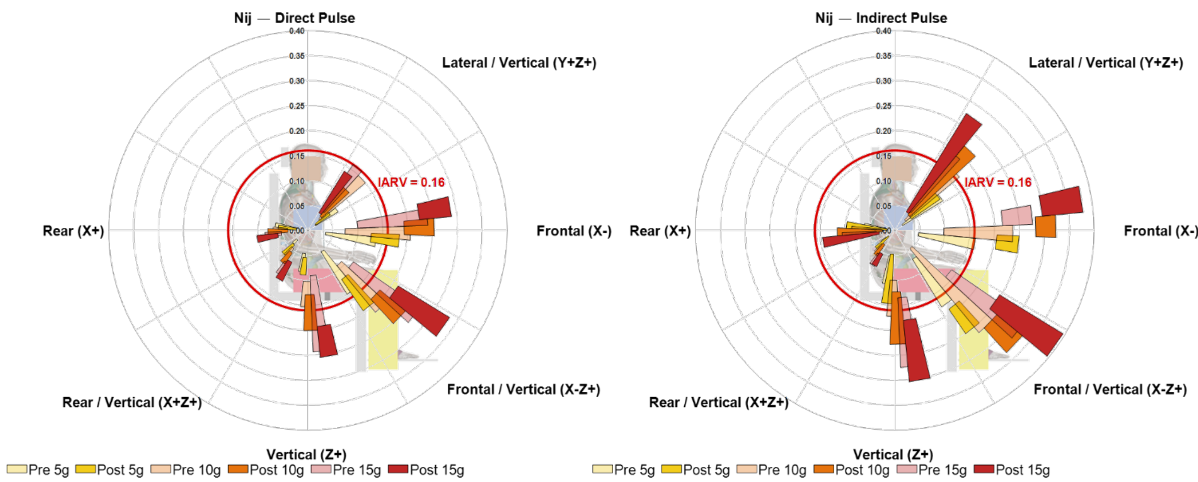

Figure 1. Minimum to maximum Neck Injury Criterion in pre- vs. post-flight simulations by loading direction and pulse severity (5, 10, 15 g) under direct vs. indirect pulse conditions.