Subject-Specific Modeling of Spinal Injury Risk Following Long Duration Spaceflight

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I. INTRODUCTION

Bone loss is a major physiological concern associated with spaceflight. Typical missions to the International Space Station (ISS) last six months or longer, during which astronauts are exposed to microgravity that can lead to substantial bone deterioration in the spine. Past ISS missions have resulted in 0.9% monthly bone loss in the spine [1–2]. Research using Global Human Body Models Consortium (GHBMC) computational Human Body Models (HBMs) revealed that the lumbar spine is particularly susceptible to loading parameters, especially loading direction. However, these studies primarily use generalised percentile GHBMC models (e.g. M50-OS) to assess injury risk [3–4]. Therefore, the degree to which subject-specific anatomical and musculoskeletal differences influence injury risk under spaceflight-related multidirectional loading remains unclear as these percentile-based models do not capture individual geometrical and biomechanical differences, or the deconditioning effects of prolonged unloading. Understanding how long-duration spaceflight alters the musculoskeletal system and influences spine injury risk during launch, landing, and off-nominal scenarios is crucial for ensuring the safety of all crew members in current and future missions.

II. METHODS

To investigate how spine injury risk varies across subjects and following long-duration spaceflight, we conducted a sensitivity analysis on the GHBMC 50th percentile male simplified occupant model, with integrated deformable spine from the detailed model, morphed to subject-specific anthropometry for nine crewmembers. Bone mineral density, muscle physiological cross-sectional areas, and anthropometric measurements determined from pre- and post-flight qCT, MRI, and external measurements were implemented into the GHBMC M50-OS+DeformSpine to generate pre- and post-flight subject-specific FE geometries. The pre- and post-flight subject-specific FE models were then used to simulate landing scenarios spanning six directions (rear, frontal, vertical, rear/vertical, frontal/vertical, lateral/vertical), three magnitudes (5, 10, 15g), and two pulse shapes (direct, indirect) in a 648-simulation design of experiments (Fig. 1). Extracted neck and spine injury metrics were subsequently compared with 50th percentile male spaceflight injury assessment reference values (IARVs) from the literature [5].

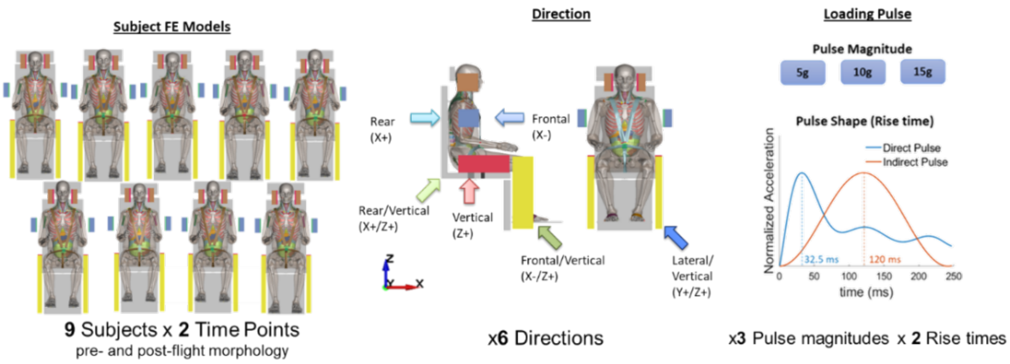

Fig. 1. Dynamic simulation setup for subject-specific full-body human finite element (FE) models in a design of experiments with a total of 648 simulations.

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III.INITIAL FINDINGS

Approximately 2% (13/648) of the simulations exceeded NASA's risk tolerance threshold for neck tension force. These exceedances were observed in the frontal (X-), frontal/vertical (X-/Z+) and lateral/vertical (Y+/Z+) directions at 15g severity only with the indirect pulse. For neck injury criterion, N_{ij}, exceedances of the 0.16 injury threshold increased as pulse severity increased: 12.9% (28/216) of 5g simulations, 29.6% (64/216) of 10g simulations, and 36.6% (79/216) of 15g simulations (Fig. 2). The largest N_{ij} value (0.40) occurred post-flight in the frontal (X-) direction, under an indirect 15g pulse. In contrast, neck compression force, neck flexion moment, neck extension moment, and thoracolumbar spine injury metrics remained below tolerance levels. The overall largest compressive force across all vertebrae (5081 N) occurred in the L5 vertebrae. In T1-T8 and L4-L5 vertebrae, the maximum force occurred in the frontal direction (X-), while for T9-L3 vertebrae the maximum occurred in the vertical (Z+) direction. Additionally, the maximum compressive force for T1-L3 vertebrae occurred under an indirect pulse, while the maximum compressive force for L4 and L5 vertebrae occurred under a direct pulse. Prominent inter-subject variability was observed across all injury metrics, with maximum responses distributed among five various crewmembers. Among these metrics, variability was the highest for the neck extension moment (15.8%) and lowest for the T3 vertebra axial compressive force (6%).

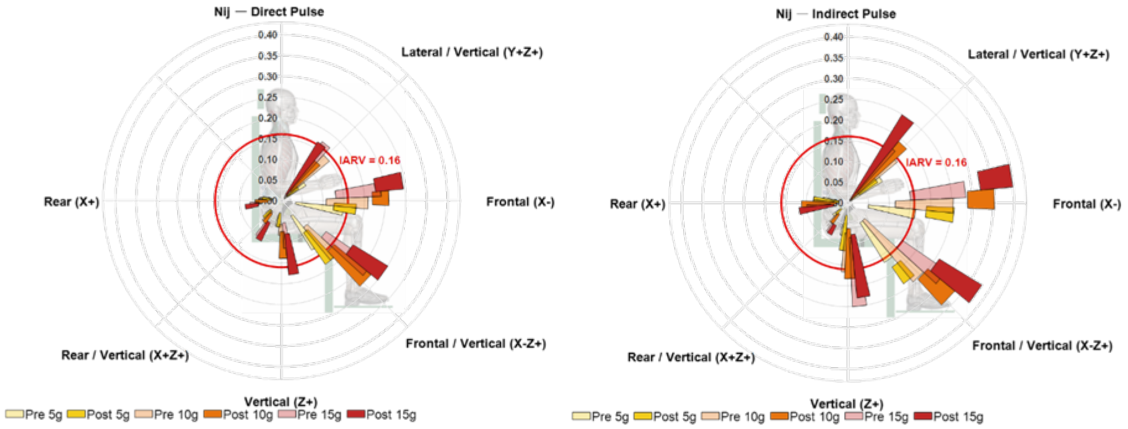

Fig. 2. Minimum to maximum N_{ij} in pre- vs. post-flight simulations by loading direction and pulse severity (5, 10, 15 g) under direct vs. indirect pulse conditions. The red ring indicates the IARV for the injury metric.

III. DISCUSSION

Neck injury metric exceedances were concentrated in frontal, frontal/vertical, lateral/vertical, and vertical directions, consistent with previous base model sensitivity findings [5]. The T1-T8 and L4-L5 vertebrae showed peak responses in the frontal direction, whereas T9-L3 showed peak responses in the vertical direction. The curvature of T1–T8 and L4–L5 away from the seat increases compressive loading as the subject moves toward the seat. In contrast, the more vertically aligned T9–L3 region experiences higher compressive loading during upward vertical acceleration from the seat. Although most exceedances occurred under severe pulse magnitudes (10-15g), nominal launch and landing pulse magnitudes peak at 7.8g, suggesting overall injury risk remains low [6]. Additionally, prominent inter-subject variability was observed across injury metrics, highlighting the importance of accounting for anatomical differences. The neck extension moment showed the highest coefficient of variability (15.8%), indicating it is the most sensitive injury metric to anatomical differences between subjects, whereas T3 axial compressive force had the lowest coefficient of variability (6%).

IV. ACKNOWLEDGEMENTS AND DISCLOSURE STATEMENT

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V. REFERENCES

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