Investigation of the Crew Injury Biomechanics during Water Landing for Human Space Flight

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I. INTRODUCTION

In order to finally achieve human space missions to the moon, Mars and beyond, and also to eventually establish accessible space travel, it is essential to enhance crew safety beyond its current level. Comprehensive design consideration should be made based on the quantitative risk assessment (QRA) in order to maximize crew safety while delivering the required performance. Improvements of both the launch vehicle's reliability and the evacuation success rate of the launch abort system (LAS) are important to ensure the crew's safety. From the initial design stages, all elements of design and operation should be based on a full understanding of the relevant injury biomechanics. During the ascent and the re-entry there are various injury risk modes, such as the excessive landing loads, the explosion overpressures, and the abort system's off-nominal accelerations. In terms of quantitative risk predictions, a physics-based model that describes the relationship between the uncertainty factors and the injury risk is needed [1-3]. As Japan Aerospace Exploration Agency (JAXA) has little experience in either the crewed spaceship design or injury risk predictions via physics-based models, this joint research project was initiated in 2013 to establish a physics-based model and to increase the technology readiness level of the spaceship seat design [4]. The key findings related to the impact biomechanics are presented and discussed here.

II. METHODS

A system development method based on QRA is the key technology to accomplish challenging space missions under the competing restrictions of schedule and budget. By this method, all possible failure modes are identified, the failure probability is evaluated (mainly based on high-fidelity numerical simulations), related uncertainties are quantified (mainly based on the sub-system or component level experiments instead of the high cost system tests) and, finally, the risk is minimized effectively based on the parameter sensitivity analysis. An overview of the quantitative crew safety analysis method is presented in Fig. 1. The vehicle's induced acceleration is predicted for all possible scenarios based on numerical simulations. Human response behaviour is mainly predicted by the computational ATD models and the finite element (FE) human body models (HBM), which are validated by comparison with the experiments. Finally, the resulting injury risk is evaluated by the injury criteria. There is a large factor of uncertainty around the acceleration level and the directions. Uncertainties regarding explosive yields and the warning time are significantly larger, resulting in the larger variation of the blast-wave overpressure level. The computed result of the explosion overpressure is shown in Fig. 2. In addition, there can be huge uncertainties regarding the water landing velocity in the case of off-nominal abort or parachute deployment failure.

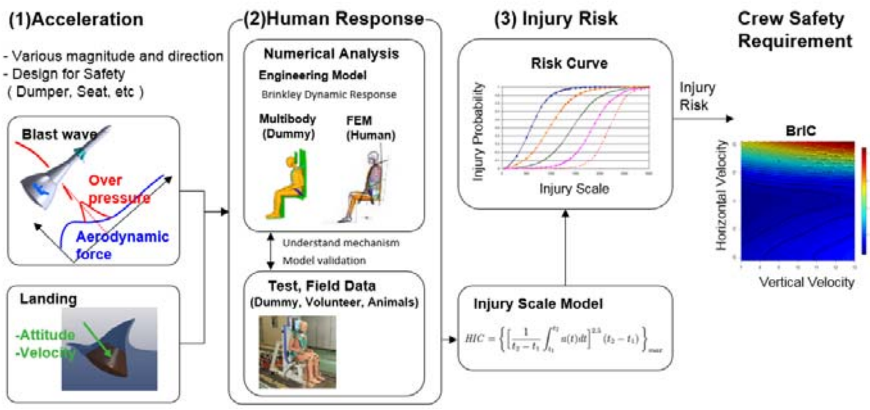

Fig. 1. Overview of quantitative crew safety analysis method.

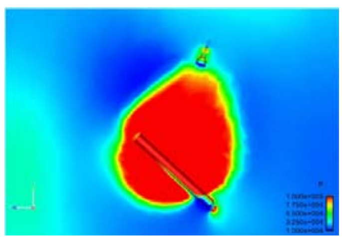

Fig. 2: Explosion overpressure.

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III. INITIAL FINDINGS

The computational human response model has been established, the injury mechanism is investigated, and the design study for the spaceship seat is carried out in this study. Capsule-type spaceship is considered and the pressurized suit and helmet are not considered in this study. At present, the vehicle is assumed to be rigid for the load prediction and the rigid seat without damper device effect has been considered, more sophisticated design of seat with damper effect is under the way. The major findings are discussed in detail below.

IV. DISCUSSION

Acceleration conditions are determined based on the computational fluid dynamics analysis for both the water landing and the blast-wave overpressure cases. In the water landing cases, water landing velocities range from -21 to 21 m/s in the horizontal direction, from 7 to 13 m/s in the vertical direction, and the pitch angle ranges from 15 to 40 degrees. Resulting acceleration peak can be 15 G, and the duration time ranges from 50 to 300 ms. Resulting acceleration peak ranges from 10 G to 100 G, and the duration time is roughly 50 ms, with steep start-up increase [2]. First, the validation study on the Hybrid-III ADT model is carried out under the vehicle acceleration for the water landing and the blast-wave overpressure. A series of sled tests is conducted to obtain the validation data and to understand the injury mechanism. By comparing the predicted HBM response behaviour with the experimental data, it can be confirmed that the multibody, dynamics-based ATD model has sufficient accuracy in its acceleration conditions for human space flight. Based on the integrated physics-based model, the injury criteria is evaluated when changing the re-entry capsule module’s water landing velocity in horizontal direction (Vh) and in vertical direction (Vv), as shown in Fig. 3. Injury risk criteria can be divided into three groups: the first group has significant correlation with axial acceleration (Ax); the second group has significant correlation with normal acceleration (Az); and the third group has significant correlation with total acceleration. Crew injury mechanisms for the three groups are shown in Fig. 4. When the capsule is landed ‘heel-in’ (negative Vh), Ax becomes large. On the other hand, when the capsule is landed ‘toe-in’ (positive Vh), Az becomes large. Under large Ax conditions, the head moves forward and the chest is compressed by the restraints. As a result, HIC and chest deformation become significant. On the other hand, under large Az conditions, and due to load in the axial load propagated through the spine, the head rotates and the neck is tensioned. As a result, BrIC and neck tension become significant. Under large total acceleration conditions, neck and lumbar compression become significant. In order to achieve a higher level of crew safety, the reduction of head translation and rotation via the damper design and layout, and the reduction of the compression force at spine and neck via the custom-made linear are the key design considerations. Further investigation of the injury risk differences obtained by Hybrid-III, THOR, and human body model and detailed design of damper device and seat are under the way.

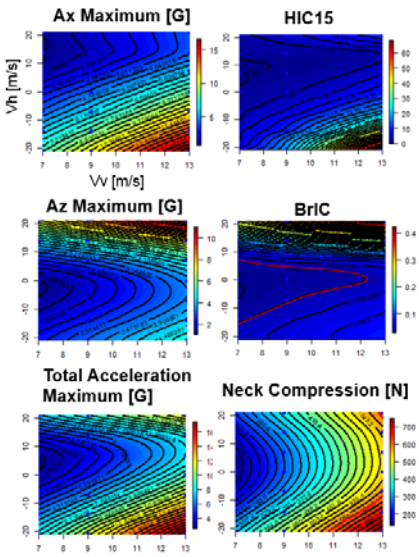

Fig. 3. Vehicle acceleration and injury criteria.

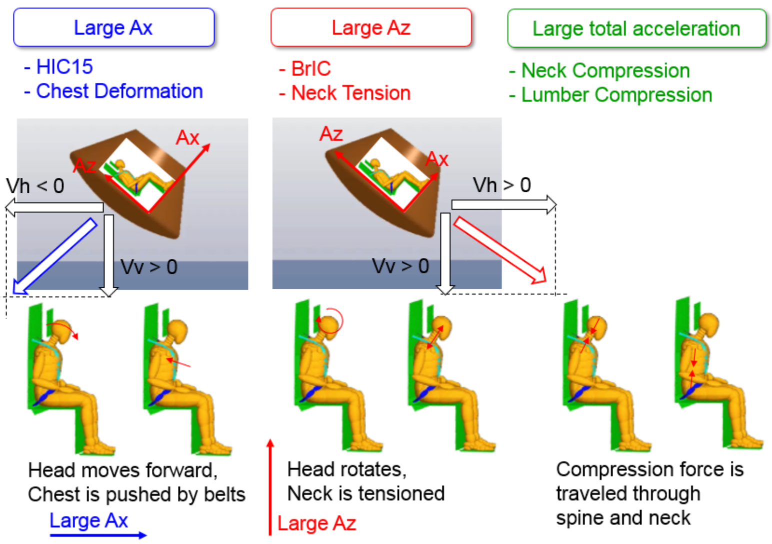

Fig. 4. Crew injury biomechanics for the dynamic load due to excessive water landing velocity.

V. REFERENCES

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[2] Tani, N., *et al.*, *EUCCAS2013*, 2013.
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