Occupant Safety Analysis for Evaluation of Injuries to the Crew Across Mission Phases

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***Abstract*—This paper addresses occupant safety analysis for evaluating potential injuries to crew members during dynamic loading events encountered in the human spaceflight missions. The study focuses on water landing scenarios, with a series of load cases simulating non-attenuated impact, mechanical attenuation, and an attenuated configuration incorporating foam padding at the seat. Biomechanical responses were assessed using various injury criteria such as the Head Injury Criterion (HIC15), Neck Injury Criterion (Nij), and force measurements at critical locations including the lumbar spine and femur. The results show the accelerations and transmitted forces, resulting in various levels of injury risk in relation to the established thresholds. These findings can be used for the design and optimization of occupant protection measures in crew modules.**

Keywords: Crew Injuries, Human Spaceflight, Impact Attenuation, Occupant Safety, Water Landing.

Nomenclature

$a(t)$	Acceleration as a function of time.
HIC	Head Injury Criterion, a measure for evaluating head injury risk.
$HIC15$	Head Injury Criterion evaluated over a 15 ms interval.
Nij	Neck Injury Criterion, which integrates axial forces and bending moments.
F_z	Axial force.
DR	Dynamic Response.
ζ	Damping ratio.
ω_n	Natural (undamped) frequency.
LC	Load Case.
ATD	Anthropomorphic Test Device.

1. Introduction

Gaganyaan is the first Indian human space flight project, which aims to send astronauts to space from India. Astronauts will be sent into a 400 km low earth orbit and then brought back safely to the Earth after spending seven days in space. The orbital module, orbiting the earth has two parts – the crew module, where the crew will be residing; and, the service module, which will service the crew module during the orbital phase. There will be two identical unmanned flights before undertaking the manned flight [13]. Indian astronauts are sent to the low earth orbit in the Human rated launch vehicle called HRLV. The orbital module consists of the crew module and the service module. The crew module will act like crew quarters throughout the mission. Crew safety will be one of the critical aspects in India's first human spaceflight program, the Gaganyaan mission [9]. Crew members will be safely seated inside the Crew Module (CM) which houses all necessary life support systems for simulating environmental parameters such as pressure, temperature and atmosphere identical to Earth's conditions. CM is also designed for re-entry to ensure crew safety during descent until touchdown [5]. Human spaceflight programs face numerous challenges in ensuring crew safety throughout all mission phases, particularly when considering the physiological impacts of dynamic loads on astronauts. The safety of crew is paramount in any human spaceflight mission. There is special attention required for ensuring there is no injury to the crew, especially in re-entry phases of the mission [9]. India's ambitious human spaceflight program ensures focus on crew safety by incorporating various systems such as viable escape systems, designed to ensure safe evacuation in case of emergencies [9]. Throughout the mission, astronauts experience various types of loads across different phases. These loads can be classified as sustained and transient based on their duration [10]. Sustained loads occur over extended periods and include the constant acceleration experienced during launch vehicle lift-off and the continuous microgravity environment while in orbit. Transient loads, conversely, are short-duration forces that occur during abrupt events such as parachute deployment, launch abort scenarios, and water or land impact during landing. Safety assessment against sustained loads involves evaluating physiological responses like cardiovascular changes, muscle atrophy, and bone density loss that occur over prolonged exposure to altered gravity conditions. However, for transient loads, particularly those experienced during landing and abort scenarios, occupant safety analysis becomes critical to evaluate potential acute injuries. Water impact during landing represents one of the most significant transient load scenarios for the Gaganyaan mission. During splashdown, the crew module experiences rapid deceleration forces that can transfer to the astronauts, potentially causing musculoskeletal and soft tissue injuries. Dynamic loading during this phase poses risks influenced by both extrinsic factors like vehicle dynamic profile, seat and harness systems, and spacesuit design, as well as intrinsic factors including age, gender, anthropometry, and spaceflight de-conditioning [2]. Various systems have been implemented in spacecraft design to mitigate injuries from impact loads. The Apollo spacecraft, for example, had crushable ribs and a crew seat pallet with stroking energy absorbers to alleviate contingency impacts [3]. Similarly, the Gaganyaan mission incorporates a crew seat attenuation system designed to reduce the load transferred to the crew during landing impact events. For safety assessment against transient loads, the aerospace industry has traditionally relied on the Brinkley Dynamic Response Index (DRI), a global injury criterion that evaluates overall injury risk based on acceleration profiles [14]. However, this method has limitations in assessing specific risks to individual body regions. A more comprehensive approach to crew safety requires detailed analysis of potential injuries to specific body parts under various landing scenarios and seat configurations. This paper aims to assess the safety of crew members during water impact landing with various configurations of the crew seating system. Through occupant safety analysis, we evaluate the biomechanical response of different body regions to transient loads experienced during splashdown. This approach goes beyond global injury criteria to provide a more nuanced understanding of injury risks and mitigation strategies for the Gaganyaan mission.

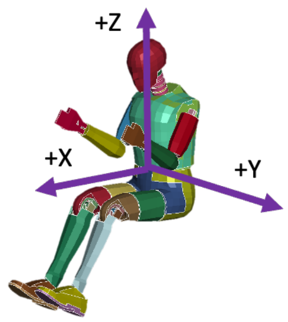

Fig. 1: Hybrid III 50th percentile male dummy

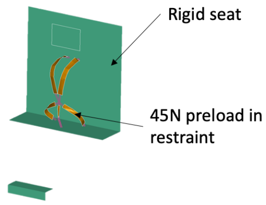

Fig. 2: Seat and 5-point restraint system

2. Material and Methods

Occupant Safety Analysis for Transient Loads NASA has developed comprehensive methodologies for assessing occupant safety during spacecraft missions. It is carried out for transient loading conditions that occur during launch, abort scenarios, and landing events. Occupant safety analysis involves the evaluation of potential injuries to crew members using biomechanical assessments, by evaluating the human body's response to dynamic loading conditions [14]. This approach has evolved from simple acceleration-based criteria to computational models that can predict specific injury risks to various body regions. For spacecraft design, NASA utilizes a combination of experimental testing and computational analysis to evaluate crew safety. The NASA Human Integration Design Handbook (HIDH) specifies injury assessment criteria for various body regions and establishes acceptable thresholds for different mission phases [10]. These criteria are derived from automotive, aviation, and military research and have been adapted for the unique conditions of spaceflight. Occupant safety analysis involves utilizing specialized anthropomorphic test devices (ATDs) or "crash test dummy" to simulate human response to impact conditions. These physical or computational models enables us to predict potential injuries without putting actual humans at risk during testing. For the Orion spacecraft, NASA has conducted extensive sled testing to validate computational models and establish injury thresholds for water landing scenarios [14].

A. Anthropomorphic Test Device (ATD)

The Hybrid III 50th percentile male dummy as shown in the 1 is the industry standard ATD used extensively in automotive, aviation, and aerospace applications to assess occupant safety. This ATD represents a standard male with a height of 175 cm and weight of 77 kg, corresponding to the 50th percentile of the adult male population [8]. The Hybrid III features instrumentation capable of measuring head acceleration, neck forces and moments, chest compression, femur loads, and other critical injury parameters. NASA has utilized the Hybrid III ATD for various testing scenarios, including Orion crew module impact testing, launch abort system evaluation, and water landing simulations [3]. During the development of the Orion spacecraft, NASA conducted drop tests with instrumented ATDs to understand the effects of water impact and to validate computational models [11]. Finite element (FE) models of the Hybrid III ATD have been developed and validated against physical test data, providing a cost-effective means for conducting parametric studies of occupant safety. The LS-DYNA H350 (Hybrid III 50th percentile) model used in this study is a detailed representation of the physical dummy, containing accurate mass distribution, joint properties, and instrumentation locations [12]. This FE model allows for the assessment of loads experienced by different body regions during impact events and enables the evaluation of various protection systems without the need for repeated physical testing.

B. Modeling Details

1) Seat Modeling

For this study, the seat was modeled as a flat-back as shown in the Fig.2, non-deformable rigid structure to establish baseline injury metrics without the influence of seat deformation. This approach is consistent with NASA's initial evaluation methodology for the Orion crew module

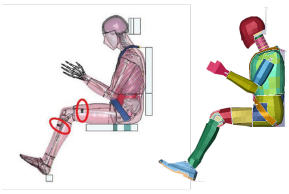

Fig. 3: Hybrid III 50th percentile dummy positioned and seated with restrained as per the reference

[3]. The seat was fixed to the spacecraft structure, with motion constrained in all degrees of freedom to simulate the seat's mounting to the crew module. In the one of the load case, the seat was modified to include foam padding with varying thicknesses to evaluate its effectiveness in attenuating impact loads. The foam was modeled using material properties representative of spacecraft seat cushioning materials, with appropriate stress-strain characteristics and energy absorption capabilities [3].

2) *Restraint System Modeling*

A five-point restraint system was modeled to secure the ATD to the seat, consisting of two shoulder straps, two lap belts, and one crotch strap as shown in the Fig.2. Each strap was modeled using shell elements with fabric material properties. The connection points were fixed to the seat structure, and contact definitions were established between the belts and the ATD to capture the load transfer during impact events [4]. The restraint pre-tensioning was set to 44.5 N for all belts, consistent with NASA's testing protocols for Orion [14]. The restraint system's geometry was designed to position the ATD in a nominal seated posture with proper belt routing across the shoulders, pelvis, and between the legs.

3) *Coordinate System Definition*

The local inertial axis system as shown in the Fig.1 has the +X-axis forward, the +Z-axis pointed toward the head, and the +Y-axis to the left. The seat coordinate system is a local system and is a non-inertial axis system. Hence, angular rotations with respect to an inertial system must be considered [3]. This coordinate system is consistent with the standard used by NASA for spacecraft occupant safety analysis and allows for direct comparison with established injury criteria thresholds [10].

C. Load Cases and Boundary Conditions

Three distinct load cases were evaluated in this study to assess occupant safety under different landing conditions and protection systems. The position of the occupant as shown in the Fig.3 was kept as per the reference from the Orion study[3].

- **Load Case 1**: Non-Attenuated Water Impact The first load case represented a non-attenuated water impact scenario similar to the Orion spacecraft's water landing conditions[17]. The acceleration profile was derived from NASA's Orion water impact testing data, with a dynamic amplification factor of 2 applied to account for structural response effects.
- **Load Case 2**: Attenuated Impact The second load case implemented an attenuated load profile where the peak acceleration was limited to 10g through an idealized attenuation system. This profile maintained the same impulse as Load Case 1 but extended the duration to reduce peak loads. This case represents the implementation of a stroking seat or other mechanical attenuation system designed to limit crew exposure to high-g loads [3].
- **Load Case 2, modified seat configuration**: Attenuated Impact with Seat Foam The third load case utilized the same attenuated acceleration profile as Load Case 2 but incorporated foam padding on the seat surface. Various foam thicknesses were evaluated to determine the optimal configuration for minimizing injury risks. This case represents a combined approach using both mechanical attenuation systems and energy-absorbing materials [4].

For all load cases, the boundary conditions included:

Fixed constraints on the seat structure, representing rigid attachment to the spacecraft The ATD was constrained only by the five-point harness system.

3. Theory and equations

The evaluation of human injury risk during spacecraft transient dynamic events, such as launch, landing, and abort scenarios, requires specialized biomechanical criteria. This section outlines both global and regional injury assessment methodologies used in spacecraft occupant safety analysis.

A. Brinkley Dynamic Response Index (DRI)

The Brinkley Dynamic Response Index (DRI) has been the primary method used by NASA for assessing injury risk during spacecraft dynamic events. This model represents the human body as a single-degree-of-freedom spring-mass-damper system with different natural frequencies and damping ratios along each of the three primary axes [1]. The DRI is calculated by solving the following differential equation for each axis:

$$\ddot{x} + 2\zeta\omega_n\dot{x} + \omega_n^2 x = A(t) \quad (1)$$

where, x is the displacement of the model mass from the equilibrium position, ζ is the damping ratio, ω_n is the undamped natural frequency, and $A(t)$ is the input acceleration.

The maximum dynamic response (DR) values are then calculated for each axis and combined using an ellipsoidal injury risk function:

$$\beta = \sqrt{\left(\frac{DR_x}{DR_{x_{\text{limit}}}}\right)^2 + \left(\frac{DR_y}{DR_{y_{\text{limit}}}}\right)^2 + \left(\frac{DR_z}{DR_{z_{\text{limit}}}}\right)^2} \quad (2)$$

where $DR_{i_{\text{limit}}}$ are the axis-specific dynamic response limits based on injury risk level.

While the Brinkley DRI model provides a global approach to assessing whole-body injury risk, it has several limitations. It oversimplifies the complex human-vehicle interaction. The model parameters are highly dependent on specific test configurations, posing challenges for extrapolation to other setups. There are concerns about the robustness of injury risk limits due to the lack of detailed supporting data [15]. Due to these limitations, NASA has developed more detailed injury criteria for specific body regions to complement the Brinkley model. These criteria provide a comprehensive understanding of injury risks during spacecraft dynamic events.

B. Head Injury Criteria

1) Head Injury Criterion (HIC)

The Head Injury Criterion (HIC) is derived from the Wayne State Tolerance Curve (WSTC), which relates acceleration magnitude and duration to skull fracture and brain injury. The HIC is defined as:

$$\text{HIC} = \max_{t_1,t_2} \left\{ (t_2 - t_1) \left[\frac{1}{t_2 - t_1} \int_{t_1}^{t_2} a(t)\, dt \right]^{2.5} \right\} \quad (3)$$

where $a(t)$ is the resultant linear acceleration of the head center of gravity in g's, and t_1 and t_2 are selected to maximize the HIC value.

For spacecraft applications, HIC_{15} is typically used, where the time interval $(t_2 - t_1)$ is limited to 15 ms. This shorter time interval is more appropriate for the brief, high-intensity impacts that may occur during spacecraft landing or abort scenarios [16].

The injury risk threshold for HIC is:

$$\text{HIC}_{15} < 700 \text{ (low risk of severe head injury)} \quad (4)$$

This value corresponds to approximately a 5% risk of Abbreviated Injury Scale (AIS) 3+ head injury, which includes skull fracture and serious brain injury [15].

4. Neck Injury Criteria

Neck Injury Criterion (N_{ij})

The N_{ij} criterion combines the effects of axial force (F_z) and sagittal plane bending moment (M_y) at the occipital condyles:

$$\text{N}ij = \frac{F_z}{F_{zc}} + \frac{M_y}{M_{yc}} \quad (5)$$

where F_{zc} and M_{yc} are critical values dependent on loading direction:

$$F_{zc} = 6806 \text{ N (tension), } 6160 \text{ N (compression)} \quad (6)$$

$$M_{yc} = 310 \text{ Nm (flexion), } 135 \text{ Nm (extension)} \quad (7)$$

The injury threshold is:

$$\text{N}_{ij} < 1.0 \quad (8)$$

This composite criterion accounts for the combined effects of tension/compression and flexion/extension loading on the neck, providing a more comprehensive assessment than individual force or moment limits [15]. This threshold is designed to prevent compression-related injuries such as vertebral fractures and spinal cord injuries [8].

A. Lumbar Load Criteria

The lumbar spine primarily experiences compressive loading during vertical acceleration events, particularly during spacecraft landing. The lumbar load criterion focuses on the compressive force measured at the lumbar spine:

$$F_z = m_{\text{effective}} \cdot a_z + F_{\text{muscle}} \quad (9)$$

where $m_{\text{effective}}$ is the effective mass supported by the lumbar spine, a_z is the vertical acceleration, and F_{muscle} represents muscle force contributions.

The injury thresholds for lumbar compression are gender-specific due to differences in bone strength:

$$F_z < 6700 \text{ N (males) } F_z \quad < 4226 \text{ N (females)} \quad (10)$$

These limits correspond to approximately a 5% risk of vertebral fracture and are particularly relevant for vertical landing scenarios where spinal compression is a primary concern [1].

B. Femur and Tibia Force Criteria

1) Femur Axial Compression

Femur loading during spacecraft dynamic events typically occurs in the form of axial compression when the knees impact forward structures. The femur force criterion is expressed as:

$$F_{\text{femur}} < F_{\text{critical}} \quad (11)$$

where F_{critical} varies based on impact duration:

$$F_{\text{critical}} = 9070 \text{ N for } t \leq 3 \text{ ms} \quad (12)$$

$$F_{\text{critical}} = 7560 \text{ N for } t > 3 \text{ ms} \quad (13)$$

For repeated loading or longer duration events, a lower threshold is recommended:

$$F_{\text{femur}} < 3980 \text{ N (10\% risk of fracture)} \quad (14)$$

These limits are derived from automotive testing and have been adapted for spacecraft applications [6].

2) Tibia Axial Compression

Tibia injuries can occur during spacecraft landing when vertical loads are transmitted through the leg structure. The tibia force criterion limits the axial compressive force to prevent fractures:

$$F_{\text{tibia}} < 8000 \text{ N} \quad (15)$$

This limit corresponds to approximately a 10% risk of tibial fracture and is applicable to both impact and sustained loading scenarios [6].

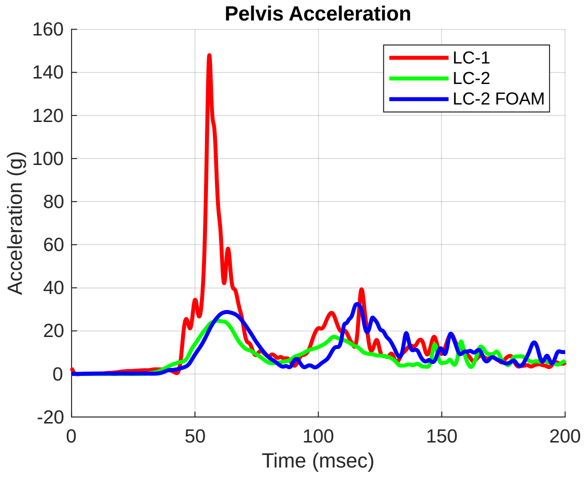

Fig. 4: Pelvis acceleration profiles for different load cases.

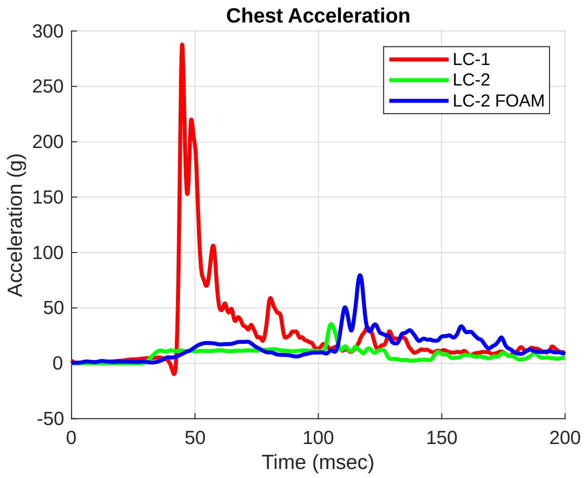

Fig. 5: Chest acceleration profiles for LC-1, LC-2, and LC-2 FOAM.

5. Results

A. Biomechanical Response Analysis

1) Head Acceleration and HIC15 Assessment

The head acceleration data across the three load cases reveals significant variations in both peak values and temporal patterns as shown in the Fig.6. Load Case 1 (LC-1), representing water impact without attenuation, demonstrated the highest peak acceleration of approximately 280g, resulting in a Head Injury Criterion (HIC15) value of 236.6 as shown in the Fig.7. This value, while below the critical injury threshold of 700 established for crew protection [14], indicates a moderate risk of head injury.

Load Case 2 (LC-2), incorporating attenuation systems, showed a reduction in peak head acceleration to approximately 120g, corresponding to a HIC15 value of only 40.9. This represents an 82.7% reduction in HIC15 compared to LC-1, demonstrating the effectiveness of the attenuation system in mitigating potential head injuries during water landing scenarios [7].

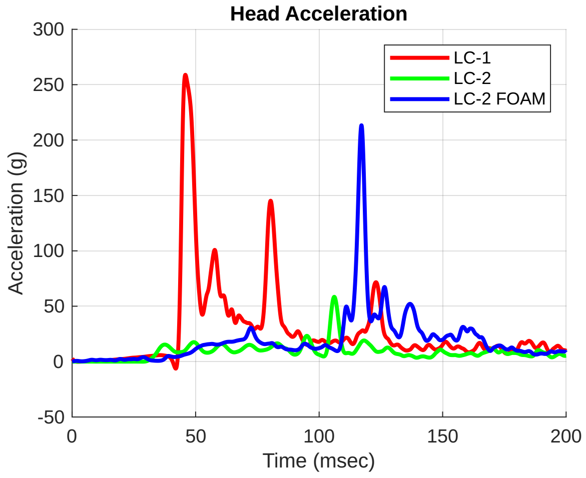

Fig. 6: Head acceleration for LC-1, LC-2, and LC-2 FOAM.

Load Case 2 with FOAM (LC-2 FOAM) exhibited intermediate performance, with peak head acceleration around 180g and a HIC15 value of 147.8.

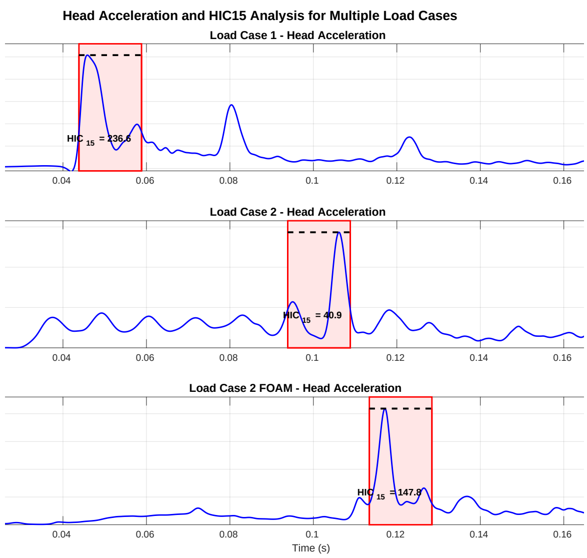

Fig. 7: Head acceleration profiles for multiple load cases with computed HIC15 values.

2) Neck Injury Criterion (Nij) Results

The Neck Injury Criterion (Nij) analysis as shown in the Fig.8 reveals LC-1 data points extend closest to the Nij = 1 envelope, indicating higher neck injury risk [?]. Both LC-2 and LC-2 FOAM demonstrate reduced neck loading, with data points remaining further from the Nij = 1 boundary.

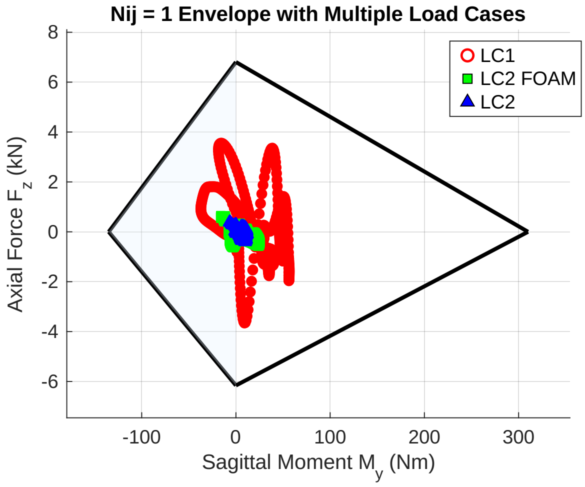

Fig. 8: Nij scatter plot for LC-1, LC-2, and LC-2 FOAM.

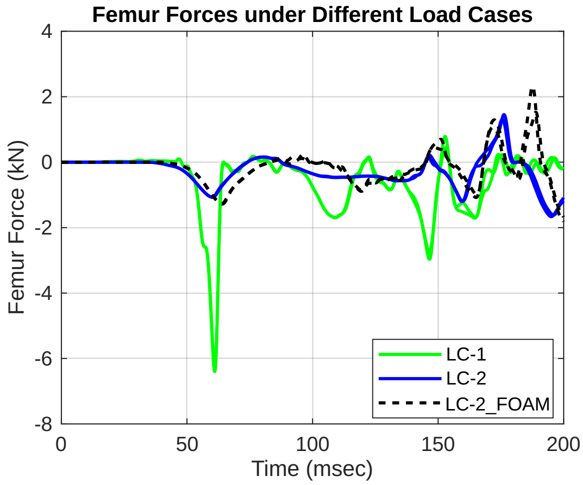

Fig. 9: Femur force responses under different load cases.

The greatest difference is observed in the axial force component, with LC-1 reaching approximately 6 kN in tension, while LC-2 remains below 3 kN. Similarly, sagittal moment values are reduced from approximately 250 Nm in LC-1 to less than 150 Nm in the attenuated cases [14].

3) Thoracic Response and Thoracic Injury Criterion

Chest acceleration data demonstrates LC-1 exhibited the highest peak chest acceleration at approximately 250g as shown in the Fig.5. Both LC-2 and LC-2 FOAM showed substantial reductions in peak chest acceleration to approximately 100g and 150g, respectively.

The temporal profile of chest acceleration differs between load cases, with LC-1 showing a sharp, narrow peak characteristic of high-energy impact events. In contrast, both attenuated cases display broader acceleration curves with peak values occurring approximately 10-15 ms later than in LC-1, indicating more gradual energy transfer and dissipation [16].

4) Lumbar Spine Force Analysis

The lumbar spine force measurements show significant variation across the load cases. LC-1 exhibited the highest peak lumbar force (5.8 kN), approaching critical thresholds for injury. The LC-2 with the attenuation system demonstrated a substantial reduction in peak lumbar force (2.7 kN), providing improved protection for the lower back region. LC-2 FOAM showed intermediate performance, with lumbar forces (4.0 kN) reduced compared to LC-1.

5) Lower Extremity Response and Femur Force

Femur force measurements reveal bidirectional loading patterns across all three cases. LC-1 showed the highest peak compressive force of approximately -6.5 kN, which approaches the femur fracture threshold of -7.8 kN [10]. LC-2 demonstrated significant reduction in peak compressive force to approximately -3.0 kN, well below injury thresholds. LC-2 FOAM showed an intermediate value of approximately -4.5 kN.

6) Pelvis Acceleration Response

Pelvic acceleration data showed LC-1 exhibiting the highest peak of approximately 150g. LC-2 showed the most significant reduction in pelvic acceleration to approximately 60g, placing it well within acceptable safety margins. LC-2 FOAM achieved an intermediate reduction to approximately 100g.

B. Injury Risk Assessment Summary

The comprehensive evaluation of injury metrics across all load cases reveals consistent patterns in the effectiveness of different protection strategies. A summary of key injury parameters compared to established thresholds is presented in Table I.

TABLE I: Summary of key injury parameters across load cases compared to acceptable thresholds

Load Case	HIC15	Nij	Femur (kN)	Lumbar (kN)
LC-1	236.6	0.8	-6.5	5.8
LC-2	40.9	0.4	-3.0	2.7
LC-2 FOAM	147.8	0.6	-4.5	4.0
Threshold	700	1.0	-7.8	6.7

The data summerized in the Table I demonstrate that while LC-1 approaches thresholds for multiple criteria, the primary attenuation system in LC-2 effectively brings all injury metrics well below critical thresholds. LC-2 FOAM provides intermediate protection [12].

6. Discussion

A. Trends Across Load Cases for Various Injury Criteria

The comprehensive analysis of multiple injury criteria across different load cases reveals some patterns that provide valuable insights into occupant protection during spacecraft water landings:

1) **Protection Effectiveness**: Across all injury metrics, a consistent protection effectiveness is observed, with LC-2 providing superior protection, followed by LC-2 FOAM, and finally LC-1 showing the highest injury potential. This consistency suggests that the fundamental acceleration reduction of the attenuation systems have broad-spectrum benefits for occupant protection [4].
2) **Varying Effectiveness by Body Region**: While the attenuation systems demonstrated benefits across all body regions, the magnitude of improvement varied considerably. Head protection (82.7% reduction in HIC15 with LC-2) showed the most dramatic improvement, followed by chest and pelvis acceleration (60% reduction), with femur force showing the least relative improvement (54% reduction).
3) **Threshold Exceedance Patterns**: The unattenuated condition (LC-1) approached established injury thresholds for multiple criteria but remained below critical thresholds for head injury criteria. This pattern indicates that thoracic and pelvic protection should be prioritized in spacecraft design, as these regions appear most vulnerable during water landings without attenuation [10].

B. Effect of Acceleration Characteristics on Injury Parameters

The analysis of acceleration profiles across different body regions provides critical insights into injury mechanisms and protection strategies:

1) **Peak Acceleration Influence**: Peak acceleration values showed strong correlation with computed injury criteria, particularly for metrics with instantaneous components like peak femur force and lumbar force [14]. LC-1 consistently produced the highest peak accelerations and corresponding elevated injury metrics.
2) **Acceleration Duration Effects**: The duration of acceleration pulses played a crucial role in injury potential, particularly for integrated criteria like HIC15 and Nij. LC-1 demonstrated sharp, narrow acceleration peaks characteristic of high injury potential, while both attenuated configurations produced broader, lower-magnitude pulses associated with reduced injury risk [1].
3) **Acceleration Onset Rate**: The rate of onset (jerk) appeared to significantly influence biomechanical response, with LC-1 showing rapid onset rates that contribute to elevated injury metrics. Both attenuation systems reduced the onset rate, with LC-2 demonstrating the most gradual acceleration development [7].

C. Duration and Onset Rate Implications

The temporal characteristics of the acceleration pulses provide particularly valuable insights for spacecraft design and occupant protection:

1) **Trade-offs in Protection Design**: The results highlight the fundamental trade-off between peak acceleration magnitude and duration. Effective attenuation systems must balance these factors to minimize injury potential across different body regions and injury mechanisms [4].
2) **Critical Duration Thresholds**: The data suggest the existence of critical duration thresholds for different injury mechanisms. Short-duration, high-magnitude events (as seen in LC-1) appeared particularly injurious for head and neck regions, while chest protection benefited significantly from temporal redistribution of loading [3].
3) **System Tuning Considerations**: The intermediate performance of LC-2 FOAM suggests that attenuation system characteristics must be carefully tuned to the specific impact conditions anticipated during spacecraft landings. The material properties, geometry, and mechanical response of attenuation systems should be optimized based on expected loading rates and durations to maximize protection effectiveness [12].

The comprehensive analysis demonstrates the critical importance of effective impact attenuation systems for crew safety during spacecraft water landings. The data provide clear evidence that properly designed attenuation systems can dramatically reduce injury potential through management of both peak acceleration magnitudes and temporal characteristics of the impact event [9].

7. Conclusion

The occupant safety analysis presented in this paper emphasizes the significant influence of dynamic load profiles on injury risks during dynamic loading event of water landings. The investigation reveals that the magnitude and temporal characteristics of the loads—such as peak acceleration values, duration, and rate of onset—play a decisive role in determining the severity of biomechanical responses across various body regions. In particular, higher load magnitudes were observed to correlate with elevated injury indices, as evidenced by metrics like HIC15 and Nij, highlighting the sensitivity of the head and neck regions to rapid deceleration events. Similarly, force measurements at the lumbar spine and lower extremities underscored the impact of dynamic load variations on the potential for skeletal injuries.

Overall, these findings illustrate that detailed characterization of load dynamics is critical for predicting and mitigating injury risks in crewed missions. A thorough understanding of how different loading scenarios affect the biomechanical response of the human body can lead to improved design strategies for spacecraft that prioritize occupant safety under a range of dynamic conditions. Future work may benefit from exploring the interplay between load distribution and individual anatomical differences to further refine injury prevention measures in human spaceflight applications.

Acknowledgments

The authors express their sincere gratitude to the Human Space Flight Centre at the Indian Space Research Organization for the significant support, technical guidance, and resources provided throughout this study.

Appendix

All the codes used in the paper for calculation of the injury assessment value based on the equation are available at following location: https://github.com/Verhonish/GLEX2025

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