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Lunar Transient Accelerations

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1.0 INTRODUCTION

Recently, the United States announced a plan to return astronauts to the moon by 2024 [8]. Lunar landing (and subsequent Mars landing) architecture was not considered when the current NASA standards and vehicle design requirements for crew injury risk were developed. Therefore, a gap exists in protecting the crew in planetary landing scenarios.

One of the interesting aspects of this design reference mission (DRM) is the consideration of having the crew stand during dynamic phases of flight. Although this approach was contemplated for the Apollo Lunar Module, current NASA standards do not address design solutions that allow the crew to stand.

Currently, NASA uses several tools and associated limits to mitigate crew injury because of dynamic loads. Some of these tools are the Brinkley Dynamic Response Criterion (BDRC) model and Hybrid III Anthropomorphic Test Devices (ATDs) [10]; and these have several limitations for assessing spaceflight loading environments, as well as specific underlying assumptions that may not be applicable in planetary landing vehicles.

The BDRC is a simple lumped mass parameter model developed by the U.S. military, and has been used primarily to evaluate injury risk associated with aircraft ejection systems. The model evaluates seat accelerations in each axis to determine injury risk. Because the model treats the human-seat-restraint system as a single system, it is contingent on a restraint system and seat with similar characteristics of the original test data underlying the model. In particular, the model requires a rigid seat with a minimum natural frequency of 15 Hz, minimal seatpan padding, side supports, and multipoint harness. The BDRC model uses undamped natural frequency and damping coefficients based on these requirements and any deviations may render the model injury predictions void. In lunar landing, one expects that a minimal or even no seat with minimal restraints will be employed. In this case, the original model parameters are likely to not be applicable.

For capsule-based spacecraft returning crew to Earth, the Hybrid III ATD in various sizes also is used to supplement the BDRC. This analytical tool was added to address limitations in the BDRC related to spacecraft landings while wearing a pressure garment and helmet. Although the Hybrid III ATD has additional measurement capability; head, neck, and lumbar spine responses were the only metrics included because of the limitations imposed by the model.

Lunar landing acceleration limits must assume the crew is standing during landing, an orientation for which we have limited data. Although the Apollo missions did employ a standing orientation for the crew, much of the data is lost. Therefore data from other sources have been examined to inform lunar landing acceleration limits.

2.0 AVAILABLE DATA

2.1 Apollo Data

The Apollo Lunar Module was used successfully in 6 lunar landings. The design was a significant departure from previous spaceflight designs, as it employed a standing orientation for the crew. This decision was made to minimize mass by eliminating the bulky seats and the need for additional windows. The system consisted of hand holds, arm rests with integrated energy attenuators, foot holds, and a restraint pulley system to provide a constant force into the floor, seen in Figures 1 and 2 [5]. This system was used to successfully land 12 men on the moon.

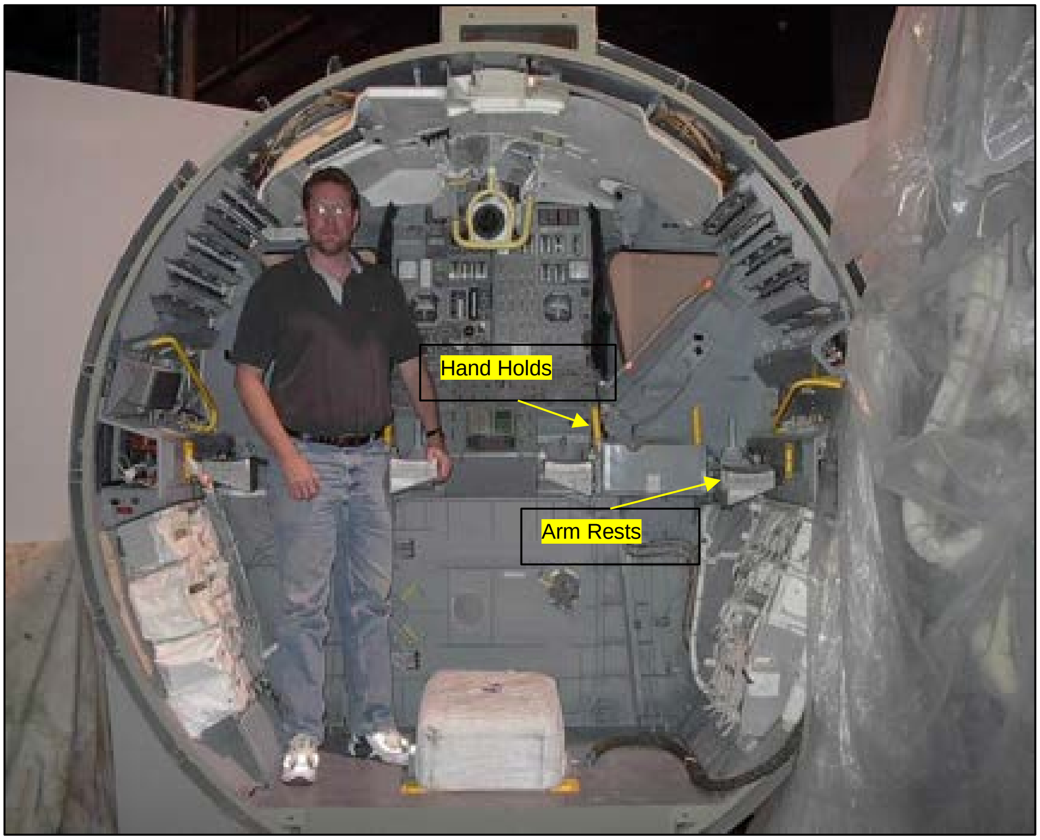

Figure 1. Interior configuration of the Apollo Lunar Module piloting positions.

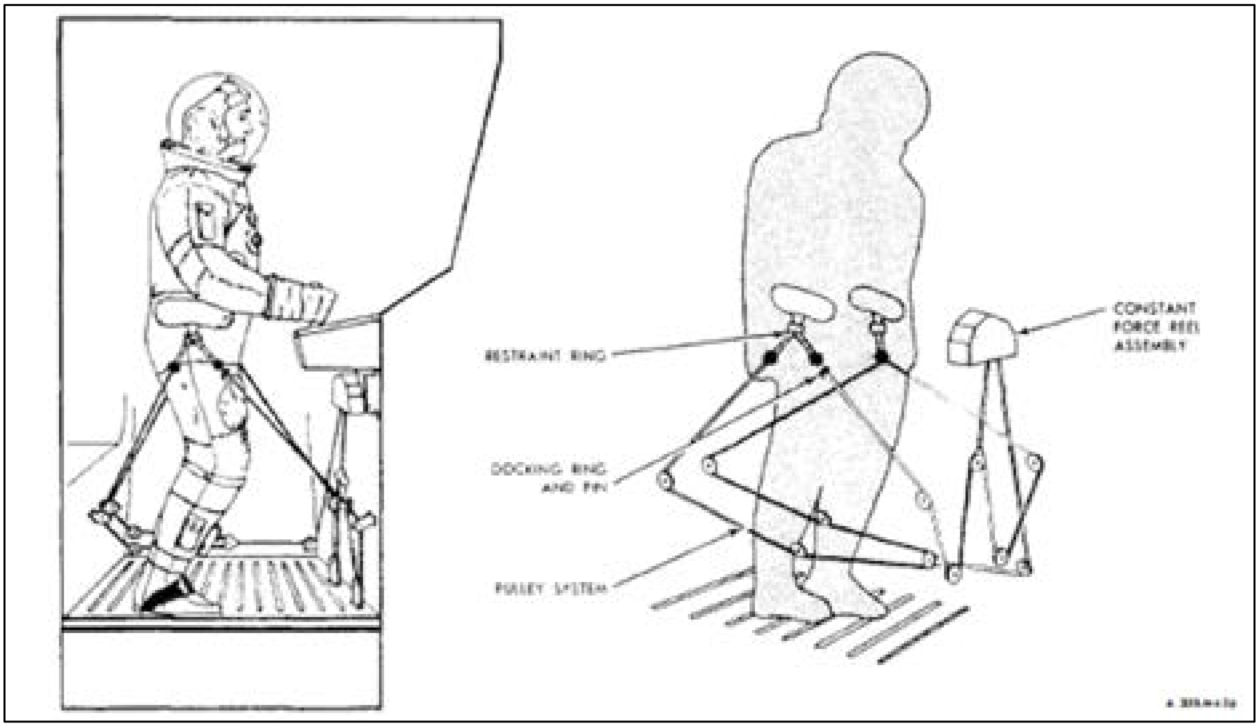

Figure 2. Apollo Lunar Module restraint configuration [4].

During dynamic phases of flight, the crew donned the Apollo A7L suit (Figure 3) configured for intravehicular activity (IVA). The total mass of the A7L suit in the landing configuration was 29.3 kg.

Specific impact acceleration data from each lunar landing mission is not available. accelerations for each landing were estimated using touchdown conditions from each Apollo landing [11], along with assumptions and simplifications about the landing dynamics. Duration of the impact was determined using guidance, navigation, and control (GN&C) time history (Figure 4). In the case shown, the overall duration of the impact event is 600 ms. A half-sine pulse was used as an approximation of the

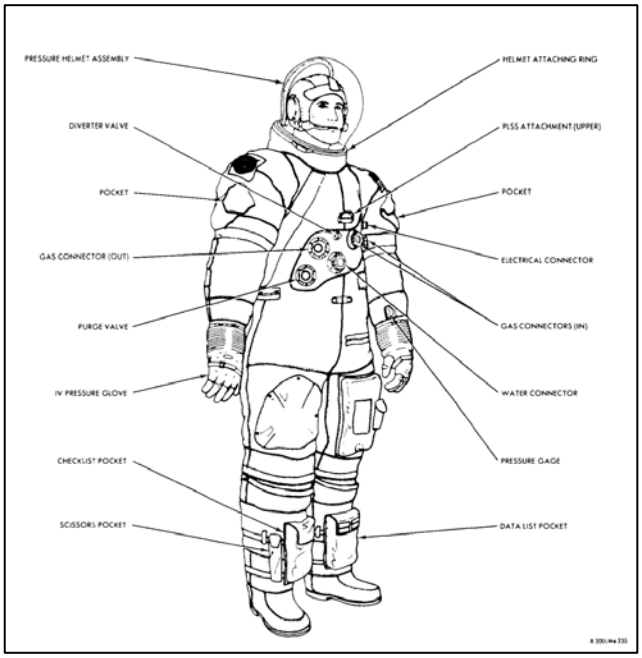

Figure 3. Apollo A7L IVA configuration**.**

shape of the acceleration event, giving a rise time (time to peak) of 300 ms. To determine the peak acceleration, velocity at footpad contact was used as the total change in vertical velocity (ΔV) (Table 1). The vertical velocity at footpad contact was given in each mission landing. Because the final velocity is 0 (stationary on the Lunar surface), an assumption of constant change in velocity was used, which may underestimate the peak acceleration because if the ΔV were to occur over a subset of the overall time extracted, the peak accelerations would be higher. This assumption is reasonable based on the shape of the GN&C tracings (Figure 5).

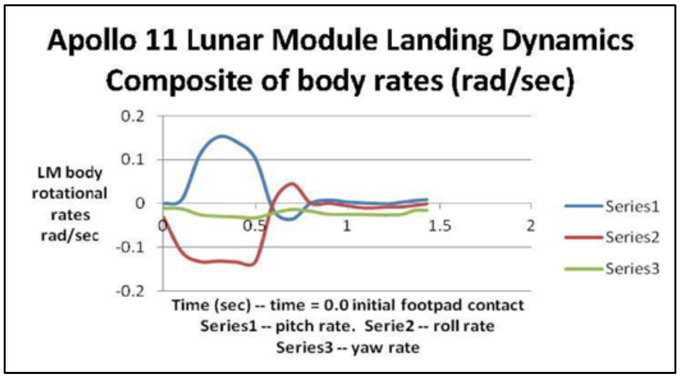

Figure 4. Example landing GN&C time history [11].

Table 1. Lander Velocity at Footpad Contact

Mission	Horizontal Velocity (m/s)*	Vertical Velocity (m/s)*	Landing Slope (rad)
Apollo 11	0.67	0.55	0.079
Apollo 12	0.52	1.00	0.084
Apollo 14	0.73	0.94	0.124
Apollo 15	0.40	2.07	0.192
Apollo 16	~0	1.71	0.044
Apollo 17	~0	0.91	0.044

*at moment of first footpad contact

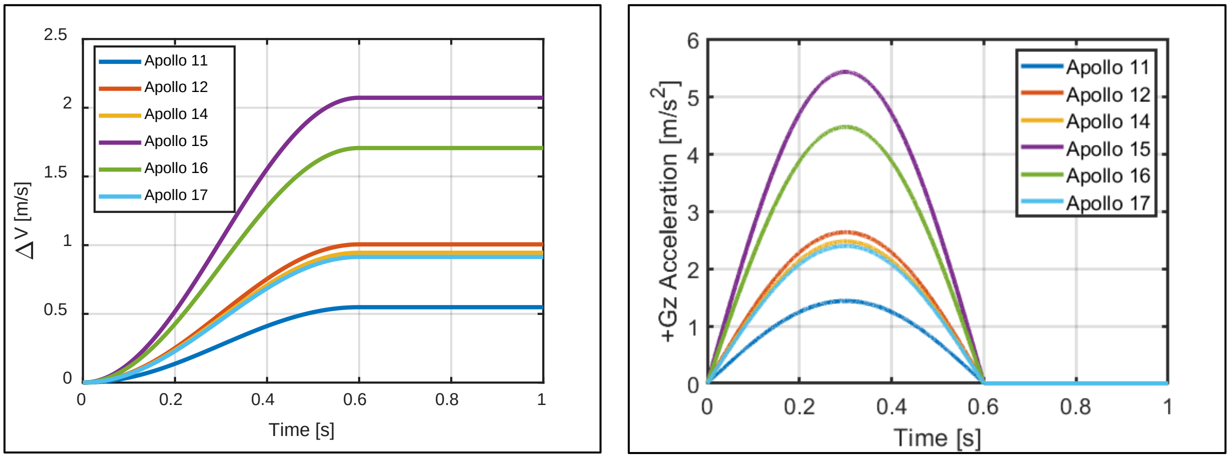

Figure 5. Change in velocity and estimated acceleration for each lunar landing.

In addition, ground testing of the landing system was also available [1]. The test program completed 21 tests of a prototype landing gear system in simulated lunar gravity. These test data points are included along with the estimated Apollo landing data (Figure 6).

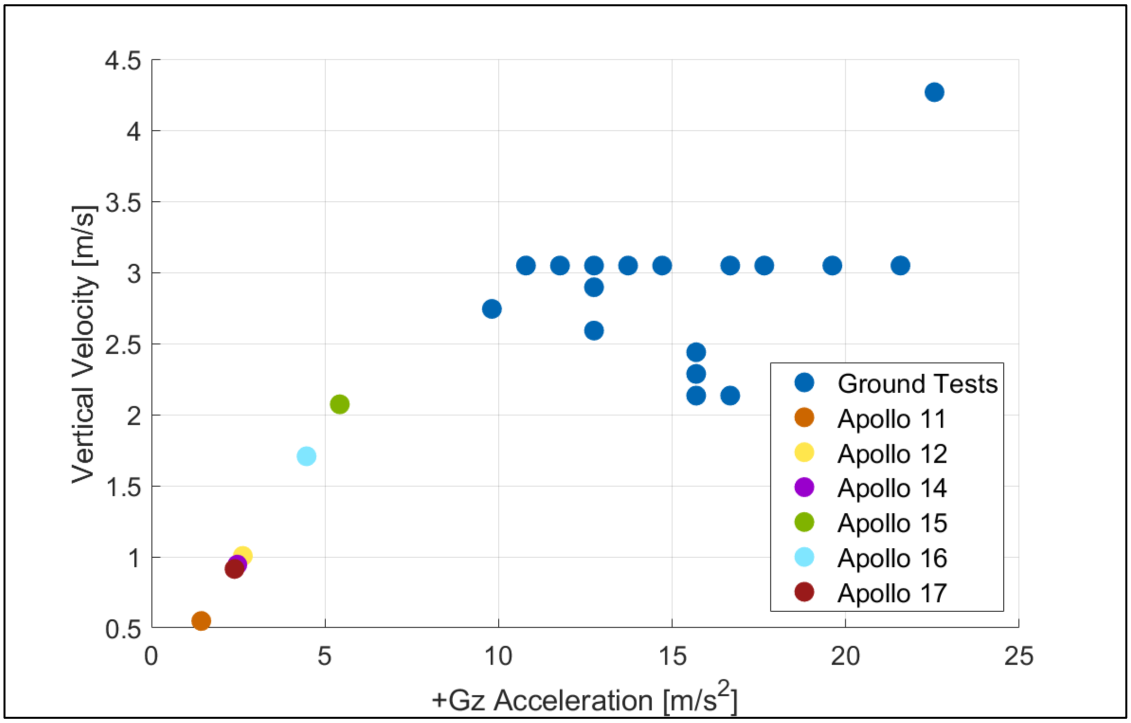

Figure 6. Estimated peak landing impact accelerations for each Apollo lunar landing.

2.2 Other Relevant Data

Ground-based and flight data also were reviewed to inform a recommendation for a new transient acceleration limit.

Figure 7 shows the treadmill foot strike data from crewmembers on the International Space Station (ISS) [3]. These data have the benefit of providing direct evidence of a tolerable acceleration to a deconditioned crew repeatedly over a long-duration mission. The rise time of each foot strike is approximately 50 ms. Peak foot strike forces ranged from 1220-1530 N. In terms of acceleration, percentage body mass as a surrogate for acceleration was used as a simplification (140% to 180% of crew body weight).

Data from a voluntary jumping task conducted on crewmembers after ISS long-duration spaceflight also were reviewed (Figure 8).

Figure 8. Voluntary jump task.

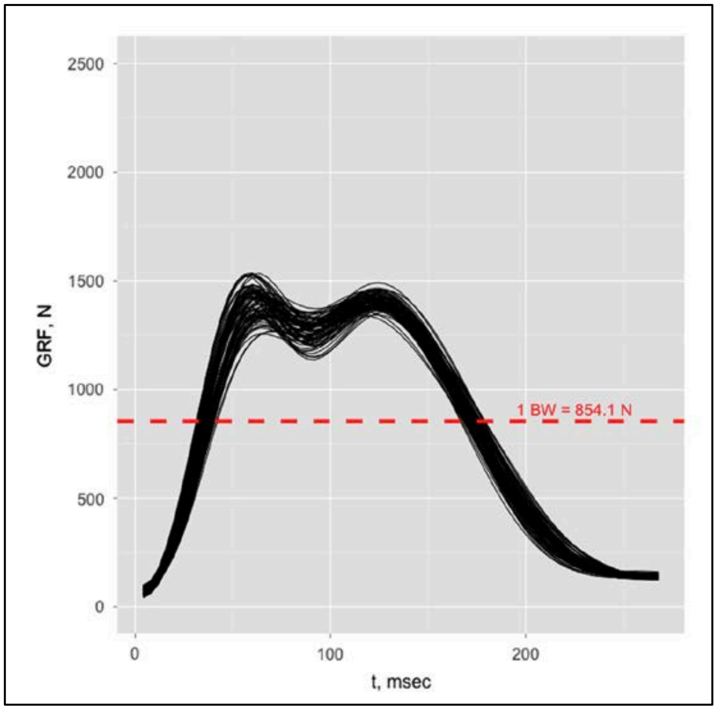

Figure 7. Foot strike data from ISS crewmembers [3].

These data show crew experience up to 3 times their normal body weight during the jumping task, with an average rise time of 150 ms. In both cases of treadmill running and voluntary jumping, the crewmember is actively reacting to the anticipated impact force. In comparison, passive acceleration transmitted through the feet is likely to transmit higher forces to the torso and spine.

Kuppa et al. [6] and Pintar et al. [9] conducted terrestrial research on lower extremity injury. Kuppa et al. reported injuries to the calcaneus, talus, ankle, and mid-foot based on conditions found in real-world automotive impacts. Pintar et al., reported calcaneus, talous, and distal tibia injuries with and without combat boots. To be conservative, results for the unbooted condition were used.

Data points from all the different sources were compiled together as shown in Figure 9.

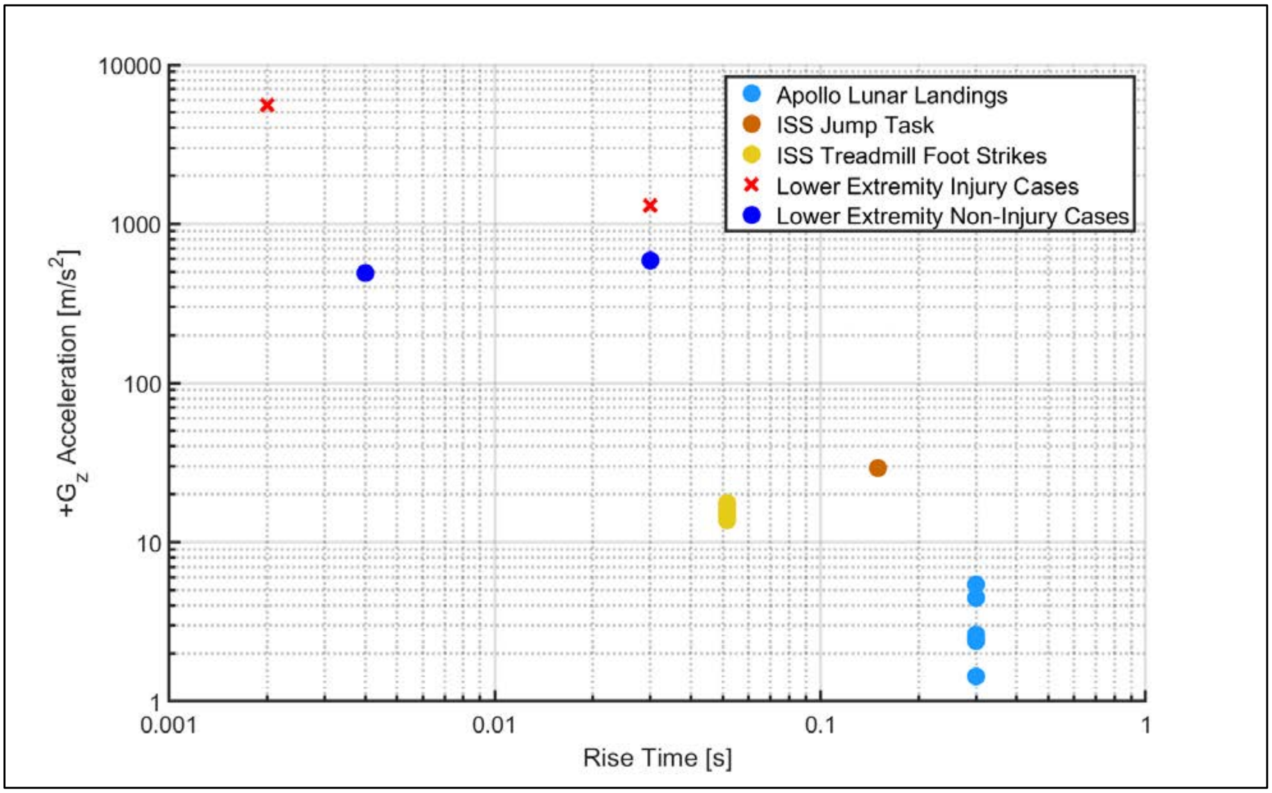

Figure 9. Compilation of available impact data in a standing posture.

3.0 CONSIDERATIONS FOR 2024 LUNAR MISSION

Currently, the DRM for the 2024 Lunar Return includes some key design elements that deviate from the Apollo mission design (Figure 10). These elements include longer mission durations before lunar landing (approximately 10-11 days from Earth launch to lunar landing versus 4.5 days for Apollo), longer stays on the lunar surface (minimum of 1 week, and may increase in 1-week increments, compared to a maximum of 3 days in the Apollo program). The new architecture includes rendezvous with the Gateway platform, which will orbit in a Near Rectilinear Halo Orbit (NRHO). This orbit necessitates greater accelerations to descend to the lunar surface and return to the Gateway platform.

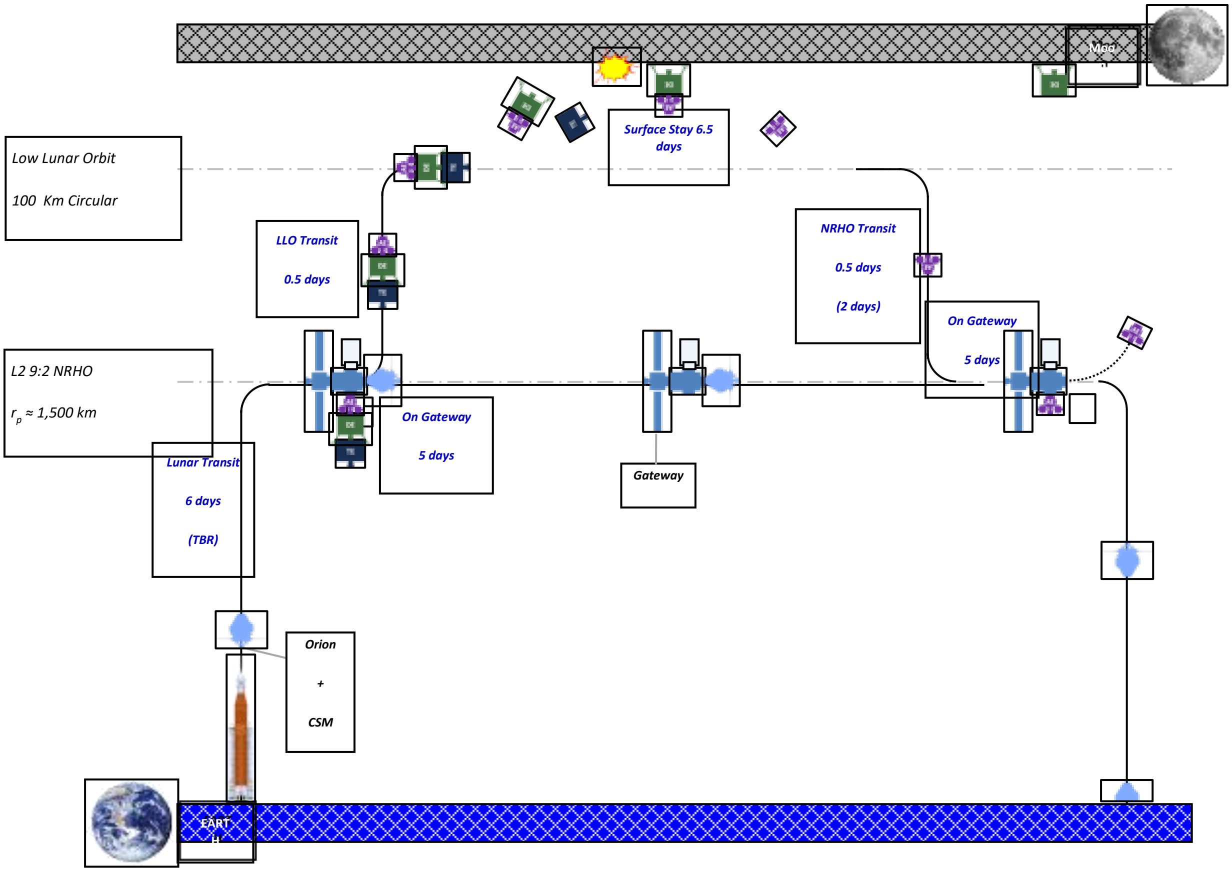

Figure 10. The 2024 design reference mission.

In addition to the Human Lander System (HLS) design, the 2024 missions are currently baselined to have the crew wear the xEMU suit for all dynamic phases of flight (Figure 11). This suit has significantly more mass than the Apollo IVA configuration (>70 kg versus ~30 kg in Apollo). This increased mass may increase loading on the crewmember in a standing posture if the additional mass is not offloaded in some manner. In addition, the xEMU has specific design elements that are expected to increase the risk of injury due to dynamic loads. The lunar configuration will include pants with bearings at the hips. These bearings preclude sitting on a conventional seat, as the bearings would interfere with the load path between the crewmember and the seat. The xEMU includes a hard, upper torso (HUT) that has the potential to cause blunt force trauma injuries to the crewmember during dynamic loads.

Figure 11. xEMU lunar configuration.

Until specific commercial designs are selected, there remains significant uncertainty in the exact environments to which the crew may be exposed. Even so, for standards that would apply to any future design, any limit associated with a specific analytical tool must not be tailored specifically to a particular design, but instead must be design agnostic.

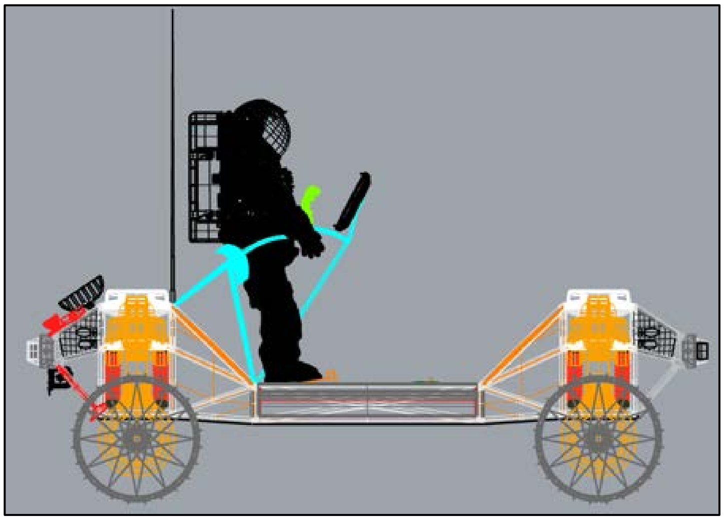

Figure 12. Notional design for an unpressurized rover.

In addition to the typical dynamic loading expected during spaceflight, planetary landing will involve EVA activities, both walking in the suit and likely driving a rover (Figure 12). Because of the reduced gravity environment, the mass of the rover, and the mass of the suited crewmember, the dynamics of driving across an uneven planetary surface may require additional consideration for protecting the crewmember from transient accelerations. For example, if the rover were to strike a large rock while driving at maximum speed, the crewmember could be ejected from the vehicle without sufficient consideration to appropriate restraint. As with the HLS, consideration will be given to a standing posture to minimize mass and to facilitate EVA efficiency by minimizing the time required to ingress and egress the vehicle at each stop. Additional consideration will be given to the reliability of the restraint systems because failure to release could be a catastrophic hazard.

4.0 ACCELERATION LIMITS RECOMMENDATION

All relevant data used to assess the +Gz tolerance of a deconditioned crewmember can be seen in the acceleration-duration plot (Figure 13). Current Earth-returning vehicles are assessed using the BDRC and Hybrid III ATDs. A model similar to the existing BDRC, which allows higher accelerations for short-duration exposures, and lower peak accelerations for longer-duration exposures, was used to assess injury limits. This approach has the benefit of simplicity for assessing a design; however, it does not directly address concerns related to crewmember restraints and suit mass. Although the model parameters (natural frequency and damping coefficient) may not accurately represent the dynamics of the lower extremities, the +Gz model parameters do represent the dynamic response of the lumbar spine, which was thought to be a conservative approach.

Using the additional data gathered from other sources, a new dynamic response (DR) limit was chosen to best represent the data and human tolerance when standing. The updated DR limit in +Gz was determined to be 2.7. To account for reduction in tolerance due to spaceflight deconditioning, a decondition factor of 0.75 was applied, resulting in a deconditioned DR limit of 2.0. This deconditioning factor was established based on fracture risk of the lower extremities and may need to be lowered to account for soft tissue injuries that may be sustained during impact. This methodology is consistent with the current approach used in the seated BDRC standard; however, these new limits represent a 5.6-fold decrease in tolerance between standing and seated.

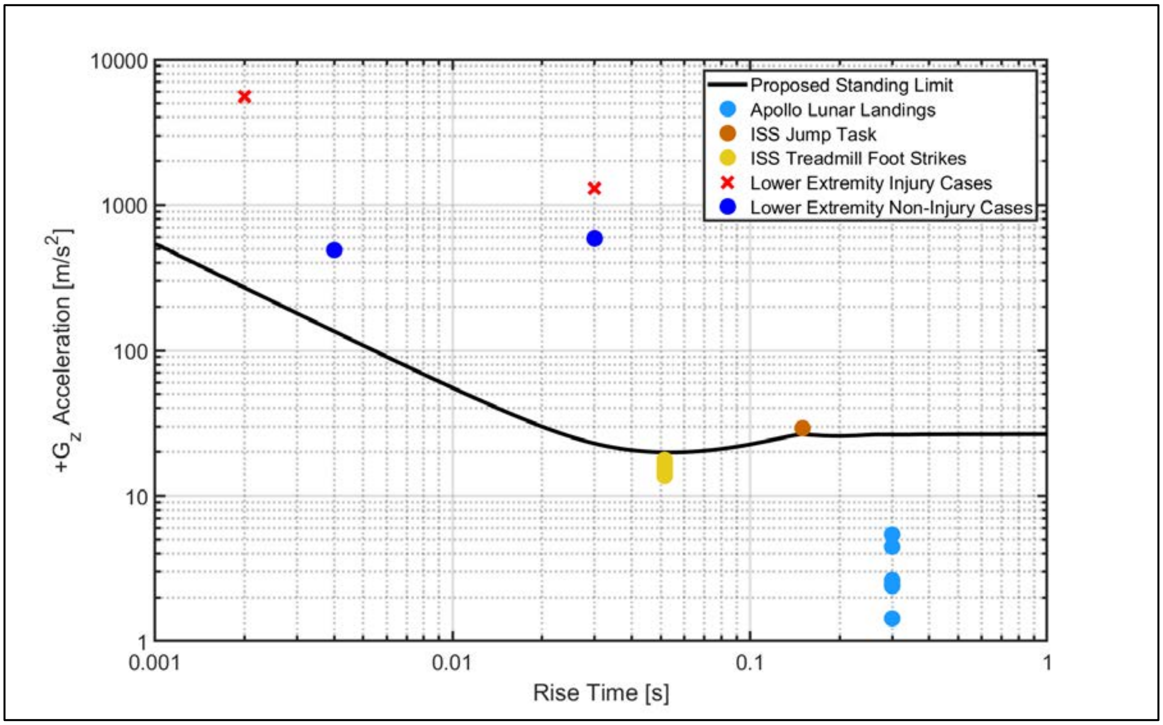

Figure 13. Proposed standing dynamic response limit for standing crewmembers (≤30 day mission).

In lieu of additional information on the design and tolerance to off-axis loads while standing, the same scaling factor used to decrement the +Gz axis was applied to the ±Gx and ±Gy axes. After the limits were scaled for standing, the appropriate deconditioning factors for ±Gy was applied for missions lasting longer than 30 days. This is thought to be consistent with the +Gz limit; however, the off-axis tolerance of the crewmembers will be highly dependent on the restraint design. The -Gz limits are set to zero, as -Gz while standing is not advised without sufficient restraints to hold the crewmember in position. Fractional accelerations that may result from rebound may be allowed if the restraint system is sufficient to arrest any resulting motion.

Table 2. Updated Dynamic Response Limits for Standing

Axis	Current		Proposed	
	Seated Non-deconditioned	**Seated Deconditioned**	**Standing Non-deconditioned**	**Standing Deconditioned**
+Gx	35.0	35.0	6.3	6.3
-Gx	-28.0	-28.0	-5.0	-5.0
±Gy	±15.0	±11.3	±2.7	±2.0
+Gz	15.2	13.0	2.7	2.0
-Gz	-13.4	-11.5	0*	0*

* Fractional rebound accelerations are allowed, provided adequate restraints are used.

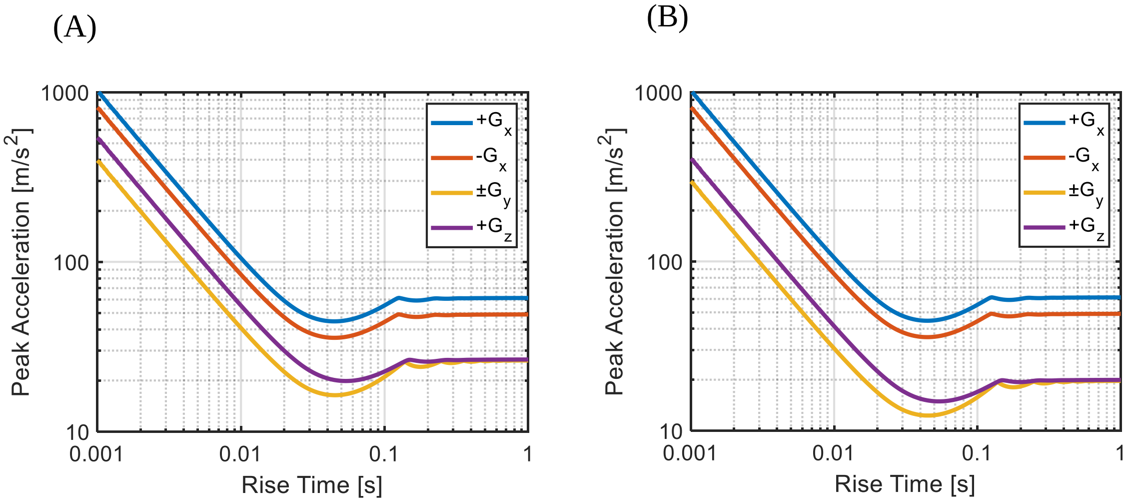

Figure 14. Peak sinusoidal acceleration allowed in each axis, (A) mission durations ≤30 days and (B) mission durations >30 days.

5.0 APPLICATION

The dynamic response limits are calculated in the same way as established by the BDRC, with one significant exception. The original BDRC requires that the DR be calculated at the seat critical point. Because this new application no longer requires a seat, the critical point definition is not applicable. In the case of no seat, meeting the BDRC requirements set out in Somers et al. (2017) [10], the critical point should be located at the center-of-gravity of the crewmember’s torso. See the NASA Human Integration Design Handbook (HIDH), Appendix B, Table 6 [7].

The injury risk criterion, β, is calculated with

Equation 1. Injury Risk Criterion Calculation

$$\beta(t) = \sqrt{\left(\frac{DR_x(t)}{DR_x^{lim}}\right)^2 + \left(\frac{DR_y(t)}{DR_y^{lim}}\right)^2 + \left(\frac{DR_z(t)}{DR_z^{lim}}\right)^2}$$

Using Equation 2, the dimensionless DR can be calculated in all 3 axes. $\delta(t)$ is the spring deflection of the dynamic system that can be found in Equation 3.

Equation 2. Dynamic Response (DR) Formulation.

$$DR(t) = \frac{\omega_n^2 + \delta(t)}{g}$$

Equation 3. DR Differential Equation.

$$\ddot{\delta}(t) + 2 * \zeta * \omega_n * \dot{\delta}(t) + \omega_n^2 * \delta(t) = A(t)$$

Where variables are defined as follows:

g	Acceleration of Earth gravity (9.81 m/s^2)
$\ddot{\delta}$(t)	Occupant's acceleration in inertial frame
$\dot{\delta}$(t)	Occupant's relative velocity with respect to the critical point
δ(t)	Displacement of the occupant's body with respect to the critical point
ζ	Damping coefficient ratio
ω_n	Undamped natural frequency of the dynamic system
A(t)	The measured acceleration, per axis, at the critical point

Table 3. Model Coefficients [10]

	X		**Y**		**Z**	
	Eyeballs out x < 0	Eyeballs in x > 0	Eyeballs left y < 0	Eyeballs right y > 0	Eyeballs up z < 0	Eyeballs down z > 0
ω_n	56.0	62.8	58.0	58.0	47.1	52.9
ζ	0.04	0.2	0.07	0.07	0.24	0.224

The following steps set out below are used to determine the risk of injury in a particular axis; the limits used are defined in Table 2.

1. Determine the transient acceleration (A(t)) at the critical point of the seated occupant in each axes (X, Y, and Z). A(t) is normally obtained by test or analysis.
2. Solve the second order differential equation for the displacement (δ(t)) of the occupant (Equation 3).
3. Determine the DR(t) for each axis at time (t) (Equation 2).

4. Determine β(t) using Equation 1.
5. Find the maximum β(t). This is the Injury Risk Criterion (IRC).

6.0 DESIGN REQUIREMENTS

A discussion of the suit and possible restraint systems when landing crewmembers in a standing posture is needed to ensure the crewmembers are protected. Even if a vehicle design were to meet the recommended DR limits, the crew may still be injured by relative motion between the crewmember, suit, restraints, and/or vehicle. Unless the space suit is rigidly attached to the vehicle, relative motion between the vehicle and suit may impart loads on the crewmember not captured by the BDRC. If the suit is not rigidly attached to the vehicle structure, the mass of the suit may then act on the crewmember imparting additional loads in ways that are not captured by the BDRC. In either case, motion of the crewmember inside the suit can result in closing velocities between portions of the body and the interior of the suit, increasing the risk of injury. To allow the use of the BDRC in a standing posture, several base assumptions must be met to mitigate any secondary impact injury mechanisms.

6.1 Suit

Blunt trauma and point loading must be addressed in the design to prevent the body from contacting rigid structures inside the suit. This may include suit-mobility bearings, rigid upper torso assembly, or helmet hardware. This should be achieved primarily by arresting relative motion of the occupant and suit interior, and secondarily by providing force attenuating design elements (e.g., padding) in areas where preventing relative motion may compromise necessary mobility.

In regard to blunt trauma, implementing chest-mounted equipment has been shown to increase injury risk to the crew member [2]**.** Because of this, there should be no equipment or rigid suit elements over the chest. Any rigid elements over the torso or head and neck area must be analyzed to ensure no blunt injury risk exists. Suit elements over the extremities are considered less crucial but must also be analyzed for fracture and immobilization risk as these injuries can have outsize effects on mission success. Extremity elements must also be considered for their effects on restraint effectiveness.

6.2 Restraints

Because the crew will likely not be seated in lunar landings, previous restraint requirements outlined by Somers et al. (2013) cannot be used [10]. With crew in a standing orientation, restraints must prevent +Gz motion and help the crew to maintain balance. Restraints could include foot holds, hand holds, a pulley restraint system, etc. To mitigate relative motion between suit and occupant, restraints may be required inside the suit.

To meet the underlying assumptions of the BDRC, closing velocities between the crewmember and suit must be well managed. In the original BDRC, a maximum gap of 1 inch between the seat structures and occupant may be a reasonable approach for ±Gy axes, but for ±Gx and -Gz, the original BDRC had an assumption that the restraints holding an occupant into the seat prevent any relative motion between the occupant and seat/restraints. To meet this underlying assumption, the suit will need to incorporate an internal restraint system to attenuate motion in these directions.

6.3 Mass Offloading

The mass of the suit must be considered to adequately protect the crew from injury due to dynamic loading. Unless a lightweight suit is employed, a method for offloading the suit mass is required. The expert panel discussed this challenge and decided on disallowing crew-borne mass greater than 20% of the crewmember's mass. Although this limitation may prevent lower extremity injury due to increased load, if the suit mass is not sufficiently restrained, even if offloaded, closing velocities between the crewmember and suit are possible and could result in injury.

7.0 LIMITATIONS

7.1 Small Dataset

In the current assessment, a small number of data points were used to develop a new injury limit for standing crew. Data from standing subjects exposed to impact are scarce (likely because standing during impact is not ideal and low tolerance). Although several different data sources were used in this assessment, the resulting recommendation was by expert consensus guided by the data. For the off-axis limits, no specific data were reviewed. Additional data collection on this posture is needed to better quantify the risk to crewmembers in a standing posture.

7.2 Brinkley Dynamic Response Criterion Model Parameters

Another major limitation of this work is the BDRC. The model parameters (undamped natural frequency and damping coefficient) are based on human testing in specific seating conditions. Without sufficient data, the panel agreed that using these model parameters as a starting point is acceptable, but not optimal. We know that the undamped natural frequency of the human body is likely not significantly affected by the restraint system, as it governed primarily by the internal structures and tissues of the human body. The damping coefficient, however, is highly dependent on the restraint effectiveness [10]. It is unlikely that the same damping coefficient would be applicable to the standing posture, unless the restraint system approached the complexity and function of a seat. For example, a seatback with torso straps and side supports for the shoulders and pelvis could provide similar support and damping in the ±Gx and ±Gy and possibly -Gz axes but would not provide similar support and damping as a seat in the +Gz.

7.3 Deconditioning

When evaluating crew injury risk due to dynamic loads, spaceflight deconditioning due to extended time in reduced gravity must be considered. In previous standards and requirements, 30 days has been used as the threshold for defining when deconditioning must be accounted for in any injury limits. Although this simplification makes it easier to define how to evaluate a vehicle design, deconditioning risk is not a step-function at 30 days. As soon as a crewmember enters Earth orbit, changes to their physiology begin. Although NASA has focused on skeletal fracture as the primary driver of deconditioning for impact, recent data collected in the HRP-funded Soyuz Risk Characterization study have implied changes to soft-tissues may represent a greater contributor to crewmember injury in Soyuz landings. Based on the current DRM, lunar landings would occur within the first 2 weeks after Earth launch, so deconditioning may not be a major concern. For Mars missions, we expect similar concerns for standing crew, because the crew would dwell in microgravity for durations similar to those currently experienced on the ISS. Additional insight into deconditioning is expected at the completion of the study “Quantitative CT and MRI-based Modeling Assessment of Dynamic Vertebral Strength and Injury Risk Following Long-Duration Spaceflight.” This study also is expected to provide some insight into the functional consequences of changes to the intervertebral disk.

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