National Aeronautics and
Space Administration

Lunar Transient Acceleration Requirements

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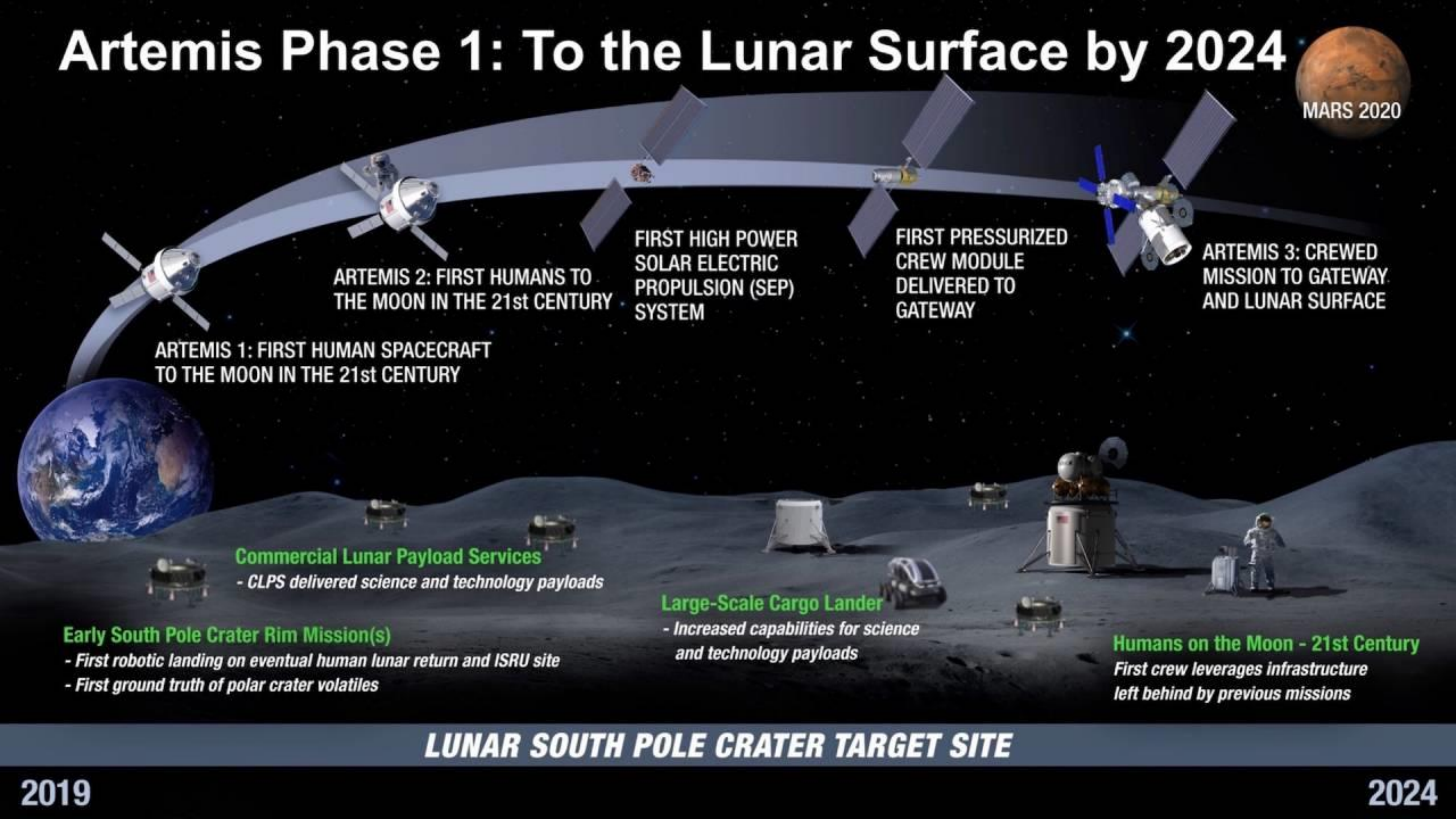
H-3PO
The Human Physiology, Performance, Protection & Operations Laboratory
Applied Injury Biomechanics


Artemis Phase 1: To the Lunar Surface by 2024
MARS 2020
ARTEMIS 1: FIRST HUMAN SPACECRAFT TO THE MOON IN THE 21st CENTURY
ARTEMIS 2: FIRST HUMANS TO THE MOON IN THE 21st CENTURY
FIRST HIGH POWER SOLAR ELECTRIC PROPULSION (SEP) SYSTEM
FIRST PRESSURIZED CREW MODULE DELIVERED TO GATEWAY
ARTEMIS 3: CREWED MISSION TO GATEWAY AND LUNAR SURFACE
Commercial Lunar Payload Services
- CLPS delivered science and technology payloads
Early South Pole Crater Rim Mission(s)
- First robotic landing on eventual human lunar return and ISRU site
- First ground truth of polar crater volatiles
Large-Scale Cargo Lander
- Increased capabilities for science and technology payloads
Humans on the Moon - 21st Century
First crew leverages infrastructure left behind by previous missions
LUNAR SOUTH POLE CRATER TARGET SITE
2019
2024

Human Landing Systems

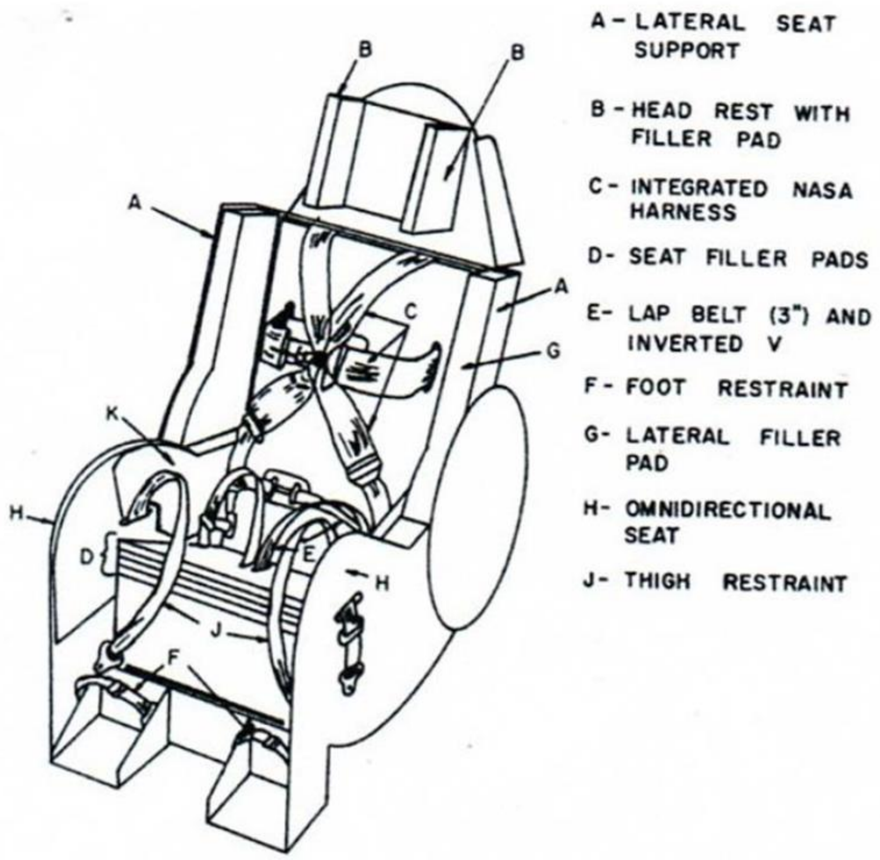
Currently working with three companies on different human landing system(HLS) designs.

Current NASA standards

- Occupant protection standards are in place to ensure that crewmembers will be safe during dynamic phases of flight
- Current NASA standards use the Brinkley Dynamic Response Criterion (BDRC) model and Hybrid III anthropomorphic test devices (ATDs)
- Lunar landing (and subsequent Mars landing) architecture was not considered when the current NASA standards and vehicle design requirements for crew injury were developed
- Consideration of having the crew stand during dynamic phases of flight – which current design standards do not address

Brinkley Dynamic Response Criterion (BDRC)

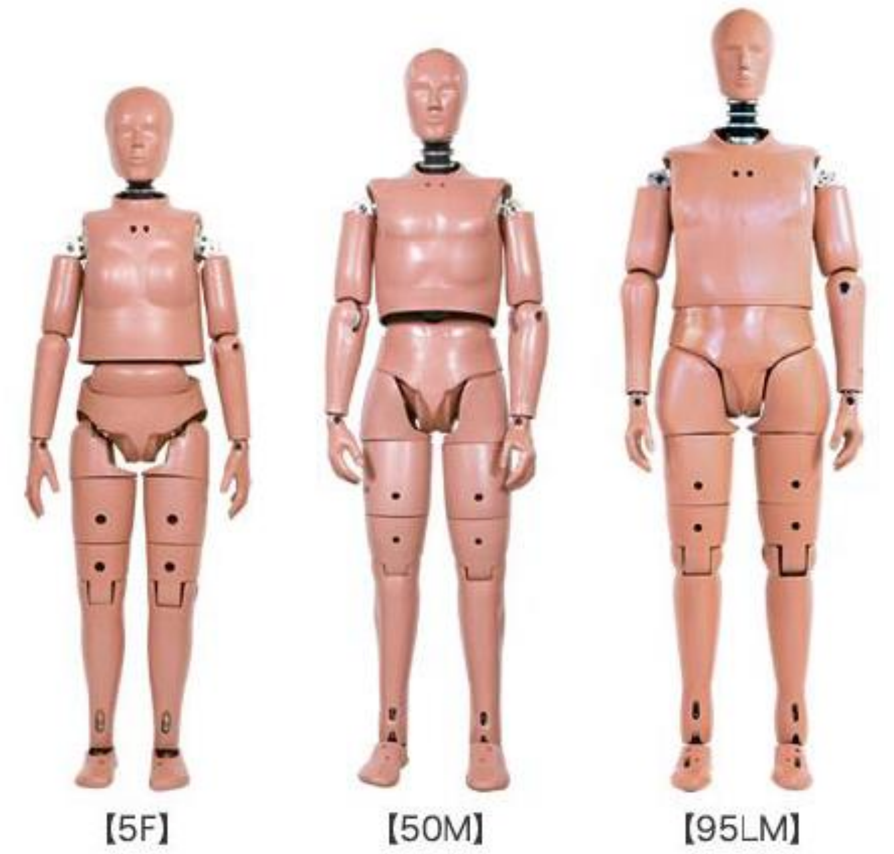
- Simple lumped mass parameter model, primarily used to evaluate injury risk associated with aircraft ejection systems
- Evaluates seat accelerations in each axis to determine injury risk
- Requires a rigid seat and specific restraint system
- Expecting minimal or no seat with minimal restraints in lunar landing
  - Original model parameters are likely not applicable



Somers J, Gohmert D, Brinkley J. Application of the Brinkley Dynamic Response Criterion to Spacecraft Transient Events. Houston, TX. National Aeronautics and Space Administration. Report No.: NASA/TM-2013-217380-REV1, 2017.

Hybrid III ATD

- Hybrid III ATD in various sizes used to supplement the BDRC
  - Added to address limitations in BDRC while wearing a pressure garment and helmet
- Head, neck, and lumbar spine responses are assessed



Objective

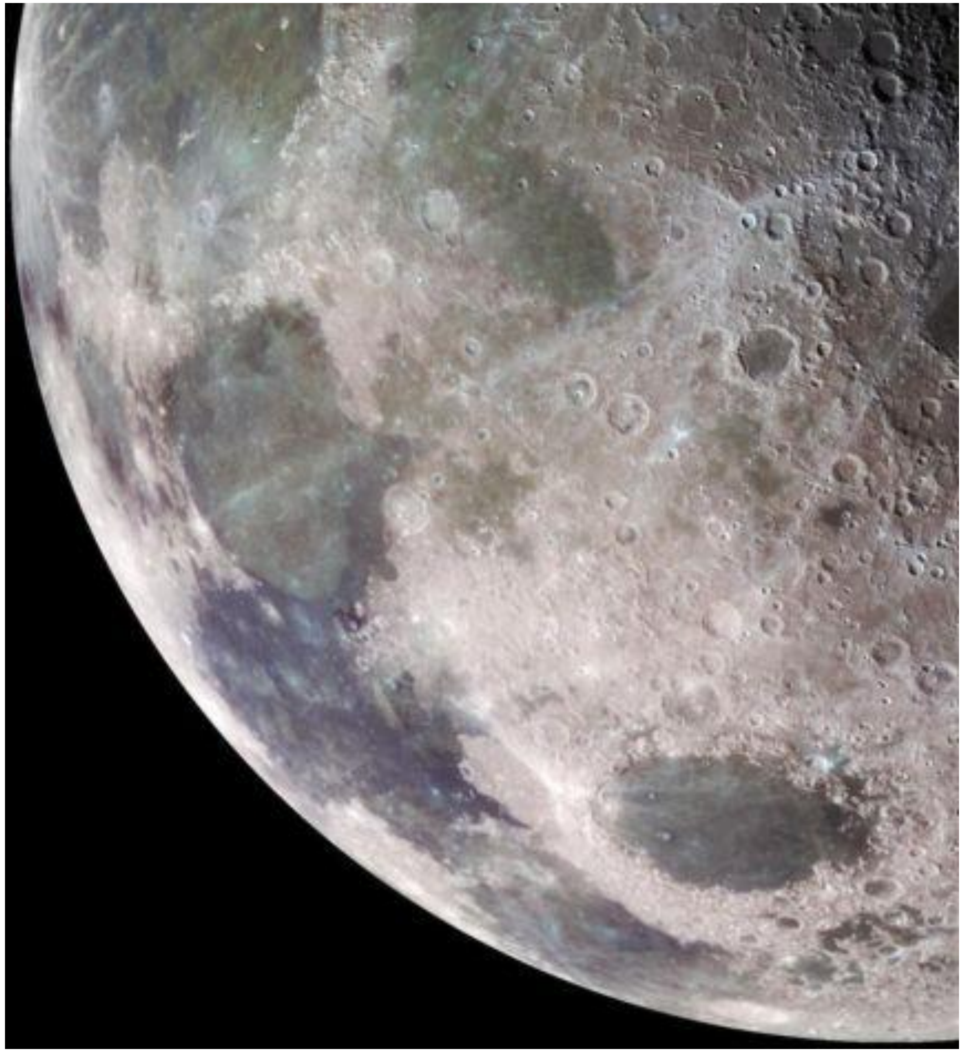
Develop new lunar landing acceleration limits with the assumption that crew is standing during landing.

Approach

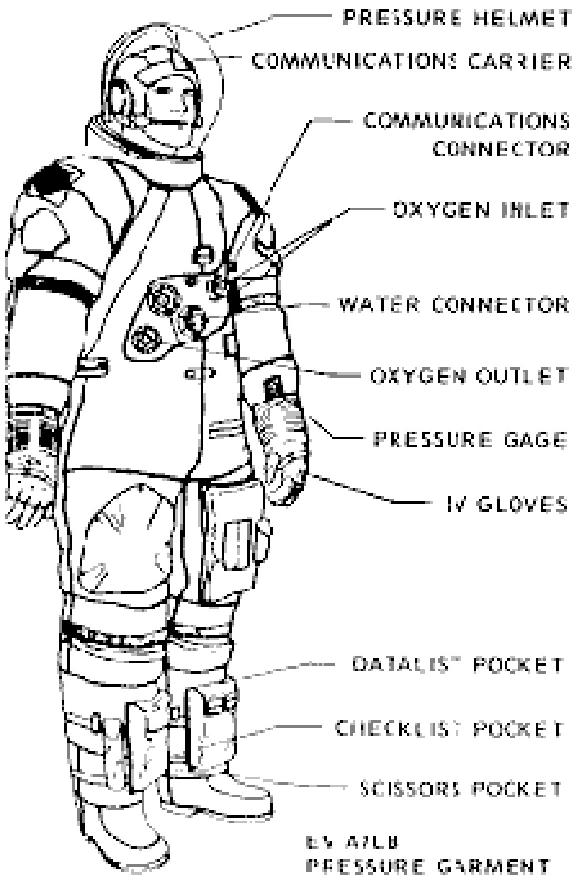
- Gather available data
  - Apollo missions
  - Treadmill foot strike data from crewmembers on the International Space Station (ISS)
  - Voluntary jumping task conducted on crewmembers after ISS long-duration spaceflight
  - Lower extremity injury based on real-world automotive impacts
- Expert panel

2024 Lunar Mission Considerations

- Longer mission duration before lunar landing compared to Apollo missions
  - Approximately 10-11 days from Earth launch to lunar landing vs. 4.5 days for Apollo
- Longer stays on lunar surface
  - Minimum of 1 week (may increase in 1-week increments) vs. maximum of 3 days in the Apollo program



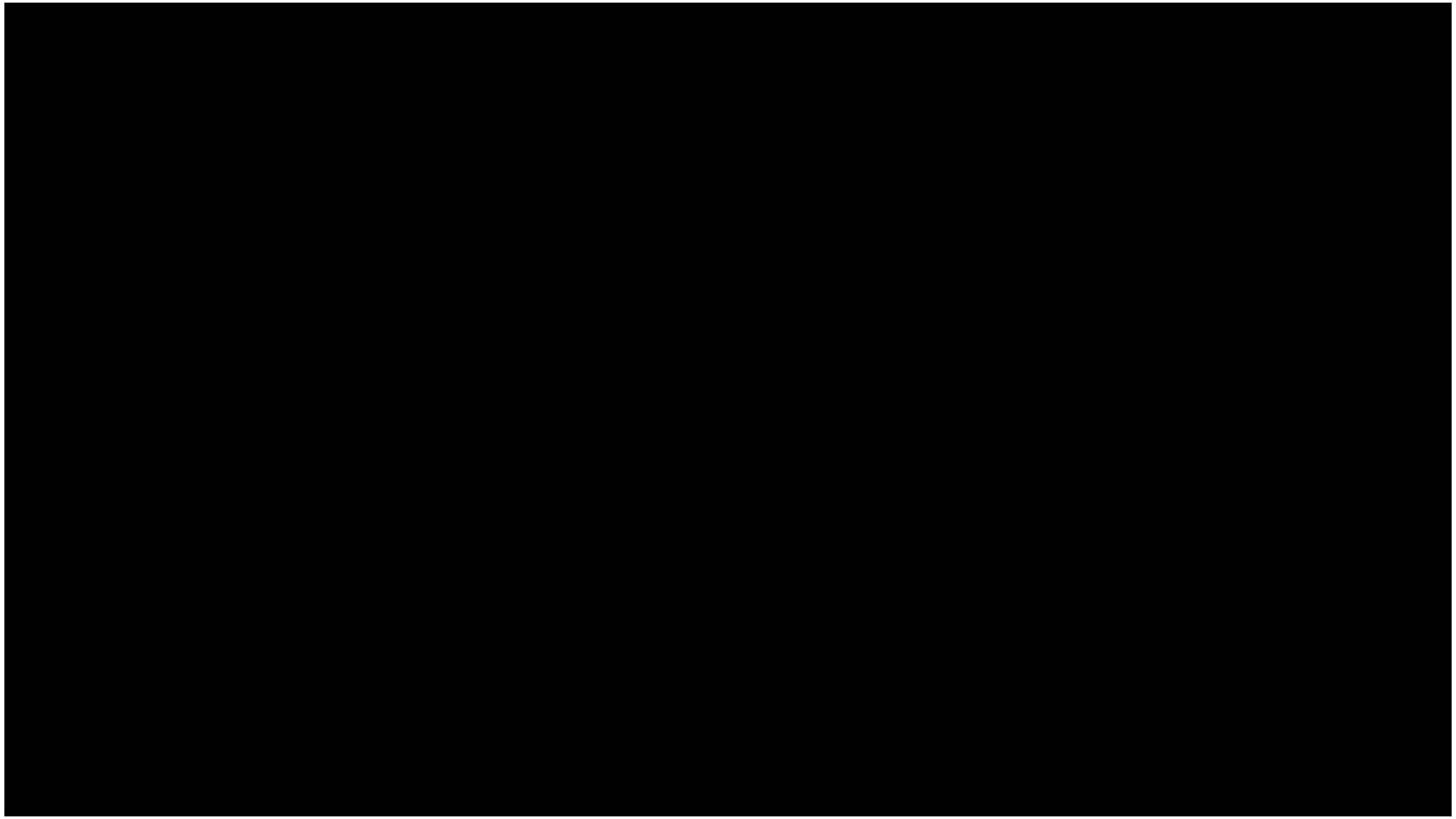
Suit Considerations



Apollo A7L IVA configuration
29.3 kg

xEMU lunar configuration
>70 kg

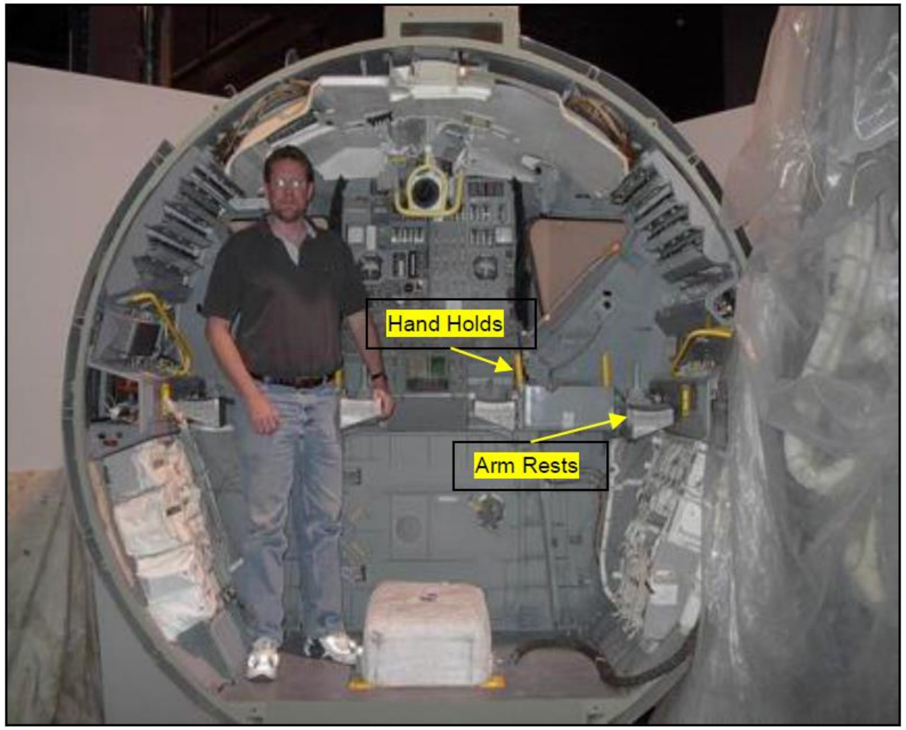
Apollo Missions



6 successful lunar landings

Apollo Missions

- Standing orientation of crew at lunar landing
  - Decision made to minimize mass by eliminating the bulky seats and need for additional windows
  - 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



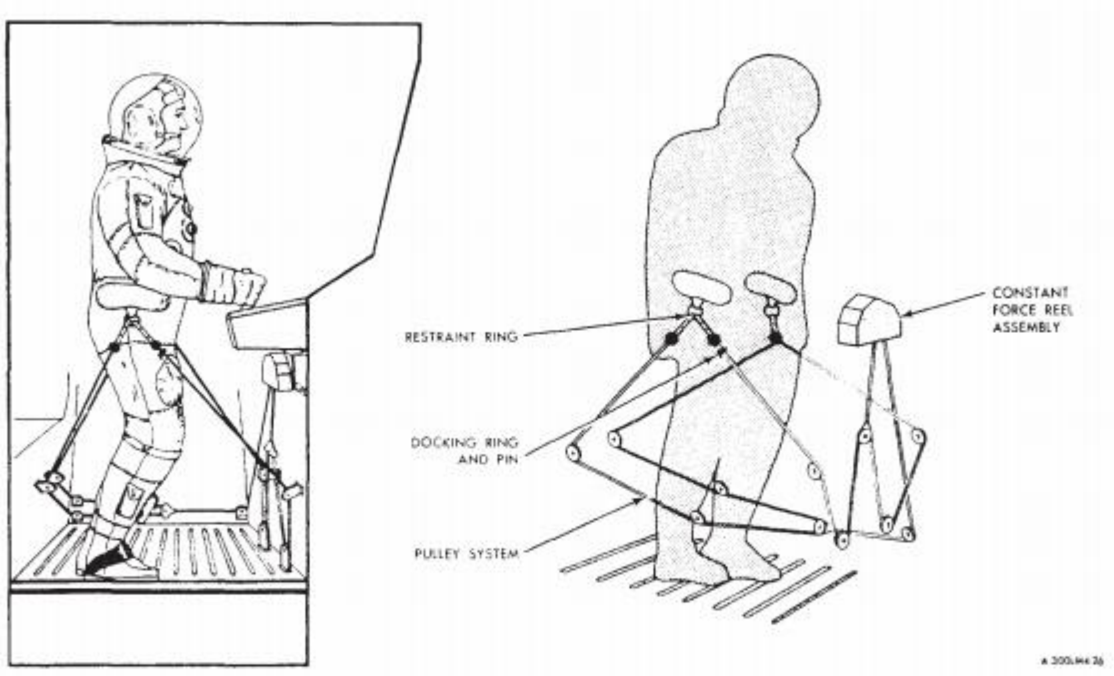


Figure 2.11-10. Restraint Equipment

Kelly TJ. Moon Lander: How We Developed the Apollo Lunar Module. Washington, D.C.: Smithsonian Books 2001.

Grumman Aerospace Corporation. Apollo Operations Handbook, Lunar Module. LM10 and Subsequent. Bethpage, NY, 1971.

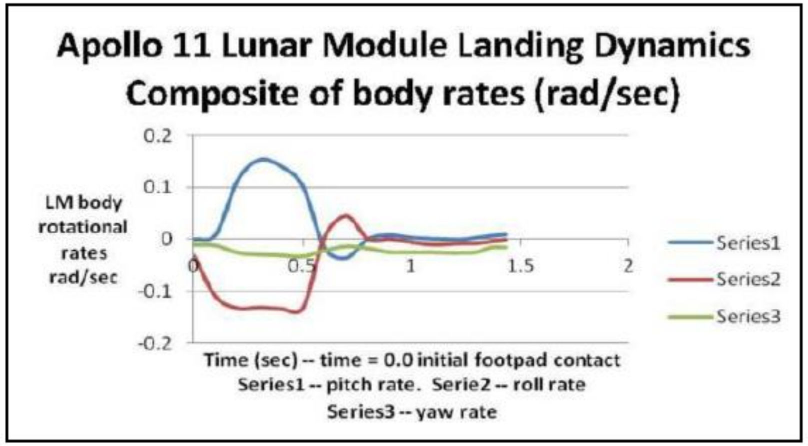
Apollo Data

Specific impact acceleration data from each lunar landing mission is not available.

Available data:

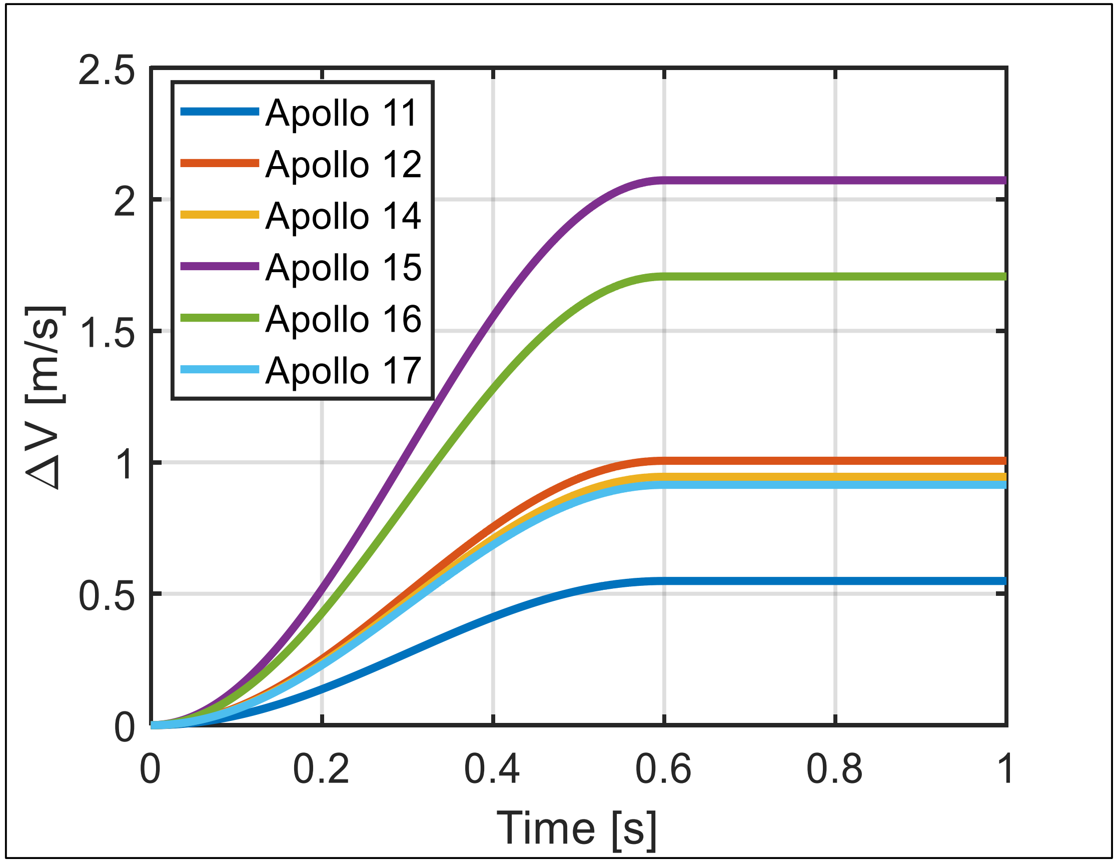
- Vertical velocity at footpad contact
  - Final velocity is 0 (stationary on lunar surface)
  - This was used to find the peak acceleration
- Guidance, navigation, and control time history
  - Shows duration of impact (600 ms)
  - Half-sine pulse used as approximation of the shape of acceleration event (rise time of 300 ms)

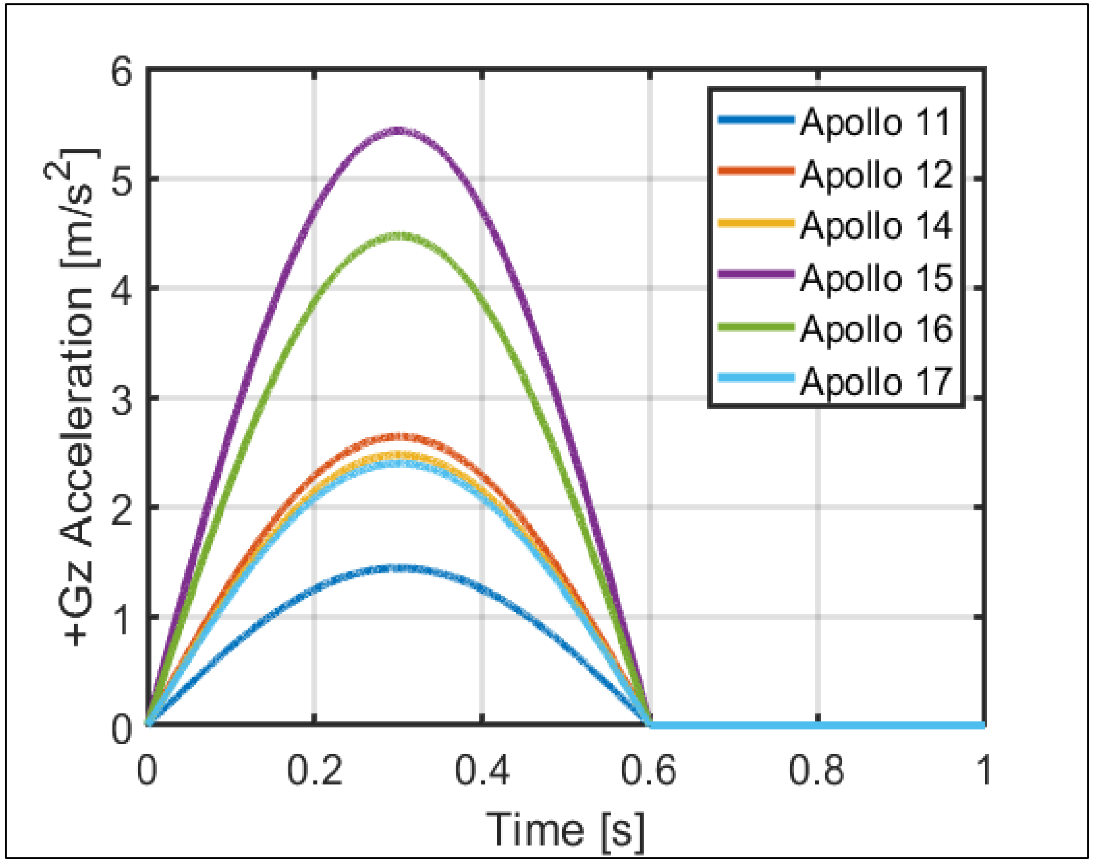
Mission	Vertical Velocity (m/s)
Apollo 11	0.55
Apollo 12	1.00
Apollo 14	0.94
Apollo 15	2.07
Apollo 16	1.71
Apollo 17	0.91



Zupp GA. An Analysis and a Historical Review of the Apollo Program Lunar Module Touchdown Dynamics. Houston, TX. National Aeronautics and Space Administration; 2013.

Apollo Data



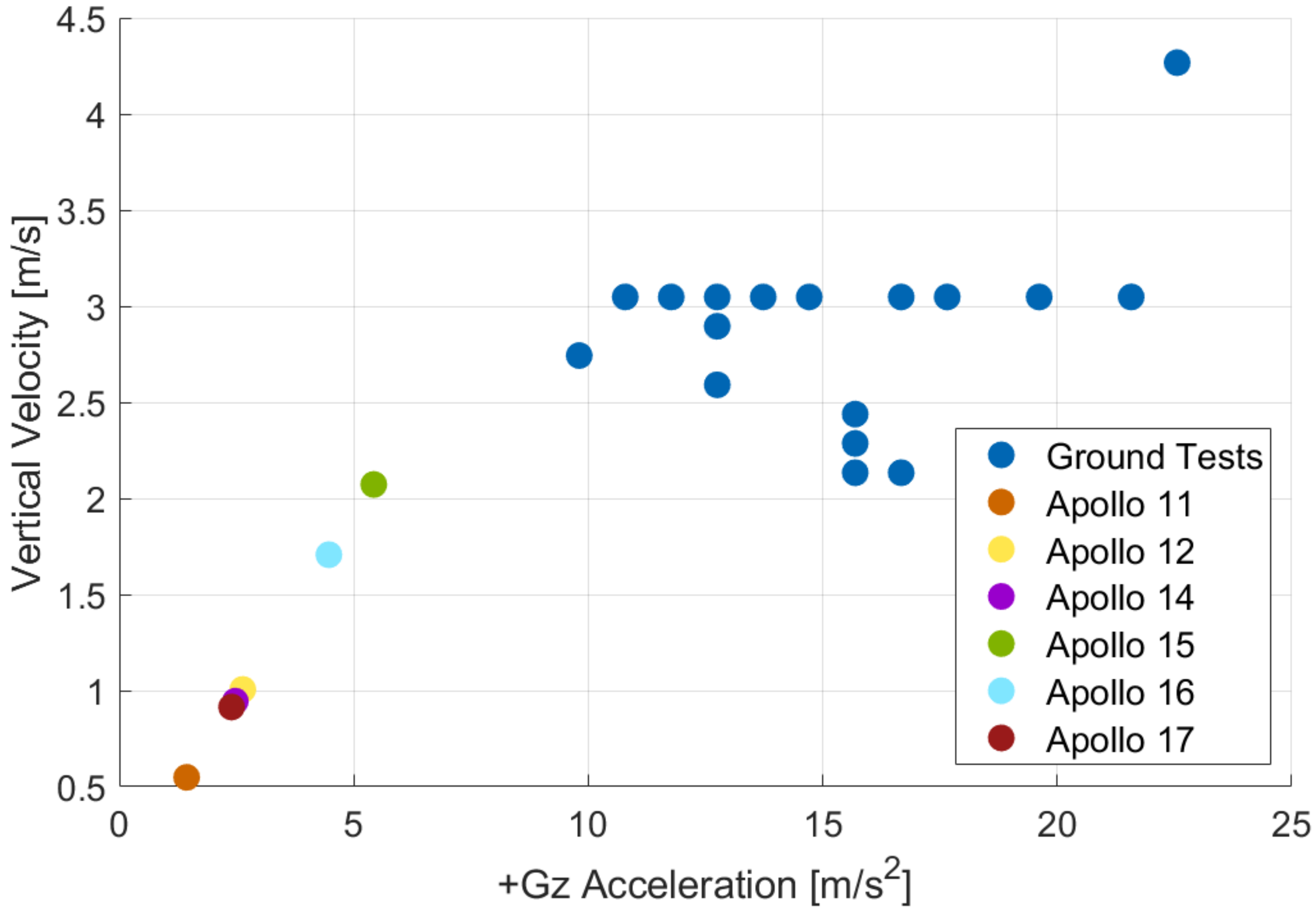


Change in velocity and estimated acceleration for each lunar landing

Apollo Data

Data from ground testing of the landing system also was available

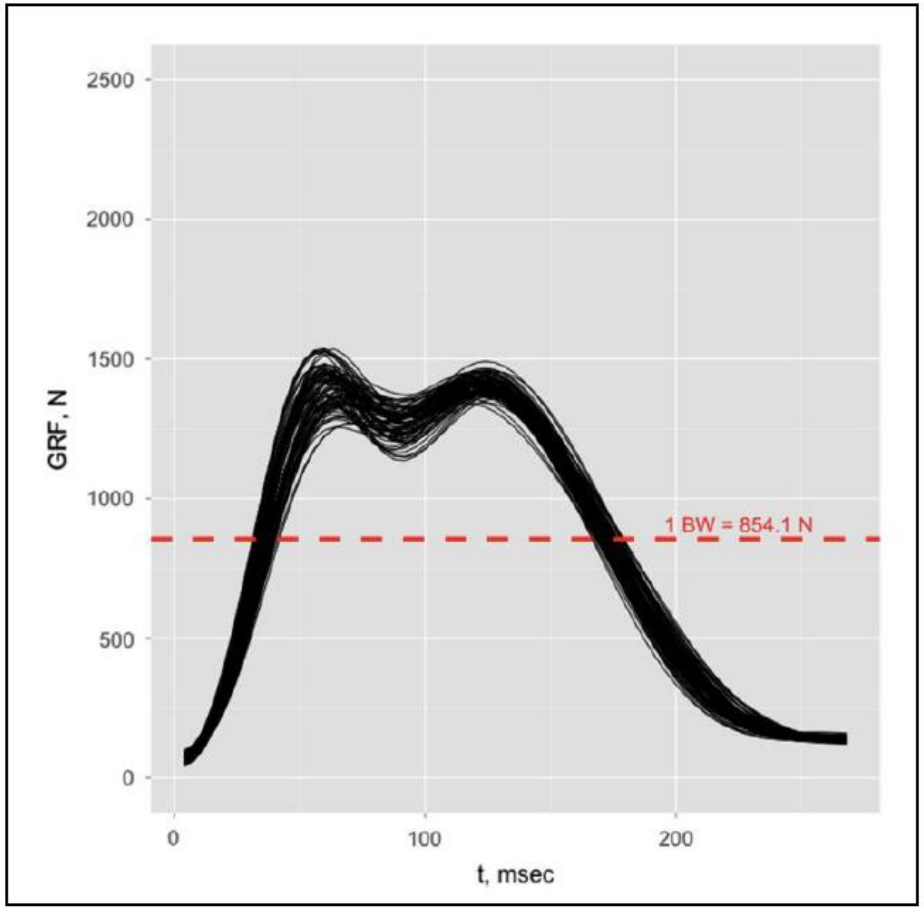
- 21 tests in simulated lunar gravity



Estimated peak landing impact accelerations for each Apollo lunar landing

Treadmill foot strike data

- Data from crewmembers on the ISS
- Provides direct evidence of a tolerable acceleration to a deconditioned crew repeatedly over a long-duration mission
- Rise time of each foot strike is approximately 50 ms
- Peak foot strike forces ranged from 1220 to 1530 N



De Witt JK, Ploutz-Snyder LL. Ground reaction forces during treadmill running in microgravity. J Biomech. 47(10):2339-47, 2014.

Voluntary Jumping Task

- Conducted on crewmembers after ISS long-duration spaceflight
- Crew experience up to 3 times their normal body weight during the jumping task (average rise time of 150 ms)
- In both treadmill running and voluntary jumping, crewmember is actively reacting to anticipated impact force
  - Passive acceleration transmitted through the feet is likely to transmit higher forces to the torso and spine

Lower Extremity Injury Research

Kuppa et al.

- Reported injuries to the calcaneus, talus, ankle, and mid-foot based on conditions found in real-world automotive impacts

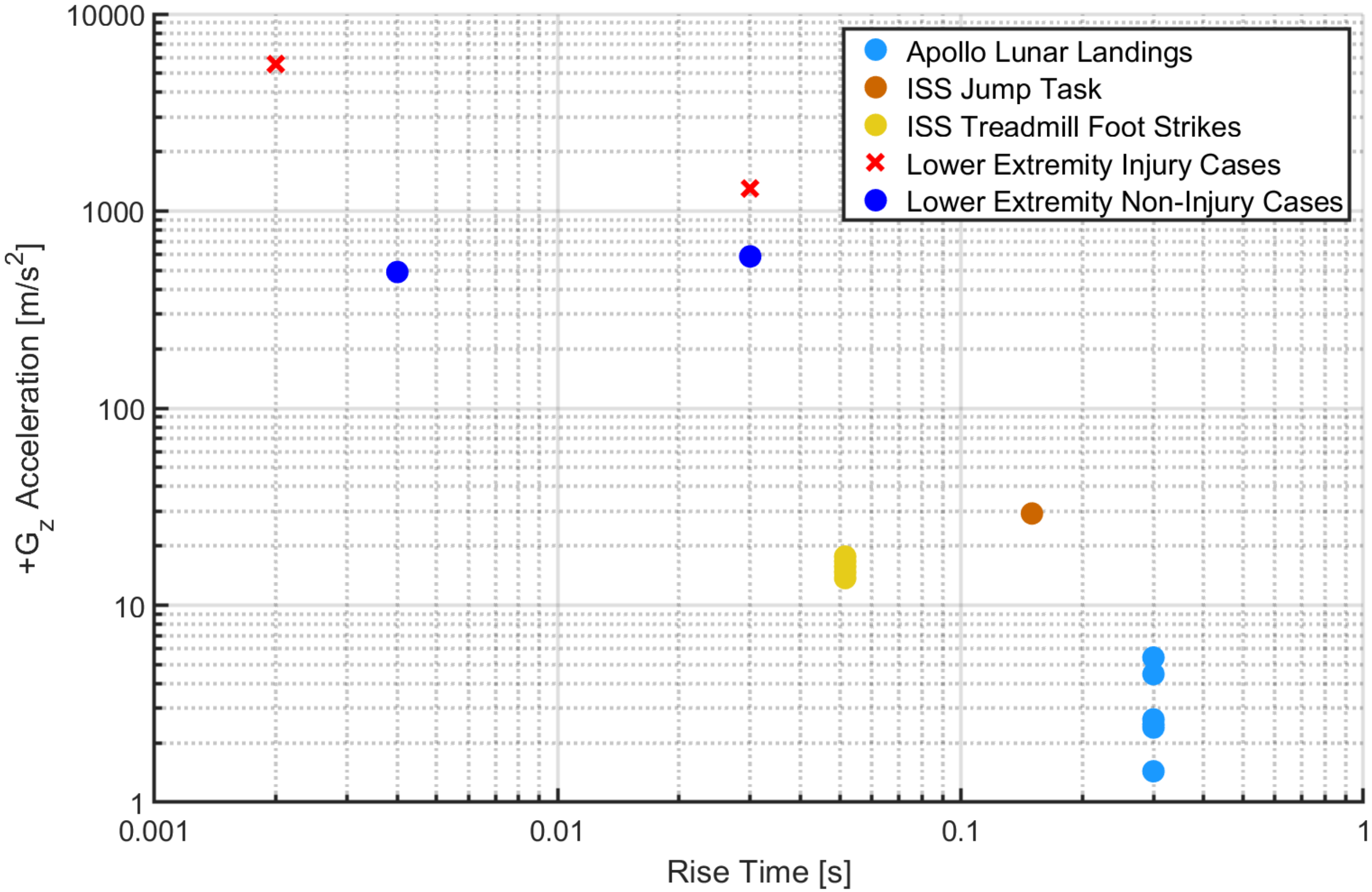
Pintar et al.

- Reported calcaneus, talus, and distal tibia injuries with and without combat boots
- To be conservative, results for the unbooted condition were used

Kuppa S, Wang J, Haffner M, Eppinger R. Lower Extremity Injuries and Associated Injury Criteria. 17th ESV Conference Paper No 457; 2001.

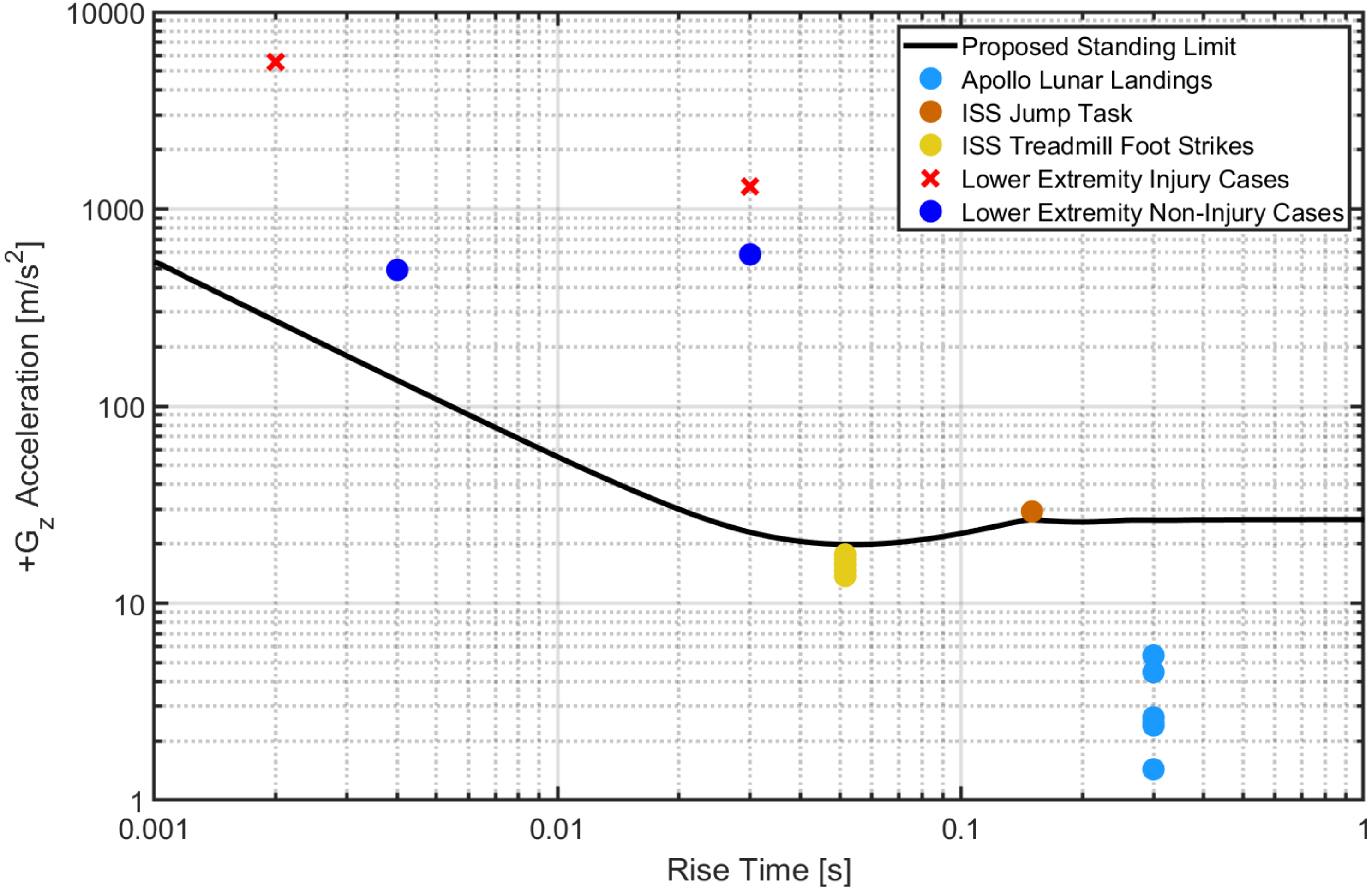
Pintar FA, Schlick MB, Yoganandan N, Voo L, Merkle AC, Kleinberger M. Biomechanical response of military booted and unbooted foot-ankle-tibia from vertical loading. Stapp Car Crash Journal, 60:247-85, 2016.

All available data



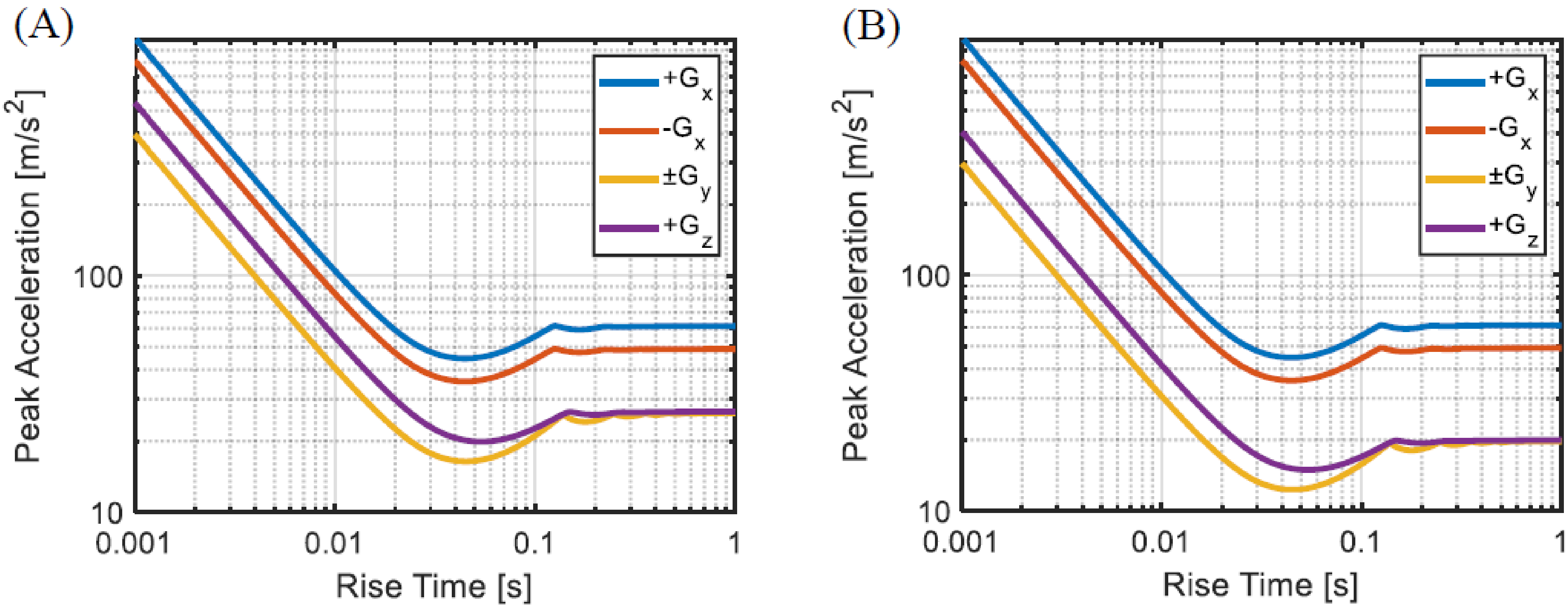
Compilation of available impact data in a standing posture.

Proposed $+G_z$ Acceleration Limits



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

Proposed Acceleration Limits

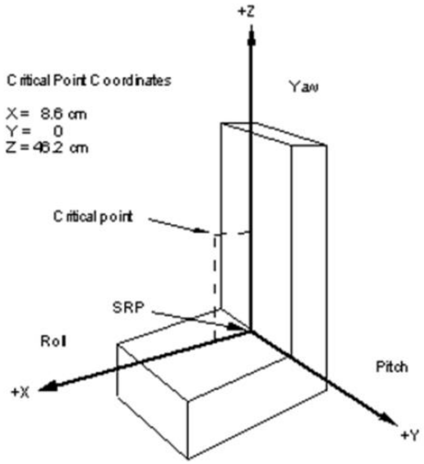


(A) Mission durations ≤30days and (B) mission durations >30 days

Dynamic Response Limits for Standing

Calculated in the same way as established by the BDRC, with one exception

- Original BDRC requires dynamic response be calculated at the seat critical point
- While this application no longer requires a seat, the critical point should be located at the center of gravity of the crewmember's torso



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.

Design Requirements

Even if the 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

- To allow use of the BDRC in a standing posture, several base assumptions must be met to mitigate any secondary impact injury mechanism

Design Requirements - Suit

- Arrest relative motion of the occupant and suit interior
  - Provide force attenuating design elements (ie, padding) in areas where preventing relative motion may compromise necessary mobility
- No equipment or rigid suit elements over the chest
  - Any rigid elements over the torso or head and neck area must be analyzed for fracture and immobilization risk

xEMU

Design Requirements - Restraints

- Restraints must prevent $+G_z$ motion and help the crew maintain balance
- The suit will need to incorporate an internal restraint system to attenuate motion in $\pm G_x$ and $-G_z$
- Maximum gap of 1 inch between suit and occupant in $\pm G_y$

Apollo Restraints

Design Requirements – Mass Offloading

- Unless a lightweight suit is employed, a method for offloading the suit mass is required
- Disallow crew-borne mass greater than 20% of the crewmembers' mass
    - 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

xEMU

Limitations

- Small dataset
  - Small number of data points were used to develop a new injury limit for standing crew
  - Resulting recommendation was by expert consensus guided by the data
  - Additional data collection on this posture is needed to better quantify risk
- Brinkley Dynamic Response Criterion Model Parameters
  - Expert panel agreed that using these model parameters as a starting point is acceptable, but not optimal
- Deconditioning

Acknowledgements

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Thank You!

Questions?