NASA-STD-3001 Technical Brief

Occupant Protection

OCHMO-TB-024
Rev D

Relevant Technical Requirements

NASA-STD-3001 Volume 2, Rev D

[V2 6064] Sustained Translational Acceleration Limits
[V2 6065] Rotational Velocity
[V2 6066] Sustained Rotational Acceleration Due to Cross-Coupled Rotation
[V2 6067] Transient Rotational Acceleration
[V2 6069] Acceleration Injury Prevention
[V2 6070] Injury Risk Criterion
[V2 6111] Dynamic Mission Phases Monitoring and Analysis
[V2 6112] Hang Time Limit
[V2 6113] Crew Limits in Launch Orientation
[V2 6089] Vibration during Preflight
[V2 6090] Vibration Exposures during Dynamic Phases of Flight
[V2 6093] Vibration Limits for Performance
[V2 6094] Hand Vibration

Executive Summary

Vehicle designers must consider the various mechanisms of a vehicle's system during dynamic phases of flight to protect the occupants, notably acceleration and vibration affects on humans. Acceleration limits are set in the x, y, and z axes for all mission phases to protect the crew from injury and other acceleration-related conditions. These limits are divided into two-time regimes:

- sustained (>0.5 seconds), and
- transient (≤0.5 seconds)

They are further divided according to:

- whether the acceleration is translational or rotational
- the phase of flight, and
- whether the crew is standing or sitting

Excessive whole-body vibration can lead to fatigue, discomfort, vision degradation, and risk resulting from hand vibration reducing fine motor control.

Several countermeasures can be used to mitigate the effects of vibration and high acceleration loads. Additional factors such as parachute sway and seat angle need to be considered when assessing risk and developing solutions.

SpaceX Crew Dragon Launch

From: https://www.youtube.com/watch?v=xY96v0OIcK4

Background

Basis of Current Acceleration Limits

- Sustained: prior crewed vehicle data; human tolerance limits
- Transient: Apollo lunar landing impact data; Shuttle & International Space Station (ISS) post-flight crew jump data; ISS inflight treadmill foot strike data

The Brinkley Dynamic Response Model

Dynamic Response (DR)

- Estimates the **transient** acceleration of the human body
- A single degree of freedom lumped mass model
- Calculated independently in each direction
- Responses are highly specific for seat used in development
    - Changes to the seat, restraints and helmet can invalidate the model natural frequency and damping coefficient
    - Ground rules established to ensure model is valid to use

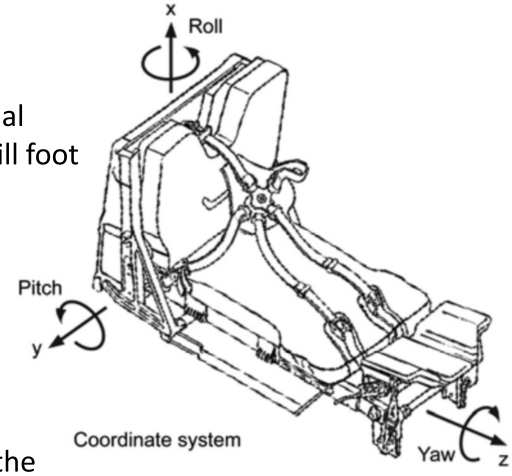
Injury Risk Criterion (β)

- Preset DR limits in each direction estimate the injury risk
- Estimates an injury risk but not severity or anatomical location

Limitations

- Subject pool limited to mostly young, male military volunteers
- DR Limits based on limited statistical analysis of injury data
- Limited validity in +X, -Z and ±Y axes

Note: Information applicable to all axes



From: Orion Crew Member Injury Predictions during Land and Water Landings (Lawrence et al., 2009)

Approximate Risk Associated with Each Brinkley Dynamic Response Criterion Category

Category	Approximate Risk
Low	0.5%
Medium	5.0%
High	50%

From: NASA/TM-2013-217380

For information on how to use this model, see NASA/TM-2013-217380, Revision 1, Application of the Brinkley Dynamic Response Criterion (BDRC) to Spacecraft Transient Dynamic Events.

The 50% probability (P) of injury for +z axis is based on an *n* greater than 100, yielding 95% confidence interval (P=0.5, *n*=100) is $0.402 \leq P \leq 0.598$. Where P=0.11 and *n*=89, the 95% confidence interval is $0.045 \leq P \leq 0.175$. The confidence intervals for the +z axis means become smaller for lower risk values (5% and lower).

Background

Health and Performance Risks of Excessive Acceleration Exposure

Sustained

- Limited/difficulty of movement & breathing; unconsciousness
- See Requirement [V2 6064] in NASA-STD-3001 Volume 2 for limits
- Reference Human Integration Design Handbook (HIDH) Table 6.5-3

Transient

- Mostly traumatic injuries
- Vertebral injuries most common
- See Requirements [V2 6069] & [V2 6070] in NASA-STD-3001 Volume 2, Rev D for limits
- Reference HIDH Section 6.5.3.2

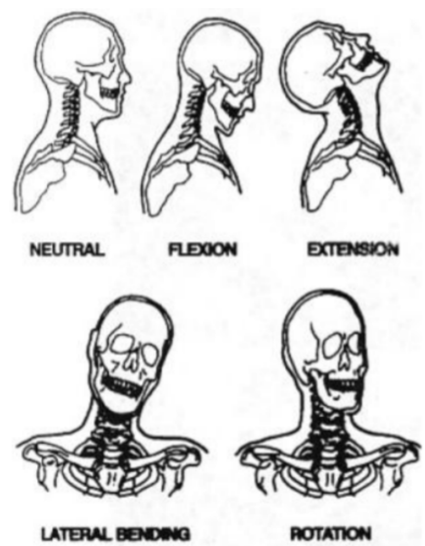
Rotational

- Disorientation; sickness; unconsciousness
- See Requirements [V2 6065-67] in NASA-STD-3001 Volume 2 for limits

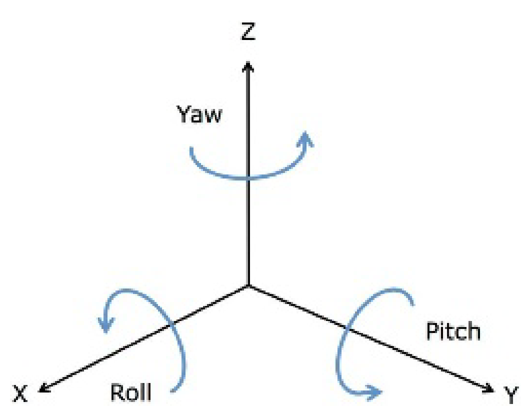
For acceleration requirements for extraterrestrial surface transport vehicles, reference OCHMO-TB-023, Extraterrestrial Surface Transport Vehicles (Rovers).

From: How Whiplash Can Cause Lasting Trauma and Pain

From: https://www.military.com/video/aircraft/jet-fighters/passing-out-at-8gs/4552888570001



From: Neck Injury Mechanisms And Injury Criteria



From: Identifying Active Travel Behaviors in Challenging Environments Using GPS, Accelerometers, and Machine Learning Algorithms (Ellis et al., 2014)

Reference Data

Sustained Acceleration

Special sustained acceleration limits for the body-Z axis while standing were defined for Artemis mission based on data from Apollo and the Cardiovascular and Vision Laboratory's database. These limits provide insight into what would be appropriate for lunar and Martian missions. See *NASA/TM-20205008196 Artemis Sustained Translational Acceleration Limits: Human Tolerance Evidence from Apollo to International Space Station* for more information. Using a lower body compression garments allows for higher magnitudes in the +Az direction.

NASA Gradient Compression Garment
From: NASA NTRS 20170000798

Transient Acceleration

The injury risks given in [V2 6069] Acceleration Injury Prevention are based on the expected rate of injuries using data from 80 flights of 4 crewmembers (320 total exposures) in the Orion vehicle. These were then separated into two categories of probability of the dynamic vehicle event occurring (with 95% representing most nominal cases and 5% some more intense, but still nominal and off-nominal cases). The Class I and II values came from the asymptotes of a binomial distribution to 500 cases where 95% and 5% of landing cases contained 75% and 25% of the total injury risk, respectively. The Class III and IV values were based off of the NASA loss of crew standard of 0.1%. The second Class III value for the 5% category was based on a pad abort land landing.

Injury Severity (Class)*	≥95% of dynamic cases	<5% of dynamic cases
Minor (I)	<4%	<23%
Moderate (II)	<1%	<4%
Severe (III)	<0.1%	<0.7% [<1%]
Life-Threatening/Fatal (IV)	<0.1%	<0.7%

Table 6.5-9—Acceptable Injury Risk Due to Dynamic Loads, from: [V2 6069] Acceptable Injury Risk Table, NASA-STD-3001 Volume 2, Rev D

The Brinkley Dynamic Response model gives estimations of risk chance for transient accelerations in the three standard body axes based off of data from a wide range of aerospace and non-aerospace sources. NASA/TM-2013-217380REV1 gives an explanation of the equations and variables used to calculate the risk value.

Background

Vibration

Factors related to the human effects of vibration exposure includes:

1. The vibration environment – how much, when, how long, in what direction(s)
2. Tasks to be performed during vibration exposure
3. Characteristics of occupant interfaces (seats, restraints, apparel, helmet)

Humans are particularly sensitive to low frequency vibration (below 20 Hz), and limiting exposure helps to preserve comfort, improve performance, and protect health and safety. Studies have demonstrated that the seated whole-body has a natural resonance frequency in the vicinity of 4 to 8 Hz during vibration exposure with body parts differentially susceptible to vibration based on the mass and elasticity of the surrounding body tissues.

Pogo Vibration Mitigation

The phenomenon when a rocket vibrates along its longitudinal axis causing longitudinal oscillations (up and down), known as 'pogo', is a coupled structure and propulsion system instability that can result in the impairment of the crew, unplanned engine shutdown, loss of mission, or structural failure. Pump tests showed that as inlet pressures were reduced toward cavitation, the pump started acting as an amplifier, causing large oscillations in the thrust chamber pressure. As the rocket engine thrust develops, liquid propellant is cyclically forced into the turbopump. This fluctuating fluid pressure is converted into an unintended and variable increase in engine thrust with the net effect being longitudinal axis vibration that could result in spacecraft structural failure. The additional sloshing of liquids in the fuel tanks could also augment the pogo effect. Various engineering controls have been historically used to mitigate this, including pump pressure accumulators and intra-tank baffles. Apollo Saturn V had an ascent oscillation at 11 Hz mitigated to 0.14 g (zero to peak).

Liquid fuel rockets are significantly more prone to pogo oscillations because their fuel flow can fluctuate, causing unstable thrust, while solid fuel rockets, once ignited, burn at a consistent rate with minimal variation, making them less susceptible to pogo issues. Solid fuel rockets are generally considered less prone to pogo due to their inherent design in controlling the burn rate.

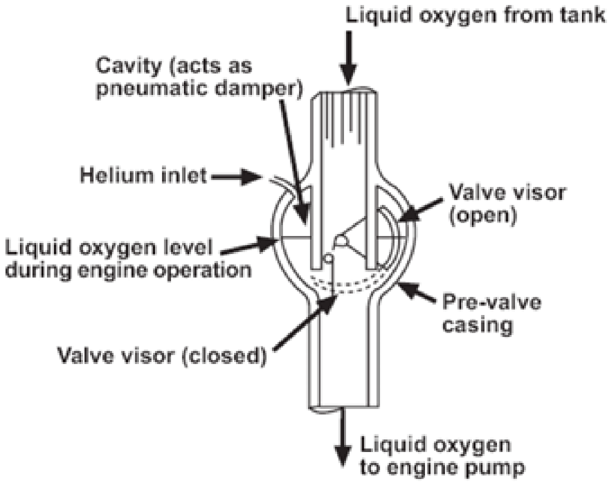


Figure 6. Saturn I-C Pogo Mitigation[11]

From: NASA Experience with Pogo in Human Spaceflight Vehicles (Larsen, 2008)

How Little Vibrations Break Big Rockets
The Vintage Space (YouTube)

After many flight test failures in attempts to solve the pogo effect observed during the development of the Gemini-Titan II program, NASA concluded that pogo should be completely eliminated or at least not allowed to exceed ±0.25g.

Reference Data

Effects of Vibration on Human Performance

In addition to health and safety concerns for vibration levels crew experience during spaceflight, the effects of vibration on human performance must also be considered.

Visual Performance

Vibration can cause degradation of vision due to the movement of the image on the retina. Movement of the retinal image occurs due to vibration of the observer, the display, or both. At an oscillation frequency of less than 1 Hz the eyes can compensate by using slow eye movements; at 1-2 Hz the eye uses quick (saccade) movements to compensate with some success but at levels above 2 Hz, the saccades are not fast enough to compensate, and the image will no longer be clear.

Manual Performance

Exposing the crew to elevated levels of vibration can affect the crewmembers' motor control and limit their ability to perform functions such as reading display panels, turning knobs, activating switches, using touch screens, and/or utilizing joystick controllers. Manual control errors increase between 2 and 16 Hz at 0.05 g_z in the vertical axis with the worse case near whole-body resonance (4-8 Hz). The largest error in fore-and-aft (X) and lateral (Y) directions is at 1.5-2 Hz.

Sensitive Vibration Frequencies Affecting Human Performance

Activity	Frequency range (Hz)
Equilibrium	30 – 300
Tactile sense	30 – 300
Speech	1 – 20
Head movement	6 – 8
Reading (texts)	1 – 50
Tracking	1 – 30
Reading errors (instruments)	5.6 - 11.2
Manual tracking	3 – 8
Depth perception	25 - 40, 60 – 40
Hand grasping handle	200 – 240
Visual task	9 – 50

From: Human Issues related to Spacecraft Vibration during Ascent (Clark)

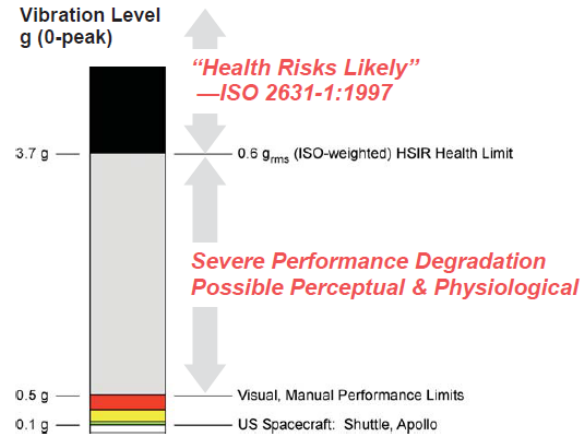


Figure 1. Vibration levels and human health and performance impacts. From: Adelstein et al. (2009)

Shuttle maximum G-loads were limited to 3.0 G and vibration loads reduced to around 0.1 g for non-astronaut crew. With the return to pre-Shuttle-era "stack" launch and "capsule" re-entry architectures, challenging induced environments not experienced since the Apollo era are now back in the picture. G-loading is expected to peak at 3.8 Gx nominally on ascent and even higher during re-entry. Without effective mitigation, levels could exceed crew vibration limits. Exposure to high sustained and transient gravito-inertial forces will generate considerable human-performance challenges, some old, but others new.

[V2 6093] Vibration Limits for Performance The system **shall** ensure the appropriate level of crew task performance (e.g., motor control accuracy and precision, vision/readability, speech clarity, attentional focus) during vibration by evaluating task performance under all expected (nominal and off-nominal) vibration levels.
From: NASA-STD-3001 Volume 2, Rev D

Reference Data – Whole–body Vibration (WBV)

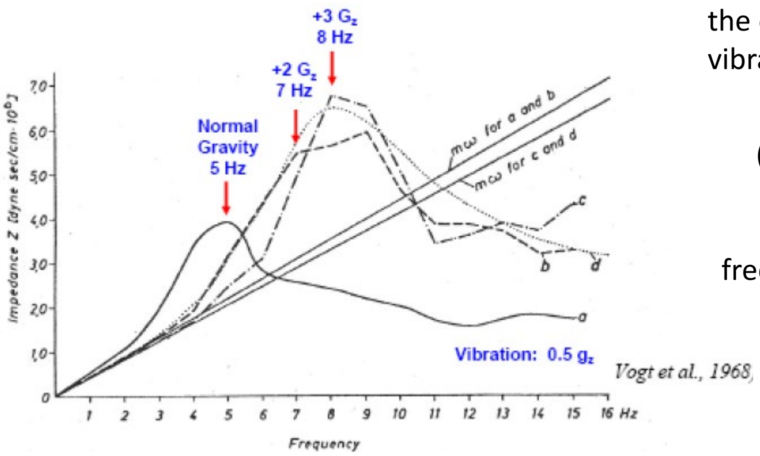
The peak magnitude and frequency of the whole-body vibration (WBV) response depends on body posture and whether one is standing or sitting. Whole body resonance is primarily related to response of the upper torso and shoulder girdle, associated with the response of other body regions.
The resonant frequency of the human body shifts to a higher frequency with increasing sustained acceleration, which may be due to a stiffening of the body under higher G. In normal gravity, the body's resonant frequency shifts downward with increase in vibratory load. During a spacecraft launch, occupants are exposed to vibration and sustained acceleration. G loading dramatically changes the vibration susceptibility of body parts because compression along the acceleration axis reduces compliance and increases stiffness.

Discomfort Symptoms for Different Vibration Frequencies

Symptom	Frequency (Hz)
Motion sickness	0.1 -0.63
Abdominal pain	3 -10
Chest pain	3 -9
General discomfort	1 -50
Complaints	4 -8
Musculoskeletal discomfort	3 -8
Head symptoms	13 -20
Lower jaw symptoms	6 -8
Influence on speech	13 -20
"Lump in throat"	12 -16
Urge to urinate	10 -18
Influence on breathing	4 -8
Muscle contractions	4 -9
Testicular pain	10
Dyspnea (shortness of breath)	1 -4

From: Human Issues related to Spacecraft Vibration during Ascent (Clark)

A review (Rakheja et al., 2020) provides a more detailed look into the biomechanical responses from WBV exposures in different operating environments (e.g., automotive, standing). Across frequency ranges up to 20 Hz, individuals have experienced headaches, speech disturbances, respiration complaints, abdominal pain, and more. Individuals have expressed a constant urge to urinate and defecate while exposed to frequencies between 10 to 18 Hz. Colon pressure was found to pass 200% of resting measurements when an individual was exposed to frequency in the range of 4-5 Hz. Resonant frequencies of the internal organs tend to fall in the same range of the torso resonant frequency, 4-5 Hz, and long-term exposure to these frequencies has been linked with associated disorders in some cases. Changes in respiratory rate have been found with a trend towards hyperventilation between 2 and 6 Hz, which is thought to occur from passive movement of the diaphragm and abdominal wall as a result of the vibration.

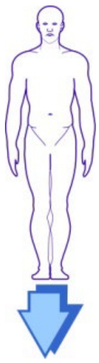


(Left): Studies investigating the effects of sustained acceleration found that the impendence magnitude and impedance frequency increased with increasing sustained acceleration in both seated and supine subjects. *Source: Vogt (1968; 1973)*

Application

Anthropometric Considerations: Sustained Acceleration

Effects of Sustained $+A_z$ Acceleration (eyeballs down)	
9.81 m/s^2	Equivalent to the erect or seated terrestrial posture
19.6 to 24.5 m/s^2	Increased weight; increased pressure on buttocks; drooping of face and body tissues; hypotension; difficult to raise oneself at 2.5g
29.4 to 39.2 m/s^2	Impossible to raise oneself; difficult to raise arms and legs; movement at right angles extremely difficult; progressive dimming of vision (grayout) after 3–4 seconds; progressive tunneling of vision
39.2 to 58.8 m/s^2	Total loss of vision (blackout) after about 5 seconds; hearing and then consciousness lost if exposure continued; mild to severe convulsions in about 50% of the subjects after unconsciousness, frequently with dreams; occasionally paresthesia (abnormal nerve sensations, such as tingling or burning); confused states; pain not common, but tension and congestion of lower limbs with cramps and tingling; inspiration difficult; loss of orientation of time and space for up to 15 seconds post acceleration; after unconsciousness, return to purposeful action takes an average of 24 seconds
> 58.8 m/s^2	Protection is needed to preserve health



Effects of Sustained $-A_z$ Acceleration (eyeballs up)	
–9.81 m/s^2	Tolerable; sense of pressure and fullness in the head; congestion of eyes
–19.6 to -29.4 m/s^2	Severe facial congestion; bradycardia; dysrhythmia; throbbing headache; blurring, graying, or occasional reddening of vision after 5 seconds; congestion disappears slowly; may leave petechial hemorrhages, swollen eyelids
> –29.4 m/s^2	The 5-second tolerance limit is rarely reached; causes mental confusion and unconsciousness

Application

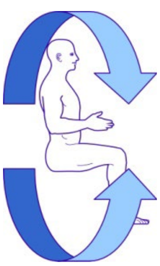
Anthropometric Considerations: Sustained Acceleration

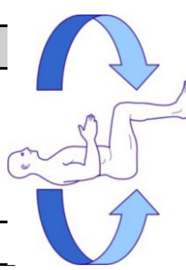
Effects of Sustained +/- A_x Acceleration (eyeballs in/out)	
9.81 m/s^2	Slight increase in abdominal pressure; respiratory rate increases
19.6 to 29.4 m/s^2	Difficulty in spatial orientation; +2g tolerable for at least 24 hours
29.4 to 58.8 m/s^2	Progressive tightness in chest and abdomen; cardiac rhythm disturbances; loss of peripheral vision; difficulty in breathing and speaking; blurring of vision, effort required to maintain focus; 4g tolerable up to at least 60 minutes
58.84 to 88.3 m/s^2	Chest pain and pressure; shallow respiration from position of nearly full inspiration; decreased oxygen uptake during acceleration; pulmonary vascular pressures increase toward dorsal part of chest and fall in alveolar pressure on the ventral part; arterial oxygen saturation falls below 85%, which can lead to cognitive impairment; further reductions in visual acuity and depth perception, increased blurring, occasional tunneling, great concentration required to maintain focus; occasional lacrimation (tears); body, legs, and arms cannot be lifted at +8g; head cannot be lifted at +9g; precise manual control compromised
88.3 to 118 m/s^2	Increased severity of symptoms; severe breathing difficulty, increased chest pain, marked fatigue, loss of peripheral vision, diminution of central acuity, lacrimation
Effects of Sustained +/- A_y Acceleration (eyeballs left/right)	
9.81 to 18.6 m/s^2	Difficulty maintaining head and shoulders upright without restraints; difficulty of precise manual control
27.4 m/s^2	Discomfort after 10 seconds; pressure on restraint system; feeling of supporting entire weight on clavicle; inertial movement of hips and legs; yawing and rotation of head toward shoulder; petechiae and bruising; engorgement of dependent elbow with pain; total body restraint system is critical
49.0 m/s^2	Conjunctival hemorrhage has been reported; severe headache after exposure

Application

Anthropometric Considerations: Rotational Motion

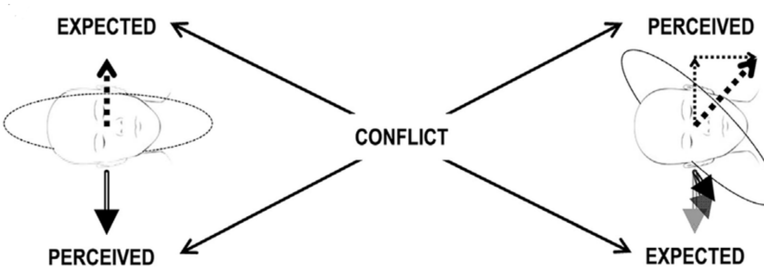
Effects of Rotational Motion About Any Axis	
6 rpm	Most individuals without previous experience can tolerate this rotation in any axis or combination of axes
> 6 rpm	Most individuals rapidly become sick and disoriented unless carefully prepared by a graduated program of exposure
12 to 30 rpm	Most individuals cannot initially tolerate rotation
random tumbles	Severe disorientation; reach and manipulative performance degradation ultimately interfere with the ability to make corrective actions
Effects of Rotational Motion about the Pitch Axis	
6 rpm	Some individuals have endured 60-minute runs
80 rpm	Generally intolerable; with the center of rotation at heart level, symptoms of backward acceleration ($-G_x$) are demonstrated and are tolerable for only a few seconds
90 rpm	Some effects of forward acceleration ($+G_x$), namely numbness and pressure in the legs, are also observed but develop slowly, with pain. No confusion or loss of consciousness is found, but in some individuals, disorientation, headache, nausea, or mental depression are noted for several minutes after a few minutes of exposure
160 rpm	Unconsciousness from circulatory effects alone occurs after 3–10 seconds with the center of rotation at the heart
180 rpm	Unconsciousness from circulatory effects alone occurs after 3–10 seconds with the center of rotation at the iliac crest (hip bone)
Effects of Rotational Motion about the Yaw Axis	
60 to 90 rpm	When the head and trunk are inclined forward out of the z-axis, rotation becomes close to limiting for 4 minutes, although some motivated individuals have endured 90 rpm in the same mode. Except for unduly susceptible individuals, tolerance tends to improve with exposure
90 to 100 rpm	Intolerable





Depending on the magnitude and duration of the rotational motion, countermeasures may include:

- The use of a g-suit to prevent excessive peripheral blood flow
- Restraints to prevent flailing
- Minimizing head movement to reduce Coriolis stimulation of the vestibular system, which could cause severe disorientation



Coriolis stimulation representation

From: Moving in a Moving World: A Review on Vestibular Motion Sickness (Bertolini & Staumann, 2016)

Application

Crew Launch Orientation

The crew launch orientation with the gravity vector through the chest and seat design can cause extreme discomfort after extended duration. Health impacts on the launch pad such as back and leg pain and incontinence have been experienced and these conditions may also persist after entering microgravity and/or leaving the seat. For this reason, the amount of time crew spend in this position needs to be limited. Using medical reports and crew experience, a nominal limit of 2 hours and 45 minutes for crew to be in this position was decided to both be medically manageable and prevent significant impact on mission objectives. In-flight reports of persisting issues from the launch orientation have occurred after 4 hours crew on back time (COBT).

From: American Space

[V2 6113] Crew Limits in Launch Orientation The time in which crewmembers are on back with feet elevated in a launch configuration shall not exceed 3 hours and 15 minutes, excluding subsequent safing and egress time.
From: NASA-STD-3001 Volume 2, Rev D

Orion seats
From: Orion Interior

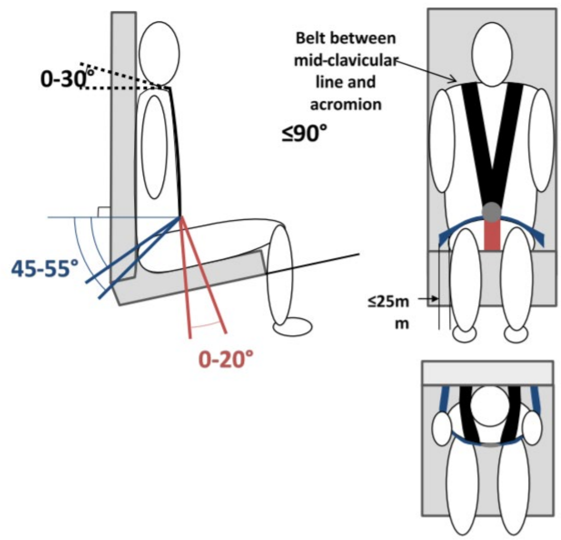
A time limit of 3 hours and 15 minutes was chosen based on technological capabilities and averages for Space Shuttle launches during the development of the Orion program. The exact time a crewmember can be in the launch orientation before feeling overwhelmed with the previously stated issues will vary between individuals and can be affected by status (e.g., hydration level, level of fatigue) before entering the orientation. Discomfort may be attenuated by seat design.

Reference Data

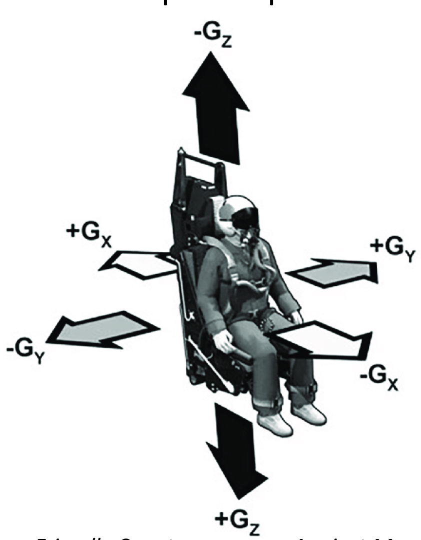
Seat Angle

For impact tolerance, the +Gx orientation is the most advantageous direction of loading. In this orientation, humans can withstand much higher accelerations (by a factor of >2) than in other vectors. However, unless a vehicle lands with a zero downrange velocity, the landing impact will not be purely confined to a single axis. The +Gz orientation is most advantageous as the secondary impact vector due to increased tolerance and greater model fidelity in predicting injury.

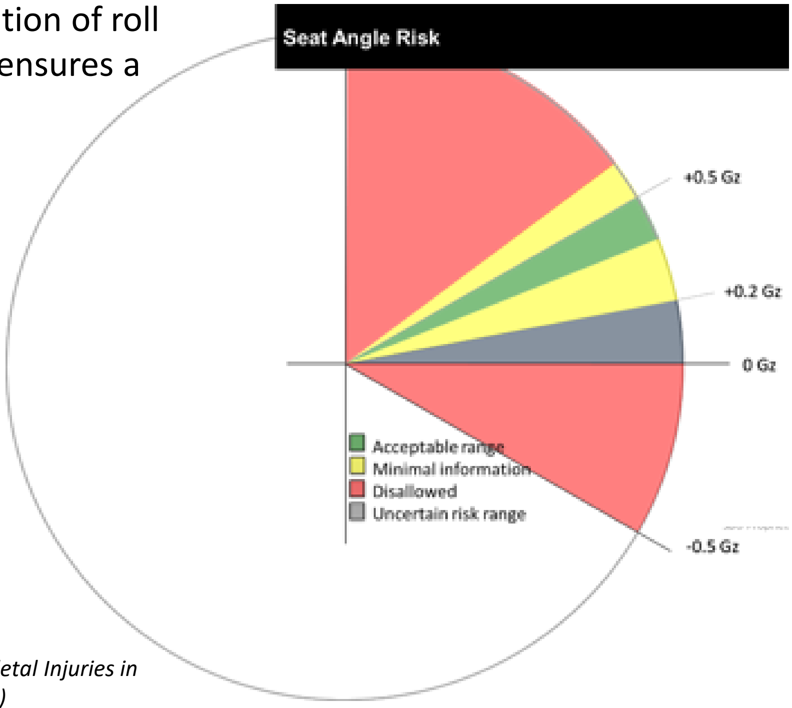
In a vehicle with no roll control, any direction of impact is equally likely. In each vehicle case, an extensive assessment of nominal, off-nominal and contingency conditions would be necessary to accurately assess the risk to the crew due to impact. Depending on the direction of impact, different seat angles could either increase or decrease the risk of injury. A combination of roll control and a seat configuration that ensures a +Gx and +Gz impact is preferred.



From: Application of the Brinkley Dynamic Response Criterion to Spacecraft Transient Dynamic Events (Somers et al., 2013)



From: Crew-Friendly Countermeasures Against Musculoskeletal Injuries in Aviation and Spaceflight (O'Conor et al., 2020)



Application

Parachute Sway

As a capsule returns to earth with parachutes deployed, it is prone to swaying back and forth in the wind. Not only does this affect the angle of impact (by up to 24.5^{o}), but velocity of impact. The capsule will fall slower or faster depending on the angular position of the sway.

Figure 1. Pendulum motion under two Mains observed from chase helicopter during CDT-3-12.

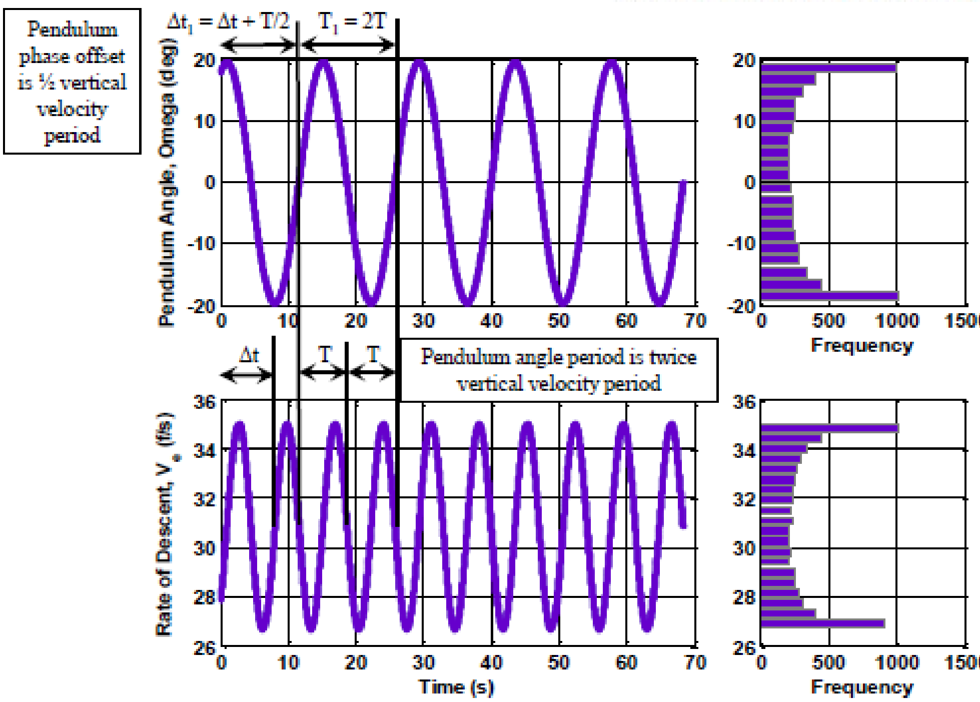


Figure 4. Relationship between pendulum swing angle and vertical velocity component.

Shortening parachute riser length to reduce the distance between the parachute and payload has been shown to mitigate sway during descent. Additionally, an Over-Inflation Control Line reduces swing amplification by restricting the canopy diameter.

Reference: AIAA 2015-2138, Pendulum Motion in Main Parachute Clusters, Ray & Machin, April 2015

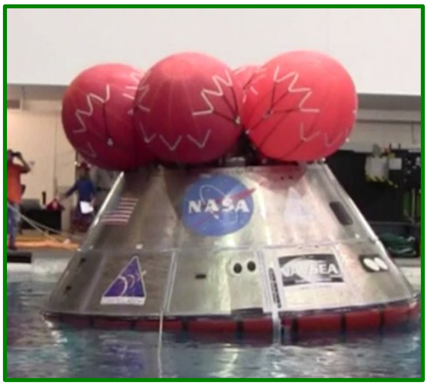
Application

Hang Time

During Orion development, discussions were held over the case of a “stable 2” (upside-down) landing position, which would introduce problems for various vehicle systems.

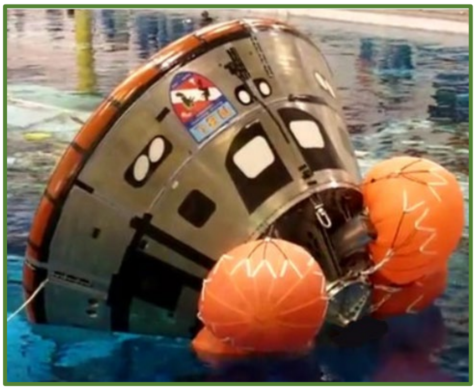
After some discussion, it was decided to establish a limit for this position based on human physiological concerns. This led to a literature review and later testing to better understand the risk and determine the appropriate time limit.

The original stable 2 position/hang time requirement was based on the terrestrial analogue of hanging in a harness in a position that would lead to harness hang syndrome (HHS), where symptoms will appear after around 3.5-10 minutes, incapacitation after around 7-30 minutes, and eventually death. In testing that matched the Orion crew module configuration, it was found that discomfort and HHS symptoms were non-issues. Some even found that the stable 2 position was more comfortable than stable 1. The observed heart rates in the five-minute timeline did not exceed the maximum, though the rate for subjects that rested in the hanging position were lower than when attempting to egress by about 9-18%, depending on the exact seat configuration. The combination of crewmember deconditioning and bobbing in a water landing increase the risk of forcing a seat egress to be above that of waiting for the uprighting system as long as the crewmembers are comfortable.



Stable 1 capsule orientation


Stable 2 capsule orientation


Stable 3 capsule orientation

From: Barr, Y., & Fogarty, J. (2010)


Approximate crewmember stable 2 position

[V2 6112] Hang Time Limit The system shall limit crew exposure to suspension trauma conditions to seven minutes or less.
From: NASA-STD-3001 Volume 2, Rev D

Application

Mitigation Methods: Sustained Acceleration

Anti-g suit (AGS) – The AGS provides positive pressure to the lower torso, preventing blood from pooling in the legs, and may also help to increase venous return. Venous occlusion and discomfort may be problematic. Studies show that although the AGS is good for short-duration g exposure, it may actually decrease tolerance for durations greater than several seconds.

Muscle contraction – Straining and tensing muscles raises the G-LOC threshold by constricting the body's vasculature, thereby preventing blood from traveling away from the head when in an upright position.

Lower-body negative pressure (LBNP) – LBNP stresses the cardiovascular system on orbit by creating a controlled pressure differential between the upper and lower body. The heart responds by increasing blood pressure to maintain proper blood flow to the head and upper body. It is possible that periodic exposure to LBNP may reduce the amount of cardiovascular deconditioning, thereby increasing orthostatic tolerance during entry.

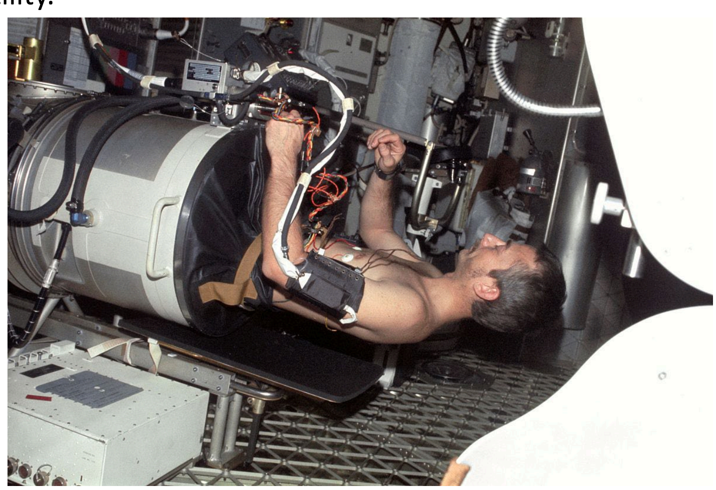
L-1 AGSM – This procedure includes muscle contraction and repeating the Valsalva maneuver and a short, deep breath every 3 to 4 seconds. It gives substantial protection by raising blood pressure at head level. Negatively, it tends to be very fatiguing and distracts the pilot from other tasks.

Positive-pressure breathing – This procedure is less fatiguing than the L-1 maneuver or using an AGS, but it can cause difficulty when trying to communicate.

Entry fluid loading –In a sample of 26 astronauts, the 17 who practiced "fluid loading," or drank 1-2 L of high-sodium liquids before entry, had lower heart rates, maintained blood pressure better, and reported no faintness, compared to 33% incidence of faintness in the 9 astronauts who did not use the countermeasure. However, it seems that the effectiveness of fluid loading is reduced as mission duration increases.

Pharmacotherapeutics – Certain medications may improve orthostatic intolerance by increasing peripheral vasoconstriction, plasma volume, or cardiac contractility.

Air force anti-G suit
From: [Luke Air Force Base]



LBNP device in use on Skylab
From: [Skylab 3 Garriott in Lower Body Negative Pressure Device]

Application

Mitigation Methods: Transient Acceleration

Restraint system – In the absence of proper restraint, whiplash and submarining injuries of the spinal column may occur. Restraint systems may affect operations by being complex to don and restricting the occupant's mobility.

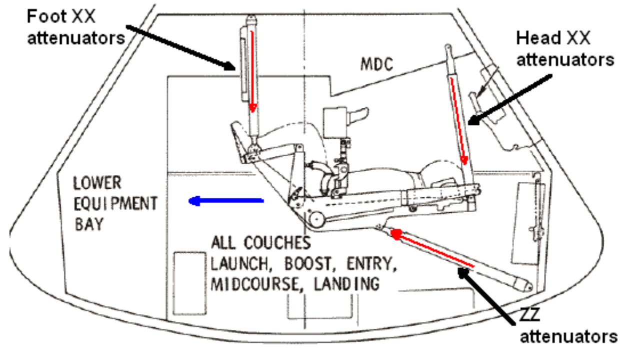
Couches – Human tolerance to impact improves when the contact area between the body and restraint system is greater. Rigid, individually contoured couches were used in the early U.S. space program and in the current Russian Soyuz capsule. This approach ensures that each external body segment will be simultaneously decelerated on landing and that the support pressure gradients exerted on the body surfaces will be minimized. Some previous designs have been uncomfortable because only one body position matched the contour, which also made different types of movement difficult.

Crushable structure – It is important to consider that the spacecraft itself could provide reduction of impact forces, with the use of structural design and materials that can absorb energy upon being crushed.

Stroking seats – The Apollo Command Module included a crew couch/frame that was supported in the crew module by struts and had built-in Y-Y struts to stroke, to attenuate landing loads for water landings and potential hard landing during aborts. However, this added design complexity and created unpredictable secondary dynamics.

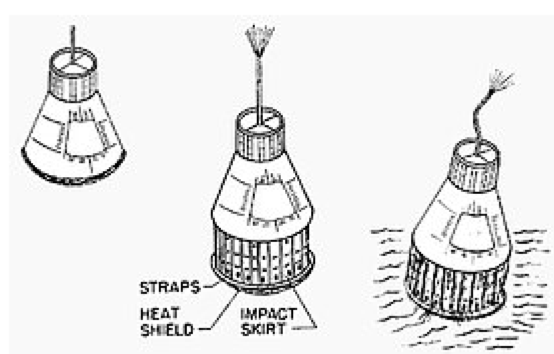
Retrorockets – The Russian Soyuz uses retrorockets in addition to contoured couches. After entry, the heat shield is discarded, exposing six retrorockets, four of which are automatically fired at about 1 m (~3 ft) above the ground. The other two rockets may be activated in the event of an off-nominal entry.

Airbags – Before splashdown, the Mercury capsules had the heat shield drop to extend a landing bag, or an impact skirt, under the spacecraft to help dampen landing loads imparted to the crew.



Apollo stroking seat design
From: Space Exploration

Soyuz retrorockets firing
From: Expedition 36 Soyuz Landing



Mercury impact skirt design
From: Project Mercury

Reference Data

Design Guidance

- Assumptions of the standing limits given in the requirements:
  - Additional equipment (suit) mass borne by the crewmember is <20% of the crewmember's shirtsleeve mass
  - Adequate restraint(s) are provided for all body postures
- Cross-discipline considerations
  - Critical to consider suit design and mass
  - Hard points on suit can cause injury during transient loads (landing)
  - Space between a crewmember and their suit, as well as the suit and the vehicle habitat, may cause physical harm
- Vibration & acceleration during dynamic phases of flight
  - If a crewmember is already experiencing high G loads (and subsequently limited movement), the effects of vibration on performance may be increased
- Potential countermeasures to orthostatic intolerance while standing
  - Physical/Vehicle (e.g., suit weight or bodyweight offloading, restraint systems)
  - Suit (e.g., anti-g suit, lower body compression)
  - Physiological (e.g., scheduled muscle contractions; breathing exercises; fluid loading and salt tablets)
  - All countermeasures should work concurrently to reduce risk and harm to the crew
- Considerations to meet transient and sustained loads requirements
  - Restraint systems during transition from microgravity
  - Offloading of suit mass that still enables crew performance
  - The suit, vehicle, and restraint systems must all interact conjointly to protect the crew from all types of acceleration loads
  - Seat design along with load attenuation is a critical design element that mitigates loads imparted to the crewmember.
- Mission elapsed time: total time from launch until the acceleration load occurs.

From: Risk of Injury from Dynamic Loads

Back-Up

Major Changes Between Revisions

Rev C→ Rev D

- Renamed technical Brief to Occupant Protection
- Updated Reference List
- Added information on vibration effects

Rev B → Rev C

- Updated information to reflect the revisions to language throughout both volumes of NASA-STD-3001
- Updated/added website links due to new NASA website launch

Rev A → Rev B

- Updated information to reflect additions to NASA-STD-3001 Volume 2
- Added slides on crew launch orientation and hang time
- Updated HIDH references to be consistent with revision

Original → Rev A

- Updated information to be consistent with NASA-STD-3001 Volume 1 Rev B and Volume 2 Rev D

Referenced Technical Requirements

View the current versions of NASA-STD-3001 Volume 1 & Volume 2 on the OCHMO Standards website

NASA-STD-3001 Volume 2 Revision D

[V2 6064] Sustained Translational Acceleration Limits The system shall limit the magnitude, direction, and duration of crew exposure to sustained (> 0.5 seconds) translational acceleration by staying below the limits in Figures 6.5-(2-7) and Tables 6.5-(1-6) for seated and standing postures.

[V2 6065] Rotational Velocity The system shall limit crew exposure to rotational velocities in yaw, pitch, and roll by staying below the limits specified in Figure 6.5-8—Rotational Velocity Limits and Table 6.5-7—Rotational Velocity Limits.

[V2 6066] Sustained Rotational Acceleration Due to Cross-Coupled Rotation The system shall prevent the crew exposure to sustained (>0.5 second) rotational accelerations caused by cross-coupled rotations greater than 2 rad/s^2.

[V2 6067] Transient Rotational Acceleration The system shall limit transient (≤0.5 seconds) rotational accelerations in yaw, pitch, or roll as specified in Table 6.5-8—Head CG Rotational Acceleration Limits, to which the crew is exposed. The limits are appropriately scaled for each crewmember size from the 50th percentile male limits of 2,200 rad/s^2 for nominal and 3,800 rad/s^2 for off-nominal cases.

[V2 6069] Acceleration Injury Prevention The system shall mitigate the risk of injury to crewmembers caused by accelerations during dynamic mission phases per Table 6.5-9—Acceptable Injury Risk Due to Dynamic Loads.

[V2 6070] Injury Risk Criterion The system shall limit crew exposure to transient translational acceleration (≤0.5 seconds) by limiting the injury risk criterion (β/beta) to no greater than 1.0 (Low) for seated or standing crew as defined by Dynamic Response (DR) limits in NASA/TM-20205008198 Table 2 "Updated Dynamic Response Limits for Standing", while crew are restrained as required in NASA/TM-2013-217380REV1 for seated crew, or NASA/TM – 20205008198 for standing crew.

[V2 6111] Dynamic Mission Phases Monitoring and Analysis The system shall collect vehicle and crewmember acceleration parameters, specific kinematic responses, and associated metadata, during all dynamic mission phases and suited operations (defined as ascent, abort, entry, descent, landing, postlanding, and EVA operations) to correlate with any injuries incurred by crewmembers.

[V2 6112] Hang Time Limit The system shall limit crew exposure to suspension trauma conditions to seven minutes or less.

[V2 6113] Crew Limits in Launch Orientation The time in which crewmembers are on back with feet elevated in a launch configuration shall not exceed 3 hours and 15 minutes, excluding subsequent safing and egress time.

[V2 6089] Vibration during Preflight The system shall limit vibration to the crew such that the frequency-weighted acceleration between 0.1 to 0.5 Hz in each of the X, Y, and Z axes is less than 0.05 g (0.5 m/s2) root mean square (RMS) for each 10-minute interval during prelaunch (when calculated in accordance with ISO 2631-1:1997(E), Mechanical Vibration and Shock - Evaluation of Human Exposure to Whole-Body Vibration - Part 1: General Requirements, Annex D, Equation D-1).

Referenced Technical Requirements

View the current versions of NASA-STD-3001 Volume 1 & Volume 2 on the OCHMO Standards website

NASA-STD-3001 Volume 2 Revision D

[V2 6090] Vibration Exposures during Dynamic Phases of Flight The system shall limit vibration during dynamic phases of flight at interfaces that transmit vibration to the crew such that the vectorial sum of the X, Y, and Z accelerations between 0.5 and 80 Hz, calculated in 1-s intervals and weighted in accordance with ISO 2631-1:1997(E), is less than or equal to the levels for the accumulated durations in Table 6.7-1— Frequency-Weighted Vibration Limits by Exposure Time during Dynamic Phases of Flight, and Figure 6.7 1— Frequency-Weighted Vibration Limits by Exposure Time during Dynamic Phases of Flight.

[V2 6093] Vibration Limits for Performance The system shall ensure the appropriate level of crew task performance (e.g., motor control accuracy and precision, vision/readability, speech clarity, attentional focus) during vibration by evaluating task performance under all expected (nominal and off-nominal) vibration levels.

[V2 6094] Hand Vibration The system, including tools, equipment, and processes, shall limit vibration to the crewmembers' hands such that the accelerations, as computed according to ANSI/ASA S2.70- 2006, Guide for the Measurement and Evaluation of Human Exposure to Vibration Transmitted to the Hand, do not exceed the Daily Exposure Action Value defined by ANSI/ASA S2.70-2006, Annex A, Figure A.1.

All referenced tables and figures are available in NASA-STD-3001 Volume 2 Revision D.

Reference List

1. Thyagarajan, R., Ramalingam, J., & Kulkarni, K.B. (2014). Occupant-Centric Platform (OCP) Technology-Enabled Capabilities Demonstration (TECD) Comparing the Use of Dynamic Response Index (DRI) and Lumbar Load as Relevant Spinal Injury Metrics. *U.S. Army Tank Automotive Research, Development, and Engineering Center Detroit Arsenal*. https://apps.dtic.mil/sti/pdfs/ADA591409.pdf
2. Human Integration Design Handbook (HIDH). (2014). NASA/SP-2010-3407/REV1. https://www.nasa.gov/organizations/ochmo/human-integration-design-handbook/
3. Somers, J.T., Gohmert, D., & Brinkley, J.W. (2017). Application of the Brinkley Dynamic Response Criterion to Spacecraft Transient Dynamic Events. NASA/TM-2013-217380-REV1. https://ntrs.nasa.gov/api/citations/20170005913/downloads/20170005913.pdf
4. Ray, E.S., & Machin, R.A. (2015). Pendulum Motion in Main Parachute Clusters. *Aerodynamic Decelerator Systems Technology Conferences.* https://eric.mnray.net/data/cpas/AIAA-2015-2138_Pendulum.pdf
5. Somers, J.T., et al. (2020). *Artemis Sustained Translational Acceleration Limits: Human Tolerance Evidence from Apollo to International Space Station*. NASA/TM-20205008196. https://www.nasa.gov/wp-content/uploads/2023/03/tm-20205008196.pdf
6. Barr, Y., & Fogarty, J. (2010). Assessment of Prone Positioning of Restrained, Seated Crewmembers in a Post Landing Stable 2 Orion Configuration. JSC-CN-19414. https://ntrs.nasa.gov/api/citations/20100005137/downloads/20100005137.pdf
7. National Aeronautics and Space Administration (2007). Space Flight Human System Standard. NASA-STD-3001. https://www.nasa.gov/directorates/esdmd/hhp/human-spaceflight-and-aviation-standards/
8. Tripp, L. (2007). Assessment of Gravito-Inertial Loads Environment (AGILE) Workshop. Houston, TX.
9. Bungo, M.W., Charles, J.B., & Johnson, P.C. Jr. (1985) Cardiovascular Deconditioning During Space Flight and the Use of Saline as a Countermeasure to Orthostatic Intolerance. Aviat Space Environ Med, 56(10), 985-90.
10. Charles, J.B. & Lathers, C.M. (1991) Cardiovascular adaptation to spaceflight. J. Clin. Pharmacol, v. 31, p. 1010-1023, 1991.
11. Evidence Report: Risk of Injury Due to Dynamic Loads. Human Research Program. Sept 15, 2021. https://humanresearchroadmap.nasa.gov/evidence/reports/OP%20Dynamic%20Loads%20EB%20FINAL_11-30-22.pdf?rnd=0.0755836554223595
12. Jonathan B. Clark. Human Issues related to Spacecraft Vibration during Ascent. Consultant Report to the Constellation Program Standing Review Board.
13. NASA Experience with Pogo in Human Spaceflight Vehicles. Curtis E. Larsen (2008). RTO-MP-AVT-152.
14. Vogt, H.L., Coermann, R.R., & Furst, D.D. (1968). Mechanical impendence of the sitting human under sustained acceleration. *Aerospace Medicine, 39*, 675-679.
15. Vogt, H.L., Krause, H.E., Hohlweck, H., & May, E. (1973). Mechanical impedance of supine humans under sustained acceleration. *Aerospace Medicine, 44*, 675-679.
16. Rakheja, S., Dewangan, K.N., Dong. R.G., Marcotte, P., & Pranesh, A. (2020). Whole-body vibration biodynamics – a critical review: II. Biodynamic modelling. *Int J Vehicle Performance, 6*(1): 52-84.