Comparison of Anthropomorphic Test Device and Human Volunteer Responses in Simulated Landing Impact Tests of U.S. Space Vehicles

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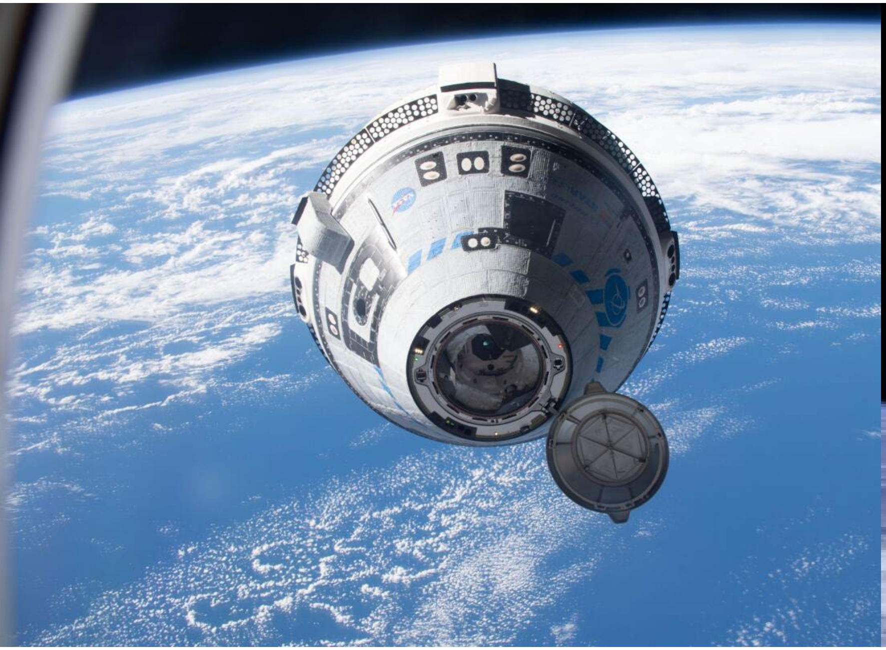
U.S. Crewed Space Vehicles



Boeing Starliner

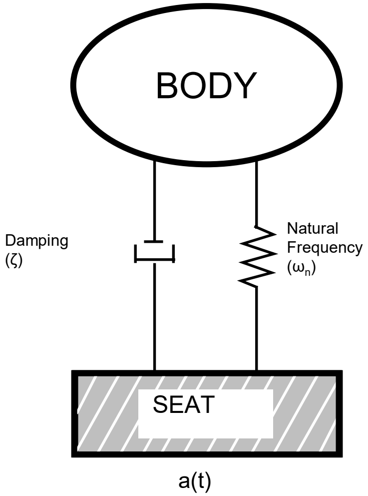
NASA/Lockheed Martin Orion

SpaceX Crew Dragon

NASA, along with commercial partners, is designing three new U.S. space vehicles

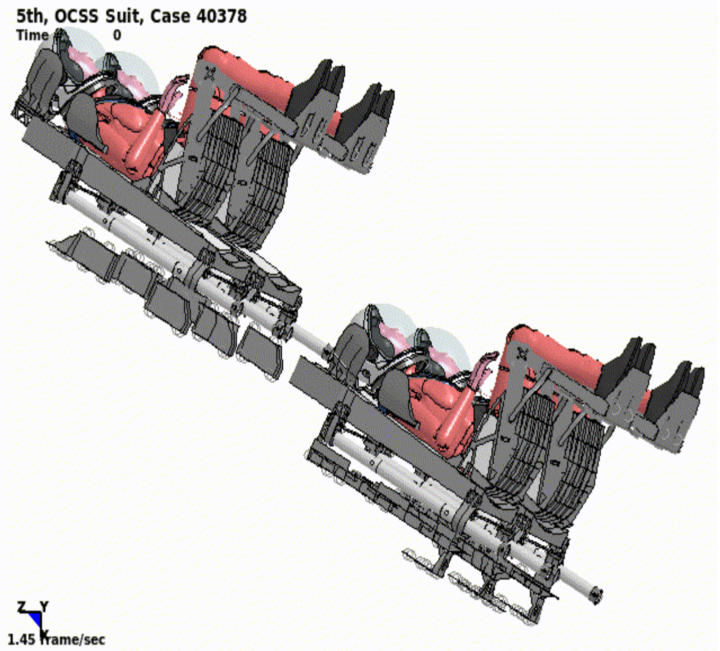
Occupant Protection Requirements

- Vehicles must be designed to meet NASA's occupant protection requirements



Brinkley Dynamic Response Criterion (BDRC)

Anthropomorphic Test Device (ATD) Physical Testing



Modeling

The combination of these criteria is limited in capturing every possible injury that might occur during spacecraft landings.

Soyuz Injury Characterization Study

- The Russian Soyuz vehicle has been transporting crew and cargo, including NASA astronauts, to the International Space Station since the 1990s
- An ongoing NASA study has gathered data from 70 crewmembers to investigate the true injury rate of crewed landings in the Soyuz vehicle
- Actual injury rates were compared to predicted injury rates using the BDRC and ATD analytical tools

Table: Actual and predicted incident rates of participating crewmembers in Soyuz landings.

Injury Classification	Number of Crew Injured	Incident Rate [%]	Brinkley Predicted Rate [%]	ATD Predicted Rate [%]
Bruising & Abrasions	17	24	-	-
Minor	3	4	<1	~1
Moderate	4	6	<<1	<1
Total	24	34		

These findings lead to less confidence in relying on the results from analytical tools and ATDs alone being used to predict landing injuries.

Human Volunteer Impact Testing

- These analytical tools are being used to certify all NASA crewed vehicles
- Therefore, it was determined that human volunteer impact testing must be conducted to understand the gaps associated with our current injury prediction tools and characterize the true risk of injury
- Tests were funded by the NASA Engineering and Safety Center (NESC) and the Commercial Crew Program (CCP)
- Conducted in a joint program with the Air Force Research Laboratory (AFRL) at Wright-Patterson Air Force Base (WPAFB)

Methods - Facilities

- Air Force Research Laboratory
  - Tests were run on the Horizontal Impulse Accelerator (HIA) and Vertical Deceleration Tower (VDT) at Wright-Patterson Air Force Base

VDT

HIA

Methods - Hardware

- Highest fidelity hardware available at the time of testing
- Seat:
  - Seat back and seat pan at a 90° angle
  - Headrest
  - Lower leg assembly
  - Lateral supports with a max 1-inch gap
  - Flight-like comfort padding
- Suit:
  - Mock-up intravehicular activity (IVA) suit helmet and USAF flight suit

    -or-
  - Full IVA suit

Methods – Subjects

Table: Human volunteer subjects' sex, weight, height, and age.

Subject ID	Sex	Weight (lbs)	Height (in)	Age (years)
C44	Male	191	68.4	27
D26	Male	167	66.2	24
G26	Male	140	67.5	26
L30	Male	154	69.5	28
W19	Male	196	67.3	30
A23	Male	196	70.7	27
B65	Male	146	65.0	33
L31	Male	178	71.3	32
S63	Male	153	70.8	30
M60	Male	177	67.8	24
B66	Male	213	68.3	36
R32	Male	211	73.3	32
W20	Female	133	65.2	38
M56	Female	126	65.3	28
S59	Female	173	66.3	22
S60	Female	180	64.3	45

16 U.S. Air Force human volunteer subjects participated in the testing.

Methods – Subjects

Tests were also conducted with the Humanetics small female and midsized male Hybrid III ATDs.

Methods – Data Collection

- VDT carriage and HIA sled were instrumented with accelerometers
- Seats were instrumented with seat pan accelerometers and shoulder belt in-line load cells
- Human subject head accelerations and angular rates were measured with custom bite blocks or an instrumented mouthguard

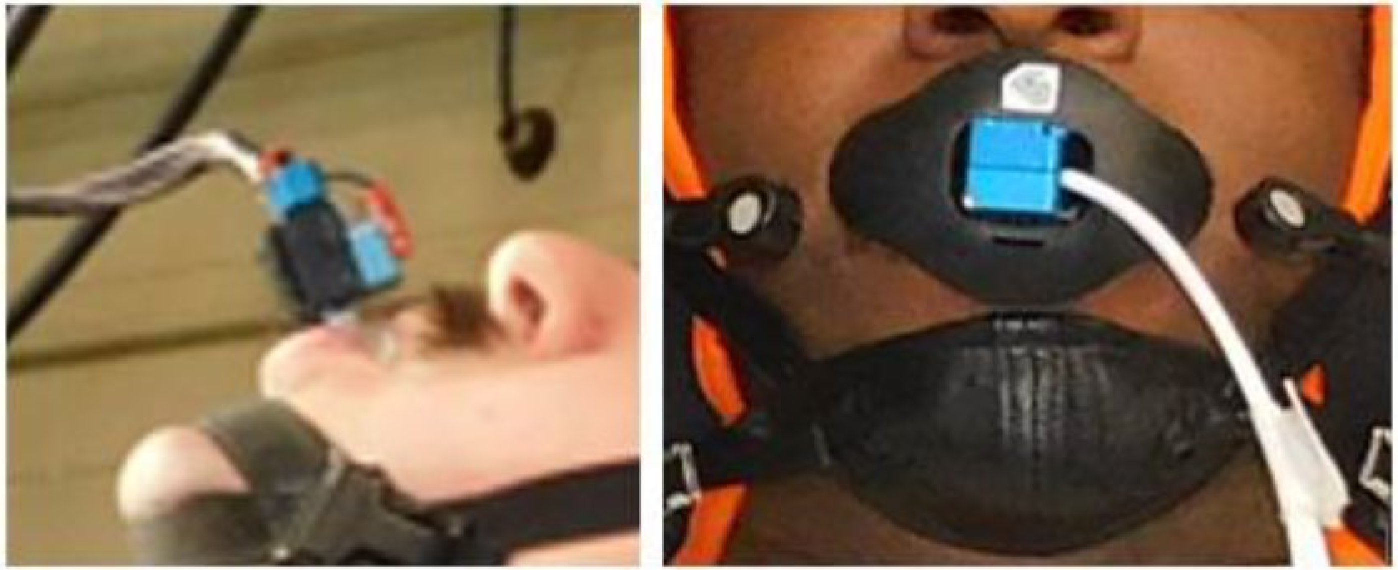


Figure: On the left, the custom-made dental bite block affixed with a tri-axial accelerometer and angular rate sensor. On the right, the novel mouthguard that was used for fully suited tests. This was a commercial-off-the-shelf mouthguard that the sensor package was press-fit into.

Methods – Data Collection

- An additional tri-axial accelerometer was mounted to subjects' chests with two-sided carpet tape

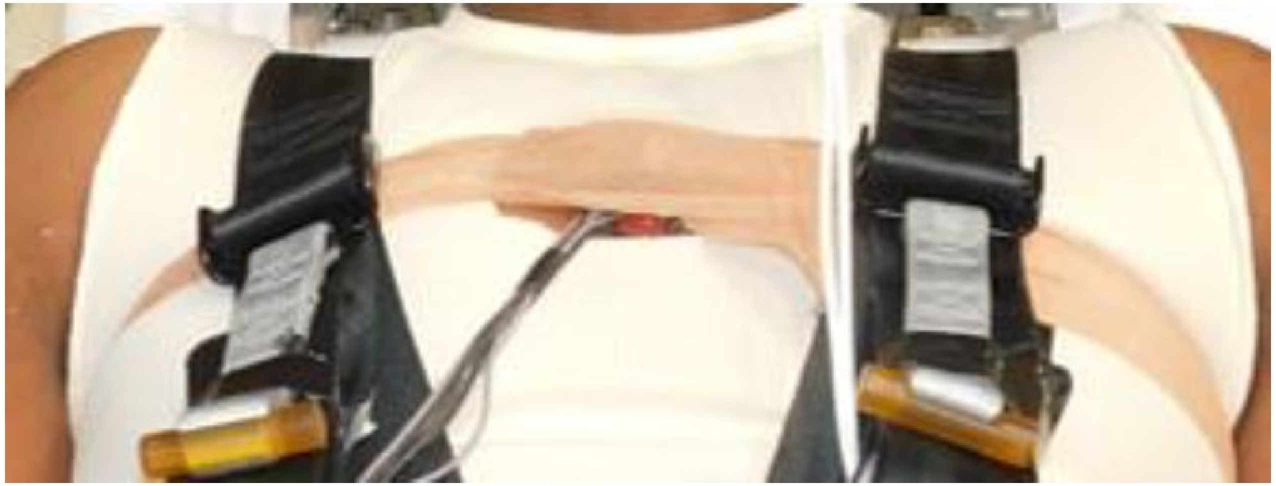


Figure: The chest accelerometer was affixed to subjects with double-sided carpet tape through a hole in their shirt. The accelerometer was wrapped in athletic tape around the torso to provide more stability.

- Subjects were given a pre- and post-questionnaire to ensure fitness for testing and to collect subjective data
  - This included their impression of the impact, head motion, comfort of the helmet and restraint hardness, and general physical discomfort or pain

Methods – Data Collection

ATD Location	Instrumentation
Head	Tri-axial acceleration package and tri-axial angular rate sensor package
Upper and Lower Neck	Six-axis load cell (3 axial forces and 3 rotational torques)
Chest	Tri-axial acceleration package
Lumbar Spine	Six-axis load cell
Pelvis	Tri-axial acceleration package

- SAE-J211 coordinate system was used
- All channels sampled at 10,000 samples per second with a 2.9 kHz anti-alias 5-pole Butterworth filter
- Human data filtered post-test at 120 Hz and the ATD data per SAE-J211

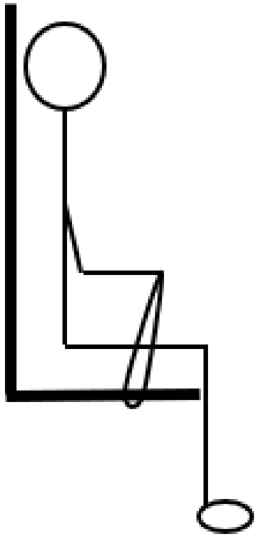
Methods – Procedures

- Prior to testing human subjects, ATDs were tested at least once in each test condition
- At the start of each test day, an ATD was tested at the highest acceleration level planned for the day to ensure proper operation of equipment prior to testing a human subject
- Subjects were fit in the appropriate suit or mock-up and screened by medical personnel
- Human subjects were not tested more than once every 48 hours and not more than 3 times per week

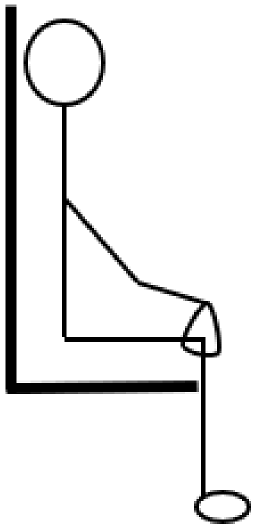
Methods – Procedures

- Each subject was instructed in the proper bracing technique based on the seat being tested (different bracing techniques below)
- All subjects were instructed to brace by pushing their heads and bodies back against the headrest and seatback, and push their feet into the foot pan
- Subjects were given a 10 second countdown
- At 1 second before impact, a call-out was given for subjects to “brace”

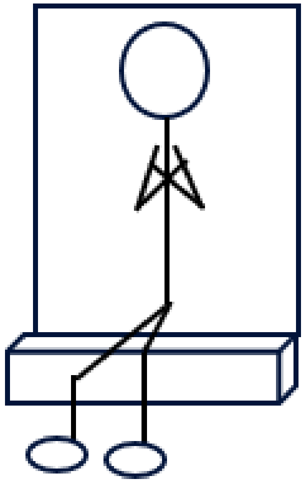
Figure: Different bracing techniques based on the seat being tested



1. Grasp flail strap anchored to seat pan



2. Grasp knee straps



3. Grasp shoulder belts with arms across the chest

Methods – Test Conditions

Figure: All conditions testing with human volunteer subjects and ATDs. Acceleration levels tested were reported as the number of standard deviations from the mean nominal landing G-levels derived from nominal landing Monte Carlos for each vehicle.

Facility	Acceleration Level (σ)	Impact Orientation	# Small Female ATD Tests	# Midsized Male ATD Tests	# Human Subject Tests
HIA	1.5	-Z/Y	4	4	11
HIA	2	-X/Y/+Z	0	4	10
HIA	2	-Z/Y	4	4	12
HIA	2.5	-X/+Z	0	2	5
HIA	3+	-Z/Y	12	12	9
VDT	0	+X/+Z	2	2	5
VDT	1	+X/+Z	4	4	9
VDT	2	+X/+Z	4	6	14
VDT	3	+X/+Z	4	3	5

Methods – Data Analysis

- For ATD tests, the following injury metrics were calculated:

$$Nij = \frac{F_Z}{F_{int}} + \frac{M_{OC}}{M_{int}}$$

$$HIC_{15} = \frac{max}{0 \le t_2 - t_1 \le 0.015}\left[\frac{1}{t_2 - t_1}\int_{t1}^{t2} a(t)dt\right]^{2.5}(t2 - t1)$$

- These injury metrics, along with head rotational acceleration and lumbar loads were compared to NASA occupant protection requirements
  - These requirements are based on a 5% risk of minor injury
- For human tests, head rotational accelerations were compared to known injury limits, and HIC was calculated over a 15 ms window

Figure: NASA occupant protection requirement ATD limits assessed in this test series and the human subject head injury limit used.

Injury Metric	Limit, Small Female HIII ATD	Limit, Midsized Male HIII ATD	Limit, Human Subject
Nij	0.4	0.4	-
Head Rot. Acc [rad/s^2]	2500	2200	4800 *
HIC	375	340	-
Lumbar Load [lbf]	674	1034	-
BDRC	Low, 1.0	Low, 1.0	-

*Rowson, et. al., Rotational Head Kinematics in Football Impacts: An Injury Risk Function for Concussion (2012)

Results – ATDs vs Human Subjects

- No NASA occupant protection ATD injury limits were exceeded in the tests
- Human head responses were collected successfully for only a portion of the tests due to concerns with sensor accuracy
  - The novel mouthguard set-up appeared to bend and move independently of the head, in some cases causing unrealistic head rotational acceleration measurements
- ATDs in the VDT tests had higher average max head rotational resultant accelerations and HIC values than the human subjects
  - Potentially due to movement of the ATD prior to impact on the VDT
    - Carriage in free-fall prior to impact
    - Human subjects instructed to brace while the ATD cannot, and the head likely pulled away from the headrest
- On the HIA, the human subjects had a higher average max head rotational resultant acceleration and HIC values
  - ATD neck is stiffer than a human neck
  - Human subjects likely had greater neck movement, along with increased probability of impacting the lateral headrest supports, during the impacts, leading to higher head accelerations

Results – Human Subject Subjective Responses

- Human subjects reported 17 notable issues of the 84 human subject impact tests; all were considered relatively mild
  - 3 due to the suit hardware fit pre-impact
  - 8 due to interactions with the hardware during impact
  - 3 due to responses to impact
  - 3 were reports of concussion-like symptoms
- Issues increased in severity and count as acceleration level increased

Figure: human subject subjective responses

Facility	Acceleration Level (σ)	Impact Orientation	Number of Human Subject Tests (Female/Male)	Summary of Human Subject Responses
HIA	1.5	-Z/Y	5F/6M	1 subject reported slight shoulder strain in leading shoulder (M/B65); this is believed to be due to nonideal fit of lateral supports leading to a gap between the shoulder and lateral support.
HIA	2	-X/Y/+Z	2F/8M	1 subject had significant head movement off the headrest, and their chin impacted their chest. They reported neck stiffness later in the day (M/B66). 2 subjects reported pain/discomfort due to suit hardware that was addressed with additional padding (M/B66, M/R32).
HIA	2	-Z/Y	6F/6M	1 subject reported a red spot and tenderness on shoulder due to impact with the lateral supports (M/B65).
HIA	3	-X/+Z	1F/4M	1 subject reported pain/discomfort due to suit hardware that was addressed with additional padding (M/B66).
HIA	3+	-Z/Y	2F/7M	3 subjects reported mild discomfort or abrasion on their shoulders due to impact with the lateral supports (M/C44, M/G26, F/M56). 1 subject reported a mild bruise on their hip due to interaction with the lap belt buckle (F/M56). 1 subject reported a mild jaw ache on both sides from head rotation (M/L30). 3 subjects reported "seeing stars". 1 later reported a headache (more detail in section I) (M/D26, M/G26, M/W19).
VDT	0	+X/+Z	2F/3M	No subject reported issues.
VDT	1	+X/+Z	3F/6M	1 subject reported a bruise the size of a quarter on their tailbone due to the padding bunching up on the seat back (M/B65).
VDT	2	+X/+Z	3F/11M	No subject reported issues.
VDT	3	+X/+Z	2F/3M	1 subject heard a neck popping sound but had no pain or soreness. Video analysis showed head was in extension during impact (M/L30). No follow-up needed.

Results – Human Subject Cognitive Symptoms

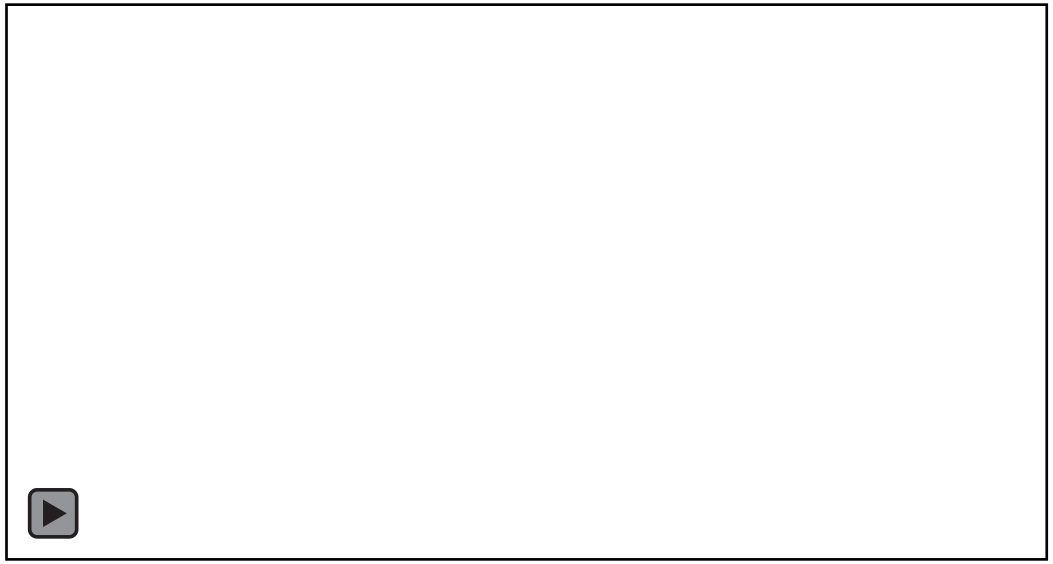
Facility	Acceleration Level (g)	Impact Orientation	Number of Human Subject Tests (Female/Male)	Summary of Human Subject Responses
HIA	3+	-Z/Y	2F/7M	3 subjects reported mild discomfort or abrasion on their shoulders due to impact with the lateral supports (M/C44, M/G26, F/M56). 1 subject reported a mild bruise on their hip due to interaction with the lap belt buckle (F/M56). 1 subject reported a mild jaw ache on both sides from head rotation (M/L30). 3 subjects reported "seeing stars". 1 later reported a headache (more detail in section I) (M/D26, M/G26, M/W19).

- In ATD tests of the same orientation and G-level, the head injury metrics were well below NASA ATD limits, indicating low risk to human subjects

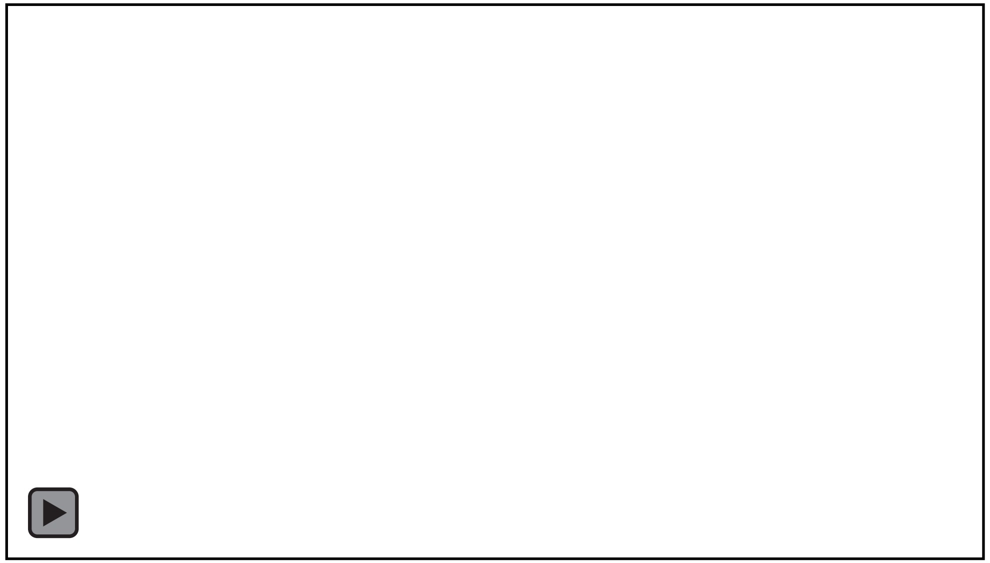
ATDs did not predict the cognitive symptoms described by human subjects

Results – Human Subject Bracing Effectiveness

- In the –X/Y/+Z orientation, 4/7 subjects' heads came off the seatback in their first test, compared to 1/6 in their second test
  - This was the first time participating in impact tests for most subjects



1st Test



2nd Test at same acceleration level

Experience influences bracing effectiveness

Results – Human Subject Seat Fit

- Human subject seat fit varied in some orientations
- For some subjects, the seat pan setting had to be raised when the subjects when from lying on their backs to a 45-degree pitch
  - It may be that gravity pushed these subjects farther down in the seat when raised at an angle
  - Potentially displaced some bodily tissue and when the restraint was tightened, pushed the pelvis farther into the seat
- Fit may also change based on gravity environment
  - Spinal elongation could alter seat fit for return
- This must be taken into consideration in a seat design's sensitivity to fit and concept of operations for fit checks

Limitations

- Gaps in injury prediction are still present when implementing human subject testing
  - Every possible acceleration pulse was not tested
  - It was not possible to test the entire anthropometric range to represent all NASA astronauts
- It is possible that some conditions or human anthropometries not tested could lead to additional results and observations concerning injury risk
- Astronaut deconditioning was not replicated in this test series
- The combination of human subject impact testing and analytical tools gives a thorough assessment of crew injury risk for each vehicle, though not without limitations

Conclusions

- Human volunteer impact testing is outside of certification requirements but was added to the campaigns of two U.S. space vehicles to study injury responses that are too low and sensitive for ATDs to capture
- Goal to increase understanding of injury risk and demonstrate the predicted safety of the crew in nominal landing impacts
- Human subjects reported 17 issues that were not evident in ATD tests
  - In addition, multiple observations were made on bracing effectiveness and seat fit
- Some issues are expected when first conducting dynamic tests with a new seat and suit design
  - It is important that these were first done in a controlled lab environment
- Lessons learned will be applied to the design and concept-of-operations for all U.S. space vehicles, ultimately improving the safety of the crew on current and future vehicles

Acknowledgments

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