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

Teresa M. Reiber[1], Preston C. Greenhalgh[2], Keegan M. Yates[3], Rachel L. Thompson[1], Aaron M. Drake[1], and Nathaniel J. Newby[4]
KBR, Houston, TX, 77058

Jeffrey T. Somers[5], Dustin M. Gohmert[6], and Jeffrey D. Suhey[7]
NASA, Johnson Space Center, Houston, TX, 77058

Chris E. Perry[8]
Air Force Research Laboratory, Wright-Patterson Air Force Base, OH, 45433

John R. Buhrman[9]
UES and DCS, Dayton, OH

Mark A. Baldwin[10]
Lockheed Martin, Denver, CO, 80127

and

Cynthia H. Null[11]
NASA, Ames Research Center, Moffet Field, CA, 94035

United States (U.S.) crewed space vehicles are being designed to support the National Aeronautics and Space Administration's (NASA's) human spaceflight programs. Vehicles must be designed to meet NASA's occupant protection requirements including landing injury assessment with anthropomorphic test devices (ATDs) and analytical models; however, these tools are limited in capturing all injuries that might occur during spacecraft landings. A NASA study of injuries during Soyuz vehicle landings has shown that analytical models are underpredicting occupant injury. Because of the inherent limitations with current analytical tools, human volunteer impact testing was employed to assess flight-like landing conditions of U.S. crewed space vehicles. A total of 84 human volunteer tests in 11 different test configurations with varying impact orientations and G-levels were completed as part of this effort in collaboration with the Air Force Research Laboratory (AFRL) at Wright-Patterson Air Force Base and U.S. vehicle development companies. Human subjects were tested at

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[1] Human Performance Engineer, Applied Injury Biomechanics Team, NASA Johnson Space Center
[2] Occupant Protection Analyst, Applied Injury Biomechanics Team, NASA Johnson Space Center
[3] Injury Biomechanics Specialist, Applied Injury Biomechanics Team, NASA Johnson Space Center
[4] Exercise Engineer and Occupant Safety Analyst, Applied Injury Biomechanics Team, NASA Johnson Space Center
[5] Human Physiology, Performance, Protection & Operations Laboratory Lead, NASA Johnson Space Center
[5] Lead Engineer, Orion Crew Survival System, NASA Johnson Space Center
[7] Structural Analyst/System Manager, NASA Johnson Space Center
[8] Senior Biomedical Engineer, Biodynamics Division, Wright-Patterson Air Force Base
[9] DCS Consultant, Biodynamics Division, Wright-Patterson Air Force Base
[10] Occupant Protection Lead, Orion Spacecraft, Lockheed Martin
[11] NASA Technical Fellow for Human Factors, NASA Engineering and Safety Center

various landing loads and in the highest fidelity seat and suit components that were available at the time of testing for two U.S. vehicles. Matched-pair ATD tests in the same human subject test conditions were also conducted with small female and midsized male Hybrid III ATDs. ATDs were fully instrumented. Head accelerations and subjective responses were recorded for human subjects. In some cases, chest accelerations were captured. Responses of the ATDs and humans in matched-pair tests were compared. No ATD tests showed evidence for risk of injury based on NASA occupant protection requirements. Human subjects reported 17 cases of discomfort or pain, and 3 human subjects reported cognitive symptoms that were not evident in the ATD tests. These results provide evidence that ATDs do not capture all potential injury risks, namely lower severity injuries, discomfort, pain, and fit issues. Overall, human testing is beneficial to understanding the true risk of injury to crewmembers during post-mission Earth landings.

I. Introduction

The National Aeronautics and Space Administration (NASA), along with commercial partners, is designing three new United States (U.S.) crewed vehicles as part of the Commercial Crew Program (CCP) and the Artemis Program. These vehicles are the Boeing CST-100 Starliner, NASA/Lockheed Martin Orion, and the SpaceX Crewed Dragon. These vehicles will carry 4–5 crewmembers at a time on missions to the International Space Station (ISS) or the moon. These vehicles must be designed to meet NASA's occupant protection requirements including the Brinkley Dynamic Response Criterion (BDRC) and the Anthropomorphic Test Device (ATD) injury limits[1].

The combination of these criteria is limited in capturing every possible injury that might occur during spacecraft landings. The BDRC is a simplified spring-mass-damper model of the human body's response to impact based on seat accelerations. The Russian Soyuz vehicle was verified for occupant protection using the BDRC but has exhibited various injuries during landing[3]. Furthermore, the ATD injury metrics are not designed to capture all injuries since ATDs are mechanical devices and do not represent all the features of the human occupant.

The Russian Soyuz vehicle has been transporting crew and cargo, including NASA astronauts, to the ISS since the 1990s. An ongoing NASA study has gathered data from 70 United States Operating Segment (USOS) crewmembers to investigate the true injury rate of crewed landings in the Soyuz vehicle. The study includes 59 male and 11 female crewmembers, 2 off-nominal landings, and 1 abort. Using the BDRC and ATD analytical tools, less than 1% of minor and moderate injuries are predicted, while actual injury rates are 4% and 6%, respectively. Bruising and abrasions cannot be predicted by the analytical tools, while the injury rate is 24% in Soyuz landings (Table 1). The data from this study shows that NASA's analytical tools are underpredicting injury rates seen in Soyuz[3].

Table 1. Actual and predicted incident rates of participating USOS 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 solely on the results from the analytical tools being used to predict landing injuries. These same analytical tools are being used to certify all NASA crewed vehicles; therefore, it was determined that conducting human impact testing must be done 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 CCP and conducted in a joint program with the Air Force Research Laboratory (AFRL) at Wright-Patterson Air Force Base (WPAFB) with hardware from U.S. crewed vehicles. Simulated landing load information from computational models was used to define test conditions. ATD and human subjects successfully completed tests in 11 different configurations with varying impact orientations and G-levels. The results of this testing will be used to better inform the true risk of injury to crewmembers in U.S. crewed space vehicles and can be used to compare ATD and human subject data in impact tests.

II. Methods

A. Facilities

All tests were conducted on the Horizontal Impulse Accelerator (HIA) and the Vertical Deceleration Tower (VDT) at WPAFB. The HIA is a horizontal impact facility that uses a thrust piston to impart an acceleration pulse to a stationary sled pushing it down a track at pre-determined acceleration levels and rise times[4]. The VDT is a vertical impact facility that raises a carriage up to pre-determined drop heights and then releases it into a free-fall guided by rails to achieve the desired acceleration and velocity levels when the carriage contacts an impact surface. Acceleration rise times, representing the rate of deceleration, are controlled with various shaped plungers mounted on the back of the carriage that displace water from a tank located at the base of the facility during the impact. With both test devices, the vehicle seat and restraint system were mounted to the HIA sled and VDT carriage. The test facilities have video systems to capture high-speed video at multiple angles, and on-board data collection systems to collect the carriage and sled accelerations, and data from the instrumented ATD and human subjects.

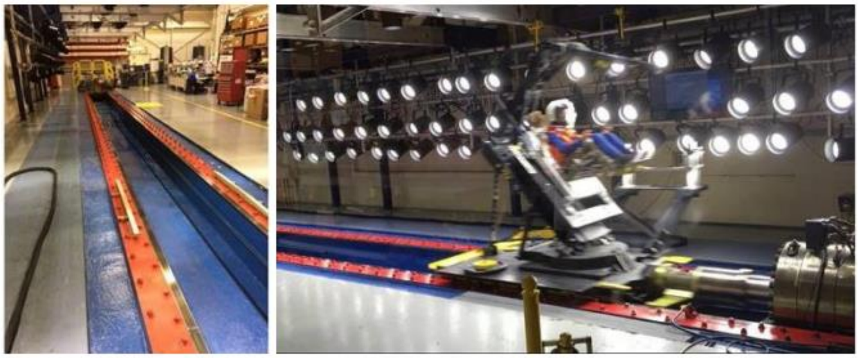

Figure 1. The HIA at WPAFB. The photo on the left shows the sled track, and the photo on the right shows an ATD suited test[4].

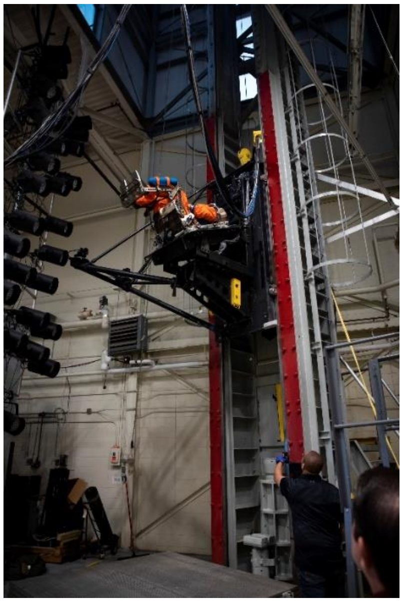

Figure 2. The VDT at WPAFB. The photo shows a human subject being raised to the required drop height[5].

B. Hardware

Hardware in development for U.S. crewed vehicles was tested using the highest fidelity hardware available at the time of testing. Because much of the seat designs are proprietary, only a general hardware description can be provided. The seats consisted of a seat back, a seat pan at a 90-degree angle, a headrest, and lower leg assembly. The seats included various types of lateral supports to restrain subjects at the head, shoulders, hips, and legs with a maximum of a 1-inch gap between the supports and the subject. The seats are designed to be configurable to fit subjects from the 1st to 99th percentile anthropometric ranges. Flight-like comfort padding on the seat back was used in all tests.

Various suit and helmet configurations were tested based on availability. Some tests were completed with a flight-like mock-up helmet to simulate the intravehicular activity (IVA) suit helmets that will be worn during landing, and they also approximated the IVA flight helmet's size and weight. This helmet resembled a communication cap and did not include the bubble helmet that will be worn for landings. The USAF flight suit was worn for these tests to mock-up the IVA suit. In some cases, a full IVA suit was donned by subjects in impact tests including the communication cap, bubble helmet, and the helmet support assembly. Only two suit sizes, the extra-small and medium-long were available at the time of testing. Any subjects who were too large for the suits wore an IVA suit bib, consisting of the suit's torso section without suit arms or legs, but did include the helmet support assembly, communication cap, and bubble helmet. Three different bracing methods were deployed. Some subjects were asked to brace using designated knee straps that provided hand-holds or by grasping the shoulder restraints with their arms crossed. One seat included a strap designated for bracing that was anchored to the seat pan and situated between the thighs that could be pulled back towards the navel.

C. Subjects

Tests were completed with the Humanetics small female and midsized male Hybrid III ATDs, designed to simulate the anthropometry of a 5th percentile female and a 50th percentile male, respectively (Table 2). The ATDs were tested with a fixed or flexible pelvis configuration—depending on the test—and a straight spine. ATDs were dressed in an appropriately sized flight suit or IVA suit bib depending on which vehicle seat was being tested.

Human testing was approved by the AFRL Institutional Review Board (IRB) under Protocol FWR202005H. Tests were completed in three phases and a total of 16 USAF human volunteer subjects were recruited to participate in the tests. Subjects were recruited by the AFRL and cleared to participate by an AF Medical Consultant. All subjects signed an Informed Consent Document (ICD). Subjects were selected to represent a range of anthropometries including both males and females (Table 3). Subjects were between the ages of 22 and 45 years old. Female subjects who were pregnant were not allowed to participate, and each took a pregnancy test 36 hours prior to each test to verify. Human subjects were not tested more than once every 48 hours and not more than three times per week. Subjects were tested in long underwear, the AF battle dress uniform pants, the IVA suit, or the IVA suit bib with appropriate head gear that was available. All subjects' data was deidentified by removing their names and instead using a designated subject ID.

Table 2. Humanetics Hybrid III 5th percentile female and 50th percentile male ATD weight and height.

Anthropomorphic Test Device Type	Weight (lbs)	Seated Height (in)
Hybrid III 5th percentile female	108	31
Hybrid III 50th percentile male	171.3	34.8

Table 3. All 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

D. Data Collection

The VDT carriage and the HIA sled were instrumented with accelerometers on rigid components of each unit. Seats in all tests were instrumented with seat pan accelerometers and shoulder belt in-line load cells at a minimum. For human subjects, a custom-made dental bite-block was used affixed with a tri-axial accelerometer and angular rate sensor to measure head linear and angular acceleration and head angular velocity (Figure 3). In tests with the full IVA suit, including a bubble helmet, the bite-block was not compatible due to interference between the front of the helmet and bite-block. A novel mouth guard set-up was used when testing this suit configuration. This mouthguard was a commercial sports mouthguard composed of a flexible rubber compound with a slot over the mouth where the sensor package could be inserted for a compression fit (Figure 3). An additional tri-axial accelerometer was mounted to subjects' chests with two-sided carpet tape (Figure 4).

Figure 3. 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.

Figure 4. 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 data included their impression of the impact, head motion, comfort of the helmet and restraint harness, and general physical discomfort or pain.

ATDs were instrumented with tri-axial acceleration packages in the head, chest, and pelvis. The head was instrumented with a tri-axial angular rate sensor package. The ATD spine was configured with an upper and lower neck six-axis load cell, and a lumbar six-axis load cell to capture three axial forces and three rotational torques at each of these locations. Data was collected on-board the sled or carriage and transmitted by whip-cable to off-board equipment for additional processing. For all sensors, the SAE-J211 coordinate system was used. All channels were sampled at 10,000 samples per second with a 2.9 kHz anti-alias 5-pole Butterworth filter. The AFRL facility post-test filtered the human subject data at 120 Hz and the ATD data per SAE-J211 requirements.

E. Procedures

Prior to testing human subjects, ATDs were tested at least once or twice in each test condition. At the start of each human subject 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. The results of the ATD tests were assessed to ensure the forces and accelerations were within safe limits prior to testing human subjects.

Prior to each test, subjects were fitted in the appropriate suit or mock-up and the test seat mounted on the facility with the help of the vehicle and suit owners to ensure ideal fit. They were screened by medical personnel with baseline vital signs to include blood pressure, pulse rate, and respiratory rate. Before their first exposure, each subject received a briefing on the test procedures, requirements, and medical risk. This briefing included instruction of proper brace technique for the particular seat being tested, which was either grasping straps at the knee, shoulder, or anchored to the seat pan.

The test fixture was set-up in the appropriate orientation as indicated by the test matrix, and the seat adjustments and lateral supports were positioned for the subject to be tested. Upon completion of pre-test protocols, zeros were taken for channel calibration of each sensor using the data collection system. Once the sensors were zeroed, the subject was positioned in the seat and restraints fastened. Shoulder restraints were affixed with in-line load cells to verify belt loads were within 20 lbs ± 5 lbs when tightened. Once restrained, fit checks were conducted to ensure proper fit of the seat, and for the human subjects, the head and chest sensors were attached. Still photos were then taken from the side and frontal view. For the VDT, the carriage was lifted to the predetermined height and for the HIA, the actuator chambers were pressurized to the specified levels. Before every test, the Safety Officer and the Test Conductor completed safety checks to ensure that the test was safe and the area secured. All non-essential personnel in the HIA test area were required to stand behind a clear protection wall during the countdown and impact event. For each test, the Test Conductor approved final computer, instrumentation, and video checks, and instructed the Facility Operator to begin a 10 second countdown. At 1 second before impact for human volunteer subject tests, a call-out was given for the subject to "brace". At 0 seconds, the VDT released the carriage to drop or the HIA piston propelled the sled to the desired acceleration level. Actual test acceleration levels were within ±0.45 and ±0.37 G of prescribed values in the test matrix for both the HIA and VDT, respectively. These ranges were within normal test facility practice and were determined acceptable by NASA and AFRL personnel.

After each human test, subjects egressed the seat and were evaluated by the Medical Technician. All subjects completed the post-test questionnaire to collect subjective feedback of the impact and hardware. Before the next test, the hardware was inspected by the test team for any damage.

F. Test Conditions

Test pulses were chosen based on the landing Monte Carlo data from simulations available at the time of the assessments. The landing Monte Carlos are done as part of vehicle ceritification to simulate all possible landing conditions, changing wind speed, weather, wave states, etc. For the purpose of this test series, all nominal landing cases were considered. All test conditions in Table 4 simulated possible nominal landing conditions the crew could expect on each vehicle. Acceleration levels that were tested were reported as the number of standard deviations from the mean nominal landing acceleration levels. The distribution of nominal landing acceleration levels was determined using a full landing Monte Carlo of nominal landing cases, specific to each vehicle tested. The orientation of the seat was rotated or pitched with respect to the acceleration vector to match desired impact orientations.

Table 4. All conditions tested 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

G. Data Analysis

AFRL Subject Matter Expert (SME) guidance was used to decide on which filter was needed for the human subject data. They recommended the use of a 120 Hz anti-aliasing 8 pole low-pass Butterworth filter which has been used for all previous human subject impact tests. The data was filtered and processed into *.mat files for analysis in MATLAB. The following injury metrics were calculated for the ATD tests: neck injury criterion (Nij), head injury criterion (HIC15), and BDRC[1].

Equation 1. The Nij that combined the effects of axial loading and bending moment. Where F_z is the axial load in the upper neck, F_{int} is the critical axial force limit in the prescribed direction, M_{OC} is the moment at the Occipital Condyle in the prescribed direction, and M_{int} is the critical saggital moment limit in the prescribed direction[1].

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

Equation 2. The HIC_{15} is based on the resultant translational acceleration. HIC_{15} is the HIC injury metric over a 15ms time interval, where t_1 and t_2 is the time interval, and a(t) is linear acceleration as a function of time[1].

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

The injury metrics along with head rotation acceleration and lumbar loads were compared to NASA occupant protection requirements[2]. These requirements are based on a 5% risk of injury. For human tests, head rotational accelerations were compared to known injury limits, and HIC was calculated over 15 ms. The human head rotational acceleration limit was derived from the injury risk curve developed by Rowson, et al[6]. The 5% injury risk value was used as the limit (Table 5).

Table 5. NASA occupant protection requirement ATD limits assessed in this test series and human subject head injury limit used[2].

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	-

Analysis of high-speed video was also conducted. Videos for each human test were assessed to investigate bracing effectiveness and if any part of the body impacted seat structures due to flail. Human subject feedback after each test was also assessed to identify trends and possible causes of issues and injuries.

III. Results and Discussion

No NASA occupant protection ATD injury limits were exceeded in any 5th or 50th ATD tests. Human subject head responses were collected successfully for only a portion of the tests due to concerns with sensor accuracy. The novel mouthguard set-up did not have the sensors hard-mounted, but only press-fit into the mouthguard for the tests using the full space helmet. This press-fit sensor used in the fully suited tests appeared to bend and move independently of the head, in some cases causing unrealistic head rotational acceleration measurements. Head response data reported herein are listed in the table below and were collected with the rigid, AFRL validated bite-block (Table 6).

Table 6. Human volunteer subject tests with human head acceleration data collected with the validated bite-block. Acceleration levels are 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	# Human Subject Tests
HIA	1.5	-Z/Y	11
HIA	2	-Z/Y	12
VDT	0	+X/+Z	5
VDT	1	+X/+Z	9

For these test conditions, the maximum values of head rotational resultant acceleration and HIC are compared in the table below (Table 7), along with the standard deviations in Table 8.

Table 7. Maximum head rotational and HIC values for the 5th and 50th ATDs, and human subjects. The value reported is the average of the maximum value of all tests of a certain condition and subject type. Acceleration levels are 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)	Average Max Head Rotational Resultant Acceleration (rad/s^2)			Average Max HIC		
		5th ATD	50th ATD	Human Subjects	5th ATD	50th ATD	Human Subjects
HIA	1.5	616	453	289	0.605	0.753	1.48
HIA	2	604	442	740	1.33	1.40	3.30
VDT	0	1170	644	320	20.8	9.61	3.55
VDT	1	1650	1130	701	50.2	34.8	10.7

Table 8. Standard deviations of average maximum head rotational accelerations and average HIC values for the 5th and 50th ATDs and human subjects. Acceleration levels are 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)	Standard Deviation of Average Max Head Rotational Resultant Acceleration (rad/s^2)			Standard Deviation of Average Max HIC		
		5th ATD	50th ATD	Human Subjects	5th ATD	50th ATD	Human Subjects
HIA	1.5	147	157	130	0.120	0.086	0.566
HIA	2	97.5	85.9	896	0.433	0.145	1.24
VDT	0	191	20.4	126	0.708	0.042	0.221
VDT	1	169	203	482	5.91	8.09	1.02

ATDs in the VDT tests had higher average max head rotational resultant accelerations and HIC values than the human subjects at both acceleration levels. On the HIA, the human subjects had a higher average max head rotational resultant acceleration and HIC values, except the average max head rotational resultant acceleration value at 1.5 σ.

This could be due to the movement of the ATD prior to impact on the VDT. On the VDT, the carriage is dropped and is in free-fall motion prior to the impact, while the HIA is stationary before impact. Before the VDT was dropped, the human subjects were instructed to brace for impact, which would decrease motion during the free-fall drop. The ATDs cannot brace, so it is possible that the manikin head was pulled away from the headrest during the drop, causing increased closing velocity at the time of impact, and increased the accelerations measured at the head. However, on the HIA, we see that generally the human subjects recorded higher head accelerations. This could be affected by the design of the ATD neck. The Hybrid III ATD neck is stiffer in response to impacts than a human neck [7]. This may have resulted in human subjects' heads having greater movement compared to the ATD during the impacts on the HIA, along with increased probability of impacting the lateral headrest supports, leading to higher head accelerations.

For all human tests listed in Table 4, subjective data was collected from the subjects after each test. Human subjects reported 15 cases of discomfort or pain, and 3 subjects reported disorientation and/or "seeing stars". There were also observations made on subjects' bracing technique and effectiveness and subject fit. Human subject results are categorized below.

H. Summary of Human Subject Subjective Reports

In total, the human subjects reported 17 notable issues of the 84 human subject impact tests (Table 9). Three were due to the suit hardware fit pre-impact, 8 were due to interactions with the hardware during impact, three were due to responses to impact, and three were reports of concussion-like symptoms post-impact. All subject responded issues were relatively mild but notable to improve crew comfort and injury risk in-flight. One subject underwent a full medical evaluation at the WPAFB clinic post-impact, but symptoms resolved quickly and did not require any follow-up (Section 0). No subjects required follow-up care, and all pain and discomfort was considered mild.

Table 9. Human subject subjective responses by orientation and acceleration level. Acceleration levels are reported as the number of standard deviations from the mean nominal landing G-levels derived from nominal landing Monte Carlos for each vehicle. Subjects who reported the issues are denoted with their sex and subject ID in parentheses.

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.

Reported issues seemed to increase in severity and count as standard deviations increased. At zero standard deviations, subjects reported no issues. At one standard deviation, 10% of subjects reported issues, consisting of easily addressed hardware anamolies. At two and three standard deviations, 14% and 56% of subjects reported issues, respectively. These included discomfort due to interaction with hardware that was quickly addressed, bracing inefficiency, as well as mild cognitive symptoms. At greater than three standard deviations, 66% of subjects reported issues, including mild cognitive symptoms (further discussed in Section I). It’s important to note that all reported issues were considered mild, and will be addressed in final design and operations. Additional recommendations and observations from human subjects are included below.

I. Human Subject Cognitive Symptoms

After the -Z/Y 3+ σ tests on the HIA, some subjects reported cognitive, concussion-like symptoms. In this orientation, the subjects were lying on their backs and rotated with respect to the track. Their heads were pointed towards the piston, legs elevated, and feet pointing down the track. The subjects were accelerated feet first down the track. At 3+ σ of nominal, subject D26 reported feeling disoriented and said he "felt like he had been hit on the head with a firm pillow". After a short recovery period, the subject was able to dismount the seat and walk un-assisted. The subject was referred to the 88th MG Flight and Operational Medicine onsite clinic to be evaluated by a Flight Doctor. The Flight Doctor did note that there were persistent symptoms, but the subject did not meet objective criteria for concussion. The subject was advised to restrict activities for a few days until symptoms resolved. D26 was the third human subject to be tested in this orientation and impact level and was the first to present with these symptoms.

It was observed that D26 did brace a second early which may have resulted in an inefficient brace during the impact. The left hard plastic hearing protector attached to the communication cap impacted the metal headrest during the impact, though measured head accelerations only showed a slight increase when compared to the prior subjects. Both of these incidents could have contributed to the presented symptoms. Following this incident, the test setup was evaluated by the Flight Doctor and Institutional Review Board (IRB) representative and testing was permitted to continue with the following mitigations: a pre-test bracing practice with the subjects and instructing the Medical Technician to stop the test if the subject initiated a brace too early (before the call-out). After reviewing the incident, the IRB considered this event to be an Unanticipated Problem Involving Risk to Subjects or Others (UPIRTSO).

Following the implementation of these mitigations, two more subjects reported similar, yet milder, symptoms of "seeing stars". The second occurrence was with subject G26. This subject reported "seeing stars" during the impact but it resolved quickly, and they were not referred to the clinic for follow-up. This subject appeared to brace on time and effectively, but the earcup did impact the headrest during the impact. Following this incident, ¼ inch felt padding was added to the headrest for subsequent tests. One additional subject, W19, was tested with the additional felt padding on the headrest and reported "seeing stars" briefly after the initial impact and said it felt like "being tackled at a football game". Due to the mildness of the symptoms, the subject was not referred to the clinic for further evaluation. The subject reported that they developed a headache after the test and did not want to continue with the HIA tests. After this third incident, testing in this orientation was halted, but the IRB approved continued testing in additional orientations.

The max HIC values for 50th Hybrid III ATD tests of the same orientation were 13, at 3+ σ of nominal. The max head resultant rotational acceleration measured on the ATD was 1192 rad/s^2. These head injury metrics all remained well below the NASA occupant protection limits at 5% risk of injury, values of 340 and 2200 rad/s^2 (Table 5), indicating low risk to human subjects. The ATD tests did not predict the cognitive symptoms described by human subjects.

Previous human subject tests conducted by AFRL in the Collaborative Biomechanics Data Network (CBDN) were reviewed[8]. One other study was conducted with subjects being acceleterated in the -Z direction with legs elevated on the HIA, this study included a total of 225 tests with 21 subjects. Acceleration levels ranged from 6−10 G and a wide range of rise times. Tests were conducted in -Z but with no yaw component. In seven tests, subjects reported experiencing dis-equilibrium, light-headedness, minimal fluid sensation, head rush, and/or temporary blurring of vision. These occurrences were reported by four out of the 21 subjects. According to experts at the AFRL, reports of these types of symptoms are not normally experienced in other orientations. The increase in occurrence for the current test series may be due to the added yaw component.

Physicians at the USAF Aerospace School of Medicine were consulted about the incidents. The doctors suggested these symptoms were most likely a vestibular response due to the increased blood flow to the brain due to time on their back in that orientation combined with the orientation of the subject relative to the input acceleration vector, and not due to head impact with the headrest. However, this conclusion is not confirmed and continued testing would be necessary to fully understand the cause of symptoms. If future testing is conducted in this orientation, it is recommended to include a nystagmogram in data collection, which would indicate possible activation of the vestibular system which could lead to the aforementioned symptoms. While the 3+ σ pulses are possible landing scenarios, those magnitudes are very unlikely to occur in nominal landings in the -Z/Y orientation. As a result, while these tests points are interesting and relevant to the injury biomechanics community, it is very unlikely that crews will experience these loads in this orientation on U.S. space vehicles. In subsequent tests, the King-Devick test which tracks eye movement as a possible indicator of cognitive impairment, was administered after each impact and compared to baseline for each subject.

J. Human Subject Bracing Technique and Effectiveness

Several observations were made regarding subjects bracing technique and effectiveness. In some tests, the subjects were instructed to brace by using straps attached to their knee braces. It was seen consistently in these tests that subjects did not maintain a desired neutral posture with their heads against the seatback throughout the impact. In a total of 20 tests, subjects were instructed to brace using the described method. Out of those 20 tests, 16 subjects pulled their shoulders and upper torso away from the seatback while bracing during the impact. Additionally, two subjects' heads were not in contact with the headrest, and four subjects did not maintain neutral head and neck posture. For those four subjects, their necks were in extension to maintain contact with the headrest while their shoulders were pulled away from the seatback. The ideal posture is to maintain spinal alignment with the shoulders and torso against the seat back and head against the headrest to reduce risk of spinal injury[9]. In the remaining tests with this vehicle's seat, subjects were instructed to brace either with their arms crossed grabbing the shoulder restraints, or with a designated anti-flail strap located between the legs and long enough for subjects to grab the strap and pull their elbows to the seatback. Both alternate bracing methods allowed subjects to brace while maintaining a neutral posture. Based on these findings, it is recommended that crewmembers be instructed to brace using the shoulder straps, seat-mounted anti-flail strap, or a similar technique that allows them to maintain a neutral posture while braced.

It was also observed that bracing effectiveness seemed to improve with experience. This was especially evident in the -X/Y/+Z 2 σ of nominal HIA tests where subjects were asked to brace with the seat-mounted anti-flail strap. The impact acceleration pulled subjects forward out of the seatback and down into the seat pan with a lateral component. In this orientation, three out of the five subjects' heads came off the seatback in their first test, compared to one out of five subjects on the second test. In one subject's first test, their head came significantly off the headrest and their chin appeared to impact their chest during the impact. The subject reported pain in their neck later that day and took a pain reliever. On their second test, the same subject was able to brace effectively and minimize head movement during the impact. It should also be noted that this impact series was the very first for all of the five subjects.

All subjects were given the same instructions to brace by pushing their heads and bodies back against the headrest and seat, respectively. Subjects were also given a 10 second countdown with a call-out to brace 1 second before impact. Currently, similar impact testing is not conducted as part of crew training, so landing on Earth or on the lunar surface will be the first time crew experience a landing impact. They will also have the effects of deconditioning which could make their brace less effective and decrease their injury tolerance, depending on the mission length[10]. Additionally, crew will not have a 10 second countdown to notify them of landing. Crew will have access to an altimeter with some margin of accuracy, that will give them an indication that landing impact is imminent with a window of uncertainty. Based on these findings, it is recommended that the crew complete similar impact testing to simulate what they will experience on landing. It is also recommended that crewmembers have a reasonably accurate notification system for landing so there is an indication of when to brace.

K. Human Subject Seat Fit

It was observed that human subject hardware fit varied in some orientations. For one vehicle seat, six human subjects were initially fit in the seat in an orientation with subjects lying on their backs and their feet up on the HIA. When the seat was moved to the VDT for a test with a −45-degree pitch angle, the seat pan setting had to be raised 1 inch for proper fit with the shoulder bolsters for two subjects. The subjects included one male and one female, L30 and M56. It is postulated that gravity pushed these subjects farther down into the seat when raised at a pitch angle and potentially displaced some bodily tissue on the buttocks, and when the subject's restraint was tightened, it pushed the pelvis farther into the seat. Proper seat fit is crucial to crew safety during dynamic phases of flight. At one σ from mean nominal acceleration, a subject reported a mild shoulder strain due to the gap between the shoulder and the lateral supports providing evidence for injury concern when not fit correctly in the seat.

Fit may change for some crewmembers based on the gravity environment. If crewmembers conduct seat fit checks before return landing in microgravity, they may fit differently with the onset of reentry G's and the return to Earth gravity. In microgravity, many crewmembers also experience spinal elongation that could alter their seat fit for return landing. This must be taken into consideration in a seat design's sensitivity to fit and concept of operations for fit checks.

L. Limitations

It is important to consider that gaps in injury risk prediction are still present when implementing human subject testing in realistic landing impact conditions to evaluate vehicle designs. It isn't feasible to test every possible acceleration pulse and orientation in physical tests or to include 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.

Another factor not replicated in the test series was astronaut deconditioning. While in decreased gravity environments, astronauts experience deconditioning which weakens their bones and muscles over time due to their offloading[10,11]. Deconditioning could lead to lower injury tolerance and decreased bracing effectiveness on landings. In this study, all participants were physically healthy Air Force subjects that are not representative of a deconditioned astronaut.

Each analysis technique deployed by NASA, including ATD finite element modeling of all possible landing conditions, physical ATD impact testing of bounding landing conditions, and human subject impact testing, has its limitations in characterizing crew injury risk. The listed techniques combined give a thorough assessment of crew injury risk for each vehicle, though not without limitations. The addition of human testing cannot be all encompassing but includes real human subject testing in dynamic conditions. This allows NASA to learn more about vehicle design and human response than possible from models and ATD testing alone.

IV. Conclusion

NASA occupant protection standards and vehicle certification requirements include ATD impact testing to verify injury limits are not exceeded. Human volunteer impact testing, while outside the certification requirements, was added to the test campaigns of two U.S. vehicles as a way to study injury responses that are too low and sensitive for ATDs to capture. In doing so, the ultimate goal is to increase understanding of injury risk and demonstrate the predicted safety of the crew in nominal landing impacts. While the ATD tests met all requirements and didn’t predict major injury risk to humans, the human volunteer tests provided valuable insight into potential soft tissue pain, discomfort, and other minor injuries. Overall, subjects reported 17 issues during dynamic impact testing 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 new seat and suit design; yet it’s important that these were first done in a controlled lab environment to learn and implement changes prior to flight. Lessons learned will be applied to the design and concept-of-operations for all U.S. vehicles, ultimately improving the safety of the crew on current and future vehicles. These insights would not be possible with ATD testing alone to certify vehicle designs for human spaceflight. This test series promotes greater confidence in the safety of our vehicles. Human testing is valuable in understanding the true risk of a broad range of injury types to crewmembers during landings.

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