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

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United States (U.S.) crewed 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 our analytical tools, human volunteer impact testing was employed to assess flight-like landing conditions of U.S. crewed vehicles. A total of 84 human volunteer tests in 11 different test 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 various realistic 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 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 1 human subject was diagnosed with a minor injury that was 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 Earth landings.

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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, 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] [2].

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 off of 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 actual human occupant.

The Russian Soyuz vehicle has been transporting crew and cargo, including NASA astronauts, to the ISS since the 1960s. 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 injury rates of participating USOS crewmembers in Soyuz landings.

Injury Classification	Number of Crew Injured	Injury 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 the analytical tools being used to predict landing injuries. These same analytical tools are being used to certify all NASA crewed vehicles. Thus, human impact testing is needed 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) 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 was used to define test conditions. In total, 11 different test orientations and g-levels were completed. Both ATDs and human subjects were tested in each condition. The outcome of this testing is used to better inform the true risk of injury to crewmembers in U.S. crewed vehicles andcan be used to compare ATD and human subject data in impact tests.

II. Methods

A. Facilities

All tests were conducted on the Horizontal Impact Accelerator (HIA) and the Vertical Deceleration Tower (VDT) at the WPAFB. The HIA is a horizontal sled that is actuated by a piston that imparts an acceleration pulse to the sled that pushes it down the track at specific acceleration levels and rise times. The VDT is a drop tower that raises the carriage up to specified heights to match desired acceleration levels and then is released into a free-fall guided by rails to the impact surface. Rise times are controlled with various shaped plungers that move through a water tower while the carriage is dropped. With both test devices, the vehicle seat and restraint system were mounted to the sled and carriage. The test devices have video systems to capture high-speed video at multiple angles. They both also have instrumentation and data collection systems to collect the carriage and sled accelerations, as well as the ATD and human response.

B. Hardware

Hardware in development for U.S. crewed vehicles was tested, and the highest fidelity hardware available at the time of testing was used.. Because much of the seat design is proprietary, a general hardware description is provided. The seats consisted of a seat back and seat pan at a 90 degree angle, a headrest and lower leg assembly. The seats included lateral supports to restrain subjects at the head, shoulders, hips, and legs with a maximum of 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 configs were also tested, based on availability. Some tests were completed with a mock-up helmet to simulate the flight-like intravehicular activity (IVA) suit helmets that will be worn during landing; matching the 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 intravehicular activity (IVA) suit was donned by subjects in impact tests including the communication cap, bubble helmet, helmet support assembly, and umbilicals. Only two suit sizes, the extra-small and medium-long were available at the time of testing. Any subjects that were too large for the suits wore an IVA suit bib, which was a partial suit that included 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 small female and midsized male Hybrid III ATDs, designed to simulate the anthropometry of a 5th percentile female and a 50th percentile male, respectively. The ATDs were tested with a fixed pelvis configuration 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.

Tests were completed in 3 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 and both males and females (Table 2). Subjects were between the ages of 22 and 45 years. Female subjects who were pregnant were not allowed to participate. 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. 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
M56	Female	126	65.3	28
S59	Female	173	66.3	22
W19	Male	196	67.3	30
A23	Male	196	70.7	27
B65	Male	146	65.0	33
L31	Male	178	71.3	32
S60	Female	180	64.3	45
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

D. Data Collection

The carriage and sled of the VDT and HIA, respectively, were instrumented with accelerometers on the fixtures. Seats in all tests were instrumented with seat pan accelerometers and shoulder belt in-line load cells.

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. 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 was used when testing this suit configuration. This mouthguard was a commercial sports rubber mouthguard that had a slot over the mouth where the sensor package could be mounted. An additional tri-axial accelerometer was mounted to subjects' chests with two-sided carpet tape. Subjects were also given a pre- and post-questionnaire 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 also instrumented with a tri-axial angular rate sensor package. The ATD lumbar spine was affixed with an upper and lower neck, and lumbar six-axis load cell to capture three axial forces and three rotational torques. Data were collected on-board the sled or carriage and transmitted by whip-cable to off-board equipment for additional processing.

For all sensors, the J211 coordinate system was used. All channels were sampled at 10,000 samples per second.

E. Procedures

Prior to testing human subjects, ATDs were tested at least twice in each test conidtion. 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 seat with the help of the vehicle and suit owners to ensure ideal fit. They were also screened by medical personnel with baseline vital signs, to include blood pressure, pulse rate, and respiratory rate. Female subjects were given a pregnancy test within 36 hours prior to each test. 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. Subjects were instructed to use the vehicle-specific brace technique, either grasping the knee or shoulder straps, or the strap anchored to the seat pan.

The test fixture was set-up in the appropriate orientation as indicated by the test matrix. Once the ATDs and human subjects had completed pre-test protocols, the subject was positioned in the seat. Before restraints were fastened, zeros were taken for channel calibration of each sensor. 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. Still photos were taken from the side and frontal view, and the carriage was lifted to the predetermined height. On the HIA, the actuator chambers were pressurized to the specified levels. Before every test, The Safety Officer completed safety checks to ensure that the test is safe and 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. For human volunteer subject tests, at 1 second before impact, a call-out was given for the subject to "brace". At 0 seconds, the VDT released the carriage, and the HIA piston propelled the sled to the desired acceleration level. Actual test acceleration levels were within ±0.45 and ±0.37 G of predetermined values in the test matrix for both the HIA and VDT, respectively.

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 available at the time of the assessments. All test conditions simulated possible nominal landing conditionsthat the crew could expect to experience on each vehicle. Acceleration levels that were tested are reported as the number of standard deviations from the mean nominal landing acceleration levels. The distribution of nominal landing acceleration levels were determined using a full landing Monte Carlo of nominal landing cases, specific to each vehicle tested.

Table 3. All conditions tested with human volunteer subjects and ATDs. Acceleration levels that were tested 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	# Small Female ATD Tests	# Midsized Male ATD Tests	# Human Subject Tests
HIA	1	-Z/Y	4	4	11
HIA	2	-X/Y/+Z	0	2	5
HIA	2	-X/Y/+Z	0	2	5
HIA	3	-X/+Z	0	2	5
HIA	2	-Z/Y	4	4	12
HIA	3	-Z/Y	6	6	6
HIA	4	-Z/Y	6	6	3
VDT	2	+X/+Z	4	2	6
VDT	2	+X/+Z	0	2	4
VDT	2	+X/+Z	0	2	4
VDT	0	+X/+Z	2	2	5
VDT	3	+X/+Z	4	3	5
VDT	1	+X/+Z	4	4	9

G. Data Analysis

Data was processed using the SAE-J211 filter specifications for ATDs. AFRL subject matter expert (SME) guidance was used in deciding on the filter used for the human subject data. They recommended the use of a 120 Hz anti-aliasing 8 pole low-pass Butterworth filter. This is the filter they have 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: Nij, HIC, and BDRC [4] [5] [1]. 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. [4]. The 5% injury risk value was used as the limit (Table 5).

Table 4. 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. A new data collection bite-block was used in some of the tests that appeared to bend and move independently of the head, causing in some cases unrealistic head rotational acceleration measurements. Head response data reported herein are listed in the table below and were collected with a rigid, validated bite-block (Table 6).

Table 5. 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	-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).

Table 6. 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	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 7. 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	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 g-levels. On the HIA, the human subjects had a higher average max head rotational resultant acceleration and HIC values, except for the average max head rotational resultant acceleration value at 1 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 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. The ATDs cannot brace, so it is possible that the manikin head was pulled away from the headrest during the drop, which would increase closing velocity at the time of impact, increasing 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 than a human neck in response to impacts [7]. This may have caused human subjects' heads having greater movement during the impact, along with increased chance of impacting the lateral headrest supports, and led to higher head accelerations.

For all human tests listed in Table 3, 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. Human Subject Bruising, Discomfort, and Pain

In total, the human subjects had a total of 19 notable reports. Five were due to the suit hardware fit pre-impact, 8 were due to interactions with the hardware during impact, 3 were due to response to impact, and 3 were reports of concussion-like symptoms post-impact. All subject noted responses 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 I). No subjects required follow-up care, and all pain and discomfort was considered mild. A summary of all subject responses is recorded in Table 9.

I. Human Subject Cognitive Symptoms

After the -Z/Y 3 and 4 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 AFRL 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, with the prior tests being conducted at 3 and 4 σ of nominal, and was the first to present with these symptoms.

It was observed the D26 did brace a second early and 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 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).

Following the implementation of these mitigations, 2 more subjects reported similar, yet milder, symptoms of seeing stars. The second occurrence was an 4 σ test 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 at 3 σ 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.

Head rotational acceleration rates were captured for these tests and did show spikes in magnitude, presumably due to interaction with the headrest. But, those data will not be published here due to concerns with accuracy of the data. The max HIC values for 50th Hybrid III ATD tests of the same orientation were 4.7 and 13, at 3 and 4 σ of nominal, respectively. The max head resultant rotational acceleration measured on the ATD was 665 and 1192 rad/s^2, at 3 and 4 σ , respectively. 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 that were described by human subjects.

Previous human subject tests conducted by AFRL in the Collaborative Biomechanics Data Network (CBDN) were reviewed. 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 7 tests, subjects reported experiencing dis-equilibrium, light-headedness, minimal fluid sensation, head rush, and/or temporary blurring of vision. These occurrences were reported by 4 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. Wright-Patterson Air Force Base flight doctors were consulted about the injuries. The doctors suggested these symptoms were most likely due to the increased blood flow to the brain due to time on back in that orientation combined with the -Z pulse, 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. While the 3 and 4 σ pulses are possible landing scenarios, those magnitudes are much higher than expected nominal landing loads in the -Z/Y orientation. So, 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.

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 at their knees. 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, 2 subjects' heads were not in contact with the headrest, and 4 subjects did not maintain neutral head and neck posture. 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 headrest to reduce risk of spinal injury [8]. In the remaining tests, subjects were instructed to brace either with their arms crossed grabbing the shoulder restraints, or with a designated anti-flail strap that was located between the legs and was long enough for subjects to be able to grab the strap and pull their elbows to the seatback. Both of the 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, 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 being pulled out of the seat in response to the acceleration. In this orientation, 3 out of the 5 subjects' heads came off of the seatback in their first test, compared to 1 out of 5 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.

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 missions length [9]. 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 but there will be a window of uncertainty. Based on these findings, it is recommended that 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 Fit

It was observed that human subject fit varied in some orientations. For one vehicle seat, 6 human subjects were initially fit in the seat in an orientation that had the subjects laying on their backs with 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 2 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 that "squished" the subjects farther into the seat.

This is an interesting finding because 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. This must be taken into consideration in a seat design's sensitivity to fit and concept of operations for fit checks.

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 was completed as a way to verify the safety of the crew in two U.S. vehicles in simulated landing impacts. While the ATD tests met all requirements and didn't give indication of injury risk to humans, the human volunteer tests provided valuable insight into potential pain, discomfort, and injuries, as well as bracing technique and fit. Some issues are to be expected when first conducting dynamic tests with new seat and suit designs, it's important that these were first done in a controlled lab environment so we can learn and implement changes prior to flight. Lessons learned will be applied to the design and conops 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 injury to crewmembers during landings.

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