

Assessment of Prone Positioning of Restrained, Seated Crewmembers in a Post Landing Stable 2 Orion Configuration

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Introduction

During the Orion landing and recovery subsystem design review, June 2009, it was noted that the human system and various vehicle systems, the environmental control and life support (ECLSS) and guidance, navigation and control (GN&C) systems for example, are negatively affected by Orion assuming a stable 2 (upside down; Figure A) configuration post landing. The stable 2 configuration is predicted to occur about 50% of the time based on Apollo landing data and modeling of the current capsule. The stable 2 configuration will be countered by an active up-righting system (crew module up-righting system; CMUS). Post landing balloons will deploy and inflate causing the vehicle to assume or maintain the stable 1 (up-right; Figure B) configuration. During the design review it was proposed that the up-righting system could be capable of righting the vehicle within 60 seconds. However, this time limit posed a series of constraints on the design which made it less robust than desired. The landing and recovery subsystem team requested an analysis of Orion vehicle systems as well as the human system with regard to the effect of stable 2 in order to determine if an up-righting response time greater than 60 seconds could be tolerated.

The following report focuses on the assessment of the human system in the posture assumed when Orion is in the stable 2 configuration. Stable 2 will place suited, seated, and restrained crewmembers in a prone (face-down), head-up position for a period of time dependent on the functionality of the up-righting systems, ability of the crew to release themselves from the seat and restraints, and/or time to arrival of rescue forces. Given that the Orion seat and restraint system design is not complete and therefore, not available for evaluation, Space Medicine assessed how long a healthy but deconditioned crewmember could stay in this prone, restrained position and the physiological consequences of this posture by researching terrestrial analogs and considered the known physiological alterations and deconditioning experienced by long duration crewmembers.

Literature Review

Upon review of the medical literature, several terrestrial analogue populations were identified that may serve as a surrogate from which data could be extrapolated and recommendations made. The most applicable and analogous is that population which uses a full-body fall protection harness with a D-ring attachment point in the mid-back. Such harnesses are used for safety in specific work environments as well as in certain recreational activities, encompassing workers at heights or at depths (industrial climbing, well construction), mountaineers, rock climbers, cavers, and parachutists, to mention just a few (Lee 2007). All of these harness users are typically young to middle aged adults that are relatively healthy and fit, mirroring the astronaut corps.

Another possible analogue population which has fewer similarities to the astronaut cadre is that of patients who are placed in a prone posture for surgery (spine, kidney, neurosurgery), recovery from surgery (closure of

macular holes in the eye), or for prone ventilation strategies in critically ill patients with sepsis or Acute Respiratory Distress Syndrome (ARDS). This population group is less applicable to the astronauts in a stable 2 configuration, as such patients, aside from being far from healthy, are placed in a flat horizontal and occasionally slightly head-down posture, which is not physiologically equivalent to that assumed to occur with stable 2 seat position.

Therefore, literature examining harnessed populations was reviewed for applicable data relating to the physiological challenges of the prone harnessed position.

The Harness Hang Syndrome (HHS)

A rapidly incapacitating and potentially fatal medical syndrome has been described in occupational medicine and in wilderness medicine literature as occurring in harnessed individuals that have sustained a fall and have remained motionless in their harness for a period of minutes to hours (Orzech 1987, Roeggla 1996, Seddon 2002, Lee 2007, Roggla 2008, Turner 2008, Werntz 2008). This syndrome has received several names, including “Harness Hang Syndrome”, “Suspension Trauma”, and “Harness-induced Pathology” (Seddon 2002, Lee 2007, Werntz 2008, Turner 2008). This syndrome is caused by the body’s physiological response to a motionless posture that is either vertical or semi-prone, depending on where the harness attaches to the pulley/rope (Seddon 2002, Lee 2007), with the main underlying mechanism for its occurrence being orthostatic hypotension. The standard OSHA-approved fall-protection harness has the point of suspension in the mid-back (Turner 2008), yielding a body position that is similar to that of a restrained crewmember in a CEV seat in a stable 2 landing configuration (Figure A). While most of the literature reviewed did not specify the angle at which subjects or victims were suspended, standards for full-body harnesses with a mid-back D-ring list angles of 30-50 degrees from vertical (Seddon 2002). Figure C shows a full body restraint system with a 41 degree angle from vertical (reproduced from Lee 2007).

Figure A



A – Approximate position of Orion seat in Stable 2

Figure B



B – Orion seat configuration in a nominal position

Figure C



C – OSHA-approved full body harness with D-ring attachment point in the mid-back, as studied by NIOSH (reproduced from Turner et al, 2008).

HHS is described as developing within 5-30 minutes in a suspended person who is either immobilized or unconscious, with the key factor being lack of sufficient leg movement to generate a pump action for return of venous blood that has pooled in the legs to the heart (Seddon 2002, Turner 2008). In experimental subjects onset of symptoms is rapid (3.5 to 10 minutes), with one of the earliest signs being cognitive impairment which makes the suspended person less likely to assist with their own rescue (Werntz 2008). Symptoms start with general malaise, progressing to intense sweating, nausea, dizziness, hot flashes, brain function impairment that quickly worsens, respiratory difficulties, tachycardia, and progressively worsening arrhythmias, followed by a sudden increase in blood pressure and loss of consciousness (Lee 2007, Werntz 2008). Death is speculated to occur a few minutes after loss of consciousness if subjects are not quickly released from their harness (Werntz 2008). Case reports of HHS survivors also describe acute renal failure, coagulopathies, prolonged circulatory dysfunction, and long-term cognitive impairment; however these may have been due to other co-existing injuries in those reported cases (Roeggla 1996, Werntz 2008).

Studies done on harnessed individuals in a controlled simulated environment also report a rapid onset of symptoms, ranging from 3.5 to 10 minutes, with very few subjects (described as being particularly fit) able to tolerate the harness for 30 minutes without developing incapacitating symptoms (Werntz 2008). Loss of consciousness occurs after a range of 7-30 minutes (Lee 2007).

In another study, Roeggla et al evaluated the cardiorespiratory response to suspension in a chest harness and noted that after 3 minutes of suspension mean forced vital capacity decreased by 34%, mean forced expiratory volume decreased by 30%, mean end-tidal CO₂ increased by 12% (with no change in arterial oxygen saturation), mean heart rate decreased by 12%, mean systolic blood pressure decreased by 28%, mean diastolic pressure decreased by 13%, and mean cardiac output decreased by 36% (Roeggla 1996). The authors speculated that the underlying mechanism for the observed hemodynamic and respiratory impairment was not only gravity-associated venous pooling, but that the rise in intra-thoracic pressure from chest strap pressure was the main mechanism, with activation of intracardiac reflexes (such as the Bezold-Jarisch reflex) as an explanation for the decrease in heart rate (Roeggla 1996).

Orzech et al conducted a study on three fall protection harnesses at the Harry G. Armstrong Aerospace Medical Research Laboratory, including a full body harness, to evaluate for physiological effects and subjective responses

to prolonged, motionless suspension (Orzech 1987). Subjects tolerated the full-body harness suspension for a mean of 14.38 minutes (range 5.08 to 30.12 minutes) with symptoms of light-headedness and nausea being the most common causes for test termination (Orzech 1987).

In a study conducted by the National Institute for Occupational Safety and Health (NIOSH) by Turner et al (Turner 2008) subjects suspended in a full body harness with a back attach point (as shown in Figure C) were found to have a 1.9 cm increase in midhigh circumference, a 1.5 L/min decrease in minute ventilation, a change in heart rate of 21.6 bpm, and a decrease in the mean arterial pressure of -2.6 mmHg. 95% of subjects tolerated the suspension for 11 minutes. 80% of tests were terminated for a medically-based tolerance limit, defined as either a decrease in systolic blood pressure of more than 20 mmHg, a decrease in diastolic blood pressure of more than 10 mmHg, an increase in heart rate of more than 28 bpm, a decrease in heart rate of more than 10 bpm, a pulse pressure decrease to less than 18 mmHg, or other signs and symptoms including shortness of breath, nausea, and dizziness (Turner 2008). Body weight was found to be a statistically significant determinant for length of tolerance time. No difference between genders was observed (Turner 2008).

The speculated physiological mechanisms underlying the Harness Hang Syndrome mainly include vascular and respiratory compromise and are briefly outlined below.

Vascular compromise

The major physiological driver of the adverse effects seen with HHS in a full body harness are thought to be related to gravity-associated pooling of venous blood in the lower extremities leading to a 20% decrease of the effective circulating blood volume and relative functional hypovolemia (Seddon 2002, Lee 2007, Werntz 2008) which results in orthostatic hypotension (increased heart rate and decreased blood pressure). Immobility of the legs reduces the return of blood to the heart, reducing preload and cardiac output, resulting in decreased perfusion of vital internal organs including the brain, leading to hypoxic injury (Seddon 2002, Lee 2007, Werntz 2008). Unlike cases of orthostatic hypotension where loss of consciousness leads to a fall and thus a horizontal position allowing for redistribution of the blood volume, a harnessed individual cannot assume a horizontal position and thus is unable to restore adequate perfusion (Seddon 2002, Lee 2007).

In addition, the thigh or groin straps that are part of a full-body harness are thought to compress the femoral veins and further decrease venous and lymphatic return from the legs (Seddon 2002, Lee 2007, Werntz 2008).

Respiratory compromise

Compression on the abdomen and thorax by the harness results in increased intra-thoracic and intra-abdominal pressures which will restrict the chest and diaphragmatic movement, causing a decrease in ventilatory capacity, as evidenced by the decrease in pulmonary function tests as described above (Roeggla 1996, Werntz 2008).

Other contributing factors

Traumatic injuries, blood loss, dehydration, and other reasons for loss of consciousness that result in immobility of the lower extremities are all possible contributing factors to the phenomena seen with the HHS (Seddon 2002, Lee 2007).

Time to rescue and possible countermeasures

The literature notes that “a person who is motionless and suspended in a harness is a medical emergency, with only minutes to rescue the person to avoid HHS” and that all workplaces using harnesses should have a “concrete and rapidly employable rescue plan” because “waiting for off-site rescuers such as the fire department or rescue squad will result in too slow a rescue and is therefore an inadequate plan” (Werntz 2008). The National Institute for Occupational Safety and Health (NIOSH) recommends that “to ensure that no more than 5% of workers would experience symptoms rescue would have to occur in 11 minutes” (Turner 2008). The recommendation for cavers using a harness is to initiate a rescue plan within 3 minutes for a harnessed hanging caver who is either immobile or unable to resolve an equipment problem. Deconditioned crewmembers who are relatively dehydrated and more susceptible to orthostatic hypotension may become symptomatic sooner than is outlined for terrestrial populations. Since rescue ships may not be available for a few hours after CEV landing, it is vital that an up-righting system be employed within minutes.

An OSHA Safety and Health information Bulletin titled “Suspension Trauma/Orthostatic Intolerance” recommends that if rescue of harnessed hanging workers cannot be performed promptly, the workers should be trained to maintain frequent leg movements in order to use the leg muscles as a pump to reduce the risk of venous pooling. This may be difficult for a deconditioned crewmember who has become unaccustomed to the terrestrial force of gravity, and whose feet are restrained to the seat using toe holds or ankle straps, and who is also suffering from vestibular challenges in an awkward post-landing posture, and motion sickness from capsule movements on the water.

Another possible countermeasure is to shorten the vertical distance that blood needs to travel from the legs to the heart to overcome the orthostasis, for example by assuming a seated position with the legs flexed (Lee 2007). This is a similar posture to that of crewmembers seated in a Soyuz seat (Figure D).



Figure D: Soyuz seat – note the higher degree of flexion in the hips and in the knees compared with the Orion seat in Figure A and B.

Treatment considerations

There is no consensus on how to approach a harnessed suspended patient after rescue. Some authors advocate keeping a patient who has been suspended motionless for greater than 30 minutes in a seated position for 30 minutes after rescue and not placing them supine. Placing a suspension victim supine is thought by some to cause “rescue death”, which is speculated to occur due to hypoxic blood from the legs being re-introduced into the systemic circulation, causing ischemic heart failure. Right ventricular overload, reperfusion injury to organs that were hypoxic during the suspension, or release of toxins from the hypoxic blood that has stagnated in the legs are also speculated to play a role in “rescue death” (Seddon 2002, Lee 2007, Werntz 2008). This may be a consideration in rescue scenarios of crewmembers if the vehicle and crew remain in stable 2 for an extended period of time.

Effects of Long Duration Microgravity

Astronauts that have completed long duration missions return to Earth in a deconditioned state. This deconditioned state is punctuated by decreased orthostatic tolerance, muscle strength, aerobic capacity and bone density, and alterations in the neurovestibular system which is easily provoked by head motion post flight resulting in disorientation, nausea, and vomiting. Long duration crewmembers have also reported that their somatosensory capability is initially impaired. This means that their ability to use their muscles is affected and their motions are not fluid or well choreographed. So, an individual may want their arms and legs to execute certain maneuvers but the body is incapable of it due to the lack of familiarity with gravity and their own weight. This effect is reversed rapidly after the exposure to gravity, within minutes to hours, but it causes a crewmember’s physical activity to be initially precariously uncoordinated. This is eluded to by Skylab astronauts in the Skylab Medial Operations Project report (NASA/TM-2009-214790; p.47) and reported by a long duration ISS crewmember (personal communication). Taken together, deconditioning can manifest in several different ways leaving the crewmembers vulnerable to injury and without physiological reserve. Any nominally planned post landing activities should be sensitive to these vulnerabilities and not unduly stress the crew.

Limitations

The exact seat, suit, and restraint system is unavailable to assess, therefore a literature review was conducted to find a suitable analog. Some limitations of that literature review are as follows: crewmembers will not be positioned as upright as the subjects in the studies; crewmembers will have the opportunity to push against the footboard to cause muscular contraction and encourage blood flow; the suit may provide some protection from pressure points caused by the restraint system which could cause blood flow restriction; and crewmember body weight maybe distributed more uniformly across the restraint system also preventing pressure points.

Conclusions

No exactly comparable population exists that would allow precise and definitive answers to the questions posed by the Landing and Recovery Subsystem designers with regard to physiological effects of being restrained in an Orion seat while in a stable 2 configuration. There are enough similarities, however, between crewmember posture in the Orion stable 2 configuration and the harness studies reviewed to make an informed recommendation for system requirements. There are drivers for conservatism in this analysis: crewmembers

are significantly more physiologically vulnerable after a long duration mission to the effects of the posture caused by stable 2, which may negate any benefits of the Orion seat and restraint system; the cabin and in-suit environment may contribute to physiological compromise via thermal stress; and the sea state will exacerbate neuro-vestibular disturbance. Without exact analysis of the suit/ seat/ restraint system to be used by Orion, a conservative analysis of the available literature must be used.

Based on the review of several terrestrial studies and the documented deconditioning of long duration crewmembers, Space Medicine has identified that symptom onset will occur in 3.5 minutes. Crewmembers will need to know if the up-righting system is active or failed within this time frame in order to determine the best course of action before cognitive deficits begin. The vehicle should be capable of up-righting itself within 7 minutes. If the system has failed the crew will have to remove themselves from the restraints to prevent worsening of symptoms and potential incapacitation. Crewmembers may be injured if they must release themselves from the restraints and the risk of injury is significantly increased when the vehicle is up-righted while the crew is not restrained. Finally, if the crew is exposed to the stable 2 posture for an extended duration (15 minutes or more), the rescue will have to be treated as a medical emergency.

Concurrence:

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