

Evidence Report

RISK OF INJURY AND COMPROMISED PERFORMANCE DUE TO EVA OPERATIONS

Contributing team

Drafted by SK/H-3PO & ABF:

Jocelyn Dunn, Elizabeth Benson, Jason Norcross, and Nate Newby

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Acronyms

ABF – Anthropometry and Biomechanics Facility

ARGOS – Active Response Gravity Offload System

BME – biomedical engineer

CG – center of gravity

CHAPS – contingency hypobaric astronaut protective suit

COM – center of mass

CO₂ – carbon dioxide

CTSD – Crew and Thermal Systems Division

DCS – decompression sickness

DOF – degrees of freedom

EMU – extravehicular mobility unit

EAMD – Exploration Analogs and Mission Development

ECS – Environmental Control System

EPSP – EVA Physiology, Systems, and Performance

ESPO – EVA Systems Project Office

EVA – extravehicular activity

EWT – EVA Walkback Test

FIU – Florida International University

FTT- functional task testing

GCPS – gravity compensation and performance scale

GRF – ground reaction force

HRP – Human Research Program

HUT – hard upper torso

IDB – in-suit drink bag

ISS – International Space Station

IST – integrated suit test

IVA – intravehicular activity

JSC – Johnson Space Center

LCG – liquid cooling garment
MACES – modified advanced crew escape suit
MAG – maximum absorbency garment
MOD – Mission Operations Directorate
NASA – National Aeronautics and Space Administration
NBL – Neutral Buoyancy Lab
NEA – near Earth asteroid
NEEMO – NASA Extreme Environment Mission Operations
PB – prebreathe
PLSS – portable life support system
POGO – Partial gravity simulator
RATS – research and technology studies
RGO – Reduced Gravity Office
RPE – rating of perceived exertion
SA – situational awareness
SCUBA – self-contained underwater breathing apparatus
SD – standard deviation
SPE – solar particle event
SPR – small pressurized rovers
SVMF – Space Vehicle Mockup Facility
U.S. – United States
VGE – venous gas emboli
WEI – work efficiency index

Status:

- *Active:* Work/research is currently being done towards this risk

Executive Summary

During future missions to the Moon and Mars, each crewmember will most likely perform up to 24 hours a week of extravehicular activity (EVA) in support of exploration, science, construction, and maintenance tasks. Achieving mission objectives will require EVA systems and operations concepts that maximize human performance and efficiency while minimizing health and safety risks for crewmembers.

Currently, over 450 EVAs have been performed in microgravity using the Extravehicular Mobility Unit (EMU). The EMU space suit has enabled the successful assembly and maintenance of the International Space Station (ISS) for over 20 years, as well as deployment of payload experiments, solar arrays, satellite launches and repairs. This EVA work was accomplished at a slower cadence than is expected for Moon and Mars, with ISS crewmembers performing no more than 7 EVAs during a single mission and without any back-to-back EVAs. Despite their success, ISS EVAs have resulted in more injury to EVA crewmembers than may be acceptable for long-duration exploration missions.

The Apollo astronauts completed EVA tasks in suits that were designed for their short-duration lunar missions, although suit mobility problems were evident. The more frequent EVAs and more varied EVA tasks that are anticipated during the future longer-duration exploration missions will require EVA suits and systems that are better oriented to human health and performance than those used during the Apollo Program. Many of the problems that were encountered with the Apollo EVA suits (e.g., limited mobility and dexterity, high and aft center of gravity, and other features requiring significant crew compensation) will need to be corrected or mitigated to optimize EVA objectives of exploration missions.

It is critical that we understand how EVA system design variables such as suit pressure, weight/mass, center-of-gravity location, joint ranges of motion, and biomedical monitoring, affects the ability of astronauts to perform safe, efficient, and effective EVAs. To achieve this understanding, EVA researchers will need to develop and execute an integrated human testing program across multiple environments. The research will provide objective data that will enable informed design decisions and crewmember standards, thereby ensuring EVA systems that optimize crewmember health, safety, efficiency, and performance.

This report describes the risks to crew health, safety, performance, and efficiency caused by EVA operations, and it provides the evidence base to substantiate the importance of the risk.

SECTION I: EVIDENCE

Introduction

During exploration missions to the Moon and Mars, extravehicular activity (EVA) is expected to be one of the primary mission operations to enable construction of surface infrastructure and scientific discovery through observation and experimentation. To enable these mission objectives, exploration EVA (xEVA) hardware and concepts for surface operations are being designed for crews to perform up to 24 hours of EVA per person per week, such that surface EVAs may include performing up to 6-8 hour duration EVAs 3-4 times per week, during missions lasting weeks or months.

Recently, in 2019-2020 timeframe, and since the last evidence report published in 2017, the Lunar Artemis missions have developed the concept of operations for the next exploration-class missions (Coan et al. 2020). It is expected that early Lunar mission operations concepts will increase EVA injury risk by requiring a higher number of EVAs with less recovery time than in previous missions. Currently, ISS crew have had a minimum of 4-5 days of rest between EVAs, while early lunar missions may require 4 EVAs within a 5-day period. Injury incidence rates during Apollo EVAs, which performed a maximum of 3 EVAs per mission, indicate high risk of potentially mission-limiting injuries during surface EVAs of this cadence. Operational controls need to be designed and implemented to reduce risk of both acute injury during high risk activities (e.g. ladder operations and translating over difficult terrain) and chronic “overuse” injuries (e.g. repetitive motions with hand, wrist, and forearm). Injuries to the lower body during surface EVAs, such as ankle or low back, are also credible scenarios that require further investigation to characterize and mitigate injury risks. There is an existing body of strong evidence for risk of shoulder injury as well as injuries in upper extremities, such as hand, forearm, or wrist, due to EVA operations. However, the risk for injury during surface EVAs in partial gravity is likely greater than during On-Orbit microgravity EVAs due to increased physical workload (e.g. gravity level) and both upper and lower body work (e.g. ambulation) compared to primarily upper body work only in microgravity.

In 2020, the agency’s Human System Risk Board (HSRB) classified the “Risk of Injury and Compromised Performance Due to EVA Operations” (known as the “EVA Risk”) as a red risk for all surface exploration Design Reference Missions (DRMs), including short duration lunar missions. The high risk of potentially mission-limiting injuries, such as shoulder injury, during surface EVA operations could result in a severe reduction of crew performance that results in loss of multiple mission objectives. These HSRB assessments are based on injury incidence rates during Apollo EVAs.

Insufficient knowledge or testing data are currently available to evaluate yet if risk of injury due to hardware designs will increase or decrease as compared with Apollo. The Exploration Extravehicular Mobility Unit (xEMU) spacesuit that is currently in development will be higher mobility and higher mass than Apollo spacesuits which has unknown impact on overall injury risk. Increased mass and mobility may increase risk of injury due to additional injury mechanisms. However, the xEMU suit design is expected to have improved shoulder design, and as a rear-entry suit, doffing and donning injuries may be reduced. Also, improved visibility will enable view of outstretched hand which could increase task efficiency and reduce injury potential. Currently, the xEMU is not yet available for testing, and the designs of other surface systems are not yet defined.

Beyond injury, there is considerable risk for impaired performance due to a wide variety of factors across a spectrum from the crewmember to hardware to operations. Crewmembers need to be

physically and mentally ready for an EVA, on orbit injuries have to be addressed and space related anthropometric changes need to be accommodated. Spacesuits and supporting EVA hardware such as tools, lights and cameras have to work as expected and be maintained and prepared for the next EVA. EVA tasks and timelines need to be planned and coordinated with the crew and ground team beforehand and then this team works with constant real-time communication to provide procedures and decision support. Due to the immense amount of resources used in the planning and execution of EVAs, the goal is to maximize each opportunity, therefore EVA durations are typically long, resulting in fatigue and recovery time needed by the crew. A breakdown in any one of those areas can result in performance decrements eventually leading to a loss of EVA content and less mission objectives completed.

Human spaceflight evidence

Gas pressurized spacesuits have been shown to cause injuries and increase metabolic expenditure (Longnecker et al. 2004; Maida et al. 1996; Williams and Johnson 2003b; Carr 2005; Jones et al. 2008; Viegas et al. 2004; Opperman et al. 2010b; Scheuring et al. 2009). The current U.S. spacesuit, the EMU, is pressurized to 4.3 psi (29.6 kPa), forcing the astronaut to expend energy to deform the suit, and limiting his or her mobility (Maida et al. 1996; Newman et al. 2000; Jaramillo et al. 2008; Norcross et al. 2010b; Norcross et al. 2010d; Schmidt et al. 2001). The EMU, causes a variety of musculoskeletal injuries in hands, feet, shoulders, etc. Apollo astronauts also sustained various hand and forearm injuries and a shoulder injury that occurred during drilling operations (Scheuring et al. 2008).

EVA injuries can be divided in two different groups: contact injuries and strain injuries. Contact injuries refer to contusions, abrasions, or hard impacts with the spacesuit, whereas strain injuries are due to overuse, repeated movements, and development of high muscle forces. Strain injuries can occur when astronauts are manipulating heavy tools, working at the limit of their work envelope, or forcing the shoulder joint against the spacesuit (Strauss 2004). A high cadence (e.g. back-to-back EVAs by the same crewmembers) may increase the likelihood of both injury types if there is not sufficient time for rest and recovery between EVAs.

Hand and finger injuries are the most common injuries during both training and flight, and include onycholysis, fingernail delamination, blisters, contusions, and abrasions (Strauss 2004; Viegas et al. 2004; Jones 2004; Opperman et al. 2010b; Scheuring et al. 2009). Preventing hand injury is one of the most difficult challenges spacesuit designers face. Shoulder injuries have occurred during training and flight EVAs inducing some of the most serious harm. Shoulder injuries have been extensively described by Williams and Johnson (Williams and Johnson 2003b) and continue to be actively researched as a somewhat likely, serious negative consequence of EVA (Laughlin et al. 2014; Murray et al. 2014). Abrasions and contusions, due to rubbing and impact against the soft suit components to move the garment, are less serious injuries that frequently occur at the wrist, arms, knees, and ankles.

Limb joint injuries occur when the convolute suit joint is not aligned well with the body joint, so the propensity for injury is increased (Benson and Rajulu 2009; Strauss 2004). Hip and trunk injuries on orbit are rare, and these are typically less serious and primarily caused by impact and rubbing with the HUT, waist bearings, and soft elements resulting in abrasions and contusions. In training, additional injuries are seen in both the supine and prone positions because the weight of the astronaut is supported by the HUT and the ventilation tubes of the LCVG. This pressure can lead to skin indentation and reddening (Scheuring et al. 2009; Strauss et al. 2005).

Many EVA tasks are performed using footholds as the primary restraint. Although the EMU is designed with limited lower body mobility, astronauts must produce a counter torque by flexing leg and ankle muscles to maintain proper orientation while they work. Poor fitting boots and boot inserts allow the astronaut to rotate backward, causing the foot and toes to impact and rub against the boot (Strauss 2004). Additional discomfort is caused by bootie and pressure layer wrinkles, which cause blisters, contusions, abrasions and loss of feeling. In one instance, this almost led to early termination of the EVA (Scheuring et al. 2009). In training and during experiments to evaluate planetary locomotion and exploration procedures, the shifting body also causes the top of the foot and distal toes to impact the boot (Norcross et al. 2009; Strauss 2004).

A large body of evidence for the risk of injury and compromised performance due to EVA operations is derived from astronauts' first-hand experience and non-experimental observations (e.g., Category III and Category IV). Evidence has also been gathered in a rigorous, controlled manner during which subjects served as their own controls from shirt-sleeved to suited conditions, and across repeated measures trials in which a single parameter is varied (e.g., Category II). This report identifies and describes the various risks, contributing factors, and associated evidence for injury and compromised performance due to EVA operations.

Injury during Apollo, Shuttle, and ISS EVAs

A comprehensive analysis was completed of all musculoskeletal injuries and minor trauma sustained in flight throughout the U.S. space program (Scheuring et al. 2009). This study identified 219 in-flight injuries, of which 50 resulted from wearing the EVA suit, making this the second leading cause of in-flight injuries. Overall, the incidence rate of EVA injuries was 0.05 per hour for 1,087.8 hours of EVA activity. This equates to an incidence rate of 1.21 injuries per day, or 0.26 injuries per EVA.

Nine of the 219 in-flight injuries were sustained by Apollo astronauts who were performing lunar surface EVAs. One Apollo astronaut suffered a wrist laceration from the suit wrist ring while working with drilling equipment, and another crewmember sustained wrist soreness due to the suit sleeve rubbing repeatedly. One crewmember injured his shoulder during a lunar EVA while attempting to complete multiple surface activities on a tight mission timeline. Unbeknownst to his flight surgeon, this crewmember later took large doses of aspirin to relieve the pain. Many Apollo astronauts noted problems with their hands. One astronaut remarked: "EVA 1 was clearly the hardest ... particularly in the hands. Our fingers were very sore." Another Apollo astronaut remarked that his hands were "very sore after each EVA"; while another astronaut stated that following the third lunar EVA, his metacarpophalangeal and proximal interphalangeal joints (knuckles) were so swollen and abraded from a poor-fitting glove and/or lack of inner liner or comfort glove that he is certain that a further EVA would have been very difficult if not impossible.

The following excerpts from this study are illustrative of the types of EVA-induced injury:

"Hand injuries were most common among EVA crewmembers, often due to the increased force needed to move pressurized, stiff gloves or repetitive motion for task completion. Many astronauts described the gloves causing small blisters and pain across their metacarpophalangeal (MCP) joints. This could be due to dorsal displacement of the MCP joints against the glove in order to flex the fingers (Viegas et al. 2004). While not mission impacting injuries, they can potentially distract an astronaut from important EVA tasks. Astronauts frequently develop onycholysis (separation of nail from nail bed) after Neutral Buoyancy

Laboratory training sessions, and it is possible some of these injuries represent exacerbations of underlying ground-based injuries.”

However, the authors later state that pre-flight conditions were not strong predisposing factors for these injuries.

“Foot injuries also caused problems for EVA astronauts. One astronaut described an episode of ‘excruciating, searing, knife-like pain’ during an EVA. The astronaut attributed the pain to excess suit pressure bladder material inside the boot, but despite attempts at correcting the problem, the pain persisted with the development of a blister...Though the EVA was completed successfully, the astronaut described the pain from this injury as ‘on the forefront of my mind.’ Another astronaut had similar symptoms after his second EVA with resultant numbness and pain on the dorsum of his feet. Pressure-associated erythema developed on the dorsal surfaces of each foot, and symptoms persisted throughout the mission and 2 to 3 weeks post-landing (Scheuring et al. 2009).”

Suit Mobility

Throughout the history of space flight, astronauts and cosmonauts have performed more than 450 EVAs. However, only 28 of those EVAs have been conducted in partial-gravity (i.e. lunar). Accordingly, the current understanding of suited human performance in partial-gravity environments is limited. A face-to-face summit with some of the Apollo astronauts provided valuable insight and yielded recommendations for the next-generation partial-gravity EVA suit. Fourteen of the 22 surviving (at the time of the summit) Apollo astronauts participated in the Apollo Medical Operations Project to identify Apollo operational issues that impacted crew health and performance. In the category of EVA Suit Operations, recommendations centered on improving the functionality of the suit as well as improving human factors and safety features. The astronauts recommended increasing ambulatory and functional capability through increased suit flexibility, decreased suit mass, lower center of gravity, and reduced internal pressure (Scheuring et al. 2007).

The following excerpt from Scheuring et al. (2007) describes the astronauts’ view on the need for increased suit mobility: “EVA suit mobility was more of an issue in terms of surface locomotion and energy expenditure. The crews often felt they were fighting the resistance in the suit. This was fatiguing, especially in the thighs.” The astronauts pointed out that the lunar surface is more similar to an ocean than a desert. The undulating surface posed a number of challenges, including ambulating against a suit that did not allow mobility at the hip. Normal human locomotion includes flexion at the hip, knee and ankle, but the Apollo A7LB (lunar surface EVA suit) had limited ability to bend the suit at the hip and rotate within the suit. This likely contributed to the loping and hopping style gait, which relied more on knee and ankle range of motion. The crewmember had to bend forward from the knee joint, which demanded considerably more workload on the quadriceps muscles. Therefore, recommendations on mobility centered on adding hip mobility and improving knee flexibility. One comment summarized this point well, ‘Bending the knee was difficult in the suit. We need a better [more flexible] knee joint.’” The Apollo crews also reported that sloped terrain on the lunar surface caused fatigue. The crews remarked that stable footing was limited and that leg fatigue would become more pronounced in terrain steeper than approximately 26°, although they estimated the exact angle of the slope. Lack of suit mobility, primarily at the hips, made getting in and out of steep terrain difficult (Scheuring et al. 2007).

The Apollo astronauts also strongly recommended improving glove flexibility, dexterity and fit. According to the crews, the most fatiguing part of surface EVA tasks was repetitive gripping. One crewmember stated that “efficiency was no more than 10% of the use of the hand” (Scheuring et al. 2007). Accordingly, it is no surprise that the Apollo astronauts were adamant that the glove flexibility, dexterity, and fit be improved (Scheuring et al. 2007). It is also interesting to note that the lunar crews stated that they did not experience hand or forearm trauma in training, though muscle fatigue occurred. However, these training sessions typically lasted only 2 to 3 hours, whereas the lunar EVA’s including pressurized prep time were 7 to 9 hours. Recent experience with ISS-related EVA's suggests that better conditioning can solve most of the forearm fatigue problems; however, lack of dexterity and hand trauma remain critical issues. Additionally, significant improvements in glove design have occurred since Apollo, however they do not completely alleviate fatigue during longer EVAs (Scheuring et al. 2007).

Suit Fit

Another issue that has complicated spacesuit operations since the early days of spaceflight is the ever-present challenge of achieving an acceptable space suit fit. In order to minimize the torque needed for movement and avoid unnecessary impingement on the wearer, the gas-pressurized enclosure of a spacesuit must be appropriately tailored to accommodate its occupant. An adequate spacesuit fit is normally achieved by either selecting humans that are approximately similar in size (Mercury, Gemini and Apollo programs) and custom-fitting their hardware, or more recently, by building multiple sizes of modular spacesuit components that can be combined to accommodate different body sizes and shapes. Even in the Apollo program, where the astronauts appeared to be more or less homogeneous in size and spacesuits were largely custom tailored, there were issues with accommodation, and a great deal of effort was spent on fit checks to tweak fit before flight.

The Apollo A7LB is often described as completely custom tailored, but to be precise, there were certain components (for example the boots and the soft suit torso) which were custom sized for each astronaut’s dimensions, whereas other segments such as the limbs on the soft suit were a set size but adjustable in length (Carson et al, 1975). The diameter of the one-size-fits-all upper arm and wrist bearings caused issues for Buzz Aldrin, whose biceps and wrists interfered with suit component as he worked in the pressurized suit on the moon (Apollo 11 Crew Systems Division). The interference at the upper arm bearing forced his fingertips out of his gloves, while the wrist disconnects caused discomfort as they rubbed against his forearm.

In the shuttle program, the selection limits for astronauts were intentionally broadened to include females and to allow a larger range of human size, shapes and backgrounds. With this increased diversity in the crewmember population, there was a need to come up with a new system for providing EVA suit capability for a broader range of people. Realizing the cost and logistics challenges associated with building custom-fitted spacesuits for each EVA crewmember, NASA chose to start building suit components in multiple sizes that could be combined to create an enclosure that fit people of varying size and shape. The added advantage of this approach was that different people could wear the same size of a particular suit component (for example the Hard Upper Torso), by swapping out distal components such as arm assemblies, gloves and boots. The challenge of this approach was that not every planned size of these suit components was built, leading to fit issues or exclusion from EVA for some members of the population.

A high-profile example of inflight suit fit challenges occurred in March 2019, where a planned EVA had a staffing change due to suit fit concerns for one of the participants (NPR article, 2019). Anne McClain, who had trained in both the Medium and Large Hard Upper Torso (HUT) configurations on the ground, determined after her first inflight EVA that the medium HUT was a better fit for her in microgravity. Because only one medium HUT was available, the decision was made to swap out the EVA assignment to avoid a rush to make the additional medium HUT flight ready. Inflight changes in suit fit are a common enough occurrence that there is time allotted for inflight fit checks, where lengths and configurations of components can be switched out before an astronaut performs an EVA. These inflight fit changes may be due to microgravity-induced changes in neutral body posture (Kim et al 2019), as well as documented changes in effective body lengths, for example the length of the spine (Young et al 2020).

A suboptimal suit fit can directly cause or contribute to injuries to the occupant through impingement (such as at the shoulder) or contact-related injuries (fingernail loss, knuckle abrasions, excessive contact at the top of the foot). When suit fit is suboptimal there can also be performance impacts if the poorly fit occupant is having to work harder than anticipated in the suit, or if the suit fit issue is significant enough to cause mobility, visibility or tactility challenges above and beyond those associated with a nominally fitting suit. Performance decrements are expected when operating in a pressurized suit, but can be exacerbated when the subject has suboptimal fit.

Compromised Performance

Even with a spacesuit that fits well and provides sufficient mobility, and even if the crew can avoid suit related injuries, there remains potential for several performance limiting issues. To the best extent possible, these performance impacts can be avoided through planning and training, but this only can happen to the extent that these issues are well characterized prior to EVA or from lessons learned about mitigating these problems after experiencing them inflight. The following sections outline spaceflight evidence of compromised performance due to Hyper/Hypothermia, Waste Management, Nutrition and Hydration, Humidity, Workload and Fatigue, and Situation Awareness.

Hyper/Hypothermia

The physiologic cost of performing work in a pressure garment is significantly greater than that of performing the same work without a suit. High workloads result in energy expenditure and the production of heat, which, in turn, increase the usage rate of suit consumables. Flight surgeons must ensure that an astronaut is not working at levels that may lead to overheating or exhaustion, and EVA planners and/or crewmember may need to make real-time adjustments to crew activity to conserve consumables that are required for life support (Waligora and Horrigan 1975) (Waligora et al. 1975).

Energy expenditure (metabolic rate) was not measured during the Project Gemini EVAs. It was nonetheless clear that, in several cases, the astronauts worked at levels that were above the heat removal capability of the gas-cooled life support system (Kelley et al. 1968; Waligora and Horrigan 1975). During the first U.S. EVA, astronaut Ed White found that opening and closing the hatch was much more difficult than planned and that he perspired enough to fog the helmet visor. Although the duration of the EVA was short, it took several hours for White to return to thermal equilibrium (Paul 2012).

Thermal homeostasis of the crewmember is crucial for safe and effective EVA performance. Heat storage above 480 Btu/hour leads to performance decrements, such as a loss of tracking skills and increased errors in judgment, and tissue damage begins at 800 Btu heat storage (Jones et al. 2006). The

observations from the Gemini experience led to the development of a liquid cooling system that could accommodate high heat production in the suit from high EVA workloads. This liquid cooling garment (LCG) consists of a system of plastic cooling tubes that run along the inside of an undergarment that is worn inside the suit. The temperature of the coolant (water) running through the tubes regulates the amount of heat that is re-moved from the surface of the skin. The Apollo LCG had three temperature settings: minimum (69.8 °F/21 °C), intermediate (59 °F/15 °C), and maximum (44.6 °F/7 °C) (Waligora et al. 1975).

Astronaut energy expenditure rates during Apollo lunar surface EVAs ranged from 780 to 1,200 Btu/hr, as determined by three independent methods (Waligora et al. 1975). The lowest metabolic rates occurred while the astronauts drove and rode in the lunar rover vehicle, whereas the highest metabolic rates were observed during egress/ingress through the tight-fitting hatch of the lunar module, offloading and setup of equipment, drilling, and stowage of lunar samples. It is estimated that 60% to 80% of the heat that was generated with these workloads was dissipated through the LCG. The minimum and intermediate LCG settings were most commonly used; however, the maximum setting was frequently used during the high workload periods that were experienced during Apollo 15 and Apollo 17 EVAs (Waligora and Horrigan 1975). In a simulation (Figure 1) using a validated thermoregulatory model (Pisacane et al. 2007), the relationship between heat storage and metabolic rate was examined as a function of LCG inlet temperature (tracings, showing 21 °C (69.8 °F) and 24 °C (75.2 °F)) (Thomas et al. 2011). These data suggest that at metabolic rates above 1200 BTU/hour, LCG inlet temperatures exceeding 21 °C may induce crewmember heat storage rates above the 480 BTU that lead to performance impairment. Although Apollo metabolic rates rarely exceeded 1200 BTU/hour and the LCG inlet temperature minimal setting was 21 °C, this data is instructive for the design of future EVA suits, which may be used in situations in which crew metabolic rates exceed levels seen during Apollo.

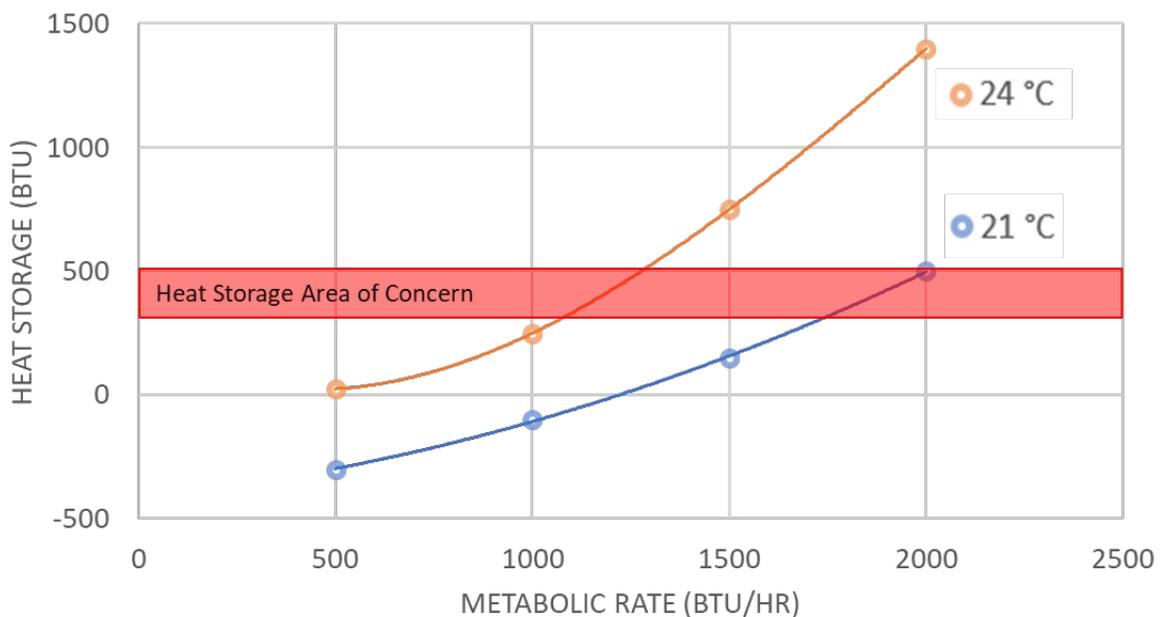


Figure 1 - Heat storage based on metabolic rate and LCG inlet water temperature. (Pisacane et al. 2007)

Recent testing points to a target LCG inlet temp of 10 °C (50 °F), accompanied by a thermal control bypass valve to maintain individual thermal comfort in the next generation Exploration suit (Watts & Vogel, 2016) which is now working to stringent heat storage requirements of <1.3 BTU/lb for nominal operations and <2.0 BTU/lb for contingency operations (NASA 2019). Although the Exploration EVA suit will be capable of maintaining the LCG inlet temp as low as 10 °C, the crewmember can bypass some or all of that cold water, therefore monitoring of LCG temperature and metabolic rate should be monitored during EVA operations to ensure the crew is within safe limits.

Waste Management

If waste is not managed appropriately during EVA, a planned long-duration EVA may have to be shortened and mission objectives could be lost. The development of an improved in-suit urine collection device was recommended by the Apollo astronauts. In some cases during lunar surface EVAs, astronaut urine was not fully contained and resulted in skin irritation (Scheuring et al. 2007). Improved in-suit waste management systems will become critical in the contingency return to Earth, a scenario where the crew is required to be suited for as many as 144 hours lest the vehicle be unable to maintain pressure. Exposure to urine and fecal waste products for that length of time may lead to skin breakdown, cellulitis, and sepsis.

Waste (i.e. urine, feces) management is an important factor in EVA suit design. The duration of the EVA governs waste management needs. The longer the EVA, the more likely it is that crewmembers will need to urinate or defecate during the EVA. This need is currently managed through the use of maximum absorbency garments (MAGs) worn by crewmembers to contain waste products during an EVA as necessary. In addition, crewmembers have been known to adopt a low residue diet and lower intake of water prior to EVAs, so as not to have to utilize the MAG. While these methods may be effective at reducing the chance of needing to urinate/defecate during an EVA, they may not be commensurate with long term health and performance as they might negatively impact crewmember hydration and nutrition.

Potential methods for mitigating this contributing factor include planning for shorter duration EVAs that preclude the need for substantial waste management. However, implementing shorter duration and more frequent EVAs could decrease that overall work efficiency if the overhead associated with O2 prebreathe and suit ingress/egress is not decreased. Alternately, the number of EVA hours could be reduced by employing pressurized roving vehicles and/or robotic assistants to complete some of the work that has been classically done only by EVA.

Nutrition and Hydration

The Apollo suit had a 15-oz drink bag; however, this amount of fluid is considered insufficient for crews that are performing surface EVA. Scheuring et al. (Scheuring et al. 2007) describe several citations from Apollo-era astronauts who walked on the Moon regarding the need for more water. The authors wrote: “The astronauts strongly agreed the amount of liquid beverage contained in the suit needed to be increased for future crewmembers, including separate capabilities for plain water and non-caffeinated high-energy drink.”

It was also recommended that the delivery systems for nutrition and hydration be improved as well. One Apollo astronaut commented: “The fruit bar mounted inside the suit was sometimes problematic

because you couldn't always get to it, but it's nice to have something solid to eat" (Scheuring et al. 2007). Similar issues have been reported with the current EVA suit, used for microgravity EVA from the ISS. Furthermore, it was suggested that the time required to prepare the nutrition and hydration systems prior to conducting an EVA be decreased. Filling and degassing the drink bag used in the current U.S. suit is time-consuming and contributes to a poor work efficiency index (WEI) of shuttle and ISS EVAs. The longer and more work-intensive EVAs that are likely to be planned for future exploration missions will need to account for astronaut nutrition and hydration. Specifically, dehydration is an issue that can lead to poor crew performance.

Proper hydration and nutrition are just as important, if not more important, during EVA as they are during the remainder of a space mission. The duration and metabolic demands of an EVA directly inform required nutrition and hydration needs. The longer duration and/or more physically demanding an EVA is, the more nutrition and hydration are required. Hydration needs in the EMU are currently managed through the availability of an in-suit drink bag (IDB) that is mounted to the inside of the hard-upper torso (HUT) of the suit. The IDB can hold 1.9 liters (32 ounces) of water and has a small tube, a straw, which is positioned next to the astronaut's mouth. Nutrition needs were partially accounted for in the EMU via inclusion of a modified commercial dried fruit bar that the astronaut could eat if he or she gets hungry during an EVA. The bars were labor intensive to make and were typically eaten prior to EVA or not all, and were therefore discontinued years ago.

Potential methods for mitigating this contributing factor include shorter duration EVAs that preclude the need for substantial nutrition and hydration supplementation during the EVA. However, implementing shorter duration and more frequent EVAs could decrease overall work efficiency if the overhead associated with O₂ prebreathe and suit ingress/egress is not decreased. Alternately, the number of EVA hours could be reduced by employing pressurized roving vehicles and/or robotic assistants to complete some of the work that has been classically done only by EVA.

EVA suit design, task design, tool design, mission objectives, and exploration environment are all key factors in understanding the hydration and nutrition needs during EVA. The required mass/volume of food and water for EVA over a mission are directly associated with the required EVA hours. The caloric and hydration requirements per hour of EVA is directly associated with the physical demands of the work performed during the EVA. The physical demands of the EVA work are directly associated with the methods and equipment available to perform the tasks and the weight and mobility of the suit in which they must be performed.

The potential ramifications of not providing appropriate nutrition and hydration during EVA include the possibility of the need to shorten a planned long-duration EVA and possible loss of mission objectives. Also, health and performance issues may occur due to inadequate hydration or nutrition, within an EVA or over the length of a mission.

Humidity

Humans perspire and exhale molecular water. In a closed environment such as a spacesuit, this quickly causes extremely humid conditions that not only cause discomfort, but it can also adversely affect the function of systems within the spacesuit. Thus, a spacesuit system must remove humidity. But removal of the humidity in the ventilation system can cause yet further difficulties. An atmosphere that is too dry can adversely affect the eyes and nasal passages of the suit user. Over 8-hour periods and repeated usage, this can affect the mission and the well-being of the astronaut. An excessively dry

atmosphere can also result in hazards from electrostatic discharge. Should a static electricity discharge occur within a spacesuit, it could involve tens of thousands of volts, but only microamps of current. This could shock, but not harm, the crewmember. However, as this could damage sensitive electronic components, suit systems must remove excess humidity while maintaining at least minimum levels of humidity for both comfort and safety (Thomas and McMann 2011).

Problems have been reported with excess moisture in suit causing face plate fogging (Paul 2012). In addition, excess humidity may be a factor in finger nail delamination during EVA (Jones et al. 2008). Excess moisture in a spacesuit may be associated with increased heat loads of EVA crew as high levels of humidity do not allow for sweating to be effective at cooling the body, which may lead to excessive sweating and eventual dehydration. Addressing this contributing factor may result in less risk to crew health and performance by reducing the hand injuries from EVA and better management of carried heat load.

Workload and Fatigue

With the increased cadence of EVA for surface exploration missions, the overall higher workload and fatigue will need to be offset with adequate rehabilitation and rest. Operational mitigations may include no exercise on EVA days, or specific stretching and mobility work to rehabilitate after EVA exposures.

Experience from Apollo indicated that mental and physical rest plans should be introduced into extended Moon stays to allow adequate rest between lunar EVA. Apollo astronauts stated, "Consider mental and physical fatigue here separately. Although there was not a lot of physical fatigue [during the lunar activity], the mind was being used quite a bit. You can sometimes wear your brain out before your body is fatigued" (Scheuring et al. 2007).

Human capabilities and limitations can be affected greatly by the duration of a mission and the degree of subsequent deconditioning. Strength and aerobic power of load-bearing muscles can decrease during spaceflight missions. On-orbit exercise regimens have been implemented to counteract these deficits, but, to date, they have been only partially effective. Crewmembers are also affected by sleep loss and circadian desynchrony, which have been linked to cognitive and physical performance decrements (Whitmire et al. 2009). Overall, the long-term effects of living in space and the effects on performance are still generally unknown. It is known that perception in every modality, reaction time, motor skills, and workload can be affected while in space, and thus affect performance (Legner 2004). Therefore, it is important to understand how tasks, procedures, and schedules may need to be modified as deconditioning occurs (Sandor et al. 2013).

Situation Awareness

Operations tempo is driven by the scheduling of mission tasks, and can affect performance, workload, and situation awareness (SA) of crewmembers. The same amount of work can be more or less taxing on crew depending on other factors such as fatigue, deconditioning, stress and anxiety, or medical conditions. Low workload levels have been associated with boredom and decreased attention to task; whereas, high workload levels have been associated with increased error rates and the narrowing of attention to the possible detriment to tasks. In addition, when materials such as procedures, directions, checklists, graphic depictions, tables, charts, or other published guidance are misleading or unclear, workload is further impacted, and an unsafe situation results. The severity of the consequences increases with the duration of the mission (Sandor et al. 2013).

Current space flight crews rely on onboard automated systems. As increasing numbers of automated/robotic systems are designed to assist the human, a synergistic relationship must be developed that allows the human and automation to work together to successfully accomplish tasks. On future longer-duration missions with greater EVA demands and increased autonomy, crews will rely even more on these systems to provide information that is appropriate, accurate, and up-to-date. In addition, increased automation will require special emphasis on task design and additional training to ensure that the crew can perform the automated tasks in the event of automation failure. Automated tasks must be carefully designed to prevent the crew from losing SA, or becoming unaware or complacent about potential hazards. These situations could ultimately result in system errors, degraded crew performance, and compromised crew and vehicle safety (Sandor et al. 2013). Additionally, coordination of crewmember responsibility and decision making will be affected because the mission commander will likely be unable to manage all systems and personnel at a single time (Endsley 1995).

Research in the area of theoretical and applied psychology identifies that humans' physical, sensory, perceptual, and cognitive capabilities have constraints that are related to performance inefficiencies, including workload increases and operator error. In the area of cognitive capabilities, for example, the amount of information that can be processed by working memory is limited (Baddeley 1992; Miller 1956). Therefore, information overload can be a problem for an operator when they try to accomplish tasks that load their working memory. On the other hand, information underload can lead to decreased vigilance and loss of situation awareness, i.e., being less aware of important aspects of the environment needed for the current task and future actions. For all these reasons, human capabilities and limitations should be taken into consideration in the design of tasks and associated procedures, hardware, and software (Sandor et al. 2013).

Human terrestrial evidence

This section on human terrestrial evidence will outline recent developments in Partial Gravity Simulation capability for EVA injury and compromised performance risk characterization then move on to discuss EVA training and injuries that occur due to ground-based suit exposures, poor fit, and glove function.

Partial Gravity Simulation

Starting with preparations for the Apollo moon landings, the effects of reduced gravity on EVA have been studied via various methods, including underwater (Trout and Bruchey 1969), parabolic flight aircraft (Moran 1969), and weight offload systems (Sanborn et al. 1967; Wortz and Prescott 1966; De Witt et al. 2014; Robertson and Wortz 1968; Wortz 1969; De Witt et al. 2014). Simulating partial gravity on Earth is difficult. While many methods exist, all have significant limitations (Chappell and Klaus 2013). The ability to accurately and effectively characterize suited human performance is wholly contingent on understanding the accuracy, limitations, and usability of partial-gravity analog environments. Although parabolic flight may simulate partial-gravity kinetics better than any other environment, the high cost, volumetric constraints, limited parabola duration, and limited data-collection capabilities limit the use of the C-9 or another parabolic aircraft as a partial-gravity analog environment for studying suited human performance (Norcross et al. 2010a).

The Active Response Gravity Offload System (ARGOS) has been designed to simulate reduced gravity environments, as an improved replacement for POGO partial gravity simulator at Johnson Space Center (JSC). Currently under continuous development and improvement, ARGOS is intended to support

testing, development, and training for future missions to the Moon and Mars. The current steel structure, which measures 41' x 24' x 25', accommodates movement in all 3 directions of motion (one vertical and two horizontal).

ARGOS uses an inline load cell to continuously offload a portion of a human or robotic payload's weight during all dynamic motions, which can include walking, running, and jumping under Lunar or Martian gravity, as well as a wide range of microgravity activities. Using a cable angle sensor, ARGOS actively tracks and follows the payload's motion in all horizontal, translational directions to maintain an accurate vertical offload force. The facility is capable of supporting surface operation studies, suit and vehicle requirements development, suit and vehicle design evaluation, robotic development, mass handling studies, and crew training with both suited and shirt-sleeved subjects (Dungan and Lewis 2013).

Although gravity offloading systems like ARGOS improve on many of the major limitations of parabolic flight, it also introduces several new sources of error including increased inertia, limited DOF, and non-optimized offload kinetics. These artifacts are primarily due to the inclusion of a gimbal for attaching the suit to the offloading system. Numerous gimbals have been designed and tested over the years to characterize the limitations and artifacts of each system. In 2021, ARGOS improved Mass and CG simulation fidelity with the addition of a mock portable life support system (PLSS) that has interfaces for connecting to various gimbals. The two gimbals currently in operation for partial gravity testing with this mockPLSS are known as the "C-Brace" and "Spreader Bar" gimbals (Figure).

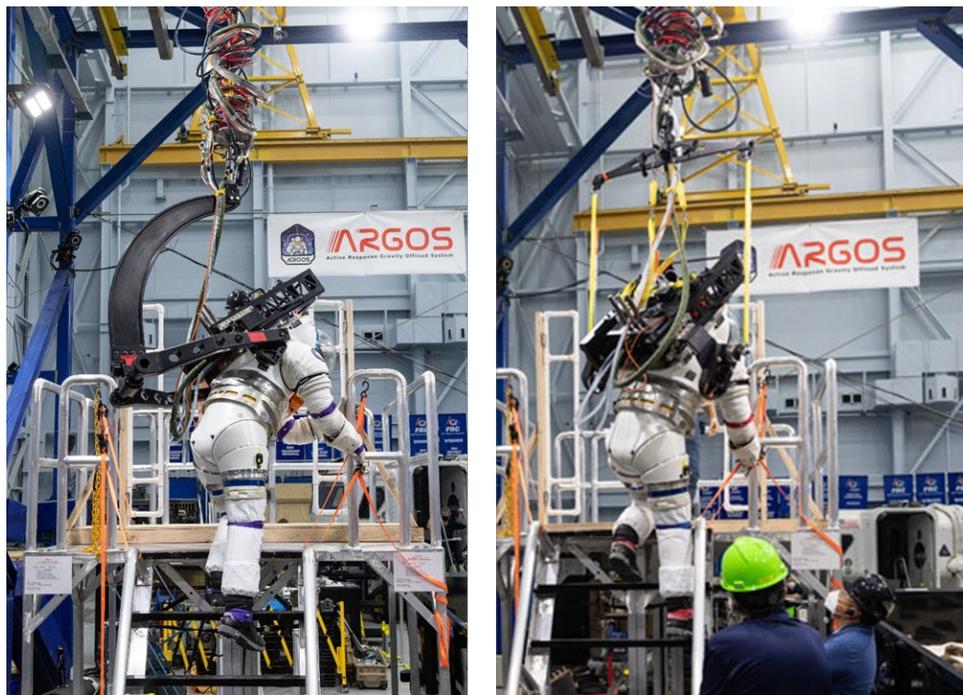


Figure 2. Side-by-side of ARGOS partial gravity testing with Mark III spacesuit using C-Brace (on left) and Spreader Bar (on right) gimbals with MockPLSS while climbing ladder of ARGOS lander mock-up

The ideal partial-gravity analog environment would combine the partial-gravity kinetics of parabolic flight with a large test area to enable field testing, advanced data collection capabilities, unlimited time,

treadmill integration, and mock-up inclusion available with ground-based analogs such as ARGOS. In the future, having an offload system that is a mobile version of ARGOS to deploy in the field would enable higher scientific fidelity of EVA simulations. The current floor space of ARGOS is limited and requires theater-like set changes of moving mock-ups in and out of the floor during testing. Mock-ups available at ARGOS currently include a treadmill (from -10% to 30% grade), a sand trailer (that can be tilted 10 or 20 degrees), a task board, and a lander platform with a ladder.

However, even with all of improvements in gravity offload systems such as ARGOS (Bekdash et al. 2020), there are still limitations that cannot be removed, including restraints in the lifting path, which is restricted to the CG and anything outside of that lifting path, particularly the limbs and any accessories, will still operate within 1g kinetics. For this reason, parabolic flight and underwater buoyancy should be used for testing that requires all materials, including the subject, suit, tools, and mock-ups to be at the same partial gravity. Parabolic flight is a key capability need for verification of ground-based data, assuming the tasks are performed in the same way in both partial-gravity analog environments (Norcross et al. 2010a).

In 2019-2020 timeframe, the NBL supported Lunar gravity 1/6-G testing as a proving ground to enable development of future training capability for Artemis missions. The testing evolved from SCUBA to surface supplied dive system with a mock PLSS to a suited Z2.5 test configuration (Figure).

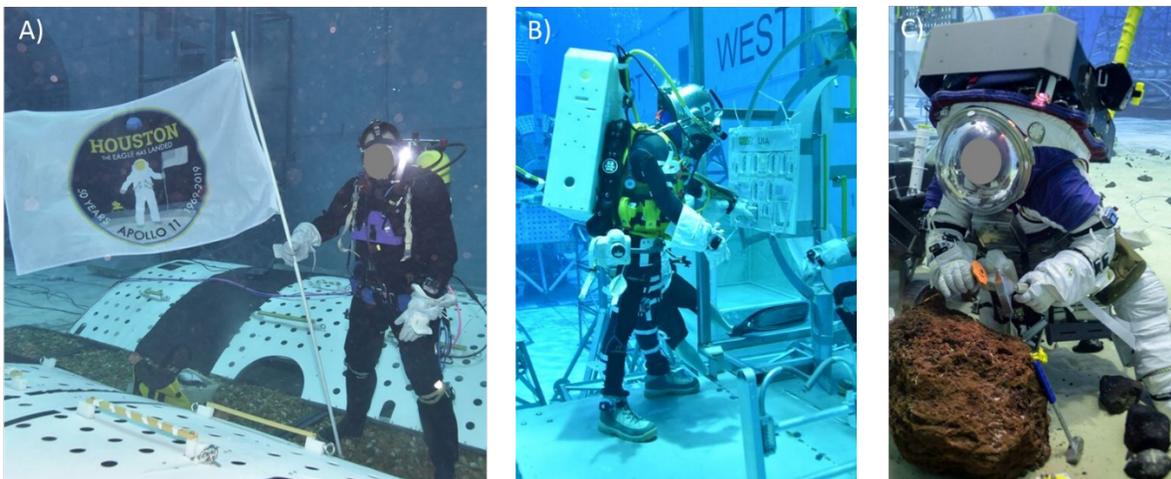


Figure 3. NBL Lunar testing in SCUBA (A), Surface Supplied Dive System with mock PLSS (B), and Z2.5 Suited testing (C)

These tests were completed as part of the Physical and Cognitive Exploration Simulations (PACES) project to develop EVA analog testing facilities with representative EVA tasks and standard protocols for quantifying workload and performance (Bekdash et al. 2021). This testing also enabled analysis of the postures and functional movements during EVA testing including the development of an algorithm for automatically detecting postures based on Inertial Measurement Unit (IMU) data (Kim et al. 2020).

Both the NBL and ARGOS testing included Mass and CG assessments and biomechanics / gait analysis to evaluate the partial gravity simulation quality. Results indicate that both environments achieved accurate ground reaction forces but need to work on moving mass higher and more aft in the PLSS to better simulate the xEMU high and aft CG. Future iterations of the mock PLSS simulators in 2021 will enable a more accurate CG and will be tested to prepare for Mass and CG acceptability testing of the

new xEMU spacesuit when available for testing in 2022. However, recent testing has still shown improvements in fidelity compared to prior data collected during Integrated Suit Test 1 and 2, which was not able to provide enough weight offload to properly simulate both the weight and mass of suits in different gravitational environments. In the future, ARGOS and NBL simulations need to be validated with parabolic flight to compare key biomechanical and subjective parameters, and any other relevant data from ARGOS and NBL with true weight/mass matching of parabolic flight.

For the NBL, as expected, water drag is a significant factor on gait kinematics (Kim et al. 2020). The differences in gait strategy found in 1/6-G NBL walking (e.g., forward trunk lean, increased swing phase, reduced gait speed) confirmed the expectation of gait adaptation to increased movement resistance because of underwater drag. At ARGOS, subjects displayed more erect upper bodies and shortened initial swing phases that may be the result of a more realistic 1/6-G environment than NBL. The added support from the offloading system and/or the treadmill could also be contributing factors.

Training

Although more injuries occur during EVA than elsewhere on-orbit, most injuries have been minor and did not affect mission success (Opperman et al. 2010b; Scheuring et al. 2009; Viegas et al. 2004). However, the number of EVA-associated injuries increased during the many EVAs and training sessions for the construction of the ISS that were conducted in the neutral buoyancy lab (NBL) training pool (Gernhardt et al. 2009). To simulate the weightlessness of microgravity in the NBL, astronauts and tools undergo a weigh-out process (with a combination of weights and floatation devices) to become neutrally buoyant, allowing realistic mission preparation with mockups of the ISS, robotic arms, and other pieces of space hardware. Many hours of training are required for each EVA, and the injuries seen on orbit are increased as more time is spent inside the suit. Also, gravity shifting inside the suit during testing causes new injuries not seen in flight.

Shoulder injuries are one of the most severe problems because some training procedures cause the weight of the body to rest on the shoulders, and this type of injury can even require surgical intervention (Opperman et al. 2009; Strauss 2004; Strauss et al. 2005; Williams and Johnson 2003b). A study by Strauss describes shoulder injury; 13 of the study's 22 participants were assessed for shoulder-related injuries, and 2 required surgical interventions (Strauss et al. 2005). There are 2 primary causes for EVA-related shoulder injury: restriction of normal shoulder movement by the Hard Upper Torso (HUT) and supporting body weight against the HUT. Depending on the lateral position of the scye bearings, scapulothoracic motion can be restricted, preventing normal shoulder abduction and adduction. To compensate, astronauts rely more heavily on the rotator cuff muscles that normally stabilize the joint, causing overuse of the rotator cuff and leading to injury (Williams and Johnson 2003b). Additionally, as astronauts shift within the suit during training, their bodies press up against the HUT, resting their weight on their shoulders. This is particularly true when the astronaut is in an inverted position, either fully head down, face forward, or face upward. Resting weight on the shoulder impinges on the rotator cuff muscles, causing tears and pinched nerves, in addition to causing uncomfortable pressure contacts (Strauss 2004; Williams and Johnson 2003b). Inverted NBL training is still performed, but in limited duration.

A study that was conducted from July 2002 to January 2004 identified the frequency and incidence rates of symptoms by general body location and characterized the mechanisms of injury and effective countermeasures (Strauss 2004). During this study, 86 astronaut-subjects were evaluated in the NBL

during 770 suited test sessions. Symptoms were reported by the test subjects in 352, or 45.7%, of the sessions. Of these symptoms, 47% involved hands; 21% involved shoulders; 11% involved feet; 6% each involved arms, legs, and neck; and 3% involved the trunk.

Hand Injury

Hand injury symptoms of primary concern were fingernail delamination, which was thought to result from excess moisture in the EVA gloves and axial loading of the fingertips (Figure). There were also abrasions, contusions, and 2 cases of peripheral nerve impingements related to glove fit and hard point contact compressions. Several studies have followed up on hand related injury and are discussed in section Error: Reference source not found EVA Glove Function, because the glove is considered a separate system within the EVA pressure garment.

Shoulder Injury

Shoulder injuries were proposed to be due to hard contact with suit components and strain mechanisms (Figure). A shoulder injury tiger team was created in December 2002 at the NASA Johnson Space Center to evaluate the possible relationship between shoulder injuries and EVA training at the NBL (Williams and Johnson 2003b). This team surveyed 22 astronauts who had participated in EVA training. In this group, 14 astronauts (64%) had experienced some degree of shoulder pain that they attributed to EVA training. A majority of these cases were classified as minor, resolving within 48 to 72 hours. However, 2 of the 14 subjects required surgical repair after injury. It was determined that the major risk factors leading to injury were: the limited range of motion in the shoulder joint due to use of the “Planar” HUT of the EVA suit, tasks in inverted body positions during NBL training, overhead tasks, repetitive motions, use of heavy tools, and frequent training sessions. Additional minor risk factors included suboptimal suit fit and lack of appropriate padding or load alleviation (Williams and Johnson 2003b). While the astronaut-tool-EMU simulation package may be neutrally buoyant as a whole, the astronaut is not weightless within the suit. In the inverted (head-down) position, gravity causes the astronaut to “fall into” the head of the spacesuit, pressing the shoulders into the HUT of the suit. This further limits scapulothoracic motion of the shoulder (Viegas et al. 2004). Key elements that can mitigate in the risk of shoulder injuries that are associated with EVA training include redesign of the EMU shoulder joint or development of the next-generation suit for ISS EVA, reduction of high-risk NBL activities, optimization of suit fit, and continued emphasis on physical conditioning (Williams and Johnson 2003b).



Figure 4 – Example fingernail and shoulder trauma sustained during EVA training.

Feet Injury

Injury occurs mainly on the top of the feet and on distal toes, and is associated with issues of boot fit. The foot is not well protected in the EVA suit, and there is no arch support built into the boot sizing inserts. The boot does not protect the feet from hard contact from the 1g effect on the front of the toes that takes place in training. There is also hard contact on the top of the feet while in the portable foot restrains. (Straus 2004)

Arms, Legs, Neck, and Trunk Injury

Elbows and knees were the most common area of pain or injury in the arms and the legs. While most of the symptoms and injuries sustained during EVA training were “mild, self-limited, and controlled by available countermeasures,” some “represented the potential for significant injury with short- and long-term consequences regarding astronaut health and interference with mission objectives” (Strauss 2004). Neck pain was mostly due to the shoulder inserts not placed properly. Problems with the trunk were due to hard contact with components within the suit.

During the 10-km EWT, subject discomfort levels were recorded and a medical monitor examined the subjects for signs of suit-induced trauma at the completion of the test. In terms of discomfort, the mean rating was 1.5 ± 1.1 (SD), which is “very low” to “low” on the 10-point discomfort scale. The knee area and the feet/toes were the most frequent sites of discomfort during and after the test (Figure 5). Fatigue and/or muscular tightness were reported most commonly in the quadriceps, thighs, gluteal muscles, and lower back (Norcross et al. 2009).



Figure 5 - Knee and foot trauma sustained during 10-km EWT (Norcross et al. 2009).

Suit Fit

The extent of performance comprises and injury risk due to suit design alone is complex to assess because one must also factor in suit fit. An EVA suit tailored for a large male is almost guaranteed to be a problem for a petite female. Therefore, EVA suit fit must be characterized and controlled to understand how suit design affects physiological performance and injury risk.

Suit sizes and subject anthropometric accommodation capability will most likely be constrained in any suit development program, even for a program that custom-tailors suits to the individual; some components are still likely to come in a standard size, as seen in the arm components in the Apollo program. During the Constellation Program, design dimensions were updated to encompass 1st percentile female to 99th percentile male dimensions (Benson 2010) to improve population accommodation. However, additional complexity stems from the fact that no one person is 99th percentile or 1st percentile in all dimensions – rather, human shape has immense variety, which can only be characterized using multivariate methods that account for different combinations in dimensions. A human can easily have a long torso and disproportionately short legs, or could have a head size that is not easily accommodated by a standard helmet. Designing a spacesuit system to accommodate a wide range of anthropometry can be complicated, but if suit fit is not appropriate, NASA runs the risk of losing that crewmember’s ability to perform the EVA with an acceptable performance and a low risk of injury.

It is possible that some EVA tasks on exploration environments could not be performed by all crewmembers in the currently planned suit design, which would limit EVA responsibilities to only certain crewmembers to minimize risks to crew health and performance. If restricting some crewmembers from EVA were not possible, some mission objectives could be lost or reduced if poor fit significantly impacted those crewmembers. Other potential effects of inadequate suit fit may be: inability of crewmember to complete EVA tasks within the time allotted; mission and EVA timeline deviations; EVA crew physical and mental workload above acceptable levels; acute or chronic injury resulting from inadequate suit fit.

Relatively little is known about how a subject moves inside of a spacesuit in order to make the suit perform necessary movements. However, it is known that inadequate suit fit can contribute to injury and the ability to adequately perform necessary tasks. It is hypothesized that some injuries are caused by an overly tight suit fit, shifting within the suit, improper use of protective garments within the suit, and repetitive motion working against an inadequately fitted suit (Benson and Rajulu 2009; Strauss 2004; Williams and Johnson 2003b). While suit fit seems to be a critical element in preventing astronaut injury, there is no universal solution to providing appropriate spacesuit fit and comfort. Achieving the best fit is highly individualized and one crewmember may experience uncomfortable “hot spots” in an area that another individual does not. It has been shown that even between EVA training sessions minor adjustments sometimes need to be made to a suit to achieve the best fit (Moore and Gast 2010). Additionally, a person’s body dimensions, especially the effective length of the torso, change as they move into microgravity (NASA 2019). Finally, mobility while working in the suit may be unnatural due to each spacesuit’s kinematic programming – the pattern in which its joints want to flex and rotate in response to the wearer’s motion (Cowley et al. 2012). Astronauts eventually learn to change their biomechanical movement strategies, rather than attempting to move as they do unsuited (Moore and Gast 2010). Although the magnitude of relative motion between a human and their spacesuit can be approximated by understanding the size and shape of the human and the size and shape of their suit, there is currently no adequate characterization of how a person moves relative to a spacesuit while performing tasks, and how this relates to suit fit. Initial attempts to quantify body joint kinematics within a suit and the resulting suit movement found that there was a 25 degree larger knee angle for the subject’s body than the movement of the suit when using the Contingency Hypobaric Astronaut Protective Suit (CHAPS) (Kobrick et al. 2012) for lower body motions.

There are formal methods for objectively defining suit fit, but they are normally done at the component level and in a baseline neutral body configuration – whereas suit fit can change with movement and posture. For example, a crewmember’s suit fit could be optimized for ambulating on the surface, but they could find themselves too low in the suit while seated. To begin the suit fitting process, measurements of the crewmember are taken and an initial suit fit is determined by a proprietary algorithm (NASA). After an initial suit fit check, the fit can be adjusted based on subjective feedback between the crew and suit engineer. Experience in both the microgravity training and flight environments provides the crewmembers and suit engineers with some knowledge about how suit fit may differ in training and flight. Suit fit is considered such an important factor that an on orbit fit check now occurs about a week before a planned EVA. This allows the crewmember to adjust his or her EVA suit if needed based on any changes in-flight.

Although much effort is placed on this iterative process of achieving an appropriate suit fit, the reality is that the final suit fit can only be classified as the best achievable suit fit for that individual subject. Two people with their best achievable fit in the same spacesuit may have important differences in absolute suit fit that could contribute to injury risk or compromised performance. Recent advances have allowed suit fit to be evaluated for suit components in specific postures, but given that suit fit can change based on posture, the lack of a comprehensive understanding of whole-body suit fit creates a significant knowledge gap that is actively being addressed by several different efforts.

In 2015, a study was conducted to assess the feasibility of using indexing pads to mitigate some fit issues within the EVA suit. The idea was to use custom padding configurations to fill in some of the empty space in the suit, with the intention of improving stability, maneuverability, and ability to perform tasks. A similar system of pads is used to fit subjects within the shuttle EMU, particularly when there is a large gap between the subject and the suit. Results of the study indicated that a back pad may assist subjects in controlling the upper body of the suit and reduce the propensity of the hands to come out of the gloves, a common issue for tasks such as crawling. The back pad also reduced torso over-rotation while suited, particularly for smaller subjects, again suggesting better indexing at the upper body. However, even when fully padded, the smallest subject was unable to perform some functional tasks. Part of their restriction may have been caused by the length of the torso in the tested suit, since they indicated that the hip bearings, meant to align with their hips, were more aligned with their thighs.

A more recent study (Hernandez 2021) focused on developing padding that indexed subjects within the upper torso of the suit while allowing them adequate mobility, by providing softer, more conformal material at areas with greater relative movement. Padding geometry was defined by conducting scans of personnel wearing 3D printed suit hardware, to see how the back changes shape during different EVA task motions. This type of padding may assist small subjects in staying indexed in the suit and lessen contact pressures between the human and the suit, while allowing enough relative movement to avoid restricting their mobility.

Determining objective suit fit using internal suit sensors remains a major topic of interest, but it is difficult to execute. Often, these studies are limited to proving the feasibility of the sensors or evaluating only one aspect of suit fit such as using a pressure mat data at the shoulder while syncing motion capture to show which motions or body postures induce the highest pressure. Of some concern with this effort is a poor understanding of the pressure threshold that results in injury. Also, the addition of sensors and the resulting wires during testing often compromises suit fit and mobility, and changes the

way the subject moves. Finally, any hardware placed within the suit must be robust enough to withstand the process of donning the suit, and then cannot fail as the user moves past the suit, sometimes aggressively. However, these issues will start to resolve as new smaller sensors become available and wireless capabilities increase.

Most recently, the ABF has worked with the University of Minnesota to develop a sophisticated lower body sensor garment that can be worn beneath the suit (Compton 2021). The intent of this project was to develop a system that could track contact points during motion, and provide insight into the suit-human interface. The sensor garment was tested on a running manikin, where it was able to track the shifting pattern of contact between the manikin legs and a 3D printed spacesuit brief mockup. If implemented in a pressurized suit, this system could be used to determine 'hot spots' between the suit and the human, and assess how these changed with any padding added within the suit.

Developing standard methods for assessing suit fit was a primary aim of the EVA Human Health and Performance Benchmarking study. Subjects were given their nominal suit fit at the time of testing based on sizing information from their fit check and subsequent suited exposures. The quality of that fit was evaluated with subjective queries relating to aspects such as discomfort, indexing (spacing within the suit volume), alignment between the body and suit joints, and mobility. Both the suited subject and the suit test engineer were asked questions pertaining to suit fit. Questionnaires were developed based on existing methods used by the suit engineer to fit subjects, with additional questions developed by the study team to assess other aspects of suit fit that may affect performance. Certain portions of the questionnaires were asked at donning and doffing of the suit, and between tasks whenever possible, to capture subjects' assessments of specific tasks. Results of the suit fit assessment were planned to be analyzed in comparison to suited human performance data to evaluate indications of suit fit affecting performance, but the use of several novel test subjects precluded definitive analysis.

An additional difficulty with defining suit fit is consideration of the environment. It is difficult to assess suit fit in a partial-gravity test on Earth because the crewmember remains in the 1-g environment. During partial gravity overhead suspension, the suit is lifted and the crewmember falls into the suit. The same artifact exists in Neutral Buoyancy Lab (NBL) testing, and can be exacerbated when the neutrally buoyant suit rotates from upright, causing the crewmember to put weight on their shoulders or rest against hard internal surfaces of the suit. During non-offloaded 1-g operations, the full weight of the suit is supported by the crewmember via shoulder straps and a waist harness. Neither of these conditions are consistent with exactly how a crewmember and EVA suit will interact in actual partial gravity or microgravity conditions and both conditions may require slightly different suit fits due to the different interactions.

Another issue associated with suit fit has arisen while testing the Modified ACES (MACES) as an EVA suit. To achieve a fit that optimizes for EVA, the crewmembers tended to prefer a tighter suit fit than normal in the IVA suit, which is usually optimized for unpressurized comfort since pressurization is generally more of a contingency function of an IVA suit. Since the suit must complete tasks in both configurations, the final suit fit may not be optimal in either, but rather a compromise between unpressurized and pressurized space suit fit (Watson 2014).

The finalized version of any formal suit fit assessment must eventually be analyzed for reliability and validated in repeated-measures suit-fit sizing and performance studies to quantify the effect of suit fit on performance.

Glove Function

There are documented cases from the Space Shuttle program, ISS, and NBL training of hand injuries and hand fatigue while using current gloves, EVA systems, and tools (Viegas et al. 2004) (Strauss et al. 2005). Minor to moderate glove-induced trauma from EVA and during EVA training in the NBL are the most frequently reported injuries. These injuries are specific to the microgravity EVA environment, where the crewmember performs the majority of tasks with his or her hands. Injury rates are likely not going to be the same in the planetary environment, where the crewmember will travel by foot and will not have to work to maintain a posture because gravity will secure the body and provide more Earth-like kinematics.

It is very expensive to custom tailor spacesuit gloves for individual astronauts, but if an astronaut cannot execute a task properly in a non-custom spacesuit glove, the ability to perform EVA effectively may be comprised. Many factors may be contributors to hand injury beyond glove design (length of EVA, suit pressure, tool/task design) and taking a system view may provide for an overall more effective and efficient way to lower the risk of poor crew health and performance due to hand issues.

Opperman et al. (Opperman et al. 2010b) evaluated data from 232 crewmembers' injury records and anthropometry, and found no significant effect of finger-to-hand size on the probability of injury. However, circumference and width of the metacarpophalangeal (MCP) joint were found to be significantly associated with injuries. A multivariate logistic regression showed that hand circumference had the dominant effect on the likelihood of onycholysis. Male crewmembers with a hand circumference > 22.86 cm (9 inches) have a 19.6% probability of finger injury, and those with hand circumferences < or = 22.86 cm (9 inches) only have a 5.6% chance of injury. Findings were similar for female crewmembers. This increased probability might be due to constriction at large MCP joints by the current NASA Phase VI glove. Constriction could lead to occlusion of vascular flow to the fingers and increase the chances of onycholysis. Injury rates are lower when using gloves such as the superseded series 4000 and the Russian Orlan, both which provide more volume for the MCP joint.

Jones (Jones et al. 2008) used the current EMU configured with a ventilation tube that extended down a single arm of the suit (E) and compared with the unventilated arm (C). Skin surface moisture was measured on both hands immediately after glove removal, and a questionnaire was administered to determine subjective measures. Astronauts (n=6) were examined before and after NBL training sessions. Consistent trends were discovered in the reduction of relative hydration ratios at dorsum (C=3.34, E=2.11) and first ring finger joint (C=2.46, E=1.96) when the ventilation tube was employed. Ventilation appeared more effective on the left versus the right hand, implying an interaction with hand anthropometry and glove fit. Symptom score was lower on the hand that had the long ventilation tube relative to the control hand in 2 out of 6 EVA crewmembers.

To determine design requirements that could reduce injury, an investigator team reviewed all existing hand related injuries in the LSAH database and the accompanying risk factor variables such as demographic characteristics, hand anthropometry, glove fit characteristics, and EVA training/flight characteristics (Charvat et al. 2015). Risk factors for hand injury were: smaller hand anthropometry, longer duration suited exposures, and improper glove-hand fit as calculated by the difference in the anthropometry middle finger length compared to the baseline EVA glove middle finger length. Within this report, analysis of fingernail delamination resulted in contradictory findings to those reported previously (Opperman et al. 2010a). This disparate result is less likely a true contradiction than a result

of inconsistent reporting and recording of EVA injury data. The most important result of this glove injury data mining was the recognition of a need to consistently record all suited exposures and suit related trauma.

Exposure Incidence System

The Suit Exposure Questionnaire and database was implemented at NASA JSC in late 2016 with the goal of including this as part of every human suited event at JSC in 2017. This tool will determine likelihood of injury due to suited exposure and provide a way to parse the consequence of these injuries as well. In 2019, the questionnaire was implemented into a web-based tool and renamed the Exposure Incidence System (EIS). Suit technicians and medical personnel are trained to operate EIS and insure that it is utilized before and after every suited testing or training event at JSC. Suited subjects are prompted to record any known injuries or discomforts before getting into the suit and then again after getting out of the suit to record any impacts of the suited exposure. To enable streamlined reporting on EIS records, data analysis pipelines are being developed to produce summary statistics and data visualizations that will then be regularly reviewed by stakeholders from the EVA community.

Computer-based modeling evidence

Suit Fit Modeling

As discussed previously, some types of spacesuit injury can potentially be mitigated by achieving an optimal suit fit. In contrast if an optimal suit fit is not achieved some injuries could be caused or exacerbated, especially if that poor suit fit has an impact on performance. Fit is classically difficult to quantify because it can be highly subjective, as can be seen even in the commercial clothing industry – some people prefer their clothing to be tight and form fitting, whereas other individuals will prefer a looser fit. Similarly, clothing fit can vary based on what tasks need to be done while wearing it; some functional types of clothing even have gores that can open and close to allow maximum range of motion for the wearer, whereas other clothing (such as a slim fit suit jacket) can notably restrict the wearer. Similarly, a microgravity suit fit (where the user is floating within the system) may need to be different than a partial gravity suit fit, where the user is ambulating and perhaps even sitting in the system. Because alignment within the suit can vary with the posture of the wearer, a compromise between different components can be required to allow the best fit possible across postures and tasks attempted.

In the Shoulder Injury Tiger Team Report (Williams 2003), early space suit fit modeling efforts visualized where the scye bearing would contact the shoulder, by scanning subjects in multiple shoulder postures and overlaying suit geometry to show how the suit would impinge upon the human as they moved. This work was further developed in a parametric shoulder model, which predicted the realistic deformation of the shoulder region in different upper body postures (Young 2016). Additional model reposing work focused on adjusting the arms from a neutral arm pose to a pose more similar to that seen in the suit, with the arms lifted away from the body (Vu 2019). Other similar model reposing techniques can be used to model the posture of the human within the suit, and better understand human-suit contact.

Whereas early spacesuit designs (Gemini, Apollo) were soft systems with minimal hard components, modern EVA spacesuits tend to incorporate more rigid structures around the body – structures which are minimally resizable and come in only a set number of sizes. As an example, the current xEMU relies on a Hard Upper Torso (HUT) and a Waist Brief Hip Assembly, both of which are built up of hard components in set sizes. During the design process, the baseline sizes of these hard components needed

to be assessed to determine if they would be adequate for the entire user population. Additionally, the total number of each size and type of component needed to be determined for logistics and sparing purposes – for example, how many people would typically wear a Large vs a Medium HUT?

To answer these questions of accommodation and to understand how much adjustment would be needed across the user population, NASA turned to a sophisticated system of virtual fit models, supplemented by testing in 3D printed suit component prototypes. The results of this virtual suit fit modeling effort were used to assess the progress of the suit system towards fitting the full population, and can be used to help select the optimal combination of components to achieve the best possible suit fit. These and similar efforts to characterize suit fit, can reduce the risk of having a poorly fitting suit and identify those members of the population who may have a lower likelihood of achieving optimal fit.

To build the virtual suit fit model, suit engineers provided inputs on how to align digital manikins within suit components, a Monte-Carlo technique was employed to iteratively place several thousand of such digital manikins within these suit components, and to evaluate overlap of these manikins with the modeled suit hardware. The results of this overlap analysis were used to assess the overall shape of several xEMU suit components, and to recommend alterations in this shape to minimize overlap between the human body manikins and the suit hardware (Kim 2019). As an example, results of these virtual fit checks were used to slightly modify the contour of the spacesuit brief, to better accommodate the intended user population. The virtual fit model was also used to predict the number of sizing rings that would be needed between the HUT and the brief to accommodate longer torso lengths. Padding can also be added to improve fit, and methods have been developed to objectively evaluate the impact of various padding thicknesses on gait performance and dynamic fit measures (Fineman et al. 2018).

Virtual fit assessments tend to treat the body as a rigid surface, whereas some areas of the body (for example the belly) can be more compressible than bonier areas (such as the clavicle region). To improve the fidelity of virtual fit models and assess where a poor fit judgment could be overly conservative, a skin compression test was done to assess the compressibility of different regions of the torso. In this study, points on the body were compressed and the distance of compression was measured using a 3D point digitizer. The tolerable compression limits for each region of the body were summarized and used as inputs to the virtual fit model, to take into account which torso regions have the most tolerance to being compressed.

Virtual suit fit modeling is a sophisticated tool for assessing accommodation but must be supplemented by physical prototype testing to ensure that the virtual model is an adequate representation of real-world interaction between the human and the suit hardware. For the xEMU, the use of 3D printed suit hardware mockups allowed component fit verification at an early stage of the design process, before the pressurized suit was available for testing. The use of a non-pressurized suit mockup also allowed for testing a greater number of subjects than would normally be practically achievable in a pressurized suit evaluation, due to the cost and logistical challenges associated with pressurized suited tests.

Prototype fit assessments were completed first with the HUT alone and then later with the brief component and finally a full 3D printed stack-up including HUT, brief, waist bearing and sizing rings. In these fit assessments, borderline subjects were identified who helped draw the border between scye in and scye out conditions, and between the medium and large HUT. Fit checking was also used to evaluate preference for a baseline length of the brief component and an elongated brief design that was

proposed for wearers with longer torsos. The 3D stack-up testing also confirmed initial preferences for the total height of the stack from HUT to brief based on body size (Davis 2020).

The results of virtual fit assessments and prototype testing have already led to design changes in suit hardware which should assist with accommodation of the wearer population. These fitting tools can also help to identify marginally fitting members of the population, who might be more at risk of injuries associated with a poor suit fit.

Injury Modeling

Risk assessment in occupational health literature informs human-space suit applications by combining occupational health kinematic constraints with computational models to account for suited biomechanical alterations (Stirling et al. 2019). Multi-rigid-body systems provide a simplified model of the human musculoskeletal system, and these models have been improved by adding torque models and muscle-force models along with the counter torques from the space suit as boundary conditions (Li et al. 2017). Musculoskeletal modeling and analysis of human-spacesuit interaction contributes to risk assessment of astronaut health and safety during EVA, informing flight surgeons, EVA operation teams, researchers and spacesuit designers (Diaz et al. 2014).

Existing human injury modeling capabilities such as those developed by the Global Human Body Models Consortium (GHBMC) which have been developed and validated for the automotive industry are being leveraged to develop tools for probabilistic injury risk assessment of EVA loading injuries. Injury assessment reference values (IARVs) are limits that are defined to allow assessment of vehicle and suit designs against a specified injury risk. Because IARVs are dependent on the injury mechanism and body region, research is needed to relate injury risk to model responses related to loading and kinematics in the xEMU. In spaceflight applications, while injury mechanisms are unique, the crew become deconditioned over a mission and only low levels of injury risk are tolerable in the EVA environment, standard automotive-based IARV curves generally need to be modified.

For chronic, repetitive, or cumulative injury prediction capability, validation of appropriate biomechanical models such as OpenSIM, or other similar biomechanics models will be required. These biomechanical models typically are used to predict joint torques and overall kinematics of the human body; however, use within the spacesuit and for predicting repetitive or cumulative injury mechanisms is a novel use that will require additional research and validation using rigorous step-by-step approach. This validation process is needed to fully understand the limitations and capabilities of each model. During each step, suit components (e.g., PLSS integration) will be incorporated into the model and validated with targeted tests. The feasibility of applying specific models to specific injury cases identified in the EVA Injury Matrix will be evaluated to confirm appropriate capabilities and functionality with existing suit models and numerical solvers.

Understanding the interaction between the human and the space suit is necessary for both identifying and improving the interrelated determinants of suit fit, suited performance, and suit injury risk. The direct observations are extremely difficult for the body inside the spacesuit, so wearable sensor technologies have been proven effective and demonstrated usable outcome from previous testing. For occupational ergonomic injury assessments, sensors-based ergonomic injury risk assessment models will be developed to understand the consequences of having to wear a bulky suit with potential interferences between the hardware components and the human.

Existing finite element, musculoskeletal, and anthropometric modeling capabilities coupled with bone modeling will be incorporated with xEMU suit models and data. The models will be assessed for their current and possible future applicability to xEMU development, sizing, training, and operations. This will form the basis of an ergonomics-based occupation risk assessment model that would be tailored for specific EVA operational tasks and provide useful information for EVA mission planners. For example, low-back loading can be quantified across different EVA tasks.

Crew State Modeling

Providing the capability for humans to work productively and safely while performing an EVA involves many important contributing factors. Maintaining sufficient total pressure and oxygen partial pressure in the EVA suit is vital not only to human health, but also to survival. Efficient prebreathe protocols must adequately reduce the amount of inert gas in astronauts' blood and tissues to prevent decompression sickness (DCS) at hypobaric suit pressures. The EVA suit must be ventilated to remove expired carbon dioxide (CO₂), both perspired and respired water vapor, and metabolically generated heat. Since ventilation flow alone may not be sufficient to control core body temperature and prevent unwanted heat storage, cooling water is typically circulated through small tubes that are located in garments worn close to the skin. Heat influx also must be controlled, and the EVA crewmember must be protected from harmful space radiation environment. During long duration EVAs, nourishment and water must be available, and accommodations must be provided for liquid and solid waste collection.

Both EVA decision support and suit habitability are contributing factors that refer to the necessity of monitoring and management of EVA systems, plans vs. actuals, consumables, etc., to help ensure the health and performance of crewmembers. For instance, the physiologic cost of performing work in a pressure garment is significantly greater than that of performing the same work without a suit. High workloads result in energy expenditure and the production of heat, which, in turn, increase the usage rate of suit consumables. Accordingly, development and testing to ensure adequate design of systems to enable monitoring of crew physiologic parameters and consumables is critical (Holden et al. 2013). Flight surgeons must ensure that an astronaut is not working at levels that may lead to overheating or exhaustion, and EVA planners must be able to make real-time adjustments to crew activity to conserve consumables that are required for life support (Waligora et al. 1975; Waligora and Horrigan 1975).

It is important to note that although the metabolic rates experienced during the Apollo EVAs were lower than had been predicted before the missions, there were several cases in which the PLSS consumables were nearly depleted, according to the Summary of Apollo G Mission Lunar Surface EMU Post Flight Thermal Analysis Results, Table E1 (Mission Operations Directorate (MOD), unpublished internal report). During Apollo 14, Apollo 15, and Apollo 17, there were 6 cases in which less than 10% usable oxygen remained at the end of the EVAs. During Apollo 14, Apollo 16, and Apollo 17, there were 7 cases in which 12% or less power remained (in one case, power was at < 4%), and 4 cases in which 11% or less usable feed water remained. Two crewmembers, on Apollo 15 and Apollo 16, completed their EVAs with only 4% and 2% remaining, respectively, of their CO₂ removal capability (lithium hydroxide (LiOH)).

Although each of the Apollo missions was limited to 2 or 3 EVAs, future missions may consist of multiple EVAs per week for up to 6 months. The increased number and frequency of exploration EVAs, coupled with labor intensive construction and exploration tasks, will require a better understanding of energy requirements, heat dissipation technologies, and consumables management.

Flight surgeons and biomedical engineers (BMEs) in the Mission Control Center monitor astronaut physical parameters during EVAs to assess workload and performance. Real-time medical monitoring can provide emergency medical assistance in response to off-nominal situations. However, bioinstrumentation systems that were used in the Apollo Program and are being used in the Space Shuttle Program have been problematic. Scheuring et al. (2007) provide approximately 75 citations from the flight surgeon logs, BME logs, and medical mission debriefings that relate to issues associated with bioinstrumentation. These range from complaints of skin irritation due to the electrode paste to signal dropouts and sensor failure (Scheuring et al., 2007). Both Apollo and shuttle/ISS EVA crewmembers have expressed frustration with the cumbersome and time-consuming process of donning/doffing their biomedical sensor systems. Improvements to the biomedical sensor systems for future missions are therefore warranted to enable next-generation crew state modeling and decision support systems.

Hypercapnia

Hypercapnia is a condition of abnormally high carbon dioxide (CO₂) levels in the blood. CO₂ is present in low concentrations (0.03%) in the standard atmosphere as well as being a gaseous product of the body's metabolism, and is normally expelled through the lungs during exhalation (Guyton and Hall 2000). Tolerance to inspired CO₂ varies as the concentration increases. Concentration levels between 1% and 5% may be able to be tolerated with mild to moderate effects (from mild respiratory stimulation to moderate respiratory stimulation with exaggerated respiratory response to exercise; increased heart rate and blood pressure, reduced hearing, dizziness, confusion, headache) for up to several hours at higher concentrations. CO₂ levels above 5% elicit more prominent respiratory stimulation, exaggerated respiratory response to exercise, mental confusion, and dyspnea. Levels above 8% induce dimmed eyesight, sweating, tremors, unconsciousness, and eventual death (Lambertsen 1971) (Glatte Jr et al. 1967).

Methods by which hypercapnia might occur during EVA are by inadequate air flow within the suit causing "dead spaces" (or local concentrations) of CO₂ that are re-inhaled, or a failure in the suit life support system's ability to scrub excess CO₂ from the breathing air. Diving research has shown that hypercapnia can occur as a diver exhales into a vessel that does not allow all of the CO₂ to escape the environment, such as a full-face diving mask or diving helmet (Lamphier 1956; Navy 2006).

EVA suits are expected to meet requirements for adequate CO₂ elimination (or "washout") to prevent significant re-inhalation. Spacesuit portable life support systems (PLSS) are also expected to meet requirements for adequate CO₂ removal. Sensors used on the inlet and outlet for suit gas flow should serve to monitor and control levels of CO₂. If the CO₂ level reaches a given criteria, then suit flow can be increased and/or activity level (thus affecting metabolic rate) of the crewmember can be reduced. If CO₂ levels cannot be improved and continue to rise over a critical threshold, the EVA can be terminated. Higher than expected metabolic rates and/or faults in the CO₂ removal or ventilation capability of the PLSS would trigger elevated in suit CO₂.

CO₂ washout studies have been conducted by the suit contractor and the NASA Johnson Space Center Crew and Thermal Systems Division (Chullen et al. 2013; Korona et al. 2014; Mitchell and Norcross 2012). These tests have been performed for several reasons, including evaluating ventilation configuration, characterizing the CO₂ washout within certain spacesuits, and ensuring safe ground based testing. Much of this work can be characterized as pilot studies that are helping to develop a

standard method of assessing CO₂ washout performance in a spacesuit for ground based testing and eventually a CO₂ washout requirement verification for a flight EVA suit.

One of several concerns with these recent CO₂ washout studies is the use of an oronasal mask to fix the sampling locations. While the mask was comfortable to wear, it did extend off of the face and take up significant volume, especially noticeable in smaller helmets. There was also concern that the mask could affect the flow around the oronasal area and increase dead space. Due to these concerns, investigators looked into several options and settled upon the use of nasal cannula as the sampling location mechanism, but debate still remains about breathing style (nasal versus oronasal), methodology to analyze and interpret the in-suit data and then relate that data to terrestrial studies, which often use different standard approaches to quantifying CO₂ exposure (Meginnis et al. 2016).

To follow-up on these concerns, investigators have begun to define errors associated with the sampling technique and establish a standardized methodology for data analysis. Bekdash et al described the necessary forward action to define a verifiable requirement for CO₂ exposure in EVA suits (Bekdash et al. 2017; Bekdash et al. 2018). Likewise, Kim et al proposed the standardized, quantitative, and automated analyzing process of the CO₂ waveform to robustly and consistently define segments and phases of a time capnogram and related metrics (Kim et al. 2020; Bekdash et al. 2020).

Of important note, throughout this series of CO₂ washout testing, subjects have exercised at metabolic rates up to 3000 BTU/hr at many different flow rates for several minutes and only rarely has a subject complained of CO₂ related symptoms while using the test termination criteria where the floor of the inspired CO₂ must remain below 30 mmHg at all times and cannot be over 23 mmHg for more than 2 minutes. Twice, both when the trial was terminated at a floor of 30 mmHg, did subjects complain of acute symptoms, but these symptoms resolved immediately by stopping the exercise that induced the high CO₂ levels. In many cases, during these studies, subjects have reported increased thermal stress and fatigue associated with the tested high suited metabolic rates, even when suited CO₂ levels were well within trial termination limits. This indicates that CO₂ is an important concern, but other factors also play a role. Once CO₂ washout performance is characterized on the ground and verified for flight, CO₂ in the suit will still need to be measured on both the inlet and outlet side during EVAs to ensure adequate CO₂ removal, as an index of CO₂ washout and to measure metabolic rate.

Overheating

During NASA's Constellation Program, a study was conducted to determine whether it is possible for a suited crewmember to walk back to a terrestrial habitat in the event of a failed rover (Norcross et al. 2009). As a starting point that is based on the Apollo Program and anticipated lunar surface operational concepts, it was assumed that 10 km (6.2 miles) would be the maximum EVA excursion distance from the lander or habitat. Results from this EVA EWT using the POGO partial gravity offload system provide key insight into how human performance may be impaired by inadequate consumables and/or inadequate cooling.

For the EWT, 6 suited subjects were instructed to attempt to translate 10 km (6.2 miles) on a level treadmill at a rapid, but sustainable, pace using a self-selected gait strategy and speed. Prior to this test, the investigators expected that crewmembers could only complete half of that distance or that the total duration would exceed 3 hours. However, all of the crewmembers finished the test, and the mean time to complete 10 km was only 96 minutes. The metabolic work level for the entire test averaged 51% of VO_{2pk}, with a range of 45% to 61%. Physiological and consumables usage data are summarized in Table

. RPEs (11.8 ± 1.57 (standard deviation (SD)) equated to a feeling between “light” (RPE=11) and “somewhat hard” (RPE=13) on the 6-20 point Borg RPE scale, which is used to gauge how much effort a person feels that he or she must exert to perform a task. Similarly, subjects averaged 3.5 ± 1.44 (SD) on the 10-point GCPS, indicating “fair” to “moderate” operator compensation was required to perform the task (Norcross et al. 2009).

Subjects’ heat production rates ranged from 1,918 to 2,667 Btu/hour, and averaged 2,374 Btu/hour; a rate that would exceed the heat removal rates of the Apollo EVA suit or current EMU. Core temperature measurements indicated an average rise (Δ) of 1 °C from normal (98.6 °F/37 °C) across the entire test, although one subject’s core temperature (103.6 °F/39.8 °C) peaked near a level of concern. Subjects unanimously reported cooling to be inadequate at the higher workloads (Norcross et al. 2009).

This limited cooling capacity will impede the improved efficiency that was observed at higher speeds. Efficiency of locomotion can be determined by the transport cost, which is expressed as oxygen consumption per kilogram per kilometer, and can be thought of as a human’s “gas mileage.” In suited conditions in lunar gravity, there was a clear trend of decreasing transport cost as speed increased. So while a crewmember might expend more energy on a per minute basis by traveling at faster speeds, the metabolic cost per kilometer would actually be less (Norcross et al. 2009).

Unfortunately, at speeds above 3 mph (Figure 2) the heat production, which is shown on the right axis and the red tracing, begins to exceed the 2,000 Btu/hour cooling limit of both the Apollo and the EMU EVA suits, resulting in increased core body heat storage. Without improvements in cooling for future suits, crewmembers performing lunar EVAs would not be able to exploit the increased efficiency (Figure 2, on the blue tracing as decreasing oxygen transport cost) available at faster ambulation speeds. This would result in increased consumable requirements to cover the same distance (Norcross et al. 2009).

Table 1 - Summary data for the lunar 10-km Walkback test (Norcross et al. 2009).

10k Walkback (averaged across enter 10 km unless noted)	Summary Data	
	MEAN	SD
Avg. Walkback Velocity (mph)	3.9	0.5
Time to Complete 10 km (min)	95.8	13.0
Avg. %VO ₂ pk	50.8%	0.3%
Avg. Absolute VO ₂ (l/min)	2.0	0.3
Avg. Metabolic Rate (Btu/hour)	2,374.0	303.9
Max. 15-min-avg Metabolic Rate (Btu/hour)	2,617.2	314.6
Total Energy Expenditure (kcal)	944.2	70.5
Water used for drinking (oz.)	~24–32	N/A
*Water used for cooling (lb.)	4.91	N/A
Oxygen Used (lb)	0.635	N/A
Planning/PLSS Sizing Data	Walkback	Apollo

Oxygen Usage (lb/hour)	0.4	0.15
Btu Average (Btu/hour)	2,374	932.8
Cooling Water (lb/hour)	3.1	0.98
Energy Expenditure (kcal/hour)	599	233

*Assumes thermally neutral case and sublimator cooling

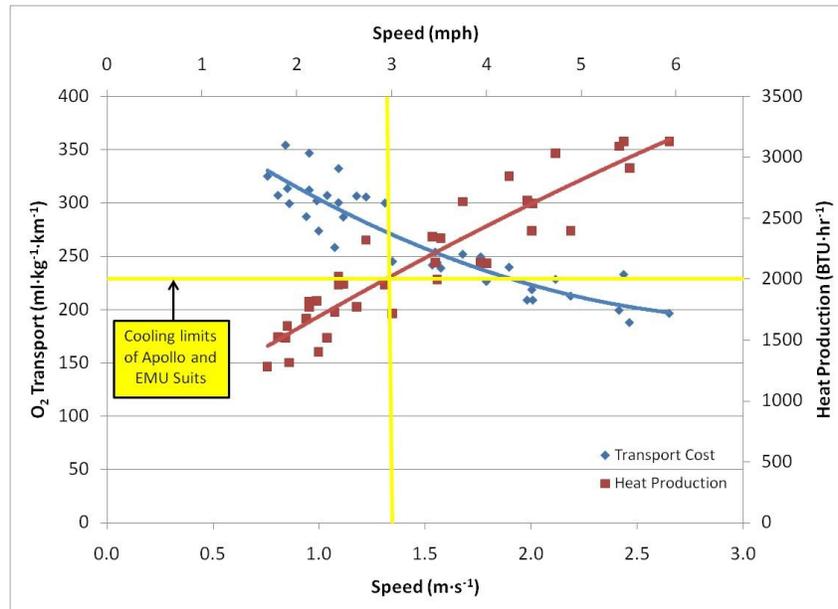


Figure 2 - Relationship between transport cost and heat production for lunar suited ambulation. (Norcross et al. 2009)

The 10-km lunar walkback test also provided important insight into hydration and nutritional requirements for a worst-case task duration and intensity (Norcross et al. 2009). All subjects were provided an in-suit drink bag with 32 oz of water, the standard for use of the MK-III suit. Crewmembers consumed 50% to 100% of the water that was provided, and one crew member would have preferred to have an additional 20%. In addition, the 10-km walkback required an average of 944 kcal. All of the crewmembers felt that a nutritional item, either food (e.g. energy bar or gel) or a flavored electrolyte drink might improve their performance and/or endurance.

Surface EVA environments

The EVA environment in which crewmembers must perform is dependent on the destinations chosen for human exploration. Destinations present inherent, unchangeable factors that must be dealt with, such as sloped and/or extreme terrain, partial gravity, lighting conditions, and dust. The EVA systems may not be designed to mitigate the effects on human health and performance of these factors without appropriate research to address them.

The effect of slope on the mechanics and metabolic cost of locomotion has been extensively studied (Minetti et al. 2002). Specific studies targeting the effects of slope have shown that internal work has no role in determining the optimal gradient (Minetti et al. 1994). It has been theorized that the different efficiencies of the muscles explain the metabolic optimum gradient for running of about -10%. Additionally, gradients as low as +15% induce about 2.5 times higher metabolic costs than the optimum

low cost of slight downhill running (Minetti et al. 1994). In other studies, electromyography has shown that uphill running activates more of the lower extremity muscles than does horizontal running through an altered pattern of muscle activation (Sloniger et al. 1997). It has been hypothesized that uphill movement allows for less storage of elastic energy, and thus is less efficient. Also theorized is that differences in posture change the orientation of the ground reaction force vector, and thus the mechanical advantage of muscles and tendons when ascending hills (Chang and Kram 1999). However, the combined effect of partial gravity and sloped terrain has a more limited research base, but in some suited operations analog research, sloped terrains of 10-30% grade were shown to have a substantial impact on the metabolic load required to ambulate in a spacesuit (Norcross et al. 2010b). Another study evaluated boot design for gradients up to 32 degrees (Hodgson et al. 2000).

Military scientists have proposed models for load carriage on sloped terrain. Results from these models have determined that the total work for uphill walking can be calculated from the baseline value for walking (with and without load) by adding a term for positive external work against gravity (Santee et al. 2001). For downhill load carriage, the force applied through the body is modified, not by muscle inefficiency, but by a combination of energy absorption into the joints and within the muscles. Any reduction in the energy cost of downhill walking due to the negative work of gravity being offset or reduced by eccentric work within the muscles, some additional energy absorption by the muscles and joints, and voluntary braking action to slow or control descent. The minimum value for VO₂ was induced during walking and running a downhill grade of -8% (Santee et al. 2001).

Overall, little attention has been paid to studying the cost of locomotion at high-angle slopes. A single study has shown that the optimum gradient for mountain paths is close to 0.2-0.3, both uphill and downhill (Minetti et al. 2002). This study shows that the running speeds adopted in downhill competition are far lower than metabolically feasible, mainly because of safety reasons. Athletes back off on speed to minimize joint and tissue injury. Also, at high angles, the body's center of mass (COM) accelerates down the hill rather than being a controlled constant braking. This may result in a lack of the fine motor control needed to maintain body trajectory on rough and slippery terrain (Minetti et al. 2002). These effects are likely to be amplified in reduced gravity environments, but no research performed to date in this area could be found in the literature.

Some studies have been performed to examine the effects of surface properties on locomotion and associated metabolic cost. There are major differences in the energy expended dependent on the surface properties. For instance, it has been determined that walking on sand requires 1.6-2.5 times more mechanical work than does walking on a hard surface at the same speed (Legeune et al. 1998). In contrast, running on sand only requires 1.15 times more mechanical work than does running on a hard surface at the same speed. The increase in energy expenditure is due primarily to two effects: the mechanical work done on the sand; and a decrease in the efficiency of positive work done by the muscles and tendons (Legeune et al. 1998). These effects are likely to be amplified in a reduced gravity environment such as the Moon and Mars, as implied by the aforementioned stability concerns. Also, the environment on the surface of the Moon and Mars consists of sand, loose soil, and scree field in many regions of scientific interest (Eckhart 1999).

Surface properties were considered a significant factor for differences observed in a speed and grade matched shirt-sleeve 10-km walkback on Devon Island and a treadmill control. Although the average 1-min speed and grade were matched more than 98% of the time on the treadmill, the treadmill

testing did not fully simulate the demands of traversing extreme terrain and underestimated the demand by about 56% (Norcross et al. 2008). This research clearly showed the necessity of both lab-based and field-based testing to understand the effects of terrain and slope on EVA operations. Future work will enable modeling of terrain features to determine expected metabolic and thermal costs of various traverses.

Expert opinion: Flight surgeon input

History of EVA injury

A brief history of activities that have gathered expert opinion on the topic of EVA injury is provided in Table below starting with the investigations of shoulder injury in 2003 timeframe.

Table 2. History of EVA injury

2003	EVA Shoulder Injury Tiger Team Recommendations
2009	Neutral Buoyancy Laboratory (NBL) Shoulder Safety Team Report
2010	Data Analysis and Implications of Planar Hard Upper Torso (HUT) Design
2012	Should Injury Technical Interchange Meeting (TIM) with Orthopedic Surgeons
2013	Implemented Magnetic Resonance Imaging (MRI) Shoulder Screening after Astronaut Selection
2013	Work Hardening Meeting with active astronauts, flight surgeons, trainers, and Astronaut Strength, Conditioning and Rehabilitation (ASCR) specialists
2013-Current	Musculoskeletal Medicine and Rehabilitation Team annual briefings on mitigation strategies
2016-2017	NASA-STD-3001, Space Flight Human-System Standard Updates for input to xEMU space suit requirements
2016-Current	Exposure Incidence System (EIS) implemented
2018-Current	Participants in xEMU design and safety reviews
2018-Current	HH&P work on xEMU open actions
2019	AES-funded EVA injury project established with integrated Crew Health and Performance (CHP) roadmap
2020-2021	Update to HSRB EVA injury and compromised performance risk

Injury Risk Mitigation Strategies

Pre-training, strengthening, and physical and cognitive demand awareness programs can help mitigate EVA injury risk. The Musculoskeletal (MSK) lead physician and ASCRs have developed the following strategies for injury mitigation for EVA training in preparation for ISS operations (see list below). While the original goal was to address shoulder related injuries, certain factors contribute to a reduced risk of all injuries, particularly recommendation #5. In this list, in particular #5 “Spacing consecutive NBL runs to a minimum of 7 days apart” will not be possible to train for the repeated EVA exposures of the proposed Lunar Artemis mission timeline of 4 EVAs within 5 days. Therefore, this list will need to continue to evolve to train for the workload and fatigue of the high cadence of EVA for exploration missions. In the future, operations may need to consider adding controls in EVA timeline for long missions to avoid overuse injuries and to identify other possible injury mechanisms beyond shoulder injury, such as fall mechanics on the surface. In parallel, operations may address some vulnerabilities / risks to injury for each DRM through hardware and task design, e.g. fall protection to address Lander egress risks.

The current EVA Fitness Program for ISS consists of a functional movement conditioning program in addition to NBL training. If an injury does occur, then post-injury EVA work hardening (WH) programs are designed to improve fitness for performing functional tasks. In the past, individuals who have current suit-related shoulder injuries/surgeries or are pre-disposed to shoulder injuries based on prior history of injury, anthropometrics, etc. would perform NBL training activities in the Pivoted Hard Upper Torso (HUT) vs. the Planar HUT. Up to 75% of NBL training can be performed in Pivoted HUT, but the pivoted HUT has not been used as much in recent years due to requiring more suit maintenance. The primary path currently for preventing injury is a focus on work hardening functional fitness program.

Pre-screening to identify injury vulnerabilities has also been successful at preventing injury. MRIs conducted by Musculoskeletal Medicine and Rehabilitation team (2013) upon astronaut crew selection were used to identify injury vulnerabilities and develop conditioning programs to prevent injury based on pre-existing conditions. This process of shoulder MRIs upon astronaut selection started in 2013, 72% of the 50 finalists had underlying pathology in MRIs that was not identified in physical exams. These MRIs were not conducted for the 2017 astronaut class, but a similar process is highly recommended for future astronaut classes, though future surface EVAs may demand a closer look at other vulnerable areas, beyond shoulders, such as lower back.

MSK Injury Mitigation Strategies:

1. Early reporting of shoulder pain following NBL EVA runs to MSK lead physician/ASCRs
2. Use of musculoskeletal ultrasound for early identification of subclinical shoulder injury
3. Enhanced suit fit check for crew with planar HUT fit issues
4. EMU lower arm assembly removal for poolside suit doff/donning
5. Spacing consecutive NBL runs to a minimum of 7 days apart
6. Substituting Pivoted vs. Planar Hard Upper Torso (HUT) for NBL training: Identify individuals who have current suit-related shoulder injuries/surgeries or are pre-disposed to shoulder injuries based on prior history of injury, anthropometrics, etc. Up to 75% of NBL training can be performed in Pivoted HUT.
7. Icing shoulders at least 20-30 minutes following NBL runs
8. Perform EMU check out with MSK lead physician/ASCRs following shoulder injury or post-op rehabilitation
9. EVA Training Fitness Program: Collaboration with DX, XA, CB, and SD developed a fitness program that matches all NBL training tasks with exercises in the gym
10. Anti-inflammatory medications as needed
11. Injury reporting tracker in the EIS
12. Limit crew time of inverted operations to no more than 15 minutes in NBL

13. Reduced weight tools for use in NBL training
14. Semi-annual DX Diver education to identify and limit biomechanically unfavorable crew positions during NBL run
15. Quarterly astronaut education on injury prevention strategies in cooperation with CB-EVA lead
16. Include bilateral MRI screening exams and functional shoulder examinations to astronaut selection requirements, beginning in 2013.
17. Enhanced shoulder injury screening during annual flight PEX. Consider adding scapular Y view plain radiograph to evaluate acromial morphology in active crewmembers.
18. Perform shoulder stretching, warm-up exercises before suiting up at the NBL prior to each run.

Depending on severity, pre-existing injuries or illness can have significant effects on EVA performance. If a crewmember sustains an arm injury that causes pain that results in disuse, there will likely be impacts on mission objectives (Viegas et al. 2004). In addition, treatment of injury or illness could delay mission objectives or prevent completion of mission objectives. Possible mitigations for this risk include cross-training crewmembers on EVA activities, thus providing a backup. Private medical conferences (PMCs) with the flight surgeon (NASA 2007) and/or a pre-EVA checklist of physical capabilities can also mitigate the risk. If a pre-check shows that the astronaut could not complete an EVA, then workarounds will be necessary. Finally, the amount of time spent on EVA during long-duration exploration can be reduced by employing robotic systems when possible (Hörz et al. 2013).

SECTION II: Risk in context of exploration operational scenarios

It is known that EVA risk differs based on operational context of DRMs with varying requirements for EVA schedule density (e.g. number of EVAs and frequency/cadence of EVAs), space suit designs (EMU vs. xEMU), gravity level (microgravity, Lunar, and Martian gravity), and mission objectives (contingency EVAs only vs. science and pioneering objectives). The availability of alternate crew is another important variable for evaluating operational impact of EVA injury. In some mission scenarios, only two crew members are available to perform EVA, which include short Lunar surface stays with highly-constrained mission timelines. Due to the requirement for the “Buddy system,” at least 2 crew are required to perform EVAs. Without back-up crew available and depending on the recovery time required for an injury (e.g. days to weeks), the operational consequence of a single injury may include loss of EVA(s) that lead to loss of mission (e.g. such as loss of critical spaceflight hardware or loss of primary science / exploration task mission objectives). Therefore, the likelihood of injury as well as the consequences of injury, both to mission objectives and to crew health, are both significant.

Comparing differences in EVA operations for each DRM:

- Low Earth Orbit (LEO): For on-orbit ISS EVAs, crew use the EMU spacesuit while working on an engineered surface. Exercise countermeasures on ISS are successful at mitigating microgravity de-conditioning. On the ISS, alternate crew are available to conduct EVAs in the case of any injury or other performance decrements.

- Lunar Orbital: For future Gateway missions, on-orbit Lunar EVAs are unlikely to occur except for in contingency scenarios only. However, crew may be at a higher risk of injury since they will undergo potentially higher levels of microgravity de-conditioning compared to ISS due to not having the full suite of exercise countermeasures available on ISS. However, these crew will use the xEMU space suit which aims to improve shoulder mobility and therefore lessen incidence of shoulder injury.
- For Lunar surface EVAs, the xEMU space suit will be utilized in partial 1/6-G gravity, while exploring various terrain for scientific and pioneering mission objectives. Lunar surface missions will require a high frequency of EVAs, and alternate crew will likely not be available. The mission objectives, xEVA hardware, task design and training are still currently in development, but it is likely that physical workload of partial gravity EVAs with both upper and lower body work will add to risk potential of injury mechanisms.
- For Mars preparatory, similar to on-orbit Lunar, crew are unlikely to perform EVAs except for contingency scenarios only for maintenance work on engineered surfaces. Crew will similarly face microgravity de-conditioning. Additionally, Mars preparatory crew may perform EVA while taking on the added challenge of delayed communications and limited support from mission control to simulate Mars transit.
- For Mars surface EVAs, modifications of xEMU spacesuit will be required to reduce mass and redesign PLSS components. The partial 3/8-G gravity will present higher workloads compared to Lunar 1/6-G. Along with distance from Earth presenting communication delays and limiting support from mission control, during the long Mars transit, de-conditioning will occur and may predispose crew to additional injury risk in early EVA scenarios. Alternate crew may or may not be available during Mars missions, as Mars mission concepts of operation vary drastically at this point.

The probabilistic assessment that the risk custodian team developed for 2020 HSRB review is limited by applying ISS and Apollo evidence to each DRM. As discussed in the *Introduction* section, limitations of applying Apollo evidence to future Lunar missions include differences in xEMU suit capabilities and unknown xEVA hardware, task design, Lander design, etc. Since test data are not available on xEVA hardware that is currently in development, past data from ISS and Apollo were leveraged to calculate likelihoods of injury. Apollo evidence was applied to surface EVAs (Lunar and Mars) and ISS evidence to microgravity EVAs (LEO, Lunar Orbital, and Mars Preparatory). One approach was calculating likelihoods for prevalence, which is the percentage of EVAs in which injury occurred (# events/ # EVA exposures); this assumes that all EVAs are similar, ignoring EVA task timeline differences. An alternative approach, calculating likelihoods for incidence rate, which is injury events per EVA hour (# events/ EVA person-time), assumes that injury risk is equal each hour, ignoring any cumulative effects.

A retrospective analysis of medical records, focusing on one injury type: shoulder injury, calculated a prevalence of 3.54% (4 in 113 EVA exposures) per ISS EVA and 3.57% (1 in 28 EVA exposures) in Apollo. This equates to a greater than 30% probability of an EVA shoulder injury in a short stay Lunar mission and a greater than 99% probability of an EVA shoulder injury during a long stay Lunar or Mars surface mission, if injury prevalence is not decreased. Using the HSRB 5x5 matrix, assuming per-EVA injury incidence is equivalent to Apollo, the likelihood of a shoulder injury is estimated as 4 (1% < P < 50%) for short duration and 5 (> 50%) for long duration lunar surface missions with the associated operational

consequence of 4 (severe reduction of crew performance that results in loss of multiple mission objectives). The results of this analysis are shown in Tables 3-5.

Table 3. Prevalence: Expected Number of Shoulder Injuries and Probability of 1 or more Shoulder Injuries for each DRM

DRM Category	Estimated Total Number of EVAs	Estimated Average EVA Duration (in hours)	Prevalence Estimate (%)	Expected Number of Injuries (95% CI)	Probability of 1 or more Injuries	Likelihood Scale (1-3)	Likelihood Scale (1-5)
LEO - Short	4	6	3.54	0.28 (0-2)	25.0	3+ Much greater than 1%	4 1% < P < 50%
LEO - Long	10	6	3.54	0.71 (0-3)	51.4	3+ Much greater than 1%	5 50% < P < 100%
Lunar Orbital - Short	2	8	3.54	0.14 (0-1)	13.4	3+ Much greater than 1%	4 1% < P < 50%
Lunar Orbital - Long	5	8	3.54	0.35 (0-2)	30.3	3+ Much greater than 1%	4 1% < P < 50%
Lunar Surface - Short	5	8	3.57	0.36 (0-2)	30.5	3+ Much greater than 1%	4 1% < P < 50%
Lunar Surface - Long	75	8	3.57	5.4 (1-10)	99.6	3+ Much greater than 1%	5 50% < P < 100%
Mars Preparatory	5	8	3.54	0.35 (0-2)	30.3	3+ Much greater than 1%	4 1% < P < 50%
Mars Surface	75	8	3.57	5.4 (1-10)	99.6	3+ Much greater than 1%	5 50% < P < 100%

Table 4. Incidence rate: Expected Number of Shoulder Injuries and Probability of 1 or more Shoulder Injuries for each DRM

DRM Category	Estimated Total Number of EVAs	Estimated Average EVA Duration (in hours)	Incidence Rate (events/EVA-hour)	Expected Number of Injuries (95% CI)	Probability of 1 or more Injuries	Likelihood Scale (1-3)	Likelihood Scale (1-5)
LEO - Short	4	6	0.0055	0.27 (0-2)	23.3	3+ Much greater than 1%	4 1% < P < 50%
LEO - Long	10	6	0.0055	0.66 (0-3)	48.4	3+ Much greater than 1%	4 1% < P < 50%
Lunar Orbital - Short	2	8	0.0055	0.18 (0-1)	16.2	3+ Much greater than 1%	4 1% < P < 50%
Lunar Orbital - Long	5	8	0.0055	0.44 (0-2)	35.7	3+ Much greater than 1%	4 1% < P < 50%
Lunar Surface - Short	5	8	0.0062	0.50 (0-2)	39.1	3+ Much greater than 1%	4 1% < P < 50%
Lunar Surface - Long	75	8	0.0062	7.45 (3-13)	99.9	3+ Much greater than 1%	5 50% < P < 100%
Mars Preparatory	5	8	0.0055	0.44 (0-2)	35.7	3+ Much greater than 1%	4 1% < P < 50%
Mars Surface	75	8	0.0062	7.45 (3-13)	99.9	3+ Much greater than 1%	5 50% < P < 100%

Table 5. Assumptions on Total Number of EVAs and Average Duration of EVAs for each DRM

DRM Category	Mission Duration	EVA Frequency (based on DRM assumptions)	Estimated Total Number of EVAs	Estimated Average EVA Duration (in hours)	Evidence to leverage for likelihood calculation
LEO	Short (<30 days)	1-4 EVAs	4	6	ISS Shoulder injury
LEO	Long (30 days to 1 year)	1-10 EVAs	10	6	ISS Shoulder injury
Lunar Orbital	Short (<30 days)	Contingency EVA only or very few EVA	2	8	ISS Shoulder injury
Lunar Orbital	Long (30 days to 1 year)	Contingency EVA only or very few EVA	5	8	ISS Shoulder injury
Lunar Surface	Short (<30 days)	5 EVAs, some back to back	5	8	Apollo Shoulder injury
Lunar Surface	Long (30 days to 1 year)	3-4 EVA per week, 20-24 EVA hrs per week	75	8	Apollo Shoulder injury
Mars Preparatory	<1 year	Contingency EVA only or very few EVA	5	8	ISS Shoulder injury
Mars Surface	1-3 years	3-4 EVA per week, 20-24 EVA hrs per week	75	8	Apollo Shoulder injury

Further limitations of the available evidence include that assessing shoulder injuries alone may under-estimate EVA Injury risk (assuming more injury mechanisms for Surface EVAs compared to On-Orbit EVAs). This analysis does not differentiate between recurrent and new injuries due to Electronic Medical Record (EMR) limitations. This analysis excluded any training injuries and is not considering if initial injury occurred due to training. There also may be potential for underreporting of cases in some of astronaut population.

EVA is a critical factor in the success of the construction, maintenance, scientific, and exploration aspects of every exploration architecture concept being considered by NASA. Some concepts of operation call for each crewmember to perform up to 24 hours of EVA per week for missions lasting up to 6 months. This corresponds to as many as 624 hours of EVA per crew member in a single mission. As described in this evidence report, the risks associated with any inadequacies that exist in current EVA systems – particularly with respect to suit-induced injury – will be greatly amplified by such frequent EVAs.

Planetary mission architectures include small pressurized rovers (SPRs) as a core element of the surface mobility system. The implications of SPRs on crew health, safety, productivity, and efficiency are potentially enormous. The availability of a pressurized safe-haven that provides DCS treatment, solar particle event (SPE) protection, and on-site injury treatment, and can be reached within 20 minutes at all times, would significantly reduce many of the risks associated with planetary exploration. Furthermore, because crewmembers would travel large distances inside the SPRs, this would reduce the overall number of in-suit EVA hours to achieve the same (or greater) science/exploration return. The possibility of performing single-person EVAs with a second crewmember inside the SPR would further reduce total EVA hours. In addition, the number of cycles on the EVA suits would be decreased, thereby increasing the life of each EVA suit and reducing hardware failure risk for crewmembers.

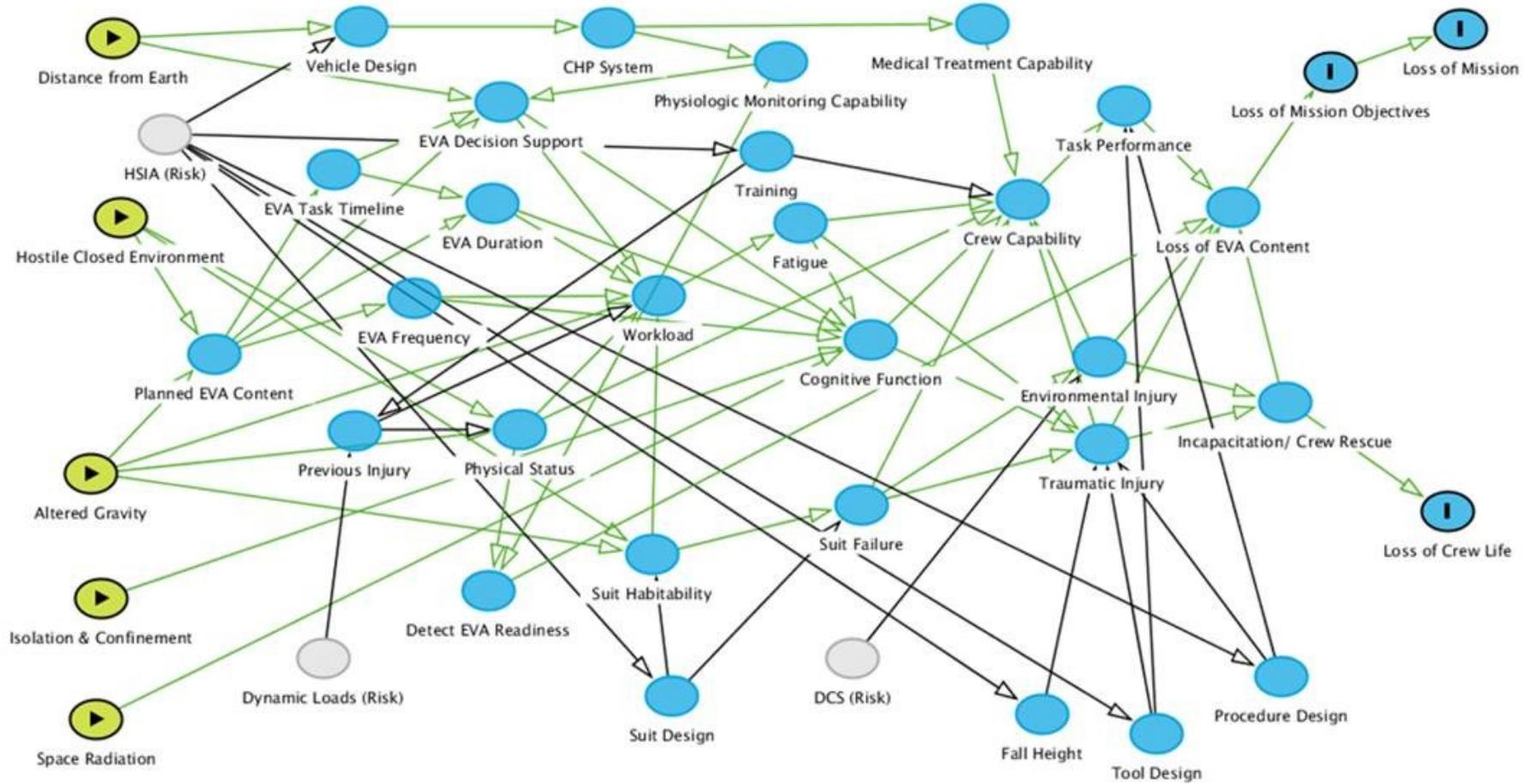
Fewer than 20 lunar surface EVAs were performed during the entire Apollo Program. Scenarios evaluated during NASA Constellation Program’s Architecture Team for lunar exploration included as many as 30,000 hours of lunar exploration EVA time. Anticipating that there could be pain and injury experienced during these EVA excursions, NASA has proposed countermeasures including on-site

medication treatment. During long-duration space missions, pain management may be required for unanticipated accidents (e.g., fractures of bones, lacerations, or blunt trauma), medical conditions such as appendicitis, or a perforated viscus (IOM 2001). Accidental wounds (such as lacerations and open fractures) may become contaminated and require therapeutic administration of antibiotics to prevent devastating infectious complications (Singer et al., 1997; Luchette et al., 2000).

The xEMU spacesuit (that is currently in development) will be higher mobility and higher mass than Apollo spacesuits. It is unknown if the higher mobility and higher mass of xEMU will overall decrease or increase injury potential; higher mobility could help enable better ergonomic positioning for tasks, but there is some concern that hip mobility will introduce the potential for low back and lower body injuries. In contrast, prior Lunar suits without hip joints restricted motion which might have reduced injury potential due to not enabling mobility. Some of the risk factors for shoulder injury in EMU will be ameliorated by xEMU having improved shoulder design and rear-entry donning and doffing. The xEMU will also have improved visibility to enable view of outstretched hand which should decrease some injury potential for upper extremities and improve task performance. Currently, the xEMU is not yet available for testing to verify these hypotheses, and also the designs of Lunar surface systems and EVA tasks for upcoming missions are not yet defined. However, based on current requirements, the Lunar surface systems are expected to enable high frequency EVA with Exploration Atmosphere prebreathe which will enable a quick 30-min transition time from Lunar lander to suited operations. This could lead to having some shorter duration frequent EVAs which could reduce injury potential compared to long 6-8 hr EVAs, but it is likely that EVAs will still be relatively long duration with at least 3-4 hours of suited operations to justify the consumables cost of the breathing gas required for airlock depress and repress operations. The xEMU spacesuit will also be a variable pressure suit that can enable even shorter prebreathe transition times and/or offer real-time DCS treatment options by operating at elevated suit pressure early in the EVA or as needed to alleviate DCS symptoms. However, operating at higher suit pressures increases workload and has unknown impact on fatigue and injury potential.

SECTION III:

DAG Review



Contributing factors to the risk of injury and compromised performance due to EVA operations are conceptualized as the interaction between the crewmember, suit, and operational tasks. EVAs are directed by a team of professionals who design, plan, and provide real-time support throughout EVAs. Currently, flight controllers supporting ISS EVAs are trained to serve either the task side of EVA procedures or systems side of suited operations. Flight rules to mitigate hazards are developed by suit/surface/tool hardware experts and safety professionals. EVAs are also supported by informatics systems for detecting off-nominal events and providing cautions and warnings to both the suited crewmember and mission control. In the future, decision support for Mars missions will be limited by communication delay and will necessitate more reliance on EVA informatics systems. Also both Lunar and Mars missions will shift to a much a higher cadence of EVA which may include up to 24 hours of EVA per week. The likelihood of injury and the operational consequence of injury are both impacted by EVA schedule; missions that are scheduled for conducting a high number of EVAs may increase injury potential due to more EVA exposures, but having more schedule opportunities for completing EVA tasks does lower the operational consequence of canceling a given EVA due to injury. As shown in the DAG, there are many relationships to consider as described below with each node of the DAG in **bold**:

- The Risk of EVA Injury focuses on **Environmental Injuries** and **Traumatic Injuries** on the right side of the DAG. The numbers, types, and severities of injuries that occur during EVA affects **Crew Capability** by introducing functional impairments that can affect **Task Performance**. These categories of injuries are explicit in the Medical Risk DAG and **Medical Treatment Capability** provided in mission determines the extent to which the consequences of these injuries can be mitigated in-mission.
- Contributing factors to **Environmental Injuries** are **Suit Failure** and Decompression Sickness – **DCS (Risk)**.
- Contributing factors to **Traumatic Injuries** includes **Suit Failure**, **Fall Height** (either from poor vehicle design or mission task attributes), **Tool Design** (such as in Apollo missions where many astronauts complained of hand injuries), and **Procedure Design**. All of these are affected by the **HISA (Risk)**.
- When severe, these injuries can lead to **Loss of EVA Content** which increases the likelihood of **Loss of Mission Objectives**, especially in short duration missions. Additionally, they can lead to **Incapacitation/Crew Rescue** during an EVA which increases the likelihood of **Loss of Crew Life**.
- **Crew Capability** is also affected by both design and operational decisions and their consequences. **Cognitive Function** and **Fatigue** are dependent on
 - Planned EVA Content and EVA Task Timeline (are they feasible and appropriate?).
 - **EVA Duration** (how long do they last?), **EVA Frequency** (how many and how often?), and **EVA Decision Support** (is decision support effective at cognitive unloading?).
 - The above all contribute to the **Workload** that crews experience during their EVAs.
- Workload is also affected by the **Altered Gravity** environment (microgravity, lunar or Martian), their **Physical Status**, and any **Previous Injuries** – either old or incurred during prior EVAs.
- Effective **Training** can affect the likelihood of having **Previous Injuries** as well as **Crew Capability** through a practiced understanding of movement and exertion limitations during an EVA. **Dynamic Loads (Risk)** also influences the likelihood of incurring a **Previous Injury** during a landing phase prior to EVA activity.
- **Distance from Earth** affects the mass, power, volume and data bandwidth available to the **CHP System** that enables **Medical Treatment Capability**, **EVA Decision Support** and **Physiologic**

Monitoring – such as the ear exams done to ensure crew can effectively clear prior to starting an EVA – that enable **Detect EVA Readiness** giving crew the green light to begin an EVA.

- The **HSIA (Risk)** interfaces at many places including **Vehicle Design, Suit Design, Training, Fall Height, Tool Design, and Procedure Design**. Inadequate attention to Human System Integration at the Mission, Vehicle and Suit level is expected to have a strong effect on the risk of EVA Injury.
- **Vehicle Design**: this includes surface assets such as Landers, Habitats, Rovers, etc.
- **CHP System**: Crew Health and Performance (CHP) system for monitoring and treatment
- **Medical Treatment Capability**: Exploration Medical Capability may include imaging technology for diagnosis of musculoskeletal injury to enable proper rehabilitation and treatment
- **Physiologic Monitoring Capability**: crew state modeling and risk assessment tools for workload, heat storage, hydration, fatigue, etc.
- **Decision Support**: bioinformatics to support EVA planning and re-planning
- Training: suit systems and task operations training on the ground at the NBL or ARGOS, in VR, and other suit training labs, as well as the rockyard and field sites for science/geology training
- **Previous Injury**: injury from prior EVAs, training, or other past life events that may pose a risk or vulnerability for future injury
- **Physical Status**: strength, aerobic capacity, and sensorimotor status
- **Detect EVA Readiness**: identify and address any concerns/issues before getting the “go” for EVA
- **Planned EVA Content**: refers to the particular equipment and methods used to perform necessary mission EVA tasks; tasks and tools planned for achieving the objectives of a given EVA
- **EVA Task Timeline**: refers to the detailed analysis and testing that is required to understand the necessary duration and sequencing of tasks and subtasks within a particular EVA or set of EVAs in order to achieve overall objectives; detailed analysis and testing that is required to understand the necessary duration and sequencing of tasks and subtasks within a particular EVA or set of EVAs in order to achieve overall objectives within the constraints of flight rules, crew capability, and suit related performance.
- **EVA Frequency**: number of EVAs per unit of time (week, month, quarter, year, etc.)
- **EVA Duration**: time duration of a given EVA
- **Workload**: weight-bearing and locomotion activity, functional mobility required and amount of content, manual material handling in 1/6-G
- **Fatigue**: physical fatigue overall due to exertion/workload over time or localized to specific muscle groups, such as hand fatigue may result from tasks requiring hand / fine motor tasks
- **Cognitive Function**: neurobehavioral status including circadian/sleep, mood, and preparedness
- **Crew Capability**: Crew available to perform EVA, including back-up crewmembers
- **Task Performance**: completion status of tasks, including both timeliness and quality
- **Suit Habitability**: Nutrition, Hydration, Waste Management, partial gravity suit fit, possible mismatching between crew size and available suit component sizes
- **Suit Design**: breadth of knowledge on existing EMU suit leading to design considerations for new xEMU suit such as capability to adjust shoulder breadth to lower shoulder injury potential, more mobility in both upper and lower body with unknown impact on injury, and similar glove.
- **Suit Failure**: suit system failures could range from
- **Environmental Injury**: frostbite risk of permanently shadowed regions (PSRs)
- **Traumatic Injury**: musculoskeletal injury during EVA operations

- **Fall Height:** fall protection will be needed to mitigate risks of falling at extreme heights such as from a ladder or side of a crater
- **Tool Design:** operating new tools and equipment
- **Procedure Design:** the particular equipment and methods used to perform necessary mission EVA tasks
- **Incapacitation / Crew Rescue:** in the event of a crew member becoming immobile or unconscious, then the other “buddy” crew member will need to attempt to rescue

Integration with other risks: The following section describes some of the known relationships with other risks.

Related risks (drafted by Evidence Report authors):

Risk of Injury from Dynamic Loads

Enduring an injury during launch or landing could impact crew capability to complete or even begin EVAs. During surface EVA, load-induced injuries may arise during falls, especially falls from heights or falls on sloped terrain. Dynamic loads may also be experienced during rover operations which will be analyzed in future work as operational surface assets are designed and tested for Artemis program.

Additional background and evidence can be found in the NASA HRP Evidence Report “Risk of Injury due to Dynamic Loads” (Caldwell, 2012) and the report on Lunar Transient Loads (Somers, 2020).

Risk of Decompression Sickness

When a diver returns from a hyperbaric environment, or an aviator or astronaut travels to a hypobaric environment, inert gas in excess of what can be held in solution at the new lower pressure has the potential to come out of solution and form gas spaces that can displace or otherwise damage tissues. Unlike other space flight related human risks, DCS is a known problem that has been mitigated since the first EVA. Various DCS mitigation strategies have effectively been used including a lower pressure high oxygen environment (Gemini, Apollo, Skylab) requiring a single 4-hr pre-launch oxygen prebreathe (PB); a resting 4-hr in-suit PB; an intermediate pressure, mildly hypoxic environment requiring a single 40- to 75-min in-suit PB; and several exercise-enhanced protocols combining both mask and in-suit PB. To date, DCS has been effectively mitigated through rigorous adherence to PB protocols validated specific to the EVA environment and primarily to the microgravity environment. While effective, these protocols can be complex and require significant pre-flight training, in-flight crew time and consumables usage.

Historically, prebreathe protocols have been developed with the goal of preventing DCS and have been designed to meet operational needs. The acceptable risk for DCS has been defined in the NASA Human Space flight Standards, therefore, the next step will be to develop and validate procedures, protocols, and countermeasures to meet this standard effectively and efficiently for

the range of nominal and off-nominal atmospheres and decompression profiles that crewmembers may experience during future exploration missions. Utilization of the Exploration Atmosphere (8.2 psia / 34% O₂), suit ports, variable pressure suits, and the inability to rapidly deorbit for medical treatment mean that existing DCS risk mitigation protocols and data sets are not applicable to future exploration missions.

To improve efficiency from a sea level atmosphere, data is needed on the potential differences in bubble formation and N₂ elimination while in microgravity. To improve safety and efficiency from any atmosphere, data is needed to describe the consequences of a break in PB. Finally, the opportunity exists to mitigate DCS primarily through engineering controls by the use of the 8.2 psia / 34% O₂ Exploration Atmosphere, suit port and variable pressure EVA suit. While promising, this strategy still requires validation to ensure it mitigates DCS risk to acceptable levels and to determine if there are any significant negative physiological effects associated with the Exploration Atmosphere's mild hypoxia of approximately 4000-ft equivalent altitude (Conkin et al. 2016).

Risk of Reduced Crew Health and Performance Due to Hypobaric Hypoxia

Hypoxia refers to low environmental oxygen conditions. Normally, 20.9% of the gas in the Earth's atmosphere is oxygen. The partial pressure of oxygen in the standard atmosphere is 20.9% of the total barometric pressure. Atmospheric hypoxia occurs naturally at high altitudes. Total atmospheric pressure decreases as altitude increases, causing a lower partial pressure of oxygen, which is defined as hypobaric hypoxia. Oxygen remains at 20.9% of the total gas mixture, differing from hypoxic hypoxia, where the percentage of oxygen in the air is decreased. Other potential causes of hypoxia include medical causes such as pulmonary or respiratory disease or obstruction.

Unlike on Earth, habitable volumes in space are completely engineered environments, allowing the endless possibility of various atmospheric constituents. The ISS is set to a typical sea level atmosphere of 14.7 psia and 21% O₂. To ensure maximum mobility, EVA suits are kept at a low operating pressure, which is akin to increasing altitude in the Earth environment. To combat hypoxia and DCS, the suit environment is kept as close to 100% O₂ as possible with some N₂ remaining even after a 10-min purge with 100% O₂. This purge is required to remove the ambient ISS gas (21% O₂, 79% N₂) present in the suit during the suit donning process. In the engineered environment, hypoxia is best discussed as a partial pressure rather than altitude. Normoxia is an inspired partial pressure of O₂ (PIO₂) of 150 mmHg calculated with the following equation:

$$PIO_2 = PB - 47 \times (FIO_2)$$

With PB defined as the total pressure in mmHg, 47 mmHg as the constant water vapor tension (PH₂O) in the human lung and FIO₂ as the fraction of inspired O₂ in the ambient air.

At higher pressures, the PH₂O in the lung may be a small portion, but as the total pressure of the environment is significantly reduced, such as EVA, this constant PH₂O become a more significant factor. A lower suit pressure may improve mobility but increases the risk of both DCS

and hypoxia. For further discussion on DCS, please see the NASA HRP Evidence Report “Risk of Decompression Sickness” (Conkin et al. 2016)

During the lunar missions, the Apollo A7L and A7LB suits were operated at 3.7 psia and 100% O₂, which results in a PIO₂ of 144 mmHg, i.e. at the low end range of values considered physiologically normoxic. This level would be equivalent to an altitude of just under 1000 ft. The EMU operates at 4.3 psia and 100% O₂ resulting in a PIO₂ of 175 mmHg. Assuming the suit can maintain adequate pressure and the life support system continues to deliver 100% O₂, hypoxia is a controlled factor for EVA risk.

Methods for mitigating hypoxia include design of the EVA suit so that it monitors and maintains appropriate breathing atmosphere pressures and oxygen concentrations under all expected EVA durations and human physiological demands. In addition, considerations should be made for contingency situations such as leaks or malfunctions that could compromise the breathing atmosphere within the suit. Current guidelines allow an EVA to continue as long as PIO₂ is maintained above 127 mmHg (approximately 4000 ft equivalent altitude), but this is for contingency only and the nominal approach is to ensure a normoxic environment.

The ramification of not mitigating the risk of hypoxia during EVA include both health and performance impacts. These impacts include headache, decreased reaction time, impaired judgment, visual impairment, drowsiness, lightheadedness, lack of coordination, reduced oxygen delivery, and reduced muscle strength and power (Guyton and Hall 2000, Houston 2005).

Risk of Adverse Outcome Due to Inadequate Human Systems Integration Architecture

The xEVA hardware path to human ratings verification is currently being defined and will require documentation and testing to address integration of various suit sub-systems and vehicles.

One of the primary functions of an EVA suit is to monitor and maintain a desired internal pressure. The internal pressure of a spacesuit must be adequate to maintain required breathing air partial pressures while the mobility and workload required to do tasks within the suit are kept at a reasonable level; it is a tradeoff of aspects of spacesuit operations that must be balanced (Abramov et al. 1994). The internal suit pressure used during EVA must also be tightly coordinated with the internal habitat or vehicle pressures to minimize the time required to transition from one environment to another. The negative pressure differences associated with moving from a habitat or vehicle to a spacesuit can cause decompression sickness, thus prebreathing higher concentrations of oxygen is required to reduce the risk of decompression sickness (Clément 2011). A detailed review of how NASA has mitigated DCS primarily through operational prebreathe protocols is discussed in the DCS risk Evidence Report (Conkin et al. 2016), but both DCS risk and prebreathe time can be reduced by the choice of optimal pressures and gas concentrations in both environments (Abercromby et al. 2013a) (Norcross et al. 2013a).

The current working assumption in the EVA community is that a lower suit pressure is better from a human performance and fatigue perspective. The main concern for operating the suit at a higher pressure is hand fatigue. Whole body tasks such as ambulation in the Mk-III did not

show much difference in metabolic and subjective measures (Norcross et al. 2010b; Norcross et al. 2010d). Although higher suit pressures would significantly reduce prebreathe time, they are also associated with higher leak rates and greater suit mass to ensure needed structures.

Currently, very little is defined in standards that govern NASA human space flight regarding operations that would serve to provide requirements for the design of effective, efficient, and safe EVA tasks and timelines (NASA 2007; NASA 2019). However, analog research has introduced a model of early human testing of prototype systems that can factor in human health and performance concepts of operations and system design as early as possible. Before the NEEMO 14 mission, extensive task and time analysis of important lunar surface EVAs informed the design of the research study to validate and collect metrics on different tasks and timelines (Chappell et al. 2011). Similar processes were used before and during NASA's Research and Technology Studies (RATS) missions from 2008-2012 (Abercromby et al. 2010; Abercromby et al. 2013b; Abercromby et al. 2012a; Abercromby et al. 2012b), which tested both planetary surface and Near-Earth asteroid missions. Near-Earth asteroid mission task analysis and timeline validation was also assessed during NEEMO 15 and 16 (Chappell et al. 2013a; Chappell et al. 2013b).

In addition to optimizing EVA operations, task related risks can be identified to reduce injury rates caused during EVA or EVA training time. Repetitive motion causes injury if too much time is spent in certain positions that cause fatigue or injury, and this can lead to a failed task or decrease in performance. As much as is possible, tasks and procedures should be designed to avoid extended time in one position and to divide up the time spent in uncomfortable positions. For example, crewmembers can experience pain if they spend too much time working with arms overhead (a non-optimal position with the current EMU scye bearing). Working at an angle can also cause problems as it may result in the crewmember placing their body into a suboptimal position. Inverted time in the NBL is now managed operationally by monitoring and restricting both for the acute exposure and the cumulative exposure over a training session.

EVA training issues can become a contributing risk factor when necessary training programs are inadequate or unavailable. There is a high likelihood of minor time losses and inefficiencies and a small, but non-zero, likelihood of serious damage to space systems due to errors resulting from inadequate training. Generally, the likelihood of issues may increase with increased mission duration and crew autonomy. In some cases, training programs may be inadequate because they do not result in appropriately generalizable skills. Additional risk factors (fatigue, stress, excessive workload) can significantly alter the conditions of task performance relative to those during task training, and this can lead to decrements in performance. In addition, the passage of time and the lack of opportunity to rehearse or refresh acquired knowledge or skills can result in performance declines, reflecting a lack of recollection of what was learned. Training programs that do not account for degradation of learned skills or knowledge (e.g., by including refresher training or by providing just-in-time training rather than advance training on the ground) may result in inferior task performance. A further complication arises as a result of the novel technologies and operational scenarios that may exist for deep space missions.

More detailed background and evidence can be found in the NASA HRP "Evidence Report: Risk of Performance Errors Due to Training Deficiencies" (Barshi 2016).

Risk of Performance and Behavioral Health Decrements Due to Inadequate Cooperation, Coordination, Communication, and Psychosocial Adaptation within a Team

Coordination and autonomy aspects of EVA will need to be addressed to optimize task performance, psychosocial performance, and teamwork during long duration missions. No formal procedure to handle coordination issues currently exists. Within the current hierarchy of the crew, it is assumed that the commander will make any final decisions. Multiple incidents of a lack of coordination between flight crew or flight and ground crews have occurred. Environment constraints, including communication delays and isolated, confined, and extreme environments over a long duration may impact issues related to crew collaboration over time. Crews may have to make decisions independent of ground control when presented with novel tasks in time critical situations, and consideration will need to be taken for the functional allocation of crewmembers (and skillsets) within the work domain (Feigh and Pritchett 2014). Understanding how teams can effectively coordinate and collaborate to accomplish the tasks and objectives set before them is imperative; the ability to complete what is required of them as a team is even more difficult when considering the context of a long duration mission, and thus it is essential that research identifies the most effective mitigation strategies to address this contributing factor.

More detailed background and evidence can be found in the NASA HRP Evidence Book: “Risk of Performance and Behavioral Health Decrements Due to Inadequate Cooperation, Coordination, Communication, and Psychosocial Adaptation within a Team” (Landon 2016), and in “Risk of performance errors due to poor team cohesion and performance, inadequate selection/team composition, inadequate training, and poor psychosocial adaptation” (Schmidt et al 2009).

Risk of Adverse Cognitive or Behavioral Conditions and Psychiatric Disorders

Stressful conditions are inherent to space missions. Working in space involves danger, isolation, and confinement; therefore, space is understood to be an extreme work environment. Survival in space requires constant shelter or protective gear, and it is also subject to equipment malfunctions. Crewmembers must adapt to a certain level of danger or threat to survive. They must also adapt to certain levels of isolation because contact with others (i.e., outside of the immediate crew) may be very limited and inconsistent at times, and isolation from family and friends may create social rifts and isolation that persist after flight. Finally, space flight crewmembers must adapt to being confined to a limited living and working space. Ground-based research in similar conditions (e.g., submarines, offshore oil rigs, polar stations) has found that such conditions are generally detrimental to psychological health and social well-being over prolonged periods (Braun and Sells 1962) (Britt and Bliese 2003) (Krueger 2001) (Schmidt et al. 2009).

Exploration space missions could require crews and ground operations to operate more or less autonomously because the degree of crew isolation increases with the distance that the spacecraft travels from the Earth. Crews are likely to have some periods of complete control as well as some periods of limited control over what tasks are done, how the tasks are done, and when they are done. Ground operations are likely to stipulate total control at certain points in the mission, and unable to provide any control during other parts of the mission. Shifts in

operational autonomy are expected to impact psychosocial adaptation to space flight demands (Kanas and Manzey 2008). It is important to understand how these factors (i.e., isolation, physical space, individual and group autonomy, etc.) influence psychosocial adaptation among crewmembers, as these factors ultimately will impact crew performance (Langfred 2000) (Schmidt et al. 2009).

More detailed background and evidence can be found in the NASA HRP Evidence Book: “Risk of Performance and Behavioral Health Decrements Due to Inadequate Cooperation, Coordination, Communication, and Psychosocial Adaptation within a Team” (Landon 2016).

Risk of Performance Decrement and Crew Illness Due to Inadequate Food and Nutrition

Given the long duration of EVAs and high workload of partial gravity EVAs, the design of an in-suit nutrition system is currently underway including requirements for nutritional content and timing as well as waste management considerations to improve crew health and performance.

Additional background and evidence can be found in the NASA HRP Evidence Report “ Risk Factor of Inadequate Nutrition” (Smith et al. 2015), “Evidence Report: Risk of Performance Decrement and Crew Illness Due to an Inadequate Food System” (Douglas et al. 2016) and “Human Adaptation to Space flight: The Role of Nutrition” (Smith et al. 2021).

Risk of Impaired Control of Spacecraft/Associated Systems and Decreased Mobility Due to Vestibular/Sensorimotor Alterations Associated with Spaceflight

Given there is an alteration in vestibular/sensorimotor function during and immediately following gravitational transitions, which manifests as changes in eye-head-hand control, postural and/or locomotor ability, gaze function, and perception, it is possible that crews will experience decreased mobility during EVA on a planetary surface after long-duration space flight.

More detailed background and evidence can be found in the Evidence Report: “Risk of Impaired Control of Spacecraft/Associated Systems and Decreased Mobility Due to Vestibular/Sensorimotor Alterations Associated with Space flight” (Bloomberg 2016) and in “Risk of sensory-motor performance failures affecting vehicle control during space missions: a review of the evidence.” (Paloski et al. 2008).

Risk of Impaired Performance Due to Reduced Muscle Mass, Strength & Endurance & Risk of Reduced Physical Performance Capabilities Due to Reduced Aerobic Capacity

Exercise countermeasures will be a part of any exploration program and future research to develop maximally effective countermeasures to protect muscle power, strength and endurance will help to ensure mission success and the safety of crewmembers. Mission architectures, EVA surface suits and systems, and EVA task plans need to consider the potential limitations of crewmembers after long duration transits in 0-g and partial gravity destination. Additional research is needed to understand if current standards are appropriate to help ensure EVA mission objectives can be achieved with acceptable levels of injury to crewmembers.

More detailed background and evidence can be found in the NASA HRP “Evidence Book: Risk of Impaired Performance Due to Reduced Muscle Mass, Strength, and Endurance” (Ploutz-Snyder et al 2016).

SECTION IV: Knowledge base

EVA-101: Determine limitations of EVA performance and physiological metrics shortly post-landing on a planetary surface (with compromised physiology based on flight duration).

Upon return to Earth from a long-duration spaceflight mission, all astronauts demonstrate significant decrements in functional performance, that are most severe in the first 24 hours after landing and resolve over the first 2 weeks as they undergo readjustment to gravity. These decrements are seen despite a comprehensive system of in-flight countermeasures such as exercise, which for most crewmembers allows maintenance of muscle strength and aerobic capacity. However, the most significant contributors to the postflight functional challenges are the deficits seen in the neurovestibular/sensorimotor system that can take days or weeks to recover, and for this type of deficit there is currently no operational countermeasure (though several are under development). The consequences of these postflight deficits are minimal when crewmembers return to Earth and land on firm ground, as they are met at the landing site with ground rescue forces who assist them with vehicle egress and other postflight activities. The situation will be different with future landings on the Moon and Mars, where the crew will need to function autonomously shortly after landing, as well as in near-future water-based landings on Earth, where off-nominal conditions may delay the arrival of support personnel. Understanding and quantifying post-landing functional capacity is necessary to design concepts of operation for Moon and Mars exploration missions. Important components of postflight capabilities include the ability to perform an unassisted capsule egress and conduct critical planetary extravehicular activity (EVA) tasks within the first 24 hours after landing. Understanding the limitations to safe crewmember postflight activities will allow development of needed countermeasures as well as enable setting standards and operational procedures.

Ongoing data collection for Sensorimotor Standard Measures provide valuable data that will contribute to discussions and future studies such as CIPHER Egress Fitness that will determine when nominal EVA operations can begin on Mars as well as the potential off-nominal or limited EVA capabilities that might be available post landing on Mars. The Functional Task Test (FTT) has assessed crewmember physical preparation and recovery following return to Earth (Bloomberg et al. 2016). The Field Test follow-on to the FTT performed functional performance tests in the field immediately post landing (Reschke et al. 2016). These studies provide comprehensive analysis of post-flight physiological readaptation to date, but some gaps in knowledge remain.

In addition to determining when and what tasks a crewmember could perform for the first EVAs on Mars, there is also a need for fitness for duty standards for EVA. Current standards do exist, but are not well defined (NASA 2007). This effort to define fitness for duty standards is the focus of the Fitness for Mission Tasks (FMT) studies (English et al. 2017). To fill in the gaps for EVA-like task timeline and energy expenditure profiles,

The long transit times in 0-g for exploration missions could cause decreases in muscle strength, power, and endurance as well as aerobic capacity that might impact the crew's ability to perform EVA tasks. This risk could potentially be prevented or mitigated by selecting astronauts that have higher baseline fitness/strength levels. Exercise countermeasures are used to mitigate other risks but their effectiveness is unknown in relation to future exploration EVA operations.

Beyond fitness for duty standards, there is also a requirement to evaluate the crewmember's physical readiness prior to an EVA. On ISS, a pre-EVA health check with ground concurrence is required before a crewmember begins an EVA, but the effectiveness of this process will be difficult to implement for missions with time delay, possibly necessitating a crewmember-based method of assessing readiness on the day of EVA.

EVA-201: Evaluate EVA performance, physiological/cognitive metrics, and injury risk when EVAs are conducted in a variable pressure suit.

The suits being designed for future missions will have the capability to operate at a variety of pressures, from a low pressure of 3.8 psi up to the 8.2 psi planned for use in the planetary vehicles/habitats. The higher pressure ranges will enable shorter pre-breathe times and decrease the amount of time required for preparations prior to each EVA. However, the pressure at which EVA suits operate affects the resistance experienced by crewmembers at individual joints, and can increase workload, with quicker onset of fatigue and possibly overuse as well as acute injuries, which can ultimately affect health and performance outcomes. Lower suit pressures are easier to operate in, but lower pressure environments increase the risk of decompression sickness (DCS). Understanding the trade-offs between suit pressure, workloads, and health and human performance outcomes such as fatigue and injuries will inform the selection of optimal suit operating pressures to be used during EVAs, as well as the design of EVA concepts of operation and countermeasures as needed.

SECTION V: Conclusions

Future human space exploration missions will be more dependent on EVA excursions away from a pressurized habitat or vehicle than any program in the history of NASA. EVA will be required to conduct planned scientific expeditions, assemble structures, perform nominal maintenance, and intervene and solve problems outside of the vehicle that cannot be solved either robotically or remotely. The ultimate success of future exploration missions is dependent on the ability to perform EVA tasks efficiently and safely in these challenging environments.

To date, our direct understanding of crew health and performance parameters in partial-gravity environments is limited to observations of, and lessons learned from, Apollo-era astronauts who performed EVAs on the lunar surface. Since the Apollo Program, and using lessons learned from microgravity EVAs aboard the Space Shuttle and ISS, new space suits have been in development for future space exploration activities. However, to date there has been limited quantification and modeling of the physiological and biomechanical variables associated with suited activities in micro and partial gravity. An integrated EVA physiology and performance roadmap has been developed (Abercromby et al. 2020) and is currently being implemented with funding from NASA Advanced Exploration Systems and Human Research Program to better characterize the impacts to crew health and performance during EVA and to develop the risk assessment and decision support capabilities required to support EVA operations.

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