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Integrated Extravehicular Activity Human Research & Testing Plan: 2019

Andrew F. J. Abercromby[1]
Brian K. Alpert[1]
J. Scott Cupples[1]
E. Lichar Dillon[2]
Alejandro Garbino[3]
Yaritza Hernandez[4]
Christine Kovich[5]
Matthew J. Miller[6]
Jason Norcross[4]
Cameron W. Pittman[6]
Sudhakar Rajulu[1]
Richard A. Rhodes[1]

[1]*NASA Johnson Space Center, Houston, Texas*
[2]*University of Texas Medical Branch, Galveston, Texas*
[3]*GeoLogics Corporation, Houston, Texas*
[4]*KBRwyle, Houston, Texas*
[5]*The Aerospace Corporation, Houston, Texas*
[6]*Jacobs Technology, Inc., Houston, Texas*

National Aeronautics and
Space Administration

Johnson Space Center
Houston, Texas 77058

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ACRONYMS

ABF = Anthropometry and Biomechanics Facility
ANSUR = US Army Anthropometry Survey
APACHE = Assessments of Physiology And Cognition in Hybrid-reality Environments
ARGOS = Active Response Gravity Offload Simulator
BASALT = Biologic Analog Science Associated with Lava Terrains
CAD = Computer-Aided Design
CG = Center of Gravity
CHP = Crew Health and Performance
CO_2 = Carbon Dioxide
CTSD = Crew and Thermal Systems Division
DCS = Decompression Sickness
DRATS = Desert Research and Technology Studies
DSS = Decision Support Systems
EEWG = EVA Exploration Working Group
EMU = Extravehicular Mobility Unit
EOS = EVA Operations System
EVA = Extravehicular Activity
HERA = Human Exploration Research Analog
HERO = Human Exploration Research Opportunities
HH&P = Human Health and Performance
HHPD = Human Health and Performance Directorate
HITL = Human-In-The-Loop
HPEG = High Performance EVA Glove
HRP = Human Research Program
HSRB = Human System Risk Board
HUT = Hard Upper Torso
IR = Intermittent Recompressions
ISS = International Space Station
IV = Intravehicular
LCVG = Liquid Cooling and Ventilation Garment
LSAH = Longitudinal Survey of Astronaut Health
MDV = Mars Descent Vehicle
MHz = megahertz
MIT = Massachusetts Institute of Technology
mmHg = millimeters of mercury
N_2 = Nitrogen

NASA = National Aeronautics and Space Administration
NBL = Neutral Buoyancy Laboratory
NEEMO = NASA Extreme Environment Mission Operations
NSTRF = NASA Space Technology Research Fellowship
O_2 = Oxygen
OFV = On-Orbit Fit Checks
PACES = Physical And Cognitive Exploration Simulations
PLSS = Portable Life Support Subsystem
psi = pounds per square inch
psia = pounds per square inch absolute
SHyRE = Scientific Hybrid Reality Environments
SMD = Science Mission Directorate
SMT = System Maturation Team
3-D = Three-Dimensional
VGE = Venous Gas Emboli
xEMU = Exploration Extravehicular Mobility Unit

EXECUTIVE SUMMARY

Multiple organizations within NASA as well as industry and academia fund and participate in research related to extravehicular activity (EVA). In October 2015, representatives of the EVA Office, the Crew and Thermal Systems Division, and the Human Health and Performance Directorate at NASA Johnson Space Center agreed on a formal framework to improve multiyear coordination and collaboration in EVA research. At the core of the framework is an Integrated EVA Human Research and Testing Plan and a process by which it is annually reviewed and updated. The overarching objective of the collaborative framework is to conduct multidisciplinary cost-effective research that will enable humans to perform EVAs safely, effectively, comfortably, and efficiently, as needed to enable and enhance human space exploration missions. Research activities must be defined, prioritized, planned, and executed to comprehensively address the right questions, avoid duplication, leverage other complementary activities where possible, and ultimately provide actionable evidence-based results in time to inform subsequent tests, developments, and/or research activities. Representation of all appropriate stakeholders in the definition, prioritization, planning, and execution of research activities is essential to accomplishing the overarching objective. A review of the Integrated EVA Human Research and Testing Plan is conducted annually. Details of this plan include descriptions of ongoing and planned research activities in the areas of: physiological and performance capabilities; suit design parameters; EVA consumables and life support parameters; EVA tasks and concepts of operations; EVA informatics and decision support systems; human-suit sensors; anthropometry and suit fit; EVA injury risk and mitigation; hardware evaluations and requirements verification; and decompression sickness risk mitigation. This paper represents the 2019 update to the Integrated EVA Human Research and Testing Plan.

1.0 INTRODUCTION

NASA's Strategic Plan [1] includes Strategic Objective 2.2: Conduct Human Exploration in Deep Space, including extravehicular activity (EVA) sorties to the surface of the moon while continuing the previous long-term goal of sending humans to Mars [2]. Current space suits and EVA concepts of operations used on the International Space Station (ISS) or during the Apollo missions to the moon are inadequate to meet the mission objectives associated with extended stays on the surface of the moon and even the shortest possible Mars exploration missions. Many technological and knowledge gaps exist with respect to the ability of EVA systems and crewmembers to function safely, reliably, and effectively for missions that may last a year or longer in the most hostile and challenging environments ever to be explored by humans.

A significant step toward returning humans to the surface of the moon was taken in the initiation of the Exploration Extravehicular Mobility Unit (xEMU) project in 2018. Scope for this new EVA suit includes an initial ISS demonstration followed by full development to support cislunar space programs such as the Deep Space Gateway and eventually lunar surface operations. Further development will be required for a Mars surface EVA suit, or mEMU.

The Integrated EVA Human Research and Testing Plan presented here is the third such release, with previous versions being published in 2016 and 2017 [3, 4]. As with the previous versions, the primary purpose of this plan is to clearly define plans and priorities with respect to EVA human research and testing activities, while improving multiyear coordination and collaboration among three of the primary participants in EVA research at NASA's Johnson Space Center; specifically, the EVA Office, the Crew and Thermal Systems Division (CTSD), and the Human Health and Performance Directorate (HHPD). While these organizations work together successfully on EVA research projects on an almost continual basis, it was recognized that the multiyear planning and coordination of research activities could be improved. To this end, a formal framework of collaboration was established in 2016.

At the core of the framework is an Integrated EVA Human Research and Testing Plan and a process by which it is periodically reviewed and updated. The overarching objective of the collaborative framework is to conduct multidisciplinary cost-effective research that will enable humans to perform EVAs safely, effectively, comfortably, and efficiently, to enable and enhance human space exploration missions. Research activities must be defined, prioritized, planned, and executed to comprehensively address the right questions, avoid unnecessary duplication, leverage other complementary activities where possible, and ultimately provide actionable evidence-based results in time to inform subsequent tests, developments, and/or research activities.

Multiple organizations within NASA and outside of NASA have been successfully conducting EVA research and development efforts since the 1960s. The Integrated EVA Human Research and Testing Plan currently reflects only a small subset of all stakeholders in the field of EVA and was intended primarily as an internal NASA creation; however, the current version of the plan is presented here in recognition of the importance of coordination and collaboration with the broader NASA community and beyond. Furthermore, this plan is not intended to be exhaustive of all relevant EVA activities but rather aims to identify the Human-In-The-Loop (HITL) research tasks that will require more coordination in terms of personnel, budgets, facilities, and test hardware as well as tasks that may provide for opportunistic add-on objectives.

It is important to understand that, other than the studies that are already in progress, the other research tasks described in this plan are only proposed, and have not yet been formally reviewed or approved by the prospective funding organizations. This review and funding process differs among organizations; this plan is intended to assist with coordination of those decisions among the respective funding organizations.

The identification and organization of EVA research priorities is described in Section 0, the technical content of the plan is described in Section 3.0, and the process by which the plan will be maintained is explained in Section 0.

2.0 IDENTIFYING AND ORGANIZING EXTRAVEHICULAR ACTIVITY RESEARCH AND TESTING PRIORITIES

A. EVA System Maturation Team Gaps

Following the creation of NASA's Space Technology Roadmaps [5], the EVA Office and CTSD led the development of an EVA System Maturation Team (SMT) Gap List, the purpose of which was to identify EVA-relevant technology research and development priorities in more detail than is included in the Space Technology Roadmaps. The EVA SMT Gap List is used by the EVA Office and CTSD in identifying and prioritizing EVA developmental research activities. A subset of SMT gaps most directly relevant to the human-suit interactions that are the focus of this plan was included in previous releases of the Integrated EVA Human Research and Testing Plan. An update to the EVA SMT gaps was undertaken during the first quarter of fiscal year 2019, and the update is ongoing at the time of this writing. The subset of EVA SMT gaps that are directly relevant to crew health and performance are expected to be incorporated into the recently added overarching Crew Health and Performance (CHP) SMT gaps, described next.

B. Crew Health and Performance System Maturation Team Gaps

The CHP SMT identifies and funds development of technologies and systems that aim to maintain and optimize crew health and performance during future exploration missions, including health and performance related to EVA. The CHP SMT recognizes and tracks a subset of EVA SMT Gaps that are directly related to crew health and performance. In coordination with the EVA SMT, these shared gaps are used as the basis for identifying and prioritizing research and development activities. However, during the review of EVA SMT gaps that is currently underway, it was recognized that the existing EVA SMT gaps cover some but not all of the open technical and knowledge gaps with respect to crew health and performance during EVA. As such, eight new SMT Gaps were created, and they exist within both the EVA SMT and the CHP SMT. These gaps, shown in Table 1, correspond directly to the existing EVA Human System Risk Gaps, described next, and also include an exploration prebreathe gap. As such, the new gaps provide a direct and consistent mapping between existing Human System Risk gaps, EVA SMT, and CHP SMT while ensuring that the full scope of crew health and performance gaps are adequately captured.

Table 1. Crew Health and Performance System Maturation Team EVA Gaps

CH&P Gap Title	CHP SMT Gap ID	EVA SMT Gap No	CH&P Gap Wording
EVA Crew Required Capabilities	CHP.EVA. CREW	EVA-Gap-88	The physiological and cognitive performance capabilities that will be required of crewmembers during exploration EVA are not adequately understood.
EVA Suit Design for Health and Performance	CHP.EVA. SUIT	EVA-Gap-89	The effects of suit design parameters on crew health and performance (physical and cognitive) during exploration EVA are not adequately understood.
EVA Suit Sizing & Fit	CHP.EVA. FIT	EVA-Gap-90	The effects of EVA suit sizing and fit on crew health, performance, and injury risk are not adequately understood.
EVA Physiological Inputs and Outputs	CHP.EVA. PHYS	EVA-Gap-91	The physiological inputs and outputs associated with EVA operations in exploration environments are not adequately understood.
EVA ConOps for Health and Performance	CHP.EVA. CONOPS	EVA-Gap-92	The effects on crew health and performance (physical and cognitive) of variations in EVA task design and operations concepts for exploration environments are not adequately understood.
EVA Informatics for Health and Performance	CHP.EVA. INFO	EVA-Gap-93	The knowledge and use of real-time physiological, system, and operational parameters during EVA operations to improve crew health and performance (physical and cognitive) is not adequately understood.
EVA Injury Risk and Mitigation	CHP.EVA. INJURY	EVA-Gap-94	The risk of crew injury due to exploration EVA operations and methods for mitigating that risk are not adequately understood.
EVA Exploration Prebreathe	CHP.EVA. DCS	EVA-Gap-95	The DCS mitigation strategies and associated impacts on mission timelines, consumables, and the design of EVA and habitat systems for exploration missions are not adequately understood.

C. Human System EVA Risk and Gaps

NASA's Health and Medical Technical Authority, primarily through the Human Health and Performance Directorate, and specifically the Human System Risk Board (HSRB), uses a well-defined and documented process for the formal identification and prioritization of safety and health risks to astronauts [6]. The gaps in knowledge or technology necessary to mitigate each risk are also identified. Within the scope of managing all risks of astronauts, the *Risk of Injury and Compromised Performance Due to EVA Operations*, often referred to as the "EVA Risk," and seven corresponding gaps are concurrently being tracked by the HSRB (Table 2).

Table 2. Human Systems EVA Risk and Gap Structure [7]

EVA Gap ID	Description
EVA 6:	What crew physiological and performance capabilities[1] are required for EVA operations[2] in exploration environments[3]?
EVA 7:	How do EVA suit system design parameters[4] affect crew health and performance in exploration environments[3]?
EVA 7B:	How does EVA suit sizing and fit affect crew health, performance, and injury risk?
EVA 8:	What are the physiological inputs and outputs associated with EVA operations[2] in exploration environments[3]?
EVA 9:	What is the effect on crew performance and health of variations in EVA task design and operations concepts for exploration environments[3]?
EVA 10:	How can knowledge and use of real-time physiological and system parameters during EVA operations[2] improve crew health and performance?
EVA 11:	How do EVA operations[2] in exploration environments[3] increase the risk of crew injury and how can the risk be mitigated?

[1]e.g. anthropometry, aerobic fitness, muscle strength and power; [2]acceptable functional performance of expected nominal and contingency suited tasks; [3]i.e., moon, NEA, Mars, L2 and other deep space microgravity locations; [4](e.g. center of gravity, mass, pressure, mobility, joint characteristics, suit fit; includes suit, portable life support system, and other enabling equipment). Note: Numbering of Human Systems EVA Gaps is not sequential starting from 1 due, in part, to previous gap reorganization and the re-categorization of decompression sickness and hypoxia gaps into separate risks (Risk of Decompression Sickness and Hypobaric Hypoxia).

EVA is still recognized as a distinct discipline by the Human Research Program (HRP); however, since EVA risk funding has been discontinued, the information that follows in this paragraph is provided for historical context and resource. The HRP EVA Discipline is responsible for coordinating a “Path to Risk Reduction” [7], which is a multiyear test plan that aims to close or mitigate the EVA-related risks and gaps to acceptable levels in time to enable human exploration missions. As of the writing of this document, the Integrated EVA Human Research and Testing Plan should be considered the primary resource for defining what work is planned relevant to the EVA risk. The HRP EVA Discipline also maintains an “EVA Evidence Report”[8], a publicly available document in which literature relevant to the EVA risks is reviewed and periodically updated as more research studies are performed. All aspects of the HRP EVA risks, gaps, schedules, and evidence reports are reviewed periodically by an external (non-NASA) review panel of experts. Additionally, proposals are submitted and externally peer-reviewed for all HRP-funded EVA studies. Studies are open to competition by industry and academia (i.e., non-NASA organizations) except where studies can only be performed using facilities, hardware and expertise available within NASA. Full details can be found on the publicly accessible HRP website: humanresearchroadmap.nasa.gov.

HRP funding for almost all EVA research was discontinued during fiscal year 2018, and remains so at the time of this writing, with the rationale provided that microgravity EVA is well understood and that research to inform development of planetary EVA space suits could be delayed several years. This decision was inconsistent with the development xEMU development schedule;

however, the highest-priority EVA human research tasks have continued through alternate funding sources. In November 2018, HRP announced the selection of the *Impaired EVA Performance* study (see Section 3.0.A.1), which was submitted as a proposal in response to an HRP solicitation (Human Exploration Research Opportunities Solicitation: 80JSC017N0001-BPBA Appendix C). While the extent to which HRP will fund other planned EVA human research activities is unknown, the organization of research priorities using the existing HRP Gap structure remains valid.

D. Human System Risks of Decompression Sickness and Hypobaric Hypoxia

In addition to the aforementioned EVA risk, two additional risks that are closely associated with EVA are the *Risk of Decompression Sickness* [9] and the *Risk of Hypobaric Hypoxia*.[10] The primary tasks associated with defining an exploration decompression sickness (DCS) risk mitigation strategy, including validation of exploration prebreathe protocols, are included in this updated plan. The strategy for mitigation of DCS during exploration missions has multiple implications for the development and operation of exploration EVA space suits and host vehicles. The risk of hypobaric hypoxia is bounded by the risk associated with hypoxic exposure during staged decompression strategies used to mitigate DCS and therefore requires a very limited research scope.

E. xEMU Testing and Development Milestones

There is currently no overarching program defining the schedule by which exploration EVA capabilities must be developed. Work on the next-generation space suit is being organized under the xEMU project, which is developing a demonstration exploration space suit (xEMU Demo) that will be delivered to the ISS in 2023. It is being designed to allow for exploration upgrades for subsequent development of the full xEMU, which supports microgravity and lunar surface operations, and eventually a Mars space suit (mEMU). For the purposes of this plan, steps required to enable the xEMU Demo by 2023, followed by lunar surface missions in late 2020s and Mars surface exploration missions in the 2030s, are used as a basis for phasing and prioritization of EVA HITL research efforts. The xEMU Demo development milestones are shown in Figure 2 along with notional milestones for subsequent development of the lunar xEMU. Specific extensibility of the xEMU to the mEMU is not within the scope of the current project. It should be noted that the extent to which aspects of the microgravity-focused xEMU Demo will be extensible to planetary exploration is not yet understood. Additionally, the milestones beyond 2023 are notional and will be updated with formal milestones once those milestones are defined by NASA. The phasing and products of the planned research tasks will also be revised at that time.

F. Organization of the Integrated EVA Human Research and Testing Plan

The HRP EVA Evidence Report [8] explains that review of the EVA Risk within the EVA research community and the NASA Human Systems Risk Board resulted in identification of 23 separate factors that contribute to the risk of injury and compromised performance due to EVA operations. These factors are separated into the interacting domains of Human, Suit, and Operations and are further grouped into categories of suit habitability, in-suit physical environment, EVA factors, crewmember physical state, and crewmember psychological state. The 3 domains, 5 categories, and 24 factors are shown in the EVA Risk Master Logic Diagram (Figure 1) and are described in the Evidence Report along with the an overview of the available evidence for each identified factor.

The mapping of the Human Systems EVA Gaps (Table 2) to the contributing factors identified in Figure 1 is included in Appendix A of the HRP EVA Evidence Report [8].

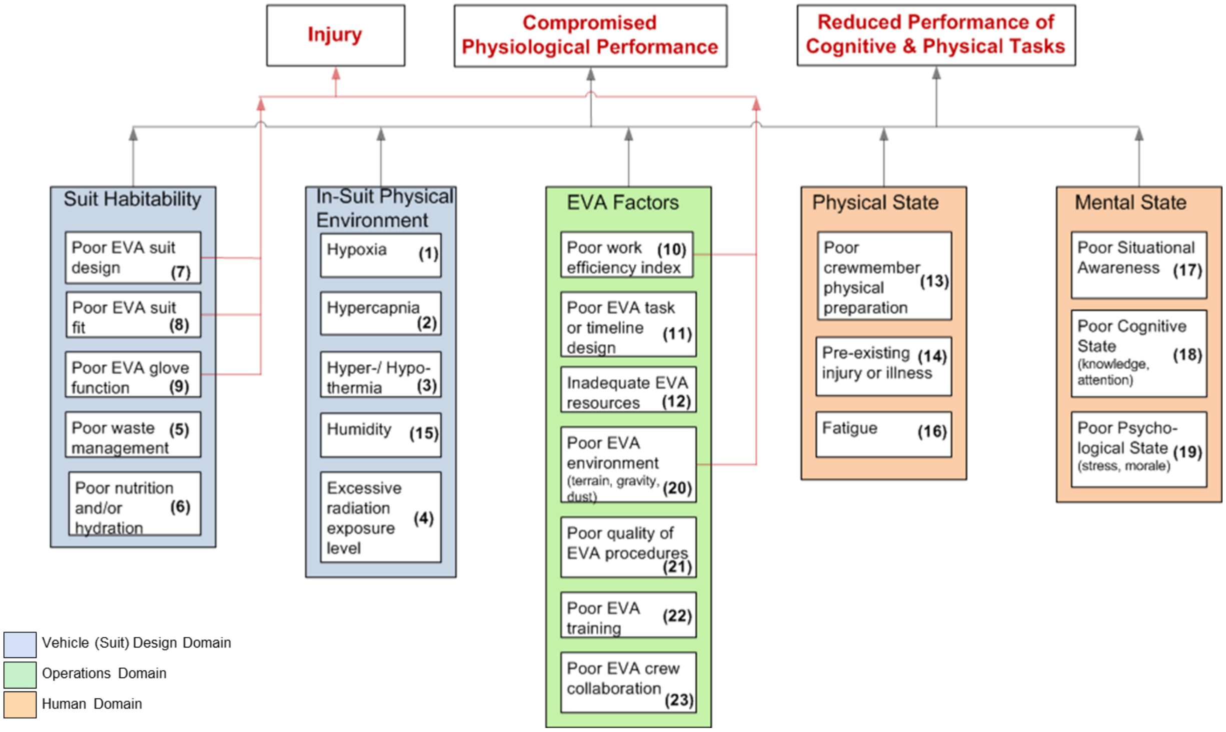


Figure 1. HRP EVA Risk Master Logic Diagram[8].

By comparison, the SMT Gaps are categorized primarily by different EVA systems such as Exploration EVA Avionics, Exploration EVA Tools, etc. Specific gaps are then identified within each system-level category. The different approaches reflect the different perspectives of the corresponding organizations and result in partial but not complete overlap between SMT and Human System Gaps.

For the purposes of organizing the Integrated EVA Human Research and Testing Plan, proposed tasks are grouped by functional areas that approximately map to the Human System EVA Gaps and DCS Risk. All tasks are mapped to at least one Human System Gap and/or an SMT Gap and are briefly described in Section 3.0. The intent of this document is to summarize the integrated plan rather than to provide significant detail on any specific study.

The initial release of the Integrated EVA Human Research and Testing Plan was presented and published as a conference paper in 2016 [3], with subsequent updates being published via a public NASA website in 2017 [4], and via presentations at the 2017 and 2018 NASA EVA Technology Workshops.

Organizationally, the most significant developments since the release of the 2017 plan are the creation of the xEMU project, the elimination of EVA funding by HRP, and the involvement of CHP SMT in EVA human research. Additional detail on organizational structures and prioritization is beyond the scope of this document.

3.0 THE INTEGRATED EXTRAVEHICULAR ACTIVITY HUMAN RESEARCH AND TESTING PLAN

The content is structured around the CHP SMT EVA Gaps. The proposed sequencing of activities within the plan is shown in Figure 2.

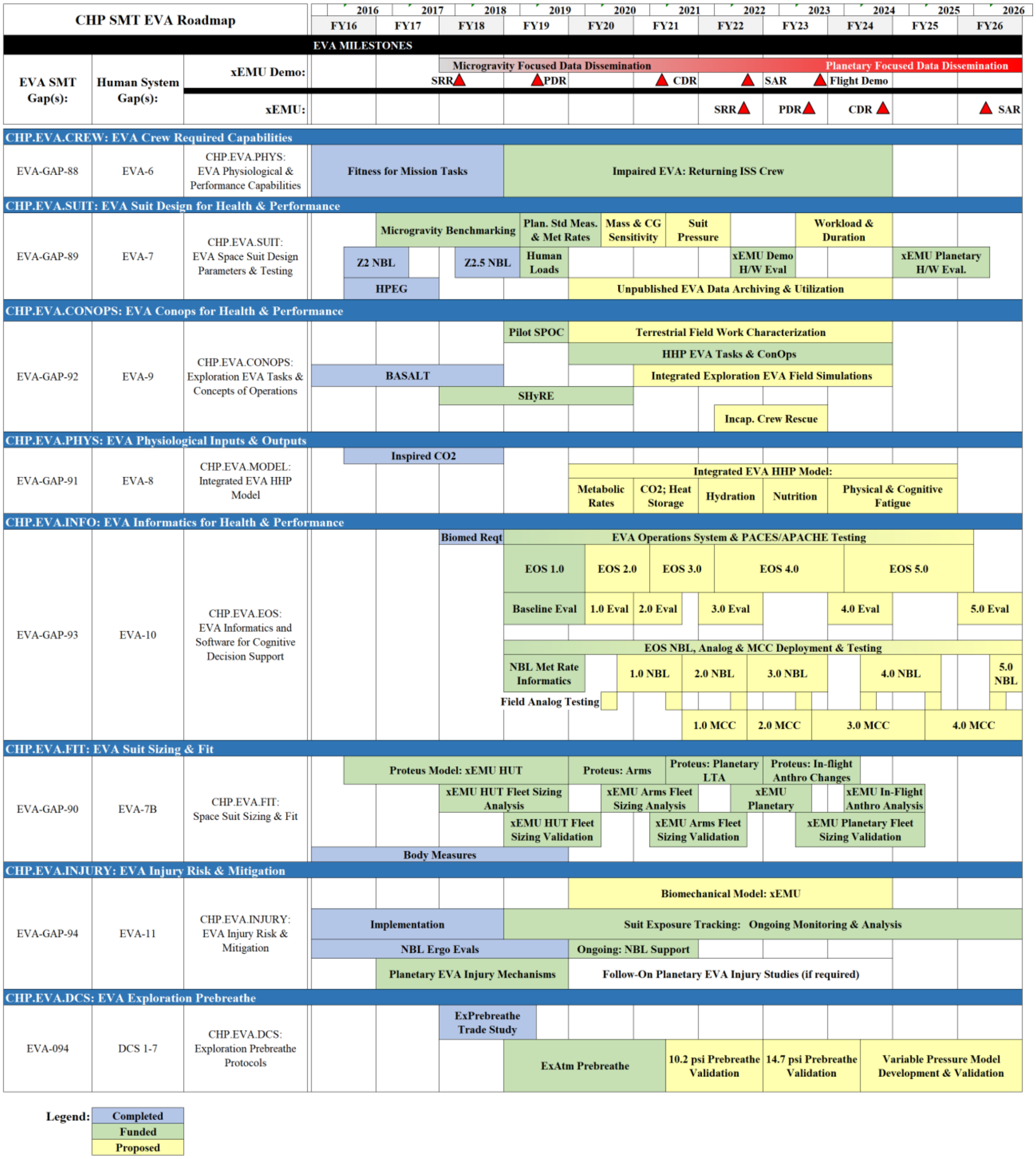


Figure 2. Proposed phasing of tasks in Integrated EVA Human Research and Testing Plan.

A. Crewmember Physiological and Performance Capabilities

Tasks in this section are relevant primarily to the CHP/EVA SMT EVA Crew Required Capabilities Gap and the Human Systems EVA Gap 6: What crew physiological and performance capabilities are required for EVA operations in exploration environments?

1. Impaired EVA Performance and Fitness for Mission Task Validation

Physiological adaptation to the microgravity environment during transit to Mars is likely to result in reduced functional capacity after landing on Mars' surface. While muscular and aerobic capacity may be preserved through inflight countermeasures, returning long-duration ISS crewmembers demonstrate significant decrements in functional performance upon return to a gravity environment due to neurovestibular/sensorimotor adaptation to microgravity that can take days or weeks from which to recover. The implications of such performance decrements are significant since they may affect the ability to perform nominal or contingency EVAs immediately post-landing, potentially requiring increased automation and teleoperation of surface systems. Performance decrements may also necessitate that the Mars Descent Vehicle (MDV) be capable of supporting astronauts for up to two weeks on Mars' surface to allow astronauts to rehabilitate before performing EVAs to egress the MDV and ingress a surface habitat or pressurized rover. Although the focus of this study is to primarily inform Mars exploration, it is unknown to what extent the transition into lunar gravity after an extended microgravity exposure may have similar concerns. Apollo missions were all direct flights to the Moon; future lunar missions may be staged from the Deep Space Gateway after an extended duration in microgravity.

The purpose of the Impaired EVA Performance study is to characterize suited health and performance outcomes in crewmembers as a function of muscular, aerobic, and vestibular/sensorimotor dysfunction after gravitational transitions, which will inform questions such as: how long crew must remain in the MDV before they are able to safely perform EVAs after landing on Mars; which EVA tasks can be performed; and whether systems or operations can be modified to enable earlier post-landing EVA. The study will utilize functional EVA performance outcomes based on the FY19 *Planetary EVA Standard Measures Development & Metabolic Task Characterization* study; however, will be adapted to focus on the "First EVA on Mars" scenario. Test subjects will be returning long-duration ISS crewmembers wearing prototype planetary space suits under simulated reduced-gravity conditions shortly after returning to Earth. Additional non-EVA functional performance testing will also be performed including performance of simulated telerobotic tasks.

Status: In initial preparations. Selected for funding via NASA Research Announcement Human Exploration Research Opportunities (HERO) Solicitation: 80JSC017N0001-BPBA Appendix C. Title: Validation of Fitness for Duty Standards Using Pre- and Post-Flight Capsule Egress and Suited Functional Performance Tasks in Simulated Reduced Gravity. PI: J. Norcross

2. Fitness for Mission Tasks Exercise Studies

HRP funded two studies to use unsuited 1-g simulations of physically demanding critical mission tasks to establish aerobic and muscular fitness for duty standards. Three of the four simulated tasks were EVA tasks and one of those tasks involved the rescue of an incapacitated EVA crewmember. Aerobic and muscular fitness for duty standard recommendations are currently being formulated based, in part, upon the results of the Fitness for Mission Tasks study. These standards will be validated as part of the Impaired EVA Performance & Fitness for Mission Task Validation Study (Section 3.0.A.1).

Status: Study complete. Journal manuscripts currently in review.

B. Suit Design Parameters

Tasks in this section are relevant primarily to the CHP/EVA SMT EVA Suit Design for Health and Performance and EVA Physiological Inputs and Outputs Gaps and the Human Systems EVA Gap 7: How do EVA suit system design parameters affect crew health and performance in exploration environments? These studies are also a primary source of data for the EVA Human Health and Performance (HH&P) Model associated with EVA Gap 8: What are the physiological inputs and outputs associated with EVA operations in exploration environments?

1. EVA Human Health and Performance Benchmarking: EMU Microgravity

Suited performance is understood qualitatively from observation and subjective feedback and decades of effort have been spent attempting to quantify space suited performance with some methodologies being more informative than others. However, a rigorous and comprehensive characterization of the HH&P implications of current and future EVA space suit designs does not yet exist. Standard methods for quantification of specific aspects of suited performance, such as metabolic expenditure or kinematic measures, serve as tools in understanding and describing desired suited performance. Specifically, tools are helpful in providing insight into the performance of full-suit mobility architectures and of individual components, with the goal of aiding selection for specific missions and motions. It is important in the development of these quantitative metrics that a) they be robust for comparisons across suit operators, b) they have sufficient rigor to assess performance across a wide range of user population, and c) that a thorough understanding exists of how the measures are affected by the selected task parameters. Consideration must also be given to the sensitivity and specificity of a selected metric when used to predict an outcome. In this manner, the quantitative metrics will enable inferences to be made across multiple gap areas.

In addition to informing suit design, standard methods are also necessary for many other tasks described in this plan, including the rigorous assessment of the effects of suit fit, aerobic fitness, strength, fatigue, and inspired carbon dioxide (CO_2) on suited human performance. Many of these features are coupled; for example, the suit fit may affect how an operator's underlying strength plays a role in the performance of a specific operational task. With the results from the Benchmarking study, some of these interactions can be examined for a better understanding of their impact. It is imperative that a valid, reliable, and comprehensive methodology for assessing HH&P in space suits is available for xEMU Demo and planetary xEMU requirements verification.

The aim of the EVA HH&P Benchmarking study, initiated in 2016, is to identify a standard set of tasks and metrics with known margins of error, to facilitate a meaningful assessment and comparison of suit configurations and test conditions in current and future studies [11]. Through collaboration with the EVA community, the study aims to identify and develop a methodology to reliably characterize HH&P metrics for individuals working inside EVA suits under microgravity spaceflight conditions. A Subjective Suit Fit assessment methodology will also be developed and implemented as a part of this study. Testing will involve a combination of static offloading and dynamic offloading using the Active Response Gravity Offload Simulator (ARGOS) [12]. The HH&P benchmarking methodology will be used to characterize and compare existing space suits and test subjects will also complete tasks unsuited to provide a reference baseline.

Status: The elimination of HRP funding for EVA human research resulted in the descoping of the initially planned study so that only the shirtsleeve and EMU space suit microgravity conditions, as shown in Figure 3, will be completed. Data collection is near completion at time of this writing. The development of standard tasks and metrics for HH&P in planetary conditions will be developed as a part of the *Planetary EVA Standard Measures & Metabolic Task Characterization* study.

Figure 3. Suited subject in the EMU performs quick disconnect task board as part of the EVA Human Health and Performance Benchmarking Study.

2. Z-2 Neutral Buoyancy Laboratory Mobility Testing and Worksite Assessments

The 'Z-series' planetary EVA suits function as xEMU prototypes with the newest of these being the Z-2.5. The prototype suits are being assessed in a series of HITL evaluations over the next several years, beginning with Neutral Buoyancy Laboratory (NBL) testing, with a particular focus on lower-body mobility requirements for the xEMU and evaluation of ISS EVA worksite access, such as airlock egress/ingress, translation, and interactions with dedicated worksites (Figure 4). The integrated data collection efforts supporting the NBL ergonomic and metabolic assessments, described in Section 3.0.G.4, were leveraged to enable support for Z-2 NBL testing in 2018. The Anthropometry and Biomechanics Facility (ABF) has developed computational photogrammetry techniques, along with commercial off-the-shelf hardware approved by the NBL, to collect underwater data on reach envelope.

During testing, suited subjects performed sets of prescribed reach motions, including isolated arm motions (Figure 5A) and whole-body reach motions (Figure 5B). Subjects held a wand with dive lights attached to each end. A tracking algorithm detected and traced the marker positions on the video images, and the corresponding three-dimensional (3-D) coordinates were triangulated.

The results from 5 subjects demonstrated that overall shapes of the isolated hand-arm reach envelopes are similar between the Z-2 and EMU (Figure 5C). However, the Z-2 suit shows envelopes that are stretched further backward compared to the EMU, with corresponding depth measurement increased by 17 cm, on average. The intersection width and the area between the left and right hand envelope is over three times larger with the Z-2, which indicates a substantially increased capability for cross reaches. For the whole-body reach envelopes (Figure 5D), the volume of reach envelopes demonstrated a 25% increase with the Z-2 compared to the EMU. Also, the intersection between the left and right hand envelopes are more than 3.4 times larger with the Z-2 than EMU. The increased reach volume and cross-reach capability in the Z-2 is potentially a result of the enhanced joints and soft goods mobility of the upper and lower torso assembly.

Status: Complete. Study results were used to inform modifications to the Z-2.5 Hard Upper Torso (HUT) [13-16].

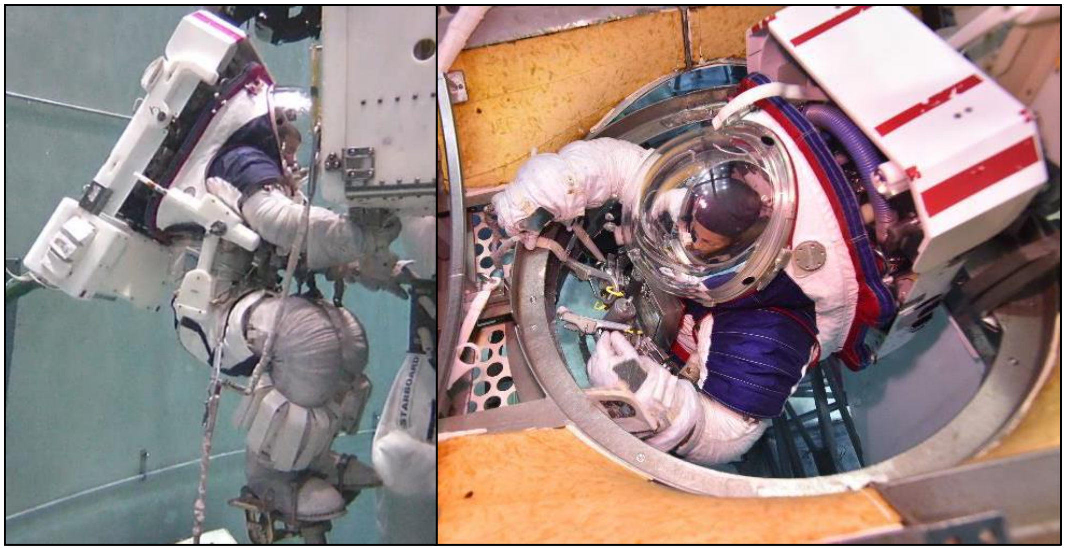


Figure 4. Evaluation of the Z-2 space suit in the NBL.

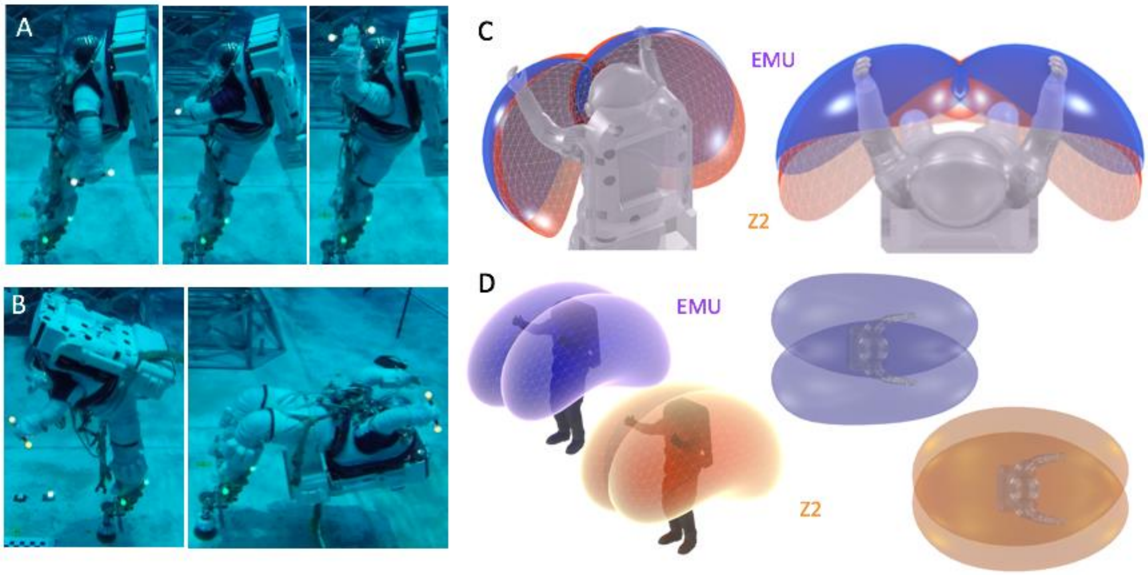


Figure 5. Reach envelope comparison results from the Z-2 NBL test [14]. A: Isolated hand-arm reach motions. B: Whole-body reach motions. C: Approximated envelopes for isolated hand-arm reaches. D: Whole-body reach envelopes.

3. Z-2.5 NBL Testing

The primary objective of the Z-2.5 NBL testing is to evaluate the ability of a crewmember in the Z-2.5 space suit with exploration Portable Life Support Subsystem (PLSS) (xEMU Demo architecture) to perform ISS microgravity tasks. Design changes were made based on data from the Z-2 NBL test series, resulting in a new prototype suit called the Z-2.5 space suit, with the design of the Z-2.5 space suit ultimately feeding into the xEMU Demo. To evaluate the architecture and validate changes from Z-2, this test series will focus on evaluating the microgravity performance of the suit and the ability to complete ISS-related tasks using a complete single NBL training run timeline.

Status: In progress. Completion expected 2019.

4. Planetary EVA Metabolic Task Characterization and Standard Measures Development

Metabolic data from Apollo EVAs are lower than metabolic rates during similar tasks performed in prototype high-mobility planetary EVA suits under simulated reduced gravity, by as much as double in some cases [17-19]. The reason(s) for these differences are not fully characterized, but they may include the limited mobility of the Apollo suit, increased work capacity enabled by higher mobility space suits, comparison of non-equivalent flight and ground-test tasks, compensation for the reduced-gravity simulation environments, and/or other factors. It is important that the xEMU be capable of supporting the anticipated metabolic work rates of crewmembers during planetary EVA and that crewmembers be capable of performing for extended periods at the work rates expected to be required when working in the xEMU. It is therefore also important to accurately predict anticipated metabolic rates during future planetary EVAs.

This collaborative study involving HHPD and CTSD subject matter experts will be designed to enable consensus estimates for metabolic rate profiles for expected planetary EVA tasks.

Additionally, this study will aim to define and implement standard measures that provide a reliable and valid methodology to evaluate the extent to which a suited test condition provides adequate mobility, dexterity, and tactility to enable crewmembers or test subjects to accomplish suited tasks within acceptable physical workload, fatigue, and comfort limits. The resulting methodology will be used in other suited research tasks described in this plan, and will be of particular importance in xEMU Hardware Evaluations, as described in Section 3.0.H.2.

Status: In progress. Completion expected late 2019 / early 2020.

5. Suit Pressure Study

The pressure at which EVA suits operate affects the resistance experienced by crewmembers at individual joints, which can affect the health and performance outcomes for those crewmembers. Lower suit pressure reduces suit joint torques but also increases the risk of DCS. The purpose of this study is to use the *Planetary EVA Standard Measures* methodology (from Section 3.0.B.4) to quantify and compare health and human performance outcomes for human subjects operating in the space suit at a range of pressures from 26.2 kPa (3.8 psia) to 56.5 kPa (8.2 psia). The duration of testing will be adequate to identify fatigue effects. It is not expected that these data will affect suit design, because it is currently assumed that the pressure garment system for exploration missions will be capable of operating at up to 56.5 kPa (8.2 psia); however, results of this study are expected to inform the selection of suit operating pressure(s) used during EVAs, which is a trade between decompression stress at lower suit pressures and increased joint resistance and fatigue at higher pressures. Findings of acceptable health and performance outcomes during extended operations at higher suit pressures could lead to the development of shorter prebreathe protocols if EVAs are to be performed at higher suit pressures, and could even preclude the need for developing habitation and life support systems capable of operating at the Exploration Atmosphere [20].

Status: Planned. Currently unfunded.

6. EVA Workload and Duration

The human health and performance implications of current architectural assumptions of up to 24 hours EVA per person per week for long-duration planetary missions have not been evaluated and may not be credible. The purpose of the *EVA Workload and Duration* study will be to characterize suited health and performance outcomes as a function of EVA duration and frequency, up to 24 hours of EVA in a week. During the Space Shuttle Program, there were times where two astronauts came close to the mark of 24 hours of EVA in a week, but they only had to do this once. The question is not whether it is possible, but whether this pace is sustainable over a longer mission.

It is anticipated that multiple test subjects will perform up to 3 x 8-hour (or 4 x 6-hour) simulated planetary EVAs on ARGOS or NBL in a week. The circuit components of the *Planetary EVA Standard Measures* study will be employed to periodically measure performance during the simulated EVAs. Criteria will be defined and assessed for ending EVAs given specific degrees of decrement in physical and/or cognitive performance. Additional measures of physical and neurocognitive fatigue resulting from EVA performance may also be incorporated based on the *NBL Ergonomic Assessments and Metabolic Rates* task (Section 3.0.G.4). The types, frequencies, and durations of tasks performed during the EVA simulations will be based on the *HH&P EVA Tasks and ConOps*. The simulated suit mass will be informed by the *Mass Sensitivity* study (Section 3.0.B.8).

Opportunities to incorporate this study within end-to-end mission simulations such as Human Exploration Research Analog (HERA) will be investigated since the pre- and post-EVA workload associated with maintenance and preparation of EVA hardware should also be considered. For best engineering data, this investigation would be performed with a high fidelity system requiring realistic maintenance to assess the success of efforts to ease and limit required maintenance.

Note: This task is also considered to apply directly to the Human Systems EVA Gap 9 (EVA Tasks and ConOps).

Status: Planned. Currently unfunded.

7. High Performance EVA Glove Prototype Evaluations

The design and fit of EVA gloves affects the performance of tasks requiring manual dexterity and gripping and also affects the risk of fingernail delamination and other hand and finger trauma. Almost all EVA suits and EVA gloves are designed with a common glove attachment mechanism, meaning that most EVA gloves are interchangeable across different suits. Thus, the benchmarking of EVA gloves will be considered separately from the benchmarking of EVA suits, although testing is preferably performed by subjects wearing a pressurized suit as opposed to a glove box. It is understood, however, that logistics may sometimes preclude the availability of suits for use in these evaluations, especially in cases where glove sizes are being built for subjects who may fall on the extreme ends of the suit sizing spectrum.

The purpose of the High Performance EVA Glove (HPEG) evaluations was to identify and use a standard set of tasks and metrics, with known margins of error, to facilitate meaningful assessment and comparison of human health and performance when using different EVA glove designs and configurations. FY17 evaluations included assessment of prototype gloves in the B34 glove box, as well as use of the ABF sensor glove in the NBL for assessment of stresses and strains as well as heat and humidity seen at the hands during EVA glove use. This task is relevant to the *Gloves I* and *Gloves II* CHP/EVA SMT Gaps.

Status: The HPEG project has concluded, and is documented with a variety of publications that detail the tests that were conducted and pertinent results [21-25].

8. Mass and Center of Gravity Sensitivity Study

It is known that the mass and center of gravity (CG) of space suits affects the ability of suited crewmembers to perform mission tasks during planetary EVA [26]. However, existing data are inadequate to accurately predict acceptable mass and CG combinations for the xEMU. The primary objective of this study is to develop an adjustable mass and CG simulation and evaluate the acceptability of the proposed mass/CG of the xEMU for performance of planetary EVA tasks using the *Planetary EVA Standard Measures*.

The secondary objective is to evaluate the sensitivity of human health and performance measures to changes in simulated suit mass, CG, and gravity level. The range of masses and CGs evaluated will be based on the likely range of achievable masses and CGs anticipated for the xEMU planetary suit. Results of this study are expected to inform suit mass and primary life support system trades. For example, results may show that mass reductions beyond a threshold value yield negligible changes in human health and performance outcomes or that increases above a threshold value result in significant increases in workload and consumables usage. In addition, results could show that overall suited mass may be the primary driver for performance in Mars gravity but that

CG impacts performance more in lunar gravity. For these reasons, results will also directly inform the design of the *EVA Workload and Duration* study.

Status: Planned. Currently unfunded.

9. Review and Archiving of Unpublished EVA Test Data

Human testing of EVA suits and suit prototypes has been ongoing for decades with many results published in conference papers, NASA technical reports, and peer-reviewed journal papers. However, results of many tests are not published or archived in a way that is readily searchable or accessible by anybody other than the person or people directly responsible for conducting the study. In many cases, the fact that the studies have even occurred is often known only by a small number of people, and many of the generation of scientists and engineers responsible for EVA testing in the 1960s and 1970s are now at or approaching retirement age. The purpose of this task is to update and/or develop a supplement to the HRP EVA Evidence Report and EVA Engineering archives with relevant findings from unpublished research studies that will be identified primarily through discussions and interviews with engineers in EVA Engineering and the EVA Office at Johnson Space Center (JSC).

Status: Currently unfunded.

C. EVA Consumables and Life Support Parameters

Tasks in this section are primarily associated with the CHP/EVA SMT EVA Physiological Inputs and Outputs and the Gap EVA Gap 8: What are the physiological inputs and outputs associated with EVA operations in exploration environments?

1. Carbon Dioxide (CO_2) Washout; Inspired CO_2 Requirement

Exposure to excessive levels of CO_2 can lead to hypercapnia, with consequences including reduced cognitive performance, fatigue, dizziness, reduced visual acuity, headache, panic, and ultimately convulsions, unconsciousness, or death [27-29]. Adequate elimination of CO_2 produced by respiration is therefore an essential requirement for space suits. The elimination of exhaled CO_2 from the space suit helmet is commonly referred to as washout and the effectiveness with which washout occurs is affected by many factors related to the design and operation of the space suit hardware as well as the characteristics and activities of the person inside the space suit.

The importance and challenge of accurately measuring CO_2 washout is not unique to space suits; a variety of methods have been developed and used to measure CO_2 washout in respiratory protective equipment (RPE) for use in industries such as diving, firefighting, and aviation. Previous studies conducted at JSC have compared different sampling methodologies but have not yet enabled definition of a standardized test procedure [30-32]. The results of these previous studies in combination with unpublished laboratory testing indicates that the accuracy and reliability of inspired CO_2 measurements inside space suits depends on many variables related to the measurement equipment setup, the analysis methods used, as well as the human subjects themselves.

The overarching objective of this task was to thoroughly review existing test methodologies and test data in conjunction with systematic quantification of potential sources of measurement error to inform the definition of a standard procedure for the measurement of inspired CO_2 in space suits. Determination of a standard methodology for quantification of inspired CO_2 inside space suits as well as definition of an evidence-based standard for acceptable levels of inspired CO_2 is relevant to Human Systems EVA Gap 7 as well as the CHP/EVA SMT Ventilation Gap.

Testing included a thorough review of existing methodologies for CO_2 washout measurement followed by unmanned laboratory testing using calibration gas, unsuited human testing, and suited human testing using the EMU. Results characterized sources of variability associated with measurement equipment and methods as well as intra-subject and inter-subject variability associated with HITL testing of CO_2 washout. The EMU data provided a reference for the current CO_2 washout capability using the newly established standard testing methodology. These results were then used to model historical EVA CO_2 exposure experience using both flight EVA and NBL training data. This work resulted in the definition of an inspired CO_2 requirement for the xEMU and an updated standard in NASA-STD-3001 Volume 2 Rev. B that is applicable to all future EVA suits.

Status: Study complete. CO_2 requirement included in SSP 51073 (xEMU Requirements) and will be included in an update to NASA-STD-3001 Volume 2 [33] Revision B, which is currently in internal NASA review. Technical reports and journal manuscripts are in preparation. Results of this effort determined the nominal CO_2 exposure requirements and some forward works exists to define an acceptable off-nominal CO_2 exposure limit.

2. EVA Human Health and Performance Model

The EVA HH&P Model will be a model for providing time-varying estimates of EVA translation distances, joint cycles, ground reaction force dose, decompression stress, workload, physical and cognitive fatigue, hydration, metabolic rates, heat storage, inspired CO_2 exposure, and consumables usage rates when given model inputs including suit mass, gravity level, task type, and other individualized health and performance predictors. Additional metrics determined through the *Planetary EVA Standard Measures* study may also prove valuable in this parametric model as surrogates for values that cannot be directly estimated or measured, and data from the *EVA Workload and Duration* study may also be used to incorporate fatigue-related effects. Model outputs will inform fitness for duty standards, exercise prescriptions, prebreathe validation protocols, suit lifecycle information for certification profiles, EVA consumables sizing, and may also inform exploration concepts of operations, task design, and eventual exploration EVA planning. This model will also function as a core component of the *EVA Operations System (EOS)*, described in Section 3.0.E.3.

The model will use a combination of data from HITL testing, flight, and training data, as well as physics-based models where available. The model will begin with existing datasets and physics-based models and will be incrementally updated and validated through prediction and incorporation of additional datasets as they become available. Studies associated with Human Systems EVA Gaps 6, 7, and 9 will provide the primary sources of empirical data; however, the EVA Biomechanical model may also eventually be capable of enhancing the predictive capacity of the EVA HH&P Model.

Status: Planned. Currently unfunded.

D. EVA Tasks and Concepts of Operations

Tasks in this section are relevant primarily to the CHP/EVA SMT EVA Tasks and Concepts of Operations (ConOps) for Health and Performance Gap and Human Systems EVA Gap 9: What is the effect on crew performance and health of variations in EVA task design and operations concepts for exploration environments?

1. Human Health and Performance EVA Tasks and ConOps

The EVA research tasks described in this plan require definition of the assumed EVA tasks and ConOps during future mission architectures and, in some cases, results of these research tasks will, in turn, inform changes or add detail to those tasks, ConOps, and even to overall mission architectures. This activity will serve as a focusing element to develop and maintain a single set of consistent assumptions with respect to EVA tasks and ConOps as they pertain to HH&P.

While EVA ConOps documents are maintained for design reference missions by the EVA Office (EVA-EXP-0042), in some cases they do not include the necessary detail to inform the design of HH&P studies or they lack detail on expected human constraints and considerations that may affect architectural decisions. Through close coordination with the EVA Office, existing ConOps documents will be supplemented with relevant HH&P data and assumptions, including information such as estimated metabolic rates, ground reaction forces, task types and frequencies, and decompression profiles. The EVA HH&P Model is expected to serve as the source of data in many cases. Through coordination with the EVA Exploration Working Group (EEWG), this document will be developed and then periodically reviewed and updated based on results of research studies, architectural trade studies, and changes to design reference missions. A similar document was developed for lunar surface operations during the Constellation Program [34].

In addition to the documentation and assimilation of existing data sets made available from other studies, this study will use existing studies such as Biologic Analog Science Associated with Lava Terrains (BASALT), funded by the Science Mission Directorate (SMD), and possibly other SMD-funded analog studies, as a source of task characterization data. At a minimum, data are expected to include the types, durations, and frequencies of tasks, distances and terrains traversed, and may also include perceived exertion, heart rate, joint kinematics, and even metabolic rate data, if possible. Although SMD-funded studies are unsuited and in 1-g, they represent real geological and biological exploration operations and therefore are reasonable approximations of what might be attempted during planetary EVAs as well as a physiological baseline against which to compare predicted planetary EVA workload. Data from 1-g unsuited exploration environments and data from suited, reduced-gravity tests such as the *Planetary EVA Standard Measures* study will then be combined within the *EVA HH&P Model*. These data are also synergistic with the *EVA Biomechanical Model* (Section 3.0.G.1) and can be used to computationally assess performance decrements for specific ConOps profiles.

Status: Planned.

2. Integrated Exploration EVA Field Simulations

Integrated exploration EVA field simulations, similar to Desert Research and Technology Studies (DRATS) tests from 2008-2011, can serve as an important opportunity to evaluate exploration ConOps, capabilities, and prototype technologies in an environment that combines high-fidelity flight-like operations, integration with multiple other systems, and includes many of the other flight-like challenges associated with field environments such as dust, rough terrain, and communication challenges. In the past, such tests have also served as valuable focusing elements and milestones for multiple separate but interrelated projects.

The scope, location, and timing of these simulations is not detailed here, but is expected to involve implementation and testing of the current exploration ConOps and surface system prototypes such as rovers and EVA tools. These tests may not include pressurized suit testing, due to the lack of a portable gravity offload system at this time, but are expected to use prototype xEMU informatics in combination with the *EVA Operations System* (*EOS* – see Section 3.0.E.3).

Status. Planned. Currently unfunded.

3. *Physical And Cognitive Exploration Simulations/Assessments of Physiology and Cognition in Hybrid Reality Environments*

The development of technologies and operations concepts to enable safe, effective, and efficient exploration EVAs requires that candidate approaches be rigorously evaluated in operationally relevant environments. ISS is a poor analog for exploration EVA research, and prototype space suits are limited in their availability and are difficult to test under conditions that are representative of exploration EVA operations due to their excessive weight when used in Earth gravity. Laboratory testing of prototype exploration space suits is typically performed to evaluate physiology, biomechanics, and human factors, and is conducted without the cognitive demands and constraints of a realistic operational environment. Meanwhile, analog testing during scientific field studies may be used to evaluate operations concepts and technologies, but are not physiologically representative of exploration EVA conditions and such tests generally include limited simulations of cognitive workload and little or no capacity to measure cognitive performance.

Physical And Cognitive Exploration Simulations (PACES) is being developed as a complement of scenarios, tasks, procedures, sensors, information systems, displays, interfaces, and metrics that simulates realistic (and variable) physical and cognitive workload using realistic exploration scenarios and wherein performance of operationally relevant tasks, both physical and cognitive, is quantified. PACES will enable in-situ measurement of operationally relevant task performance under realistic exploration scenarios and will be usable (in part or in whole) across multiple test environments.

PACES is being developed such that most elements of the simulations, including the embedded physical and cognitive performance metrics, will be usable under shirt-sleeve, hybrid reality, and suited test conditions. This approach will mean that testing of preliminary concepts or candidate technologies can be performed at relatively low cost and with larger sample sizes, with follow-on testing of down-selected concepts or with smaller sample sizes possible under suited conditions using comparable methods and metrics.

PACES is being developed such that the impact of changes to EVA design parameters such as displays, biosensors, informatics, and metabolic- and thermal-control algorithms, as well as different concepts of operation, can be evaluated using simulated EVA scenarios that accurately replicate the physical and cognitive workload of real EVAs, while also using quantitative and operationally relevant metrics of physical and cognitive performance. The EOS, described later in this document (Section 3.0.E.3), consists of a suite of EVA support software, information systems, data visualizations, decision support systems, and the framework and process by which these are developed, tested, and implemented. The “baseline” version of EOS approximates present-day capabilities and is considered a part of PACES. Future EOS builds will be developed and tested using the PACES methodology. It is also anticipated that PACES will also be used to evaluate the implications of factors such as fatigue, hydration, heat storage, and humidity.

Within the PACES methodology, subjects will be outfitted and tasked so as to reproduce approximate physical workloads measured during multiple previous suit tests in reduced-gravity simulations. Cognitive workloads will be simulated through a combination of flight-like tasks including life support monitoring, timeline management, communication, navigation, and procedure execution. Performance on simulated cognitive tasks will be measured using a combination of subjective measures, explicit queries, and implicit performance measures such as task completion times, error rates, and deviation rates. Initially, PACES consists of a single EVA test subject and an intravehicular (IV) surrogate or test operator. It is planned that the simulation will later expand to include multiple EV and IV crewmembers, as well as non-EVA scenarios, which will enable further evaluations of operational concepts, communication methods, and research questions of team dynamics and trust. "Modules" of exploration tasks (e.g., airlock egress and ingress; EVA maintenance task; instrument deployment task, etc.) are being developed, which can be combined to enable multi-hour end-to-end simulations.

Assessments of Physiology And Cognition in Hybrid-reality Environments (APACHE) is the primary test environment within which the PACES complement is being developed and will be utilized during future studies. A hybrid-reality EVA environment as well as computer models of spacecraft systems have already been developed and are continuing to be evolved by internal NASA engineering collaborators. The purpose of APACHE is to adapt and implement existing hybrid reality efforts into an integrated hybrid reality simulation, incorporating the full PACES complement of scenarios, tasks, procedures, sensors, information systems, displays, interfaces, and metrics. APACHE is being developed within the hi-bay area of the Human Performance Laboratory (JSC Building 21) and will provide a rigorous, repeatable, affordable, and readily available environment for the iterative development, testing, and utilization of PACES.

Status: Ongoing. Pilot work is being conducted in 2019.

4. Scientific Hybrid Reality Environments

The use of analog environments in preparing for future planetary surface exploration is key in ensuring we both understand the processes shaping other planetary surfaces as well as develop the technology, systems, and concepts of operations necessary to operate in these geologic environments. While conducting fieldwork and testing technology in relevant terrestrial field environments is crucial in this development, it is often the case that operational testing requires a time-intensive iterative process that is hampered by the rigorous conditions (e.g. terrain, weather, location, etc.) found in most field environments. Additionally, field deployments can be costly and logistically challenging, typically limiting the testing opportunities to only once or twice per year.

To overcome these inherent challenges, Scientific Hybrid Reality Environments (SHyRE) is a Planetary Science and Technology from Analog Research (PSTAR) funded, multiyear campaign aimed at developing a scientifically robust analog environment using a new and innovative hybrid reality (HR) setting that addresses these limitations [35, 36]. HR is unique in that operators not only work within a virtual environment, but physical objects, advanced tracking systems, and various other technologies (e.g. procedure assistant, voice recognition, feature tracking, etc.) are also incorporated to create a highly realistic and immersive simulated environment.

To date, the SHyRE program has integrated handheld scientific instruments into a scientifically relevant geologic scene and developed a preliminary set of human planetary exploration testing scenarios. These scenarios include part-task training and procedure development of the scientific instruments as well as prototyped informatics displays to study in-situ data analysis and utilization.

The application of this analog environment has immediate implications and opportunities to inform future planetary missions and science investigations by rapidly prototyping and testing new scientific instruments with relevant data processing activities (e.g. archiving and analysis) embedded within realistic/envisioned flight operational constraints. It is anticipated that relevant elements of the SHyRE environment will be incorporated as "modules" into future PACES simulations and vice-versa, with significant overlap in personnel and technologies already existing between the projects.

Status: Ongoing [35, 36].

5. Biologic Analog Science Associated with Lava Terrains

The BASALT project is investigating tools and techniques for conducting real (non-simulated) Mars-relevant field science under simulated spaceflight mission conditions. This is accomplished through science-driven field deployments to Mars-analog terrestrial locations during which iterative development, testing, and assessment of candidate operational concepts (ConOps) and capabilities for future Mars exploration EVA is conducted. BASALT builds upon the heritage testing and lessons learned from the NASA DRATS, Pavilion Lake Research Project (PLRP), and NASA Extreme Environment Mission Operations (NEEMO). BASALT also incorporates current NASA architectural assumptions for future planetary missions, including long-duration (i.e., multiyear) exploration programs, limited crew size (i.e., 4-6), space-to-ground communication challenges, and data transfer limitations.

BASALT research objectives focus on ConOps and capabilities that enable remote, Earth-based scientists to provide meaningful scientific input to EV and IV crewmembers within an EVA while subject to Mars-relevant time delays and bandwidth constraints. Results from field testing to-date have revealed that through the strategic design of EVA timelines and traverses and the inclusion of appropriate capabilities, remote scientists can indeed provide meaningful recommendations that enhance science return without incurring crew idle (i.e., nonproductive) time. The BASALT project has also identified and evaluated a number of new capabilities, including a host of additional features and functions associated with capabilities previously investigated at other NASA analogs that support EV, IV, and MSC science operations. Virtual training environments, mixed-reality 3-D terrain models, and telepresence systems have proven especially fruitful and are anticipated to be the focus of follow-on work.

Status: Nearing Completion. Several publications were recently published in a special issue of Astrobiology focused on the BASALT project [37-41].

6. Terrestrial Fieldwork Characterization

There remains a lack of understanding regarding the intrinsic operational challenges, success criteria, cadence, and behaviors that field scientists must overcome and exhibit to achieve their fieldwork objectives in present-day terrestrial settings, let alone hypothesized future spaceflight missions. This task aims to rigorously characterize the physical and cognitive demands associated with "Earth-normal" scientific fieldwork, results of which will then be used to inform the development and testing of ConOps, tools, technologies, and techniques in laboratory environments such as PACES, SHyRE, and ARGOS, where the physical, cognitive, and operational constraints of spaceflight can be more realistically simulated as compared with field analogs.

Pilot work has been initiated, the purpose of which is to separate the confounding relationships between analog fieldwork influenced by speculative spaceflight capabilities and constraints, and more directly study the rudimentary components of the scientific process within traditional terrestrial fieldwork. This work aims to characterize the work performed by field scientists to understand the moment-to-moment relationships between the cognitive challenges and physical behaviors demonstrated throughout their lunar-relevant field campaigns. These insights will then integrate into ongoing complementary development and testing activities at NASA JSC that incorporate high-fidelity spaceflight constraints. As a result, this project will generate grounded work representations that span multiday, multisite fieldwork campaigns to better define spaceflight exploration concepts and technologies that account for realistic scientific fieldwork demands and productivity.

The *EVA Workload and Duration* study, as well as future evaluations of EOS and xEMU Informatics using PACES will utilize ConOps that are based on the results of these studies.

Status: Pilot work initiated. Full project planned but currently unfunded.

7. Incapacitated Crewmember Rescue

The Incapacitated Crewmember Rescue CHP/EVA SMT Gap specifically identifies the need to develop methodology for transfer/transport of an incapacitated crewmember at each destination and how to transfer him/her onto the ingress/egress hardware or through side hatch, and doff suit. As described previously, the Fitness for Mission Tasks studies also plan to use this task in determining fitness for duty standards. While previous studies have been conducted [42, 43], the limited fidelity and scope of those studies have precluded the establishment of a baseline protocol for this important contingency EVA task. The purpose of this study is to design, build, and test high-fidelity concepts for incapacitated EVA crewmember rescue. Test environments may include NEEMO [42], NBL, and/or ARGOS, as well as 1-g testing. Results are expected to directly inform design features required to facilitate EVA rescue.

Status: Planned.

E. EVA Informatics and Decision Support Systems

The tasks described in this section are relevant to the CHP/EVA SMT Informatics for Health and Performance Gap and EVA Human Systems Risk Gap 10: How can knowledge and use of real-time physiological and system parameters during EVA operations improve crew health and performance?

This version of the Integrated EVA Human Research and Testing Plan includes significant additional detail in the area of EVA Decision Support Systems (DSS). DSS can be thought of as a distinct class of work support tools that fit within a suite of operations systems that enable human spaceflight operations across all phases of a mission. Existing technology development roadmaps lack an overarching program that feeds directly to the design and development of software capabilities that support the volume and variety of work support needs to enable future spaceflight operations beyond ISS operations. This document does not address the broader DSS needs of future missions, but focuses on EVA DSS.

During ISS EVA operations, a fleet of ground support personnel use Microsoft Office products, custom console displays, mental calculations, and handwritten notes to manually monitor suit/vehicle systems as well as manually adjust timeline elements such as tasks and detailed procedures, all while the crewmembers are actively engaged in manual tasks. More critically, solutions to issues/hazards such as hardware configurations, incorrect procedure execution, and life support system diagnosis are mostly provided in real-time by ground support personnel [44]. While this has worked acceptably for ISS EVAs, lunar and Martian exploration EVAs will be more physically demanding, more frequent, more hazardous, and less structured than ISS EVAs, which are typically very well-rehearsed by all members of the flight and ground crew prior to execution. The inherently unpredictable nature of exploration EVAs in combination with the decreased communication bandwidths and increasing communication latencies between ground support teams and inflight crewmembers will further necessitate the reallocation of system monitoring and decision-making responsibilities to the inflight crewmembers and their support systems.

There is a prevalent assumption that, by providing future crewmembers with all the available information on a helmet-mounted or arm-cuff display, they will be able to both manage the EVA timeline and systems all while actually executing the EVA tasks. Such an approach is not feasible without significant investment in decision support systems; the experience, cognitive capacity, and judgement of multiple expert EVA ground controllers cannot simply be replaced by provision of additional crewmember displays. Empowering crewmembers and ground controllers with the information they need, when they need it, is critical to enabling the increasingly autonomous operations required by Exploration-class missions.

Decision support systems for exploration will consist of suites of tools and capabilities for the creation, distribution, manipulation, and utilization of operationally relevant workflows and data. Tools and capabilities are expected to consist of sensors, displays, interfaces, models and software distributed across vehicle, space suit, and ground control systems. In some cases, within- and between-individual differences in metabolic profiles, CO_2 production, aerobic capacity, muscle strength, task performance, cognitive and physiological state, and other operationally relevant factors may also be incorporated to enable individualized decision support (as currently provided through ground-based flight surgeon judgement).

Applications of an EVA DSS capability will span all mission phases, including mission planning and development, training, mission execution, and post-mission analysis and archiving. Some specific design and development efforts that resemble this concept have occurred in recent years [45, 46] and more broadly to support EVA operations from an IV operator position [47-50]. However, there remains the need for construction of an EVA DSS framework and strategy that encompasses the broad range of DSS capabilities to support the future exploration EVA work domain. Tasks described in this section are intended to provide this framework and strategy.

1. EVA Biomedical Monitoring Requirements Definition

This task involved coordination between numerous EVA stakeholders to seek consensus on the biomedical monitoring requirements for exploration EVA missions. Beginning with requirements and rationale developed during the Constellation Program, the multidisciplinary team considered which data are minimally necessary. The final products were an update to NASA Standard 3001 Volume 2 [33] and the xEMU requirements documents (SSP 51073 and CTSD-ADV-1188).

Status: Ongoing. Although the minimum set of requirements has been established, the concept of operations is still in work, and will be defined in new Exploration programs and led by xEMU documentation. Other tasks including *PACES, EOS,* and *xEMU Informatics Interfaces* will further define these concept of operations. Open questions include whether data should be self-monitored, monitored by another crewmember, monitored by the ground, and/or monitored by an algorithm.

More specific knowledge gaps and associated tests may be identified if existing literature and experience are found to be inadequate to make specific recommendations.

2. NBL Metabolic Rate Informatics

The H-3PO Laboratory measures and records metabolic rates during certain EVA training runs at the NBL as part of a medical requirement for ISS. These metabolic rate profiles provide flight surgeons, biomedical engineers, and EVA planners with important information regarding normal and expected metabolic rates for specific tasks, which can vary significantly from crewmember to crewmember. Metabolic rate feedback has also been requested by some crewmembers for use as a training aid, with lower metabolic rates often associated with improved task performance efficiency. The data are also valuable in investigating mishaps or anomalies that can occur during NBL training and testing.

In 2018, H-3PO was asked to begin collecting metabolic rates during all NBL runs, rather than the subset of runs during which they were previously recorded. Additionally, the H-3PO team recognized opportunities to improve the efficiency with which metabolic rate data were both recorded and processed, as well as possibly improving the utility of the data to trainers and crewmembers by making it available immediately post-run, and possibly in real-time during runs.

The purpose of this task is to automate the metabolic rate data collection, to make the unprocessed data available to trainers in the control room during NBL runs, and to begin expediting the process by which data is processed to provide individualized task-by-task metabolic rate estimates for each crewmember.

Status: Ongoing. Funded by CHP SMT and led by H-3PO Laboratory. Completion is expected in 2019. This is a component task of the broader *EOS*, described next.

3. EVA Operations System

EOS is a suite of decision support tools and capabilities for the creation, distribution, and utilization of operationally relevant EVA workflows and data. Tools and capabilities are expected to consist of sensors, displays, interfaces, models, and software distributed across EVA systems, including not only EVA crewmembers and their space suits, but also IV crewmembers and Mission Control Center (MCC). Applications of EOS span all EVA mission phases, including mission planning and development, mission execution, and post-mission analysis and archiving. The EOS platform aims to iteratively prototype and evaluate potential EVA data streams, visualization tools, algorithms, and interfaces within current operations and proto-flight testing environments with the purpose of meaningfully influencing and enhancing EVA operations and informatics.

The relevant communities of EVA stakeholders that EOS aims to support include: EVA and Program Management, Engineering, Crew Health and Performance, Operations, Safety and Mission Assurance, and Researchers. Each of these EVA stakeholders all have specific EVA interests, needs, and desired contributions to the development of future EVA concepts to which EOS can provide customized and extensible solutions to meet these users' needs. In doing so, specific capabilities that are demonstrated to meaningfully enhance EVA operations will be brought forward for consideration for flight implementation.

The EOS platform enables users to prepare, live, and re-live EVA experience(s) to discover higher-level insights/structure whether it be within present-day EVA operations or for future Exploration EVA settings. Specifically, EOS provides a suite of user-friendly tools to:

1. Reliably ingest relevant data sources into a platform for real-time operations support and post-hoc research/analysis
2. Visualization tools for time series data to overcome challenges associated with multiple time series data streams collected from disparate data sources
3. Create reproducible and collaborative data archiving and analysis pipelines
4. Share data and processes with other EVA stakeholders
5. Interface with other Crew Health and Performance data systems (e.g., habitat, exercise, medical) to provide a comprehensive analysis of crew status

In summary, the EOS platform enables a 'practice like you play' approach to the EVA community to more appropriately discover and demonstrate the capabilities desired to support present-day and future EVA operations.

Figure 6 provides an example of users' needs related to the integration of physiological and operational data. In the example, data that are collected during real and simulated EVA conditions can be automatically associated with tasks being performed using an EVA planner (i.e., digital timeline tool). Task execution and physiological performance data can be archived during EVA execution, generating an ever-increasing relational database of physiological and life support data. These data can then be combined with physics-based and data-based models of life support systems, physiology, health, and performance, which together provide an extensible capacity to predict the capabilities and constraints of the EVA-human system to the resolution of specific crew and hardware. The intent here is that *a priori* EVA data can inform EVA operations and vice versa, thereby 'closing the loop' between the EVA development, planning, execution, and analysis processes.

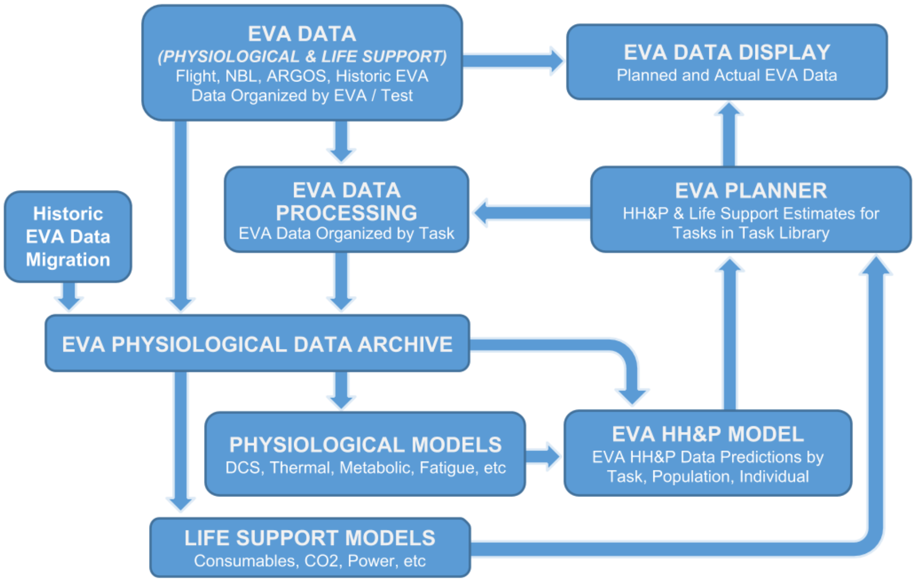


Figure 6. Example of EVA data sources, models, and capabilities integrated to provide enhanced functionality. Note that this example is not encompassing of all anticipated EOS functions and user cases.

EOS will be iteratively developed, tested, and implemented across multiple laboratory, analog, training, and, ultimately, flight environments, using open source and existing software tools and teams (e.g., OpenMCT) wherever possible. Prototype EVA data streams, visualization tools, and algorithms will first be developed and tested within a lab-based EVA simulation environment (i.e., APACHE) before being deployed to actual EVA training environments (e.g., NBL, ARGOS) for further evaluation and user feedback. Deployments into Mission Control and future spacecraft and potentially space suits for flight use will follow. Capabilities will be developed, tested, and deployed incrementally over multiple years.

The identification and design of future EOS features will be based on quantitative assessments and prioritized user needs. Table 3 identifies a notional list of capabilities and progression for the capabilities to be developed, deployed, and evaluated during instances of EOS; however, the actual progression will be continually evaluated and updated as EOS capabilities and user needs are better understood.

Table 3. Notional Capabilities and Progression of the EVA Operations System

Users	**Parameter**	**Baseline**	**EOS 1**	**EOS 2**	**EOS 3**	**EOS 4**
Crew Health/ Performance Flight surgeon	Physiological /Thermal	Rate, rhythm Biomed harness	Rate, HRV TBD physio monitor	Rate, ?HRV **xEMU** biomed	-	-
Crew Health/ Performance Flight surgeon	Cognitive load	-	Basic metrics	Track errors	Predict errors/warning for cognitive overload	
Additional Users	-	-	-	-	-	-

Development, testing, and implementation within ground laboratory environments enables rapid and cost-effective design-build-test cycles. The utilization of analogs such as HERA and other settings may also be utilized on a case-by-case basis, depending on the specific capabilities being evaluated, compatibility with other analog mission objectives, and the availability of necessary data infrastructure. It is anticipated that the NBL will be a valuable test environment on the path to flight due to the availability of space suits, EVA-trained astronauts, EVA flight-controllers and trainers, and a control room. In fact, the capabilities provided by EOS are expected to provide direct benefit to the NBL training environment. Likewise, the NBL will be used as an analog environment to evaluate the utility of EOS functions in current and future flight-like EVA simulations.

Eventually, if one or more EOS capabilities are evaluated as being sufficiently enhancing to justify use during EVA operations, those capabilities will be transitioned to flight. The path by which EOS capabilities are transitioned to flight will depend on whether those capabilities are sensors, displays, interfaces, and/or software, and whether that hardware or software is extravehicular, IV, or within MCC. In the case of IV, MCC, and NBL software tools, it is anticipated that EOS capabilities could be transitioned to ISS EVA operations in time to support the xEMU Demo EVAs in 2023, and potentially before.

Status: Elements of EOS are currently being developed under multiple existing tasks and projects, including *NBL Metabolic Rate Informatics, PACES, APACHE, SHyRE, Terrestrial Fieldwork Characterization*, and *NEEMO*. A detailed EOS vision and project plan document is being developed that is intended to ensure that these complementary efforts are appropriately coordinated and planned with input from the broader EVA community. The extent to which future EOS development will be funded is not yet known.

4. xEMU Informatics Interfaces

A human interface is required to navigate the noncritical informatics system, while not interfering with critical display information. This technology would be required for full evaluation of the informatics system, since it is an integrated package with a menu-driven system that must be designed with the particular interface in mind. For example, a voice-navigated menu would look different than a gesture-driven system. This task will develop and evaluate information systems and interfaces for processing, displaying, and interacting with physiological, system, and operational parameters during EVAs. These systems may be multimodal in terms of input by and output to the operator. Evaluations should consider the operational use cases of the interfaces, which present physical and cognitive loads to the user, potentially interfering with system operation. Considerations in development should be made to minimize interference in operating the EVA informatics and controlling external systems or vehicles such that ConOps are not hindered.

It is anticipated that initial testing will use body-worn interface prototypes in the APACHE environment under a range of nominal and contingency simulated EVA scenarios to allow for rapid, cost-effective, and rigorous evaluations of prototype concepts with large sample sizes. Subsequent suited evaluations with flight-like prototypes will use many of the same PACES methods and metrics but under suited conditions. Critically, all PACES evaluations will incorporate the simulated IV and MCC functions, their associated work support systems (i.e., *EOS*), and high-fidelity operational scenarios with realistic physical and cognitive workloads.

Secondary opportunities to evaluate xEMU Informatics Interfaces may include unsuited assessments in operational field (i.e., non-laboratory) environments such as the BASALT project and/or pother field-based analogs. Suited test opportunities such as the *EVA Workload and Duration* study (D.2) may also be used to determine the acceptability of user interfaces and the utility of the physiological and system data in improving crew health and/or performance.

While identified as a separate task in this document, the *xEMU Informatics Interfaces* task will be performed within the EOS organizational framework, because decision support systems must be considered within the context of the overall EVA system, including not only the EVA suit and crewmember, but also the functions and support systems associated with IV and MCC.

Status: Planned. See *EOS* status.

F. Anthropometry and Suit Fit

Tasks in this section are relevant to the CHP/EVA SMT Suit Sizing and Fit Gap and also EVA Human System Risk Gap 7B: How does EVA suit sizing and fit affect crew health, performance, and injury risk?

It is understood that certain critical dimensions of EVA suits relative to critical anthropometric dimensions of the human inside the suit can significantly affect the comfort and performance of that human in that suit. During development of the Space Suit Assembly Enhancements, crewmembers reported sensitivities to changes in arm length of 6 mm (1/4 inch); changes in sizing smaller than that were not discernable by the crew. Suit fit sensitivity is also likely to differ between microgravity and planetary EVA environments. However, the sensitivity of suit fit with respect to suited health and performance outcomes has not been systematically characterized for microgravity or planetary environments [51]. These data are necessary to inform the degree of customization that must be provided by space suits, including spares, to ensure that inadequate suit fit will not significantly impact crew health and performance during EVA, including accommodation for the potential impact of in-flight anthropometric changes. Suit fit sensitivity characterization will also enable definition of test subject selection criteria to mitigate suit fit as a potentially confounding factor in EVA research studies for which a very limited degree of suit sizing is typically available. An accurate and valid model may also reduce the fit check iterations necessary to obtain an acceptable suit fit.

1. Human-Space Suit Interaction Modeling and Visualization

A simulation of human-suit interaction can help improve suit designs by developing optimized hardware solutions for human performance and anthropometric accommodation. Optimization of the bearing type, size, orientation, and location with respect to human body joint centers of rotation may reduce the risk of injury, increase comfort, and increase human task performance capabilities. Computer models of the suit and its wearers (Figure 7) that can be repositioned and animated through different motions can be used to predict potential suit design issues and functional limitations, as well as aid in predicting suit sizing for a given individual. The goal is to develop a predictive model that, given inputs of an individual's anthropometric dimensions and a space suit's design features, will provide a quantitative estimate of performance aspects such as range of motion. Additionally, the model will be able to inform suit fit for specific individuals in each of the critical dimensions, which will require developing the criteria for permissible interaction forces as a function of location, as well as permissible misalignments between the human joint and the suit. In addition to individual predictions of suit fit, the model will be used to perform fleet sizing analyses, providing estimates of the proportion of the general or astronaut population accommodated with acceptable suit fit by different suit design and sizing strategies.

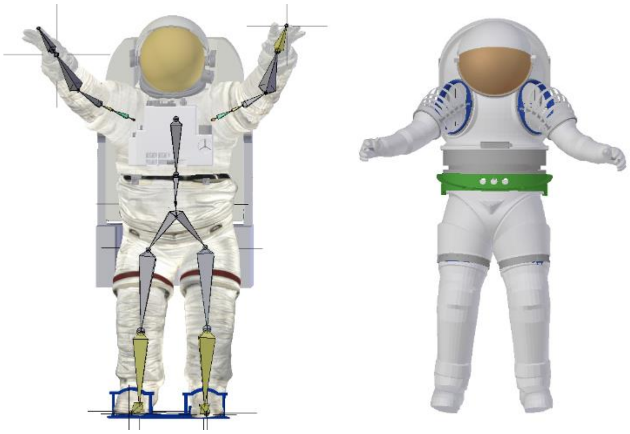


Figure 7. Prototype versions of the EMU (left) and MKIII (right) computer models showing the armature that is used to control the posture of the suit.

The focus of recent work on human-space suit interaction models was integration of a parametric human model with existing suit computer-aided design (CAD) models. This has improved upon previous efforts to model humans based on linear anthropometry by adding greater fidelity to the body shape represented for each individual that is modeled. Current work is focused on incorporation of soft goods suit components to more realistically constrain the human within the suit from head to toe. Interference detection mapping between the human and suit is also under current development, which will further enhance understanding about fit in the suit.

The current space suit models, and therefore the analyses that they can perform, are limited to the hard goods of the EMU and the MKIII space suits. Future suit designs, such as the Z2, are being added as they become available and will be fully built out with the same mobility and animation capabilities that are currently being developed for the EMU and MKIII models. As the capabilities of the human-space suit interaction models increase, associated fleet sizing analyses will be performed, and HITL testing will be used for validation of each analysis.

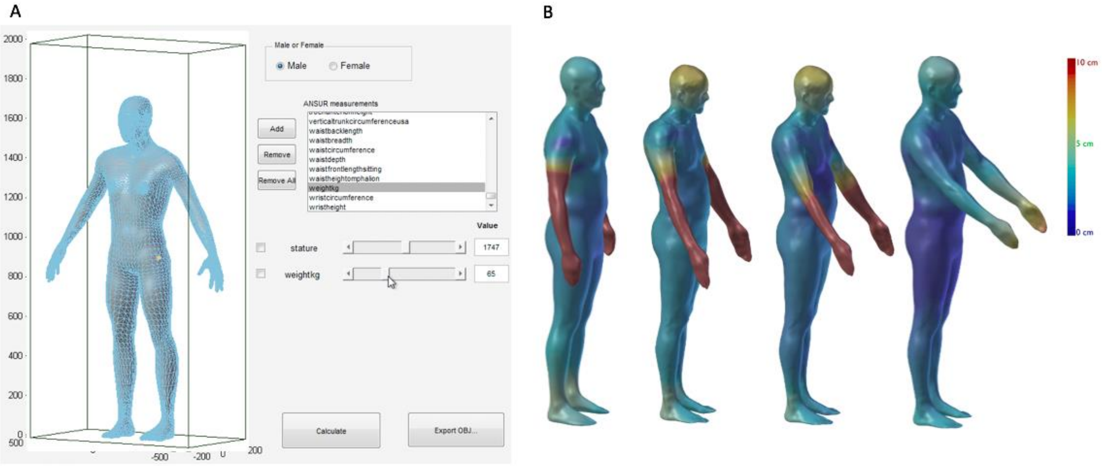
Status: In progress. Project is currently funded by the EVA Office and led by the ABF.

2. Virtual Suit Fit Assessments for xEMU Fleet Sizing

Customized models of human body shape (manikins) are a critical component of the *Human-Space suit Interaction Models*. The ABF maintains a database of 3-D scans collected from crewmembers and test subjects that can be used for predictive assessments. Although the database includes an extensive number of scans in multiple different poses, it may not represent the entire population of current and future crewmembers. Thus, when a body shape that does not exist in the current database has been needed for suit evaluations (e.g., extremely large- or small-size persons), the scan of the subject with closest anthropometry dimensions has been used in substitution.

A new technique was developed in which a statistical model was created based on the scans. The scan geometry data were dimensionally reduced, and statistically predicted from the anthropometry dimensions critical to suit design, such as stature, shoulder width, etc. The new technique essentially enables scaling, interpolating, and extrapolating the scan dataset to approximate the body shapes that do not exist in the current database. The technique was developed into a software tool with a graphical user interface (Figure 8A). The user can enter the desired anthropometry dimensions and the tool can visualize and export 3-D manikins in standard CAD formats.

Larger 3-D body databases, such as the US Army Anthropometry Survey (ANSUR), can be also infused into the ABF database to expand the quantity of scan data. However, such databases often lack postures that are relevant to space suit or hardware evaluations. Thus, the scans in the external databases were transformed into the standard ABF postures relevant to suit fit evaluation. For example, the ANSUR scans in which the arms are down along the torso (Figure 8B leftmost manikin) were transformed through an iterative algorithm and the outcome is the ABF posture in which the arms are outstretched at 45° of forward flexion (rightmost manikin).



Male or Female: ● Male ○ Female

☐ stature 1747

☐ weightkg 65

Figure 8. A: Software tool for the statistical prediction of anthropometric body models. B: interactive posture transformation algorithm. Color represents the prediction error.

Virtual fit assessment is the predictive evaluation of suit design for fit and performance. The assessment can be performed *before* building an actual suit or physical mock-up, thus substantially reducing the time and cost of iterative design modifications. Historically, virtual fit assessment has been performed using a limited number of boundary manikins representing the "worst-case" conditions (e.g., the 99th percentile large or 1st percentile small persons). Then the selected body manikins are overlaid within a suit CAD model and the probability of fit is predicted from the suit-to-body clearance and overlap estimations. Although the boundary manikin technique provides a rough approximation of the accommodated population, the assessments using a limited number of worst-case conditions do not reveal the specific characteristics of the body and suit geometry inducing fit or lack of fit (‘unfit’).

A new Monte-Carlo technique was developed based on a large number of body shape models, which cover a large area of the target anthropometry space. Each body shape is automatically tested against the suit model and provides a 'fit' or 'unfit' decision (Figure 9A). Once fit is evaluated for each body shape, the proportion of accommodated population is explicitly counted. Compared to the previous boundary manikin technique, the Monte-Carlo technique has an advantage of identifying the marginally fitting cases (i.e., the border between the accommodated and unaccommodated segment in Figure 9B). The marginally fitting cases provide the critical anthropometry dimensions and specific body parts of persons related to suit fit. Furthermore, the boundary cases can help to identify the design issues, such as specific contours of the suit components that can lead to a restricted clearance or unwanted overlap. The Monte-Carlo assessment can be repeated for a set of proposed sizes or configurations of suits. The outcome of the multilayer analyses (i.e., fleet sizing evaluations) can quantify the specific directions and magnitudes of the changes in population accommodation. It is expected that the new technique will provide more direct assessments of suit fit and accommodation than traditional methods, and can be used for design improvements and decisions. A series of HUT fleet sizing analyses are currently underway at the time of writing, with HITL validation testing planned, as described below.

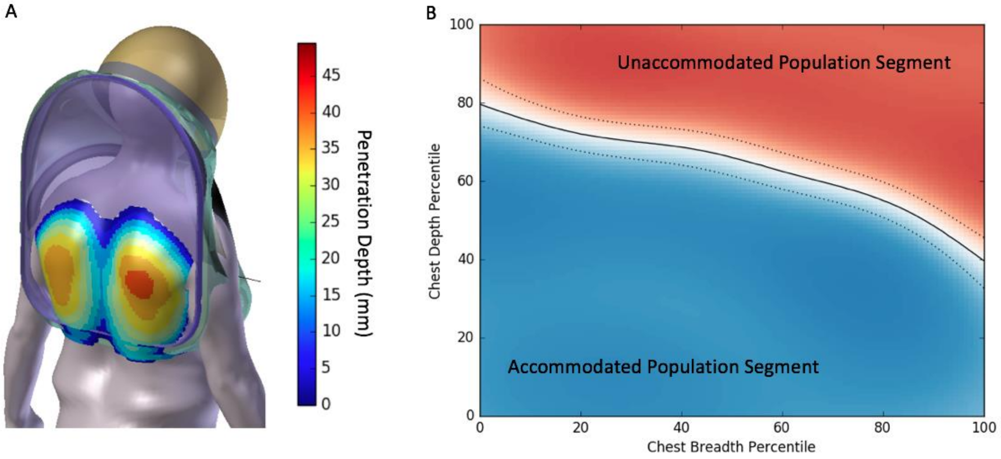


Figure 9. A: Virtual assessment of suit-to-body overlap. B: Accommodated vs. unaccommodated population segments represented as a function of anthropometry dimensions.

Status: Ongoing. Conference papers in work.

3. Validation of Proteus xEMU Fleet Sizing Analyses

Extensive work has been performed to model the fit interactions between the xEMU HUT and its intended wearer population. A HITL validation study will follow each of the xEMU Fleet Sizing analyses described above. During these studies, test subjects will be evaluated for their fit and performance in the xEMU, to validate the model and to determine whether additional metrics of suit fit should be incorporated. The subject pool will include large subjects who fall on the fit/non-fit boundary, as well as small subjects, who may easily don the suit but may exhibit compromised performance. Building on the EVA HH&P Benchmarking methods, and Planetary EVA Standard Measures in future studies, subjects' performance and discomfort will be measured on controlled, isolated tasks such as maximal reach envelope, as well as functional tasks such as a quick disconnect assembly/disassembly task. Suited conditions will include initial fit assessments in a 3-D printed HUT, as well as unpressurized and fully pressurized testing in the xEMU. Results from this test series will be used to distinguish the fit/non-fit boundary, as well as to fine tune the virtual fit model.

Status: In progress. HITL validation testing of the xEMU HUT Fleet Sizing analysis is expected to be completed in 2019.

4. In-Flight Anthropometry Changes

Changes in anthropometry occur during spaceflight due to fluid shifts, spinal elongation, and changes in body composition. These changes are known to affect suit fit, resulting in the need to add the requirement to collected measurements during the on-orbit fit checks (OFV) prior to EVAs on the ISS to ensure acceptable fit. In the future, the measurements collected during OFV will help to reduce overall crew time prior to EVAs by using the change in measurements from preflight to help predict how the suit sizing will need to be adjusted. However, at this time (FY19), there is not enough information to fully predict suit sizing changes. Ensuring acceptable suit fit during all phases of exploration missions requires that anthropometric variability be predicted and accommodated within the suit design and sizing strategy.

An inflight study on the ISS, titled “Body Measures,” was completed. This study measured in-flight changes in anthropometry using measurements critical to suit sizing parameters. In-flight physical changes due to neutral body postures and the associated spinal elongation effect on neutral body postures during extended exposure to microgravity were also gathered. The study involved collecting anthropometric data using standard equipment (i.e., anthropometer, tape measure, weight scale), video imaging (i.e., digital still photographs and video), and a 3-D whole-body scanner to measure changes in body shape, size, and posture during space flight.

The results from the study indicate that anthropometry changes throughout the duration of a mission with most changes occurring within the first 15 to 20 days of the mission except for some circumferences. After the initial period of significant changes, minor fluctuations were noted up until the end of the mission. For future planning, the suit needs to be adjustable based on the length of the mission. Future operations may also require prediction of anthropometry changes to ensure proper suit fit and if any additional sizing adjustments are necessary. To accomplish this objective, a portable and easily operable scanner may be required for future missions. The human-space suit interaction models and associated HITL testing may inform the extent to which in-flight anthropometry changes can be expected to affect suited comfort and performance.

Pre-flight, in-flight, and post-flight anthropometry data from the Body Measures study were incorporated into the xEMU requirements (SSP 51073). Although no data exist for anthropometric changes in lunar or Martian gravity, it is expected that Earth gravity and microgravity represent the two bounding cases.

Status: Body Measures Study is complete but OFV is still required inflight for EMU operations. In-flight anthropometry changes were included in xEMU requirements document SSP 51073. Draft manuscripts for Body Measures and Spinal Elongation will be completed in FY19.

5. Astronaut and Test Subject Anthropometry; Scanner Validation

As the Consolidated Center for Astronaut Anthropometric Data, the ABF is solely responsible for extracting all vital and critical anthropometric measurements that are necessary for vehicle, suit, Soyuz, Extravehicular Mobility Unit (EMU), glove design, verification purposes, and other analyses and data requests. The data collected allow the ABF to obtain and maintain an anthropometric database that can be used for population analyses, univariate and multivariate analyses, volumetric data analyses, and, when requested, in releasing data as per the guidelines set forth in the ABF IRB Master Protocol.

A 3dMD scanner system based on photogrammetry is an alternative scanning system to the laser scanner(s) previously used by the ABF. During FY17 and FY18, the ABF performed a certification task for the successful implementation of using the 3dMD system. This task consisted of comparing scans obtained in the 3dMD and Human Solutions laser scanners. It was anticipated that the systems would be complementary and not interchangeable. The 3dMD system provides the added capabilities of collecting: semi-dynamic poses; color; texture; larger capture volume; and the use of color surface markers. With these advanced capabilities, procedures were developed to document how to optimize the hardware and software to perform data collection and data extraction of anthropometric measurements using the 3dMD system.

Based on the results of the study, the 3dMD scanner was found to be a beneficial tool for its added capabilities including a large capture volume, but not a system to replace the Human Solutions laser scanner for gathering specific anthropometry dimensions for space suit sizing. During this process, the ABF team, along with help from vendor tech support, developed improved strategies for consistent quality in 3-D scans as well as further understanding of the capabilities and applications of the 3dMD systems. Lessons learned included the improved understanding of the dependence of scan quality to well-executed and consistent calibration. Also, the ABF team learned how to troubleshoot different technical issues as well as camera reconfiguration for future specific postures or regions of interest.

The unique capabilities of the current 3dMD system include the ability to take advantage of several batch-processed 3-D scans that feature color and texture data. Recent applications included mapping of shoulder deformation, lumbar kinematics with stretch sensors; and near-future studies include compression evaluation for fit validation studies as well as suit posture scans for xEMU fleet sizing analyses. These studies are based on the current static model of the system, with natural limitations in trying to analyze dynamic ranges of posture and motion. A dynamic "temporal" system is available, which can vastly improve ABF's scan-based modeling capabilities. Potential gains include the ability to create 360-degree models of the space suit with movement, quantification of soft tissue or surface deformation during movement, and evaluation of subject posture and balance in a space suit. Furthermore, the system can be synced to motion capture cameras to improve understanding of the nuances in human range of motion in the space suit and human interaction with space-specific instrumentation, which in turn may be used to assess injury mechanisms.

Status: Complete.

6. Objective Suit Fit

A separate-but-related task will aim to complement subjective ratings of suit fit with objective measures of critical suit fit dimensions. The objective suit fit task is a counterpart to the subjective suit fit methodology that is being developed under the *EVA HH&P Benchmarking* study, and it is possible that elements of both objective and subjective suit fit assessment methodologies could be utilized during future studies. While the Human-Suit Interaction Sensors will quantify forces, pressures, and kinematics between the human and suit, this task will attempt to quantify offsets between the human and the suit in critical dimensions; for example, offsets between joint centers. If successful, the Objective Suit Fit methodology will be employed, along with the subjective suit fit methodology, during the Fleet Sizing Validation Study (Section 3.0.F.3), during which the statistical reliability of objective and subjective suit fit measures may be calculated and compared. Depending on the overhead and efficacy of the Objective Suit Fit methodology, it may also be used routinely during suit fit checks for objective verification of acceptable fit. Alternatively, if the comparison of objective and subjective suit fit assessment methods during the Suit Sizing and Fit Study shows close agreement between methods, then the simpler subjective approach may be adequate in most cases. Any approach to assessment of suit fit must allow for the possibility that multiple acceptable suit sizing approaches may exist for subjects.

Status: No dedicated work currently underway at JSC. Work ongoing at Massachusetts Institute of Technology (MIT) under a NASA Space Technology Research Fellowship (NSTRF) grant [52].

G. Injury Risk and Mitigation

Tasks in this section are relevant primarily to the CHP/EVA SMT EVA Injury Risk and Mitigation Gap and the EVA Human System Risk Gap 11: How do EVA operations in exploration environments increase the risk of crew injury and how can the risk be mitigated?

1. EVA Biomechanical Model

The EVA Biomechanical Model will combine suit geometry and customized anthropometric manikins, while also incorporating musculoskeletal modeling and finite element modeling to predict human-suit interaction forces, pressure distributions, human loads, bearing loading, and crewmember injury risk for different combinations of subjects, tasks, suit designs, and suit sizes. Extending the manikins used in the model with dynamic properties (e.g., bearing resistance torques, inertias) enables a dynamic motion analysis, permitting an understanding of the added torques (e.g. due to bearing design [53]) and a decomposition of the overall joint torques to quantify the effect of design decisions [54]. Converting the solid model to finite element model permits estimating the location and magnitude of the interaction forces. These interaction forces can then be input into a musculoskeletal model to estimate joint torques, muscle activation, and metabolic expenditure.

Initially, the model is expected to assist with identification and mitigation of injury mechanisms for the EMU; application will also extend to informing development and operation of the xEMU. For example, the effects of bearing torques versus inertial torques due to lower-body kinematics may be estimated, optimized, and fed back into suit design [54]. In this manner, the EVA Biomechanical model can leverage the kinematic trajectories of the human to determine the effect on human performance in a way that is not possible experimentally, thus extending what is understood about the human-suit system.

These models can be validated with data collected through human studies with select suit designs. Once validated, these models could be embedded within an optimization framework to determine specific design parameters as well as to identify potential planetary EVA injury mechanisms associated with specific tasks and combinations of anthropometry and suit sizing.

Status: Unfunded. No dedicated work currently underway at JSC. Previous work performed at MIT under a NSTRF grant [53].

2. EVA Suit Occupational Surveillance

A critical element in future EVA risk and injury mitigation efforts is the systematic collection and archiving of suit occupational surveillance data. Specifically, data regarding the suit used, how it was sized, assessment of suit fit, tasks performed, the person using the suit, any existing health conditions, and any discomfort, trauma, or injuries that result from suit exposure. Previous data-mining efforts have provided valuable insights, but have been limited by inconsistent and incomplete datasets [55, 56]. A task is currently underway to implement a standard tracking questionnaire, database, and process for the systematic collection of these data for all EVA suit exposures including testing, training, and flight EVAs.

The data collected will be continually analyzed and used to identify potential injury mechanisms and predictors of negative health consequences. Over time, the data will also be used to assess the efficacy of countermeasures as they are implemented in the form of modifications to hardware, training, and/or operations.

Status: In progress. Yearly briefings to various NASA risk boards are expected to start in FY19.

3. Historical EVA Health Data Mining

Existing data on EVA-related injuries and suit trauma from the Longitudinal Survey of Astronaut Health (LSAH) combined with anthropometry, shoulder anatomy, strength data, and suit size information, where available, were analyzed to determine whether any predictors could be identified to help prevent EVA training injuries in the future. The focus of the study was limited to predictors of EMU shoulder injury; however, the scope was planned to increase to look at a broader dataset. This study began in FY14 with a Pilot study and continued into FY17 with the full study using an expanded set of subjects. The goal of the study was to compare the anthropometry information and data from LSAH, such as suit experience at time of injury, type of injury, suit sizing, and task being performed when injury occurred. The ABF looked at the human factor characteristics of the injury, anthropometry, shoulder anatomy, strength, and suit experience to determine whether risk factors for injury can be identified that may indicate increased likelihood of shoulder injury during EVA training and operations.

No anthropometric measurements were found to be associated with increased likelihood of shoulder injury; however, limited data regarding training, task, injury definition, and shoulder anatomy of the subjects were available and limited the statistical power of the study to find any relationships that may exist.

One factor that the ABF was unable to fully evaluate was the volumetric factors and assessment. Based on linear and statistical information, the data needed to be evaluated in a more multivariate method by evaluating the body shape and size as opposed to just the linear anthropometric measurements (e.g., bideltoid breadth, stature, etc.). Currently, there are several mitigation strategies to prevent shoulder injury including exercise, nutrition, suit sizing, and modifications to EVA training operations.

Status: Complete. Results not publically available.

4. NBL Ergonomic Assessments and Metabolic Rates

To prepare for mission operations, astronauts undergo a substantial amount of space suit training, a large portion of which occurs in the NBL. On average, an astronaut performs 11.6 hours of suited training in the NBL for every hour of EVA performed in flight [55]. It has previously been reported that 64% of EVA trainees wearing EMU space suit have experienced some amount of shoulder pain, 14% of whom had injuries requiring surgical treatment [57]. Inverted body positions and overhead tasks were identified as the potential risk factors of the shoulder injuries. Overall, the evidence suggests that an association may exist between EMU operations and astronaut injury. However, the specific prevalence of the ergonomic risk factors such as the duration, frequency, and duty cycle of the suited body poses have not been scientifically quantified from the NBL trainings sessions.

Ergonomists have been observing NBL training runs and visually quantifying ergonomic risk exposures to crewmembers while performing various common tasks by logging space suit postures throughout the duration of archive NBL trainings. Metabolic rate data are also routinely collected during NBL training runs as a requirement for EVA medical monitoring, and these data have been combined with the ergonomic assessment data to further understanding of crew exertion during common training operations. This evaluation quantifies the magnitude and frequency of off-nominal space suit orientations specifically for the upper body with an example shown in Figure 10. It has been reported that off-nominal upper-body orientation is a potential risk factor for the astronauts' injury in NBL training [55]. The spatial and temporal distributions of the suit poses is statistically analyzed across different training factors, such as task activities.

It is anticipated that results of these analyses will provide guidelines regarding risk-prone poses, and the frequency and duration of such poses occurring. Assessment of these poses and development of mitigation protocols can be implemented to reduce or prevent future trainees from engaging in such postures during training. The outcome will be used to improve and optimize the NBL training protocols and hardware configurations to minimize the injury risks and physical loading on the trainees. It should be noted that the specific correlation between the suit pose angle in the NBL and the risks of musculoskeletal injuries has not been clearly defined. These types of assessments of specific body orientations will help identify musculoskeletal stressors that are experienced in analog environments like the NBL, such as suit inversion and acceptable durations of the maintained position.

The ergonomics evaluations will be expanded in 2019 to include arm orientations for the same NBL training runs to quantitatively log time spent in overhead reach and to potentially find a correlation between risk-prone upper-body poses and arm orientations as it is known that a combination of off-nominal upper-body postures and arm abduction have a higher risk of injury [55].

Results are expected to lead to recommendations for reducing crew injury risk. Additional resources may also be directed toward ergonomic training for NBL divers and crewmembers to aid in identification of activities with an increased potential for injury risk. Although not planned, this type of evaluation may also extend into other offload environments, such as ARGOS.

Status: Ongoing.

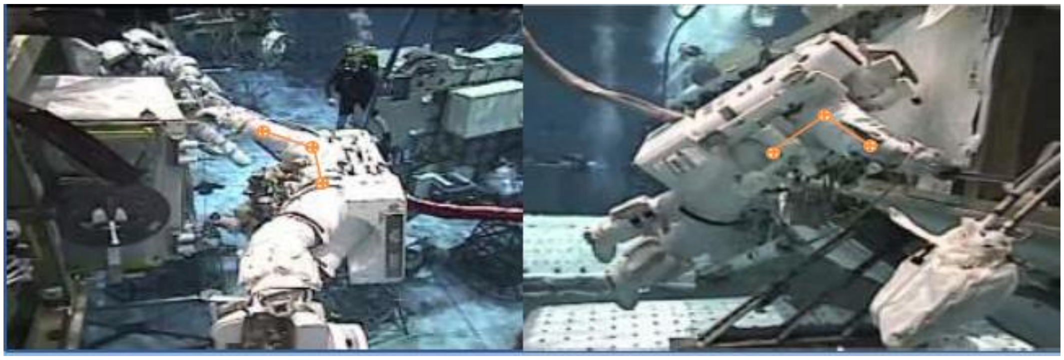


Figure 10. Ergonomic assessment example of in-water evaluation of functional strength at the NBL.

5. Planetary EVA Injury Mechanisms

Although there is some familiarity with the type of injuries that occur during microgravity EVA, there is limited knowledge of how operation in a planetary suit may expose a crewmember to injury risk. In addition to self-report of significant physical and cognitive fatigue, nine injuries of varying severity were reported during the 14 total Apollo EVAs [58, 59] future lunar and Martian missions may involve significantly more EVA time per crewmember as compared with Apollo missions. Although still in the planning stages, preliminary estimates for planetary EVA estimates consider 10 to 100 times more EVA than Apollo missions (EVA-EXP-0042).

The Planetary EVA Injury Mechanisms task will attempt to anticipate the types of injuries that may result from planetary EVA through a combination of occupational surveillance data mining, ergonomic assessments, literature review, and predictions from the EVA Biomechanical Model (Section 3.0.G.1).

Low-back injury poses a great risk to the planetary EVA mission. Previous reports have indicated that there is an increased risk for the development of degenerative disc disease and herniated nucleus pulposus (HNP) for astronauts that have returned from spaceflight [60]. It is theorized that the reintroduction to a gravitational environment can have adverse effects on the deconditioned and microgravity-adapted spine, which can facilitate low-back injuries. Since planetary missions may be preceded by long-duration microgravity exposure during which physiological deconditioning is expected to occur, astronauts will be at increased risk for injury in their deconditioned state. This injury risk is further compounded during EVA as the suit can increase task demands by reducing strength and range of motion [61].

The very large inertial masses associated with the PLSS in combination with the high-mobility planetary EVA suits that are expected to be used during future planetary EVAs represent an additional cause for concern. It is likely that the limited mobility afforded by EVA suits during Apollo limited the extent of angular accelerations and associated joint torques experienced by astronauts, especially in the spine.

Another potential source of injury risk comes from the sheer quantity of EVA that is planned for exploration missions – up to 24 hours per person per week – which will increase the likelihood of injuries due to repetitive strain, rubbing, chafing, and abrasions.

To better understand the low-back injury risks associated with planetary operations inside of the suit, a method is being developed to collect lumbar kinematic data inside the suit using a matrix of fabric strain sensors (described below). During evaluation of the planetary space suits and EVA tasks, the monitoring of lumbar kinematics will be helpful to mitigate potential issues by analyzing how a suited crewmember is using his or her back while performing mission tasks.

In addition to monitoring of lumbar kinematics during planetary suit testing, suit exposure tracking data will be collected and analyzed on an annual basis (see Section 3.0.G.2), and a review of literature will be performed to identify and quantify the types of relevant injuries observed in analogous populations performing similarly frequent and physically demanding work, such as soldiers, wildland firefighters, field scientists, and commercial divers using atmospheric diving suits. Analyses using the EVA Biomechanical Model will be performed if and when the model is sufficiently developed and validated.

Status: Funded and ongoing.

6. Human-Suit Interaction Sensors Assessment

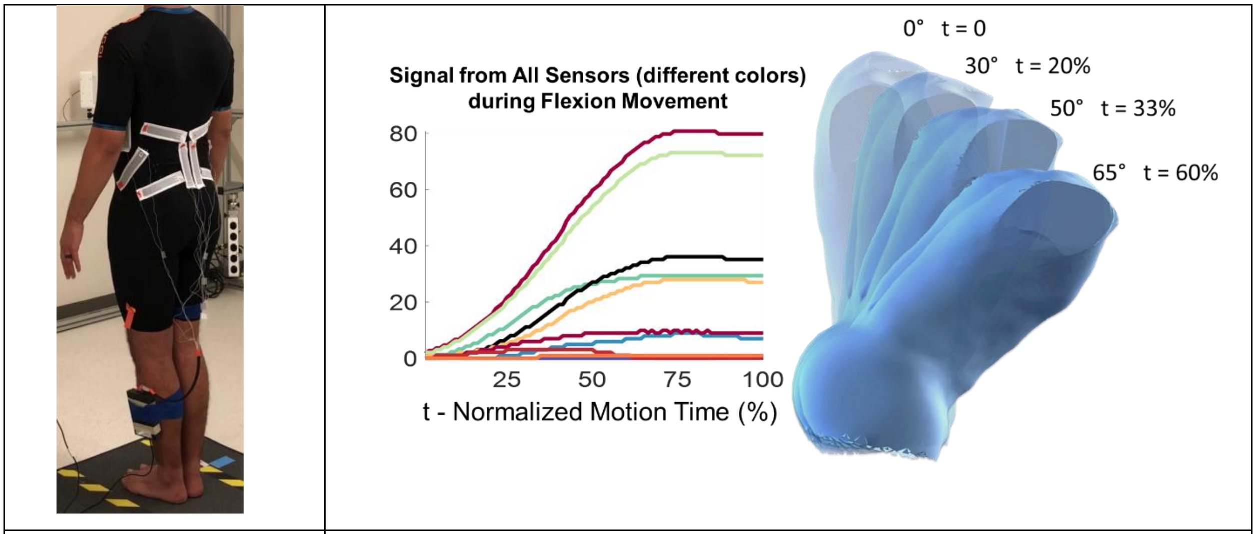
This task, while closely related to the Objective Suit Fit task in the previous section, focuses on the forces, pressures, and kinematics between the human and suit for the primary purpose of identifying and mitigating injury risk, rather than quantifying the fit of the human within the suit per se. Nonetheless, both tasks are related to suit fit and to injury risk.

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. Much of what is known today comes from valuable subjective data provided by test subjects and crewmembers. Incorporating sensor technology to measure human-suit interactions (i.e., forces, pressures, and human/suit kinematics) could provide a valuable objective complement to the subjective data [62]. In particular, ergonomic suit design could be informed by improved understanding of where the human drives the suit, the contact forces required to drive the suit, and the resulting forces and pressures experienced by the human. These systems also provide an innovative testing product for engineers to substantiate subjective fit claims and perform objectively quantifiable suit fit assessments. However, many technical challenges remain, including the possibility that sensors inside the suit will themselves affect fit, discomfort, injury risk, and the ability of the crewmember to perform EVA tasks – all of which could confound the primary test objectives.

The objective of this task is to identify technologies and methods that provide valid and reliable quantification of human-suit interactions that can be related to specific locations on the human and the suit. This includes generating an understanding of the sensitivity of the measures to detect relevant effects and the specificity of the measures to direct to the relevant cause in the context of general suit use. If a valid and reliable approach is identified, it will be incorporated into the xEMU Fleet sizing Validation studies to measure human-suit interactions as a function of suit fit and tasks, and to identify and mitigate potential mechanisms of suit trauma and injury.

In support of this overarching task, pilot work has been performed on the development a wearable sensor garment that can estimate upper-body kinematics and shape changes inside of the suit. The information gained by this system can be combined with suit hardware models to quantify the human-suit interactions. Soft-body and low-profile strain sensors were used in the sensor garment due to volumetric constraints and ferrous magnetic interference in the suit. The strain sensors yields a capacitance measurement varying with the sensor elongation and have provided useful information on lumbar movement in previous studies. Thus, an array of the strain sensors were embedded into a tight-fitting garment in a specific pattern that would maximally respond to the wearer's skin deformation from motions (Figure 11A).

To build a model that predicts upper body kinematics and skin deformation from the sensor measurements, data were collected from subjects wearing the garment. Subjects performed several unsuited trunk postures while 3-D scans and sensor measurements were collected. A machine learning framework was developed to discriminate the unique sensor deformation patterns associated with each posture and predict upper-body shape as a function of the strain sensor measurements (Figure 11B). This work is being expanded to include the measurement of upper-arm kinematics using the strain sensors and suit analog tests to better understand sensor performance inside the space suit. The tight-fitting garment has been used as a test bed for the sensors and the sensors can be possibly embedded in the Liquid Cooling and Ventilation Garment (LCVG).



(A) (B)

Figure 11. A) Sensor garment. B) Body shape prediction from sensor measurements during flexion movement.

Additional work has focused on measuring body-garment contact through sensing electric potential between the body and contact surface. This concept has been tested by affixing textile electrodes to the LCVG surface and measuring body-to-garment contact timing and location during body movements. This work may be expanded to apply this concept to measure the magnitude, timing, and location of contact between the LCVG and the suit hardware. The proposed system would measure the electrical potential between a sensor layer integrated into the LCVG layup and a conductive sensor mesh on affixed to the interior of the suit hardware.

Status: Ongoing. Funded by the EVA Office and led by the ABF [63].

7. Second-Generation Suit Trauma Countermeasures

HRP solicited for proposals to develop and a test a second generation suit trauma countermeasure in a 2015 HERO announcement (NNJ15ZSA001N-FLAGSHIP). The work was planned to be performed by a research team from the University of Colorado – Boulder and the Massachusetts Institute of Technology during FY2017 and FY2018, after their proposal was selected, but shortly after selection, HRP terminated most EVA risk research funding and this project was not started. The task planned to involve the design, build, and test of a garment that is intended to improve health and comfort outcomes for EVA crewmembers during training and flight without unacceptable decreases in functional performance. The content of the project has the potential to leverage and complement multiple other studies described in this plan.

Status: Unfunded. With development of xEMU having been initiated since this study was first solicited, its applicability to NASA's future EVA plans should be evaluated in the event that it is funded.

H. xEMU Hardware Evaluations and Requirements Verifications

Tasks in this section are relevant primarily to the mapped xEMU Development Milestones and are needed either as requirements/design inputs, intermediate developmental tests, or requirements verification.

1. xEMU Human Loads (aka "Manloads") Verification Testing

The forces exerted by the human into the axial restraint system of the suit are referred to as manloads [64] and must be measured so that appropriate conservatism is incorporated into the suit structure design, ensuring that the suit cannot be damaged by the movement of the human. The manloads input to suit structure is suit design dependent and, as such, the test set-up is specific to the suit load path and suit hardware being evaluated. Measured manloads are also dependent on suit sizing and fit; in most cases, a subject wearing a tighter-fitting suit (fingertip-to-fingertip, heel-to-shoulder, crotch-to shoulder) will induce greater manloads than a subject wearing a loosely fitting suit.

Testing of the Space Shuttle EMU indicated that satellite handling manloads impart higher loads into the suit than the so-called isometric manloads that occur during normal or exaggerated motions in the suit. These satellite handling manloads were used as inputs to the Z2 structural design, but must be verified. Manload distribution throughout a suit's components is geometry dependent, therefore the actual magnitudes and locations of maximum manloading must be evaluated for the new suit design. The manloads associated with the Z-2 suit mobility architecture will be measured during this study using on-suit axial sensors, during HITL testing on the ARGOS.

Status: Ongoing. Funded by the EVA Office and led by the ABF and CTSD. Completion of this task is expected in 2019.

2. xEMU Demo and xEMU Planetary Hardware Evaluations

Several xEMU requirements derived in part or in whole from NASA-STD-3001 point to the need to verify the acceptability of the xEMU Demo and subsequent xEMU planetary space suits with respect to human health and performance. Details of these future verification and validation tests will be developed in collaboration between the EVA Office, engineering, and the Human Health and Performance Directorate. The scope of the testing will ensure that xEMU Demo and subsequent xEMU space suits provide mobility, dexterity, and tactility to enable crewmembers to accomplish suited tasks within acceptable physical workload, fatigue, and comfort limits for all microgravity and partial-gravity EVA scheduled and contingency mobility tasks. The testing will also ensure that the cognitive performance capabilities shall be accommodated in the design of all system elements that interface with the crew for all levels of crew capability and all levels of task demands. It is anticipated that the accommodation of cognitive capabilities will be demonstrated, in part or in whole, through the acceptable performance of simulated EVA tasks using the tasks and assessment methods being developed for *PACES*.

xEMU hardware evaluations will also include characterization of CO_2 washout performance using the methodology described in Section 3.0.C.1, results of which will verify compliance with the associated xEMU requirements, and will also be incorporated into the EVA Human Health and Performance model.

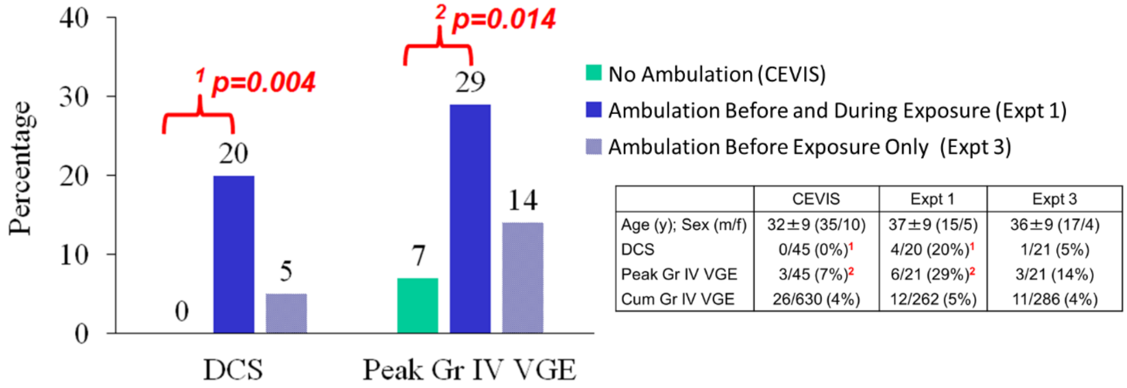
Status: Planned.

I. Exploration DCS Mitigation Strategy

Tasks in this section are relevant primarily to the CHP/EVA SMT *EVA Exploration Prebreathe* Gap and the DCS Human System Risk.

Oxygen prebreathe protocols are used to mitigate the risk of decompression sickness (DCS) before EVAs are performed from the ISS. Existing protocols used on board the ISS require significant amounts of crew time and consumables (i.e., gas) but are consistent with the ISS operations concept of infrequent EVAs, large crews, and relatively simple resupply of consumables from Earth. Existing prebreathe protocols used on the ISS also rely significantly on the existing hardware and facilities related to the Quest airlock. Existing protocols require both mask and in-suit O_2 prebreathe, and require suit donning at an intermediate pressure of 10.2 psia to avoid a break in prebreathe. The airlock must then be repressurized to allow the IV crewmember to leave prior to final depressurization. Existing protocols assume a single suit pressure of 4.3 psia and infrequent longer-duration (>4 hour, typically >6.5 hour) microgravity EVAs. Finally, DCS treatment can only be provided on the ISS with recompression in the airlock and then further treatment requires the bends treatment apparatus, which is installed onto the suit to allow for increased pressure to the crewmember, but at the price of decertifying the EMU for EVA.

Prebreathe protocols that have been validated and used during Space Shuttle and ISS for microgravity EVAs are not acceptable for use during planetary EVA because the risk of DCS is significantly increased by ambulation. For example, Conkin et al [65] observed significantly greater DCS incidence (20% vs. 0%) when subjects ambulated before and during the decompression vs. remaining non-ambulatory throughout (Figure 12). Significantly greater Grade IV Venous Gas Emboli (VGE) was also observed among ambulatory subjects; Grade IV VGE represents the highest score assigned to bubbles moving with the blood through the pulmonary artery on the way to the lungs to be filtered (removed) from the venous blood.



	CEVIS	Expt 1	Expt 3
Age (y); Sex (m/f)	32±9 (35/10)	37±9 (15/5)	36±9 (17/4)
DCS	0/45 (0%)[1]	4/20 (20%)[1]	1/21 (5%)
Peak Gr IV VGE	3/45 (7%)[2]	6/21 (29%)[2]	3/21 (14%)
Cum Gr IV VGE	26/630 (4%)	12/262 (5%)	11/286 (4%)

Figure 12. Effect of ambulation on DCS and Grade IV VGE [65].

While microgravity prebreathe protocols (from ISS and Space Shuttle) are expected to be applicable to EVAs on Gateway or other microgravity environments, no validated prebreathe protocols exist for planetary EVA. Apollo used a 100% oxygen atmosphere throughout the mission, which made prebreathe unnecessary, as nitrogen had already been eliminated from the astronauts’ bodies. However, all atmospheres being considered by NASA for future exploration missions will include at least 66% nitrogen due to the flammability risks and costs associated with higher oxygen environments, meaning that one or more prebreathe protocols must be developed and validated using ground trials before operational implementation during exploration missions. Development and validation of a suite of exploration prebreathe options is included in this plan.

1. Exploration Prebreathe Trade Study and Strategy Development

A multidisciplinary team, called the Exploration Atmospheres Working Group, conducted a detailed study in 2006 that evaluated prebreathe options for future exploration missions that would involve high-frequency EVA [66]. The purpose of this task, which was recently completed, was to evaluate options for an exploration prebreathe strategy that encompasses not only high-frequency EVA, but also lower-frequency EVA ConOps, while also exploring options for developing shorter prebreathe protocols that would take advantage of the xEMU's variable pressure capability.

The trade study used DCS risk estimation models to evaluate a wide range of scenarios, including different habitat saturation atmospheres, prebreathe durations, EVA breathing gases, EVA durations, EVA suit pressure profiles, as well as the possibility of using intermittent recompressions (IR) to reduce DCS risk and prebreathe durations. Implications of different prebreathe options for xEMU requirements and exploration ConOps were also studied and presented.

A small subset of scenarios that were evaluated are included in Table 4. Prebreathe durations of 5 hours or more may be acceptable for infrequent EVAs; however, they are inconsistent with exploration ConOps involving multiple EVAs per week. Three-hour prebreathe durations would also routinely violate crew sleep constraints and xEMU requirements for EVA overhead.

Table 4. Estimated Prebreathe Durations for Microgravity vs Planetary EVAs, Assuming 4.3 psi Operating Pressure

Saturation Atmosphere (balance N_2)	**Microgravity Prebreathe (h:mm)**	**Planetary Prebreathe (h:mm)**
14.7 psi, 21% O_2	4:00 ~2:40 (ISLE – requires 10.2 psi, 26.5% O_2)	Minimum 4:30 [67] Likely 5:00+
10.2 psi, 26.5% O_2	0:40	3:00 [68]
8.2 psi, 34% O_2	0:00-0:15	0:00-0:15 [69]
5.0 psi, 100% O_2 (Apollo, Gemini)	0:00	0:00

While the benefits of decreased DCS risk that result from operating at higher suit pressures are obvious, in contrast, there are few or no data or experience base with which to quantitatively evaluate the potential increased risks to human health and performance that would be associated with higher suit operating pressures for planetary EVA. Protocols that are validated based on a 4.3 psi operating pressure can be safely used at higher suit pressures; however, the converse is not true. As such, it was recommended that a suite of exploration prebreathe protocols be developed and validated. The proposed suite of prebreathe protocols will assume nominal operation at 4.3 psi for the initial protocol development and validation, with subsequent studies proposed that would validate protocols for a range of suit operating pressures, with the goal of realizing increased efficiencies as compared with the 4.3 psi protocols.

Status: Complete. The study found that prebreathe benefits of variable pressure suits are limited if crewmembers are initially saturated at 14.7 psia 21% O_2 / 79% N_2 [69]. However, meaningful prebreathe benefits may be achievable when used from reduced pN_2 environments (e.g., 10.2 psi, 26.5% O_2 / 73.5% N_2 or 8.2 psi, 34% O_2 / 66% N_2), both through gradated decreases in-suit pressure as well as through IR during EVA [68]. The potential benefits suggested by models must be weighed against potential decreased mobility and dexterity combined with increased fatigue, injury risk, and gas phase nucleation associated with working in high-pressure suits.

2. Exploration Atmosphere Prebreathe Validation and Hypoxia Characterization

NASA's design reference missions for human exploration of Mars and the moon depend on periods of high-frequency EVAs with crew time and consumables availability that will be significantly more constrained than during current ISS operations. Recognizing this challenge, NASA has followed the recommendations of the Exploration Atmospheres Working Group [66], and has directed that NASA exploration missions involving periods of high-frequency EVA be designed to use an atmosphere of 8.2 psia / 34% O_2 / 66% N_2, often referred to as the "Exploration Atmosphere." The lower partial pressure of N_2 compared with ISS will enable significantly reduced prebreathe durations. However, while the estimated DCS risk is very low, a prebreathe protocol for planetary EVAs must still be developed and validated using ground trials before operational implementation of the Exploration Atmosphere.

The proposed denitrogenation prebreathe protocol is based on the assumption that subjects will be equilibrated with the exploration atmosphere at 8.2 psia / 34% O_2. Human testing is required to verify with 95% statistical confidence that any new protocol meets the following requirements for acceptance: $\leq$ 15% incidence of Type I DCS, $\leq$ 20% incidence of Grade IV VGE with no Type II DCS symptoms. A repeated-measures, sequential statistical design is planned, in which at least two groups of six subjects with physical characteristics similar to those of active-duty astronauts first equilibrate over a 48-hour period to an 8.2 psia atmosphere in a hypobaric chamber containing 34% O_2 / 66% N_2, and then each perform a total of five EVAs at 4.3 psia, each lasting 6 hours, performed every second day over the next 9 days.

During the simulated EVAs, subjects will simulate EVA work on a planetary surface because DCS risk is affected by the type and intensity of physical work that is being performed during a decompression exposure. For simulated EVAs, each subject will don a mask and breathe 85% O_2 (normoxic at 4.3 psia) before each EVA. Using 85% rather than 100% O_2 will enable reduced pre-EVA purge durations during exploration missions, saving valuable crew time and consumables, with very minimal anticipated impact on DCS risk [20].

Subjects will follow prescribed repetitive activity against loads in the upper and lower body to simulate ambulatory work in a planetary environment. Doppler ultrasound (2.5 MHz) monitoring for VGE in the pulmonary artery will be performed on six subjects by 2 Doppler technicians at 15-min intervals during the 4.3 psia exposure, then repressurization will return all to 8.2 psia. The cycle will be repeated four additional times with a day of hypoxia characterization and rest between each of the simulated EVAs. A statistical power analysis indicates that, given our best estimate of DCS incidence as $\leq$ 3.1% for the planetary EVA simulation, then 12 subjects repeated five times has 88% probability of meeting the accept condition. The study design includes a liberal reject criterion, to minimize the probability of conducting an expensive trial and neither meeting the criteria for acceptance nor rejection of the protocol. If a protocol is rejected, the prebreathe protocol will be made more conservative by increasing prebreathe time.

Hypoxia characterization quantifies the nature of a breathing atmosphere with an inspired O_2 partial pressure of 128 mmHg and includes measures of neurocognitive function, sleep performance, immune stress and oxidative damage, vision, and cardiorespiratory function at rest and mild exercise, as well as assessment of any classic hypoxia symptoms.

Status: Ongoing. The study will be performed in the 20-ft chamber in Building 7 of JSC and is being led by the H-3PO laboratory, which is funded by CHP SMT. Data collection is expected to be completed in 2020.

3. Exploration Prebreathe from 10.2 psia / 26.5% O_2 Atmosphere

Although the 10.2 psia staged prebreathe protocol was used extensively on the Space Shuttle, it was only validated for microgravity use. This staged atmosphere is within the design requirements for most future NASA habitable vehicles, but no validated prebreathe protocol exists for use in planetary gravity. This protocol will need to be developed and validated with new operational considerations for the xEMU in microgravity and for exploration use on planetary surfaces including the moon and Mars.

This study will be similar in design to the Exploration Atmosphere Prebreathe Validation study using the same hypobaric chamber facility and planetary EVA simulation, but with subjects being saturated at 10.2 psi 26.5% O_2.

Status: Planned. Currently unfunded.

4. Exploration Prebreathe from 14.7 psia / 21% O_2 Atmosphere

Exploration missions will need validated prebreathe protocols to enable EVA capabilities from habitats that operate at 14.7 psia. Much like the ISS, these habitats are expected to either be science focused laboratories where atmosphere is desired to be similar to Earth or they may be vehicles with only contingency or infrequent EVA needs.

Although several validated prebreathe protocols have been used on the ISS, these all assume a specific architecture and capability associated with the ISS and the EMU. Exploration vehicles may not have or even need to have the added cost and complexity of certain needed factors such as mask prebreathe, exercise capability, donning the suit at an intermediate atmosphere of 10.2 psia and 26.5%, or repressurization to 14.7 psia to allow the IVA crewmember to exit the airlock prior to final depressurization.

This study will use the same hypobaric chamber facility and planetary EVA simulation as the other exploration prebreathe validation studies; however, because subjects will be saturated at Earth-normal atmospheric conditions, it will not be necessary to have test subjects living in the hypobaric chamber for multiple days.

Status: Planned. Currently unfunded.

5. Variable Pressure Model Development and Validation

The purpose of this study will be to develop one or more exploration prebreathe protocols that assume some or all of the EVA is performed at greater than 4.3 psi. This study will be conducted after the Suit Pressure study and Workload & Duration study have been completed, results of which are expected to inform the pressure profile(s) that are acceptable with respect to dexterity, mobility, fatigue, and discomfort. If funding allows, this study may also include evaluation of intermittent recompression profiles, which are hypothesized to further decrease necessary prebreathe durations. It is anticipated that this study will yield a validated model that provides for maximum flexibility with respect to initial saturation atmosphere and EVA suit pressure profiles.

Status: Planned. Currently unfunded.

4.0 MAINTAINING AND EXECUTING THE PLAN

The Integrated EVA Human Research and Testing Plan presented here is intended as a tool to facilitate collaboration and coordination on human-in-the-loop EVA research and testing. Representation of all appropriate stakeholders in the definition, prioritization, planning and execution of research activities is essential to accomplishing the overarching objective. Coordination with stakeholders outside of the EVA Office, CTSD, and HH&P is already in effect on a study-by-study basis; however, closer coordination on multiyear planning with other EVA stakeholders, including academia, is being pursued.

Given the dynamic nature of NASA organizations, budgets, and priorities, it is understood that this plan must be continually reviewed and revised to remain useful. As specified in the formal framework of collaboration that led to creation of this plan, representatives of – at a minimum – the EVA Office, HHPD, and CTSD will review the plan on an annual basis and make updates as necessary. The plan will also directly inform budget planning and prioritization for the respective organizations. It is intended that updates to the plan be made publicly available each year, either through publication on a NASA website and/or through publication and presentation at a national or international conference.

The primary focus of human EVA research and testing in the near future will be to inform near-term development of the xEMU, verify xEMU requirements, and to further define the exploration EVA concept of operations including prebreathe protocols.

It is unknown to what extent HRP will resume support of EVA research. Maintenance of the EVA Evidence Report and external peer-review of multiyear research plans (the “Path to Risk Reduction”), previously funded by HRP, is currently unplanned. As research calls are opened by HRP, it may once again provide the EVA research community with an opportunity to submit detailed proposals for studies that focus primarily on mitigation of human-centric EVA risks described in this plan. Any of these proposals selected will be subjected to external peer review. Studies that require the unique facilities and expertise available at NASA JSC, as determined by HRP management, will be performed as directed studies, meaning that they will be led from JSC but will still allow for external collaborators and will still be subject to external peer review. All other HRP-funded studies will be competed through research announcements.

As studies are performed, results will continue to be published via conference papers and presentations, scientific journals, and NASA technical reports. Results will be presented to NASA’s HSRB and EVA Configuration Control Board. Updates to xEMU and Exploration EVA ConOps documents will be made during standard review processes. Updates will be made to the EVA risk classification via the HSRB where results are determined to have reduced or closed knowledge gaps. Updates to the status and evidence associated with SMT gaps will be coordinated via the EEWG.

5.0 REFERENCES

1. NASA, *NASA Strategic Plan*, NASA, Editor. 2018.
2. *NASA Strategic Plan 2014*. 2014, National Aeronautics & Space Administration, Office of the Administrator: http://science.nasa.gov/media/medialibrary/2014/04/18/FY2014_NASA_StrategicPlan_508c.pdf.
3. Abercromby, A.F., et al. *Integrated Extravehicular Activity Human Research Plan: 2016*. in *46th International Conference on Environmental Systems*. 2016. Vienna, Austria.
4. Abercromby, A.F.J., *Integrated Extravehicular Activity Human Research Plan: 2017*, NASA, Editor. 2017.
5. *2015 NASA Technology Roadmaps*. 2015 [cited 2016 February 15]; Available from: http://www.nasa.gov/offices/oct/home/roadmaps/index.html.
6. NASA. *Human Research Program Architecture*. [cited 2019; Available from: https://humanresearchroadmap.nasa.gov/architecture/.
7. *Human Research Program EVA Risk: Path to Risk Reduction*. 2015 [cited 2016 February 18]; Available from: http://humanresearchroadmap/schedules/?i=84.
8. Chappell, S.P., et al., *Risk of Injury and Compromised Performance Due to EVA Operations.* Human Research Program Evidence Report, 2015.
9. Conkin, J., et al., *Evidence Report: Risk of Decompression Sickness (DCS)*, N.H.R. Program, Editor. 2016, NASA Johnson Space Center.
10. Norcross, J.R., et al., *Risk of Hypobaric Hypoxia from the Exploration Atmosphere*, N.H.R. Program, Editor. 2015, NASA Johnson Space Center.
11. Abercromby, A.F.J., J.R. Norcross, and S.L. Jarvis, *EVA Human Health and Performance Benchmarking Study*, in *Human Research Program Investigators' Workshop*. 2016: Galveston Island Convention Center.
12. Valle, P., et al., *Active Response Gravity Offload System*, in *NASA Tech Brief MSC-24815-1/24-1*. 2011.
13. Meginnis, I., K. Davis, and R. Rhodes. *Performance of the Z-2 Space Suit in a Simulated Microgravity Environment*. in *48th International Conference on Environmental Systems*. 2018. Albuquerque, NM.
14. Meginnis, I., et al. *Testing of the Z-2 Space Suit at the Neutral Buoyancy Laboratory*. in *47th International Conference on Environmental Systems*. 2017. Charleston, SC.
15. Bernal, Y., et al., *Development of Underwater Motion Capture System for Space Suit Mobility Assessment*, in *Human Factors and Ergonomics Society Annual Meeting*. 2017. p. 945-949.
16. Kim, K.H., et al., *Underwater Assessments of Space Suit Reach Envelopes*, in *5th International Digital Human Modeling Symposium*, S. Wischniewski and D. Bonin, Editors. 2017, Federal Institute for Occupational Safety and Health: Dortmund, Germany. p. 173-183.

17. Norcross, J.R., et al., *Metabolic Costs and Biomechanics of Level Ambulation in a Planetary Suit*, in *NASA/TP-2010-216115*. 2010, NASA Johnson Space Center: Houston, TX.

18. Norcross, J.R., et al., *Metabolic Costs and Biomechanics of Inclined Ambulation and Exploration Tasks in a Planetary Suit*, in *NASA/TP-2010-216125*. 2010, NASA Johnson Space Center: Houston, TX.

19. Waligora, J.M. and D.J. Horrigan, *Metabolism and Heat Dissipation during Apollo EVA Periods*, in *Biomedical Results of Apollo*, R.S. Johnston, C.A. Berry, and L.F. Dietlein, Editors. 1975.

20. Abercromby, A.F.J., J. Conkin, and M.L. Gernhardt, *Modeling a fifteen-minute extravehicular activity prebreathe protocol using NASA's exploration atmosphere (56.5 kPa / 34% O2).* Acta Astronautica, 2015(0).

21. Charvat, J.M., et al. *Spacesuit Glove-Induced Hand Trauma and Analysis of Potentially Related Risk Variables*. in *45th International Conference on Environmental Systems*. 2015. Bellevue, WA.

22. Korona, F.A., S.K. Walsh, and S.M. McFarland. *NASA EVA Glove Characterization Protocol Development*. in *48th International Conference on Environmental Systems*. 2018. Albuquerque, New Mexico.

23. McFarland, S.M. and D. Nguyen, *Analysis of Potential Glove-Induced Hand Injury Metrics during Typical Neutral Buoyancy Training Operations*, in *47th International Conference on Environmental Systems* 2017: Charleston, SC. p. ICES-2017-99.

24. McFarland, S.M. and S.K. Walsh, *NASA's High Performance EVA Glove: Project Element Summary*, in *48th International Conference on Environmental Systems*. 2018: Albuquerque, New Mexico. p. ICES-2018-068.

25. Reid, C.R. and S.M. McFarland, *Feasibility Assessment of an Extravehicular Activity Glove Sensing Platform to Evaluate Potential Hand Injury Risk Factors* 2015. Proceedings of the 45th International Conference on Environmental Systems (ICES 2015), Bellevue, WA.

26. Chappell, S.P., et al., *Evidence Report: RISK OF INJURY AND COMPROMISED PERFORMANCE DUE TO EVA OPERATIONS*. 2017, NASA Johnson Space Center: NASA.

27. Law, J., S. Watkins, and D. Alexander, *In-flight carbon dioxide exposures and related symptoms: association, susceptibility, and operational implications.* NASA Technical Paper, 2010. 216126.

28. Glatte Jr, H., G. Motsay, and B. Welch, *CARBON DIOXIDE TOLERANCE STUDIES.* 1967.

29. Lambertsen, C., *Carbon dioxide tolerance and toxicity*. 1971, PENNSYLVANIA UNIV PHILADELPHIA SCHOOL OF MEDICINE.

30. Korona, F.A., et al., *Carbon Dioxide Washout Testing Using Various Inlet Vent Configurations in the Mark-III Space Suit.* 2014.

31. Mitchell, K. and J. Norcross. *CO2 washout testing of the REI and EM-ACES space suits*. in *42nd International Conference on Environmental Systems, San Diego, CA*. 2012.

32. Meginnis, I.M., et al., *Characterization of Carbon Dioxide Washout Measurement Techniques in the Mark-III Space Suit.* 2016.

33. NASA, *NASA SPACE FLIGHT HUMAN-SYSTEM STANDARD VOLUME 2: HUMAN FACTORS, HABITABILITY, AND ENVIRONMENTAL HEALTH*. 2015.

34. Chappell, S.P., et al., *Life Sciences Implications of Lunar Surface Operations.* NASA Technical Report, 2010. NASA/TM-2010-216138.

35. Miller, M.J., et al. *Scientific Hybrid Reality Environments (SHyRE): Leveraging Terrestrial Fieldwork for Future Planetary Exploration*. in *American Geophysical Union Fall Meeting*. 2018. Washington D.C.

36. Miller, M.J., et al. *Scientific Hybrid Reality Environments (SHyRE): Bringing Field Work into the Laboratory*. in *Planetary Science Informatics and Data Analytics Conference*. 2018. St. Louis, MO.

37. Beaton, K.H., et al., *Extravehicular Activity Operations Concepts under Communication Latency and Bandwidth Constraints*, in *IEEE Aerospace Conference*. 2017: Big Sky, MT.

38. Lim, D.S.S., et al., *The BASALT Research Program: Designing and Developing Mission Elements in Support of Human Scientific Exploration of Mars.* Astrobiology, 2019. 19(3): p. 245-259.

39. Kobs Nawotniak, S.E., et al., *Opportunities and Challenges of Promoting Scientific Dialog throughout Execution of Future Science-Driven Extravehicular Activity.* Astrobiology, 2019. 19(3): p. 426-439.

40. Beaton, K.H., et al., *Using Science-Driven Analog Research to Investigate Extravehicular Activity Science Operations Concepts and Capabilities for Human Planetary Exploration.* Astrobiology, 2019. 19(3): p. 300-320.

41. Beaton, K.H., et al., *Assessing the Acceptability of Science Operations Concepts and the Level of Mission Enhancement of Capabilities for Human Mars Exploration Extravehicular Activity.* Astrobiology, 2019. 19(3): p. 321-346.

42. Chappell, S.P., A.F. Abercromby, and M.L. Gernhardt, *NEEMO 14: Evaluation of Human Performance for Rover, Cargo Lander, Crew Lander, and Exploration Tasks in Simulated Partial Gravity.* NASA Technical Report, 2011. NASA/TP-2011-216152

43. Chappell, S., et al., *Access Systems for Partial Gravity Exploration & Rescue: Results from Prototype Testing in an Analog Environment*. 2007, SAE Technical Paper.

44. Miller, M.J., K.M. McGuire, and K.M. Feigh. *Information flow model of human extravehicular activity operations*. in *2015 IEEE Aerospace Conference*. 2015.

45. Billman, D., et al., *Needs Analysis and Technology Evaluation:Evaluation Case Study of Alternative Software for Controller Planning Work–Part 2.* Journal of Cognitive Engineering and Decision Making, 2015. 9(2): p. 186-207.

46. Billman, D., et al., *Needs Analysis and Technology Alignment Method:A Case Study of Planning Work in an International Space Station Controller Group–Part 1.* Journal of Cognitive Engineering and Decision Making, 2015. 9(2): p. 169-185.

47. Miller, M.J., *Decision Support System Development for Human Extravehicular Activity*, in *Department of Aerospace Engineering*. 2017, Georgia Institute of Technology: Atlanta, GA.

48. Miller, M.J., et al., *Design and Development of Support Systems for Future Human Extravehicular Activity*, in *55th AIAA Aerospace Sciences Meeting*. 2017, American Institute of Aeronautics and Astronautics.

49. Miller, M.J., K.M. McGuire, and K.M. Feigh, *Decision Support System Requirements Definition for Human Extravehicular Activity Based on Cognitive Work Analysis.* Journal of Cognitive Engineering and Decision Making, 2017. 11(2): p. 136-165.

50. Miller, M.J., C.W. Pittman, and K.M. Feigh. *Next-Generation Human Extravehicular Spaceflight Operations Support Systems Development*. in *68th International Astronautical Congress*. 2017. Adelaid, Australia.

51. Kim, K.H., et al., *Human Modeling Tools for Spacesuit and Hardware Design and Assessment*, in *Digital Human Modeling and Posturography*, S. Scataglini and G. Paul, Editors. in press, Elsevier S&T Books: San Diego, CA.

52. Fineman, R.A., et al., *Objective Metrics Quantifying Fit and Performance in Spacesuit Assemblies.* Aerospace Medicine and Human Performance, 2018. 89(11): p. 985-995.

53. Cullinane, C., Rhodes, R., Stirling, L. A *Pilot Study Evaluation of Mobility and Agility During Locomotion in the Mark III Space Suit Assembly.* . Aerospace Medicine and Human Performance, 2017. Accepted.

54. Cullinane, C., Rhodes, R., and Stirling, L. *Implementation of a Mark III Computational Model to Decompose Hip Joint Torques*. in *Annual Meeting of the Aerospace Medical Association*. 2017. Denver, CO.

55. Strauss, S., R.L. Krog, and A.H. Feiveson, *Extravehicular mobility unit training and astronaut injuries.* Aviation, space, and environmental medicine, 2005. 76(5): p. 469-474.

56. Anderson, A.P., D.J. Newman, and R.E. Welsch, *Statistical evaluation of causal factors associated with astronaut shoulder injury in space suits.* Aerospace medicine and human performance, 2015. 86(7): p. 606-613.

57. Williams, D.R. and B.J. Johnson, *EMU shoulder injury tiger team report*. 2003, Johnson Space Center: Houston, TX.

58. Scheuring, R.A., et al., *Musculoskeletal injuries and minor trauma in space: incidence and injury mechanisms in US astronauts.* Aviation, space, and environmental medicine, 2009. 80(2): p. 117-124.

59. Scheuring, R.A., et al., *The Apollo Medical Operations Project: Recommendations to improve crew health and performance for future exploration missions and lunar surface operations.* Acta Astronautica, 2008. 63(7): p. 980-987.

60. Johnston, S.L., et al., *Risk of Herniated Nucleus Pulposus Among U.S. Astronauts.* Aviation, Space, and Environmental Medicine, 2010. 81(6): p. 566-574.

61. Ross, A.J., *Z-1 Prototype Space Suit Testing Summary,* in *43rd International Conference on Environmental Systems*. 2013, American Institute of Aeronautics and Astronautics.

62. Anderson, A., et al. *In-suit sensor systems for characterizing human-space suit interaction*. 2014. 44th International Conference on Environmental Systems.

63. Vu, L.Q., et al., *Evaluation of lumbar motion with fabric strain sensors: A pilot study.* International Journal of Industrial Ergonomics, 2019. 69: p. 194-199.

64. Pantaleano, M.J. and D.F. Lacey, *Satellite Handling Loads on the Shuttle Extravehicular Mobility Unit (EMU) Spacesuit: An Examination of the Loads Imparted to the Suit as a Result of Handling Massive Objects in EVA*. 1992, SAE Technical Paper.

65. Conkin, J., et al., *Venous Gas Emboli and Ambulation at 4.3 psia.* Aerosp Med Hum Perform, 2017. 88(4): p. 370-376.

66. NASA, E.A.W.G., *Recommendations for exploration spacecraft internal atmospheres: The final report of the NASA exploration atmospheres working group. NASA Technical Publication NASA/TP-2010-216134,* in *NASA Technical Publication*. 2010.

67. Abercromby, A.F.J., et al., *Suited Ground Vacuum Chamber Testing Decompression Sickness Tiger Team Report*. 2018: NASA Johnson Space Center.

68. Abercromby, A.F., et al. *Using the Shuttle Staged Prebreathe Atmosphere and Variable Pressure Sapcesuits for Exploration Extravehicular Activity*. in *89th Annual Scientific Meeting of the Aerospace Medical Association*. 2018. Dallas, TX.

69. Abercromby, A.F., J. Conkin, and M.L. Gernhardt. *Modeling Oxygen Prebreathe Protocols For Exploration Extravehicular Activities Using Variable Pressure Suits*. in *88th Annual Scientific Meeting of the Aerospace Medical Association*. 2017. Denver, CO.