Developing a Hybrid Spacesuit Simulator as a Research Tool for Assessing Extravehicular Activity Relevant Workload

Monica Hew, Ph.D.[1], Bradley Hoffmann, Ph.D.[1], Zachary Wusk, M.S.[1],
[1]*KBR, Houston, TX, 77058*

Karina Marshall-Goebel, Ph.D.[3] and Jeffrey Somers, M.S.[2]
[3]*NASA Johnson Space Center, Houston, TX, 77058*

Conducting human tests in a pressurized spacesuit is limited by availability, cost, and manpower; however, pressurized spacesuits are not always needed depending on the objectives of testing, including the development and testing of new informatics capabilities. The Human Physiology, Performance, Protection & Operations Laboratory (H-3PO) at NASA is developing a Hybrid Spacesuit Simulator (HS3) to support testing and characterization of human performance during analog planetary exploration extravehicular activities (EVAs). The goal of HS3 is to create a low-cost, modular, and unpressurized spacesuit simulator as a research tool that provides relevant physical and cognitive workload approximations with EVA-like immersion. HS3 consists of a soft outer suit, thermal control, gloves, boots, helmet, and integrated bioinformatics and communications.

Baseline HS3 assessments were performed during 3-hour EVA simulations in two different subjects (DEMO1 and DEMO2) that included traverses at variable resistances and geological sampling activities. Liquid cooling garment (LCG) temperature, mean skin temperature, heart rate, motion capture, and metabolic rate were collected during each 3-hour simulated EVA. During DEMO1 and DEMO2, baseline metabolic rates at rest were 836 ± 327 BTU/hr and 869 ± 207 BTU/hr and increased to 2124 ± 548 BTU/hr and 2269 ± 559 BTU/hr, respectively, during 500m traverse. Average inlet LCG temperatures were 29.57 ± 6.62 °C and 25.63 ± 6.48 °C for DEMO1 and DEMO2 with increased outlet LCG temperatures of 33.53 ± 6.62 °C and 29.21 ± 4.79 °C, respectively. Overall, HS3 will enable future studies to characterize EVA tasks, human performance, and test future EVA capabilities in analog test environments without the need for pressurized suited environments.

Nomenclature

APACHE	=	Assessments of Physiology and Cognition in Hybrid-reality Environments
ARGOS	=	Active Response Gravity Offload System
ConOps	=	Concept of operation
EVA	=	Extravehicular activity
FOV	=	Field of View
H-3PO	=	Human Physiology, Performance, Protection & Operations
HH&P	=	Human health and performance
HRM	=	Heart Rate Monitoring
HS3	=	Hybrid Spacesuit Simulator
HUT	=	Hard upper torso
LCG	=	Liquid Cooling Garment
NASA	=	National Aeronautics and Space Administration
NBL	=	Neutral Buoyancy Lab
NZGL	=	NASA Zero Gravity Lever
PACES	=	Physical and Cognitive Exploration Simulations
PLSS	=	portable life support system

[1] Human Performance Engineer, H-3PO Laboratory, NASA JSC, 2101 E NASA Pkwy., Houston, TX 77058
[2] H-3PO Co-lead, H-3PO Laboratory, NASA JSC, 2101 E NASA Pkwy., Houston, TX 77058

ROM = Range of Motion
xEMU = Exploration Extravehicular Mobility Unit
$\%HR_{max}$ = percentage of age-estimated heart rate

I. Introduction

In the Artemis Program, NASA will return to the Moon for the first time since the Apollo program. To meet the ambitious schedule of landing the first woman and first person of color on the Moon by the mid-2020s, a plethora of human health and performance (HH&P) risks and knowledge gaps must be addressed to ensure safe and successful execution of extravehicular activities (EVA) on the lunar surface.[1] Some studies, such as those focused on understanding spacesuit fit and injury, require access to high-fidelity, pressurized spacesuits and/or mockups; however, many HH&P objectives do not require a full pressurized spacesuit. Examples of these types of studies may include developing and testing novel EVA informatics and decision support systems, biomedical monitoring systems, and assessment of physical and cognitive responses during EVA training. Additionally, access to NASA spacesuits and/or mockup spacesuits can be limited and costly. Thus, there is a cost/schedule incentive in developing a spacesuit simulator that provides study-specific required fidelity to meet the HH&P objectives.

The use of a spacesuit simulator is not a novel concept.[2-6] Spacesuit simulators can be categorized into five categories[5] with increasing cost and complexity, ranging from unsuited analog (shirt-sleeve environment), limited interface (using only a limited number of components for simulating specific aspects), representational simulation (using visually representative garments to provide immersion during an EVA), unpressurized full-spectrum simulation (may have various suit functions like ventilation, mobility restriction), and pressurized spacesuits (Figure 1). Each spacesuit simulator has different advantages and disadvantages in supporting different needs of EVA research and development. To study HH&P risks and knowledge gaps associated with EVA, the Human Physiology, Performance, Protection, and Operations (H-3PO) Laboratory at NASA developed a hybrid spacesuit simulator (HS3) as a cost and schedule-effective research tool for EVA analog testing. A modular spacesuit simulator like HS3 significantly simplifies and reduces overhead while providing simulation assets like those seen in the limited interface and unpressurized full-spectrum simulator categories shown above.

The primary goal of HS3 is to create a low-cost, unpressurized spacesuit simulator for use as a research tool with modular capabilities to provide physical and cognitive workload approximations as required by individual study aims during EVA simulations. This paper describes the design, development and subsequent technology demonstration of the HS3 during simulated EVA as a modular, customizable research tool with integrated human physiological sensors to address HH&P study needs.

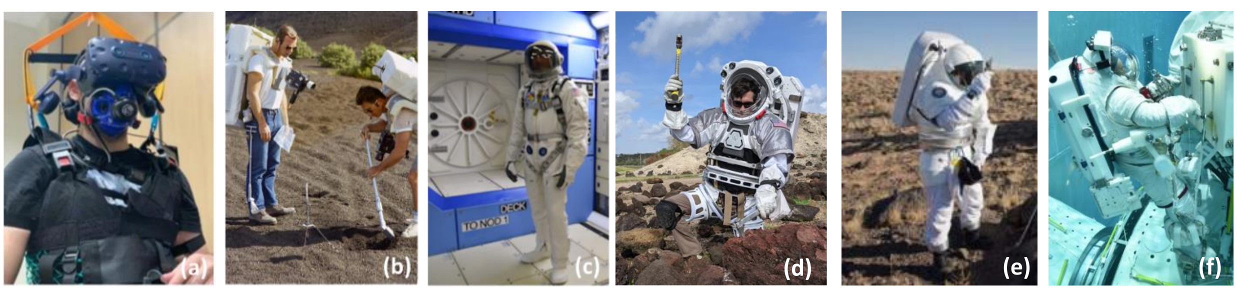


Figure 1. Examples of spacesuit simulators used in human spaceflight. *(a) Unsuited analog used in the Assessments of Physiology and Cognition in Hybrid-reality Environments (APACHE) study.[7] (b) Limited interface simulator used by Apollo crew to conduct geological training (source: NASA). (c) Representational simulator used by public affair teams. (d) Unpressurized full-spectrum simulator built by Atlas Devices to provide realistic range of motion, and ergonomic capabilities of the NASA's xEMU suit.[8,9] (e) Unpressurized full-spectrum suit with multiple roll joints used by the Desert Research and Technology Studies (DRATS).[3,6] (f) Fully pressurized suit (Z-2.5) used in the NASA neutral buoyancy laboratory (NBL) for crew training.[10]*

II. Hardware Overview

The HS3 is subdivided into eight subsystems including a helmet, soft suit garment, hard upper torso (HUT), gloves, boots, portable life support system (PLSS), ventilation, and thermal control system (Figure 2). The operational principle of HS3 focuses on modularity with various subsystem requirements. During HS3 development, a down selection process occurred utilizing a mixture of commercial-off-the-shelf (COTS) items and custom 3D printing rapid manufacturing for the final baseline HS3 system.

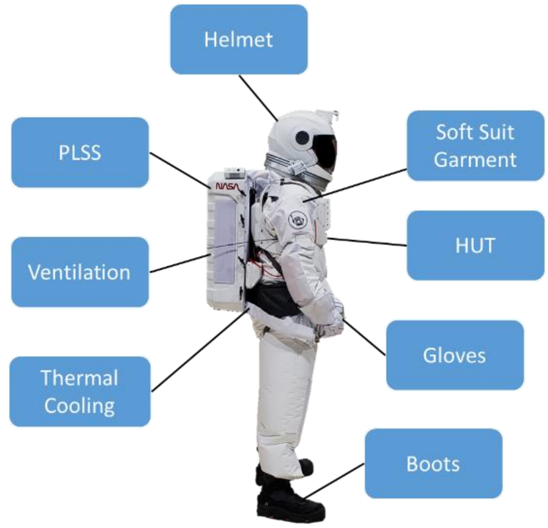


Figure 2. The HS3 system consists of eight subsystems including the helmet, soft suit garment, HUT, gloves, boots, PLSS, ventilation, and thermal cooling.

The helmet subsystem was designed using a COTS motorcycle helmet and adapted using custom 3D printed neck ring attachments to interface with the soft suit garment. Ventilation was added into the helmet to provide cooling and defogging on the helmet visor. The neck ring is secured using multiple small magnetic couplings for quick removal if necessary. Additionally, the helmet subsystem includes a communication system as an option using a COTS headset and microphone assembly. The helmet is also designed to allow customizable low-fidelity lighting and camera options via attachment to the top of the helmet and the sides of the neck ring. During the baseline assessment engineering runs the helmet was modified to allow for metabolic energy expenditure data to be collected.

The soft suit is the outer garment worn by the subject. This subsystem includes ventilation and LCG pass-throughs, knee padding, elbow padding, glove coupling rings, a helmet neck ring attachment, and customizable sizing components. The soft suit garment design consists of a lighter Ottertex Nylon Ripstop 70 Denier fabric material with Ottertex waterproof canvas reinforcement around joint areas.

Encasing the outer chest portion of the soft suit garment is the HUT subsystem. The HUT consists of 3D-printed components and was incorporated into the HS3 as a volumetric constraint on mobility but also serves as a coupling with the PLSS and a hip offloading system. The HUT is constructed with front and back pieces with interchangeable shoulders and waist parts for sizing chest depth. The HS3 system is hip offloaded with shoulder and chest straps that aid in alignment. The HUT couples this axillary system to the PLSS for offloading. Also housed in the HUT are bioinformatics systems such as heart rate monitor displays and a thermal control switch for LCG flow.

The glove subsystem consists of COTS lacrosse gloves that were adapted by adding a soft outer garment on the gauntlet to attach a wrist coupling ring. The gauntlet wrist coupling ring attaches to the soft suit garment wrist ring via friction fit and magnetic coupling. This connection design was implemented to allow for quick doffing if needed. The COTS gloves were chosen for their light weight and to induce limited dexterity for immersion purposes. Similar to the glove subsystem, the HS3 boots are COTS boots and were chosen due to having interchangeable soles for tread changes depending on the analog environment. The soft suit garment is secured via placing the fabric in the boot and tightening.

Thermal cooling is controlled using a COTS LCG. Both a chest vest and full-body LCG option can be utilized with HS3. Chest vest options for the LCG allow for additional harnesses on the subject for fall protection if using a treadmill without limiting cooling capability. Two pass-throughs for the inlet and outlet LCG ports are used at the waist and coupled via two QD fittings with poppet shut-off when released. The LCG is charged via a 3L feedwater bladder that is secured in the PLSS. The pump is fixed near the feedwater to allow flow from the PLSS to the LCG. The thermal control loop connection schematic (Figure 3) shows circulation from feedwater through the LCG via the water pump. The EV has the option to turn the LCG flow on or off using a push-button switch secured to the front of the HUT. The LCG does not allow for fine control of the feedwater temperature and is cooled prior to donning the HS3.

The ventilation subsystem (Figure 3) is controlled via a COTS 12v DC fan blower capable of providing 30L/min of airflow to each ventilation path that is mounted inside the PLSS. HS3 is not a closed system but provides airflow through the PLSS and into the soft suit garment. The air is not entirely re-circulated and leaks out of the soft suit garment. Ventilation airflow is pulled through a filter on the outside of the PLSS into a secondary HEPA filter inside

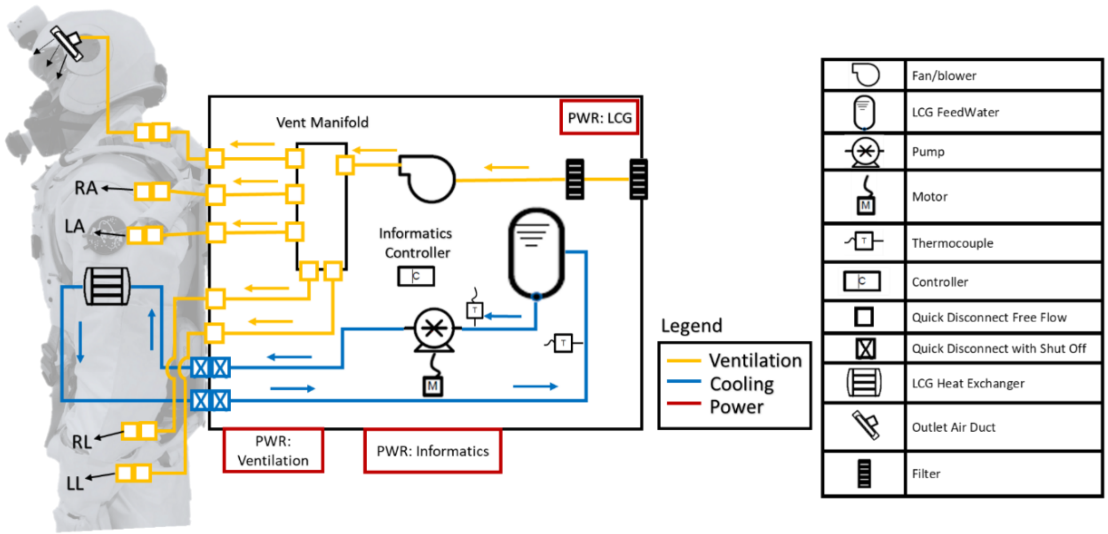


Figure 3. The HS3 PLSS schematic. *The suit is not an enclosed system but allows for air flow via the ventilation loop (Yellow). The air flows into the PLSS via a filter opening. The circulation path feeds into a secondary HEPA filter pulled via a COTS fan bower. The outlet of the fan is fed into a ventilation manifold splitting into five paths that fed into the soft suit garment via quick disconnects (QDs) with open flow for the head, right arm (RA), left arm (LA), right leg (RL), and left leg (LL). The open flow feeds into the suit and exits the soft suit garment as it is not fully enclosed. The thermal cooling loop (blue) provides water cooling to the LCG. The LCG is fed via a 3L feedwater bladder that is pre-cooled prior to donning. A pump pulls the water into the LCG via QDs with poppet with return into the bladder for constant flow that can be turned on or off. The PLSS power (Red) consists of two external COTS batteries that provide power to the ventilation fan blower and informatics controller. There is additional power inside the PLSS for LCG control.*

the PLSS and through a fan blower (Figure 3). The ventilation flow then passes through the fan into a ventilation manifold that splits the airflow equally into five paths that are connected to the soft suit garment via QDs with open flow. The five paths are for each extremity of the helmet, right arm (RA), left arm (LA), right leg (RL), and left leg (LL). There is an additional QD with the open flow at the neck of the soft suit garment that couples with a QD on the helmet (Figure 3). This allows for quick removal of the helmet but allows for ventilation to feed up over the head and down onto the visor of the helmet. The QD connections are friction fit plug and cap style fitting that are more secure and robust while also being quick to remove if needed.

The final subsystem of HS3 is the PLSS hard structure (Figure 3). The PLSS is coupled to the back plate of the HUT and a COTS backpacking spine that feeds to the waist offloading belt. The load of the PLSS is then solely supported on the hips with shoulder straps that keep it aligned. The PLSS structure is divided into three sections. Section one of the PLSS is for power input into the PLSS and ventilation pathway management. Section two section divides the power from the LCG feedwater. This middle section houses the 3L LCG bladder and the ventilation fan blower. Section three includes the HEPA filter and outer filter of the ventilation path and the power for the LCG. Two external DeWALT COTS batteries are attached to the outside of the PLSS that power the informatics and the ventilation fan blower. These batteries were chosen to provide the ability to quickly swap them if power is depleted. The structure of the PLSS is comprised of miniature T-slotted framing allowing for customizable positioning of PLSS components. The PLSS backplate is constructed using PVC/Acrylic that couples to the T-slotted frame. The external housing of the PLSS is a modified COTS heavy-duty waterproof storage container.

III. Methods

To evaluate HS3 hardware and testing capabilities across a variety of EVA-related tasks, two subjects completed a three-hour simulated assessment EVA with the HS3 (DEMO1 and DEMO2). DEMO1 and DEMO2 consisted of hardware checkouts and subsystem capability demonstration (with minor adjustments made in DEMO2 configuration after receiving feedbacks in DEMO1). HS3 system performance data as well as human physiology data were collected during each simulated EVA. The simulated EVA timeline was designed based on similar functional movements and exploration tasks as part of the Physical and Cognitive Exploration Simulations (PACES) procedures,[11, 20, 21] which are commonly used in HH&P characterization testing using NASA's Active Response Gravity Offload System (ARGOS).[12]

A. Independent Variables and Environments

Assessments of Physiology and Cognition in Hybrid-reality Environments (APACHE) provides a simulated planetary EVA environment for evaluation and can be used with virtual reality, hybrid reality, and physical reality simulations. As shown in Figure 4, the APACHE space contains a 6.1-meter x 4.6-meter sandbox and a passive treadmill, allowing for a variety of physical and cognitive tasks to be performed and assessed.

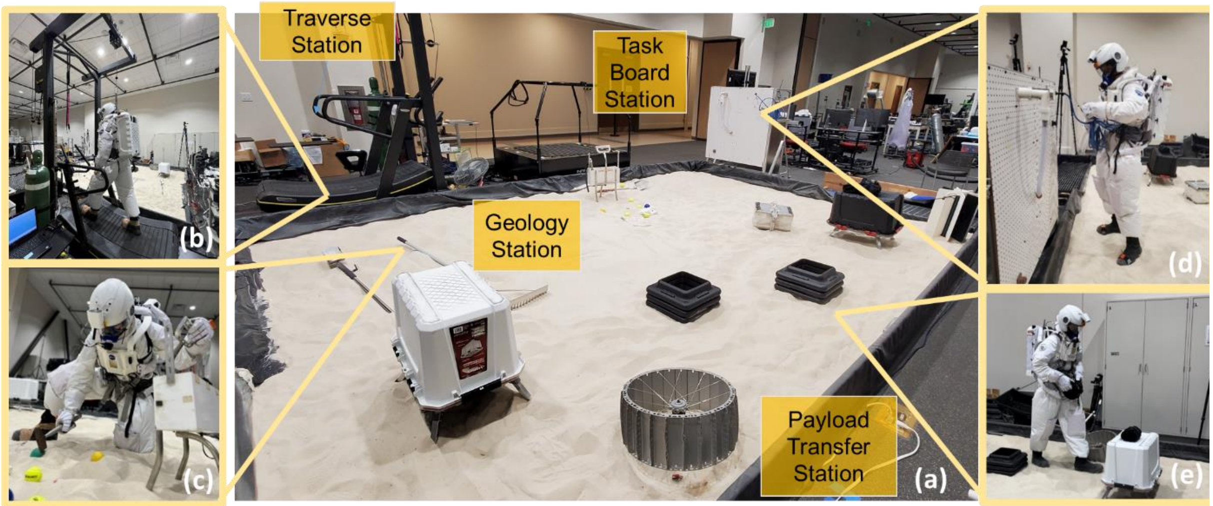


Figure 4. APACHE test environment with HS3 EVA simulation task stations. *(a) Overall layout. (b) Traverse station includes a passive treadmill with fall restraint system. (c) Geology station includes chip sampling/hammering (shown in subset), trenching, and raking. (d) Task board station includes connectors, cable management and routing operations. (e) Payload transfer station involves simulated object relocation.*

B. Task Breakdown

As shown in Table 1 and Figure 4, subjects performed a series of EVA-related tasks in the sandbox and three traverses on a passive treadmill. Within the sandbox, this study used additional simulation tools such as a task board station for cable routing and connection tasks, a geology station, and a payload transfer station with a rough terrain path for object relocation around obstacles.[21]

1. Traverse Station

This station utilized a curved, passive treadmill (Skillmill Connect, Technogym, Italy) to evaluate the effects of HS3 on physical workload during set-distance traverses. The treadmill has ten incremental resistance levels that increase the effort required to walk. This HS3 testing utilized three resistance levels to evaluate human performance at increased physically demanding tasks. The different resistance levels were chosen to mimic the percent grade incline levels used in the H-3PO ARGOS metabolic rate characterization study traverses[12]. Previous work has compared varying resistance levels to both the JSC rock yard and set percent-grade inclines on a motorized treadmill that was used at ARGOS for suited testing.[7] The trends in gait across the passive treadmill resistances matched similar trends for the increased percent-grade incline on the motorized treadmill, and the following resistances were defined for the passive treadmill testing (Table 2). Subject traverse speed was monitored and instructed to self-pace at 2 mph to simulate partial-g suited walking speeds.

Each subject conducted three traverses of 500 meters within a 10-minute window during their EVA. The first traverse is on the minimal resistance setting (3/4), the second traverse is on the high resistance setting (7/8), and the last traverse is at the medium resistance setting (5/6). The traverses were spaced out between various other tasks in the EVA to simulate a situation where they will have to traverse between locations for EVA tasks. Subjects were equipped with a customized full-body safety harness system (GM Climbing, Beijing, China) which was connected to the treadmill overhead safety restraint as seen in Figure 4(b).

Table 1. Detailed test timeline of HS3 assessments.

EVA Timeline Tasks	Planned Task Time
Sensor Setup	0:25
Suit Donning	0:25
Baseline Data Collection/Mounting	0:05
Traverse station 1: 500m (Resistance 3/4)	0:10
3-minute Break + Surveys	0:03
Task Board Station	0:05
3-minute Break + Surveys	0:03
Traverse station 2: 500 m (Resistance 7/8)	0:10
3-minute Break + Surveys	0:03
Geology Station 1: Trenching	0:05
3-minute Break	0:03
Geology Station 2: Chip Sample hammering)	0:05
3-minute Break	0:03
Geology Station 3: Raking	0:05
3-minute Break + Surveys	0:03
Traverse station 3: 500m (Resistance 5/6)	0:10
3-minute Break + Surveys	0:03
Payload transfer station: 10lb Large, rocks	0:05
3-minute Break + Surveys	0:03
EVA cleanup	0:05
Suit Doffing	0:30
Total Planned time:	**2:49**

2. Task Board Station

The task board station (Figure 4(d)) combined a variety of functional movements and EVA-relevant tasks to assess the mobility and functionality of the HS3. Subjects had a five-minute block that involved mating and de-mating a 3D-printed recreation of a NASA zero gravity lever (NZGL) connector, routing the NZGL cable to a simulated radioisotope thermoelectric generator (RTG), performing cable management with copper wire ties, mating, and de-mating a fluid quick disconnect (FQD) cable, and stowing cables. These tasks required the subject to perform a variety of single and double-hand object manipulations, kneeling and standing postures, and vertical and cross-body reaches.

3. Geology Station

The geology station, shown in Figure 4(c) with the chip sampling example, consisted of three different geology tasks: raking, trenching, and chip sampling. The raking and trenching tasks were accomplished in a standing position, while chip sampling was completed in a single-leg kneel. The specific geology tasks were chosen because of their relevance to early lunar EVA missions, and to provide a variety of postures and motions for the HS3 evaluation.

4. Payload Transfer Station

The payload transfer station, shown in Figure 4(e), tasked the subject to perform object relocation by retrieving, transporting, and returning payloads back and forth between two platforms, approximately 5 meters, with various obstacles in their path for a five-minute block. Two weighted bags, ten and twenty pounds, were used as simulated payloads. This task evaluated the subject's ability to perform a weighted carry on an uneven surface while navigating obstacles along the way.

Table 2. Comparable passive treadmill resistance levels to the percent-grade incline at the ARGOS motorized treadmill based off gait. *All passive treadmill resistances are at 2 mph.*

Passive Treadmill Resistance Level	Motorized Treadmill % Grade at ARGOS
3/4	0%
5/6	10%
7/8	20%

C. Protocol

Throughout the simulated EVAs, three-minute breaks were placed between tasks to allow subjects' metabolic rate and heart rate to return to baseline before starting the next task. Each task time had a minimal time limit of five minutes to allow the subject to achieve a steady state for that specific task. A full, detailed, chronological test timeline is shown in Table 1, and individual tasks are described in Figure 4. For subject safety, heart rate measurements were monitored throughout the EVA to avoid subjects operating at above 85% of their age-calculated maximum heart rate *(HR_{max})* for longer than 2-minutes continuously. The HR_{max} was estimated by age using Eq. (1).[13]

$$HR_{max} = 208 - 0.7\ x\ age \tag{1}$$

Subjects' heart rate zone can then be computed by evaluating the measured heart rate and the percentage of HR_{max} using Eq. (2). The $\%HR_{max}$ can be used to assess the physical workload of the subject.

$$\%HR_{max} = \frac{HR}{HR_{max}}\ x\ 100\% \tag{2}$$

After each test block, subjects were asked to report their subjective feedback via a series of surveys commonly used in ground-based EVA analogs to evaluate their simulation quality rating,[10,14] simulation task acceptability,[14] perceived physical workload via Rating of Perceived Exertion (RPE),[11] cognitive workload via NASA Task Load Index (TLX)[15], comfort, thermal acceptability, and fatigue scales.

The simulation quality (Figure 5) were used to determine the extent to which an analog environment (HS3) were able to provide an accurate simulation of a partial gravity exploration EVA. Ratings of 1-3 indicate that the simulation quality is high enough to allow for utilization of the data as there were at most some simulation limitations, but they were not significant. This data will be used to evaluate how well the HS3 is able to simulate the EVA tasks performed.

No Limitations	Minor Limitations	Marginal Limitations	Significant Limitations	Major Limitations	No Rating
Simulation quality (e.g. hardware, software, procedures, comm, environment) presented either zero problems or only minor ones that had no impact to the validity of test data	Some simulation limitations or anomalies encountered, but minimal impact to the validity of test data	Simulation limitations or anomalies made test data marginally adequate to provide meaningful evaluation of test objectives (please describe)	Significant simulation limitations or anomalies precluded meaningful evaluation of major test objectives (please describe)	Major simulation limitations or anomalies precluded meaningful evaluation of all test objectives (please describe)	Unable to assess simulation
1	2	3	4	5	NR

Figure 5. Subjective Simulation Quality Rating Scale.

The simulation task acceptability scale (Figure 6) assessed task acceptability, to understand how well the HS3 analog, task, procedure, and tools enable effective, efficient, and reliable completion of exploration EVA tasks, without significant discomfort, exertion, fatigue, or avoidable inefficiencies, and without risk of injury to self or damage to equipment.

Examples of deficiencies: inefficiency, high mental workload, increased physical exertion,

Totally Acceptable		Acceptable		Borderline		Unacceptable		Totally Unacceptable	
No improvements necessary and/or No deficiencies		Minor improvements desired and/or Minor deficiencies		Improvements warranted and/or Moderate deficiencies		Improvements required and/or Unacceptable deficiencies		Major improvements required and/or Totally unacceptable	
1	2	3	4	5	6	7	8	9	10

Acceptability Ratings should reflect the extent to which the condition overall was considered an "Acceptable" approach to conducting human exploration and the extent to which improvements, if any, are desired or required.
Operational Acceptability *: Able to reliably conduct operations with accurate exchange of all pertinent information and without excessive workload or (in-sim) avoidable inefficiencies or delay.*
Task Acceptability *: Able to reliably complete a task without significant discomfort, exertion, fatigue, or avoidable inefficiencies, and without risk of injury to self or damage to equipment.*

Figure 6. Subjective Simulation Acceptability Rating Scale.

As show in Figure 7, several subjective scales are shown. The Perceived Exertion Scale (RPE) provided a subjective assessment of level of effort a subject may be experiencing. The comfort level provided an assessment of any discomfort or localized fatigue resulting from HS3 during the simulation. The thermal acceptability survery provided a rating of thermal comfort changes compared to an initial starting state for HS3 cooling. Subjects was asked to assess their general fatigue level resulting from the overall testing up to that point taking into consideration physical and cognitive state. This contrasted with the comfort ratings previously described which are aimed at localized discomfort/fatigue.

(a) Rating of Perceived Exertion (RPE)

6	No exertion at all
7	Extremely light
8	
9	Very light
10	
11	Light
12	
13	Somewhat hard
14	
15	Hard (heavy)
16	
17	Very hard
18	
19	Extremely hard
20	

(b) Thermal Rating Scale

Thermal sensation		Thermal preference		Thermal acceptability		Overall comfort	
No.	Scale	No.	Scale	No.	Scale	No.	Scale
−3	Cold	−2	Much warmer	1	Acceptable	1	Very comfortable
−2	Cool	−1	Slightly warmer	0	Not acceptable	2	Comfortable
−1	Slightly cool	0	No change			3	Slightly comfortable
0	Neutral	1	Slightly cooler			4	Slightly uncomfortable
1	Slightly warm	2	Much cooler			5	Uncomfortable
2	Warm					6	Very uncomfortable
3	Hot						

Thermal sensation 7-point scale of the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE)

(c) Comfort Scale

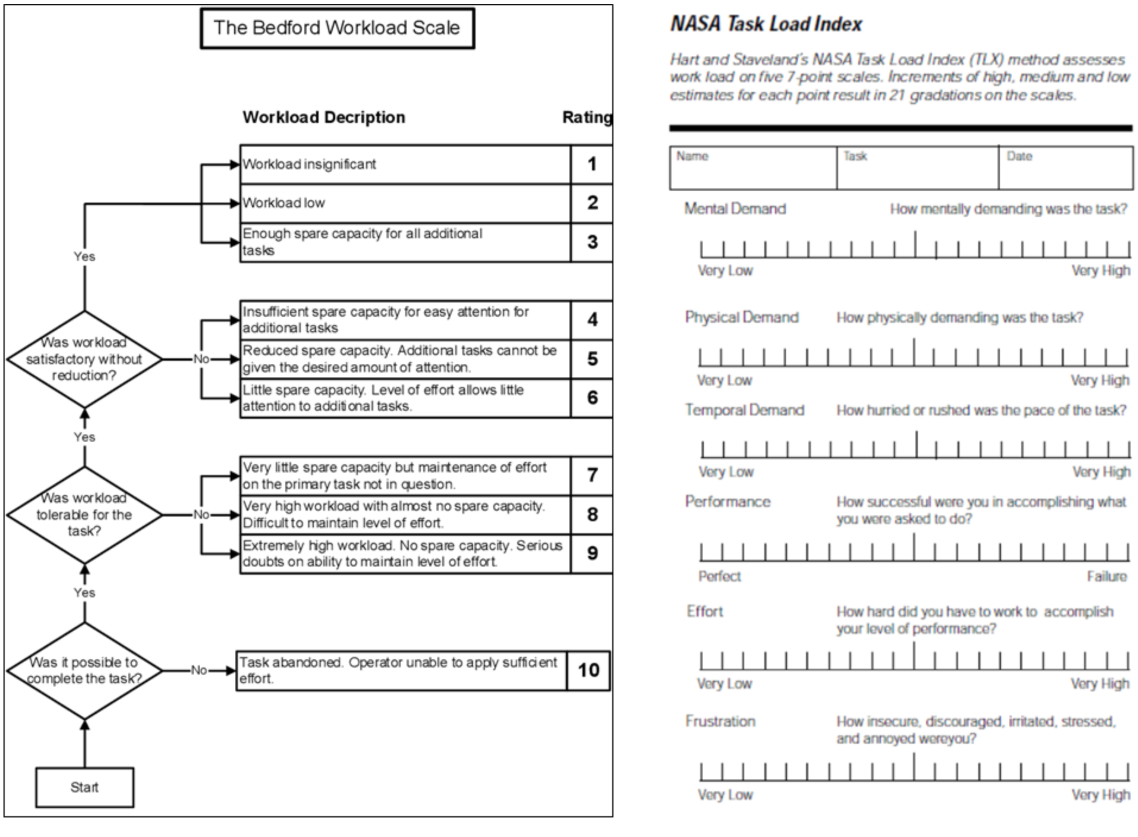
Comfort						
Greatest Imaginable Comfort	Very Comfortable	Slightly Comfortable	Neither Comfortable nor Uncomfortable	Slightly Uncomfortable	Very Uncomfortable	Greatest Imaginable Discomfort
1	2	3	4	5	6	7

(d) Fatigue Scale

No Fatigue		Minor Fatigue		Moderate Fatigue		Significant Fatigue		Extreme Fatigue	
Performance not compromised		Performance not compromised		Performance will likely be compromised if continued		Performance is compromised		Unable to continue with adequate performance	
1	2	3	4	5	6	7	8	9	10

Figure 7. Subjective Scales for (a) Reported Perceived Exertion (RPE), (b) Comfort, (c) and Thermal Acceptability, and (d) Fatigue.

As shown in Figure 8, two workload scales were administered during the geology task section to access the cognitive workload. The Bedford workload rating (Figure 8(a)) was used as a uni-dimensional rating scale designed to identify subjects's spare mental capacity while completing a task. Additionally, subjects were also asked to complete the NASA task load index (TLX), a tool for measuring and conducting a subjective mental workload (MWL) assessment while they are performing a task (Figure 8(b)).



a.) b.)

Figure 8. Subjective cognitive rating scales for the (a) Bedford Workload and (b) NASA Task Load Index (TLX) rated in percentage.

D. Dependent Variables and Sensor Instrumentation

1. Metabolic Rate and Heart Rate Analysis

Metabolic rate was used as a metric to evaluate physical workload and was collected with the COSMED K5 portable metabolic analyzer (COSMED, Rome, Italy). K5 calculates the volume of oxygen consumed (VO_2) by the volume of carbon dioxide produced (VCO_2), which are captured using the Dräger X-plore 4740 face mask (Hoogvliet Rotterdam, Netherlands). Metabolic rate was calculated separately by using the Péronnet Formula[16] (Eq. 3).

$$Energy\ Expenditure\ \left(\frac{BTU}{hr}\right) = 60 * 3.96 * (4.039 * VO_2 + 1.157 * VCO_2) \quad (3)$$

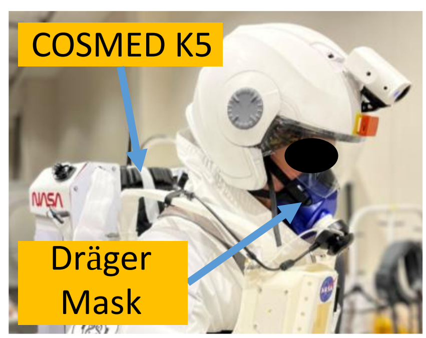


Figure 5. Subject wearing a COSMED system with a Drager mask underneath the helmet with cables routed to the K5 secured in the PLSS.

To integrate the COSMED K5 into HS3, modifications were made to the helmet so that the Dräger mask could fit underneath the helmet's face shield, and additional straps were added to the PLSS to secure the device, as seen in Figure 5. Heart rate data was collected using a Polar H10 heart rate strap (Polar Electro, Kempele, Poland), and used to calculate $\%HR_{max}$ to estimate physical workload. Both metabolic rate and heart rate were displayed in real-time with OMNIA software (COSMED, Rome, Italy). The real-time display allowed for live monitoring to ensure subjects were not exceeding the predicted 85 $\%HR_{max}$ threshold. Within the OMNIA software, timestamp markers labeled the start of each task, allowing tasks to be easily identifiable when reviewing the data.

2. Thermal Analysis

Skin temperature and humidity can give insight into the physical workload of the subject and help identify the efficiency of the LCG and ventilation systems in cooling down the subject.[17] Six thermal DS1923 Hygrochron Temperature and Humidity Sensors (iButtonLink Technology, Whitewater, WI USA) were placed across the subject's body (lower chest, upper arm, outer forearm, upper back, quadricep, calf) directly on the skin and recorded temperature and humidity every 30 seconds. Mean skin temperature (MST) was calculated using the Ramanahtan Method[17-19] (Eq. 4) to provide a single metric for thermal analysis.

$$MST = 0.3(T_{chest} + T_{arm}) + 0.2(T_{thigh} + T_{leg}) \tag{4}$$

Thermal sensation rating surveys were administered throughout the run to gain subjective feedback on temperature and comfort that could be compared to the skin temperature data collected from the iButtons.

IV. Results and Discussion

Two successful simulated EVA assessments have been conducted with HS3 and human performance data were collected during a structured task timeline (Table 1). Minor subsystem upgrades were implemented in DEMO2 including addition of shoulder straps to improve PLSS positioning and the addition of a pre-chilled cooling water procedure to improve thermal performance of the HS3. The data represents a feasibility analysis in preparation for future full characterization of HS3.

A. HS3 System Characteristics

The current HS3 system configuration weighs 40 lbs and is composed of 6 isolated battery power systems integrated into the PLSS as shown in **Error! Reference source not found.**. HS3 has an average power consumption of less than 30W with an average limiting system battery life of 2 to 2.5 hours depending on thermal system regulation demands. Primary electrical loads are the ventilation system and the heart rate monitoring (HRM)/Thermocouple system. Power systems E and F are supported by proprietary batteries from the manufacturers. All biosensors are equipped with offline data-saving capability with >4-hour battery life. A quick battery pack "hot swap" for power system C and COSMED K5 during the simulation can extend the overall system battery life to 5-8 hours, which would be needed for a simulated lunar EVA (~6-8 hr).[12] The optimal range of the communication headset is 60 feet (commercial wireless earbuds) or greater than 100 feet (when using the integrated motorcycle communication headset).

Table 3. HS3 Electrical System Characteristics

Power Systems	Main Load	Power (W)	Battery Life (hr)	Battery Type
A	HRM, Thermocouples for LCG	6.52	12	DeWalt 203 Li-ion rechargeable battery pack (80Wh)
B	LCG	1.63	10	Rechargeable battery (16.8Wh)
C	Ventilation	16.0	2.5	DeWalt 203 Li-ion rechargeable battery pack (40Wh)
D	COSMED K5	5.58	4	Rechargeable battery pack (22.3Wh)
E	Communication & lighting	·	6-7	Rechargeable battery pack, disposable alkaline batteries (light)
F	Thermal (iButton)	·	10 years	Single-use battery
Total		**29.7**		

B. HS3 Subjective Assessment

A range of motion (ROM) reach test demonstrated slightly restricted ROM in vertical and horizontal directions but allowed for successful completion of all scheduled EVA tasks. Subjects reported some ROM restriction, reduced field of view (FOV), and an added level of fatigue and cognitive burden that provides feasibility for future characterization of EVA-like analog simulations. A potential pressure point was reported on the nose bridge of one subject due to the tight mask seal of the K5; however, this is a common problem observed in the breathing mask system and is not unique to the HS3 setup. Additional nose bridge padding or better mask fit during the sizing process can potentially remove this concern.

A subjective questionnaire was administered throughout the simulation asking subjects to rank their various aspects of HS3 on the following scale. Both subjects who participated in this study have no suited experience, but have been test operators supporting suited testing and subjects of non-suited analogs. On average, simulation quality was ranked "acceptable" (no/minor limitation that will impact the validity of test data) with possible feasibility of EVA immersion. Subject rated simulation task acceptability to be acceptable. Subject comfort level was averaged between neutral or slightly comfortable, which is likely contributed from the physical and thermal workload during treadmill traverse activity. The thermal condition was ranked acceptable across all phases of the simulation but was warmer during the traverse/higher workload tasks. One limitation of the ventilation system observed was that the treadmill safety harness restricted air flow to the upper body which reduced the efficiency of the cooling system. This likely explained the decrease in thermal comfort during traverses. One subject also reflected a similar level of fatigue between treadmill traverses (low resistance grade), geology, and task board activities. This is consistent with the RPE being lower for geology, taskboard, and traverse at low resistance grade. Cognitive workload questions also reveal an average relative effort between 10% to 50% on TLX scale and 2 to 3 for Bedford scale for the geology and task board activities.

B. Thermal Analysis Outputs

The baseline HS3 EVA simulation assessments ran for three hours including sensor donning, suit donning and doffing time. Thermal data was collected to assess the general trends of the HS3 subsystems and LCG cooling on mean skin temperature. Analysis was conducted only on the EVA task time consisting of one hour and twenty minutes. Prior to egressing the donning stand, the ventilation system is set to a 30L/min flow rate. This provides peripheral cooling along with the LCG. LCG inlet and outlet temperatures to the soft suit garment were collected and averages are shown inTable 4. Mean skin temperature averages are also presented in Table 4 for to demonstrate the general cooling effectiveness of the LCG. The mean skin temperature did not show drastic changes and stayed relatively stable at 32.75 ± 0.94 °C for DEMO1 and 34.04 ± 0.71 °C for DEMO2 (Figure 6(a)). As the LCG feedwater is required to be pre-chilled prior to donning the HS3, the LCG temperatures for both the inlet and outlet lines showed a gradual increase as the simulated EVA progressed (Figure 6(b)). To mitigate this in the future, extending the chill time and adding backup feedwater bladders are recommended. From the preliminary assessments, the LCG mixed with higher ventilation flow rates showed adequate cooling during higher metabolically driven tasks. Delta temperature between the inlet and outlet showed a general offload of 3 to 4 °C out of the HS3 system through the LCG which kept mean skin temperature stable.

Table 4. HS3 Sensor Data Summary

HS3 Sensor Data		
Suit Outputs	**DEMO1**	**DEMO2**
LCG Inlet Temperature (ºC)	29.57 ± 6.62	25.63 ± 6.48
LCG Outlet Temperature (ºC)	33.53 ± 6.62	29.21 ± 4.79
PLSS Temperature (ºC)	22.71 ± 0.68	23.11 ± 1.32
PLSS Humidity (%)	34.06 ± 1.35	31.32 ± 1.51
Mean Skin Teamperature (ºC)	32.75 ± 0.94	34.04 ± 0.71

Data are presented as mean ±standard deviation

Core temperature and heat storage were not collected or calculated during these assessments as the system operation was being evaluated. The PLSS internal environment temperature and humidity data were collected via a Vaisala HMP7 (Vaisala Oyj, Vantaa, Finland) to determine if the LCG influenced cooling or humidity in the PLSS. The temperature remained stable at room temperature and humidity stayed between 31-35%. During DEMO2, the temperature of the PLSS rose during through the test, likely due to the pre-chilled LCG feedwater progressively warming (Figure 7).

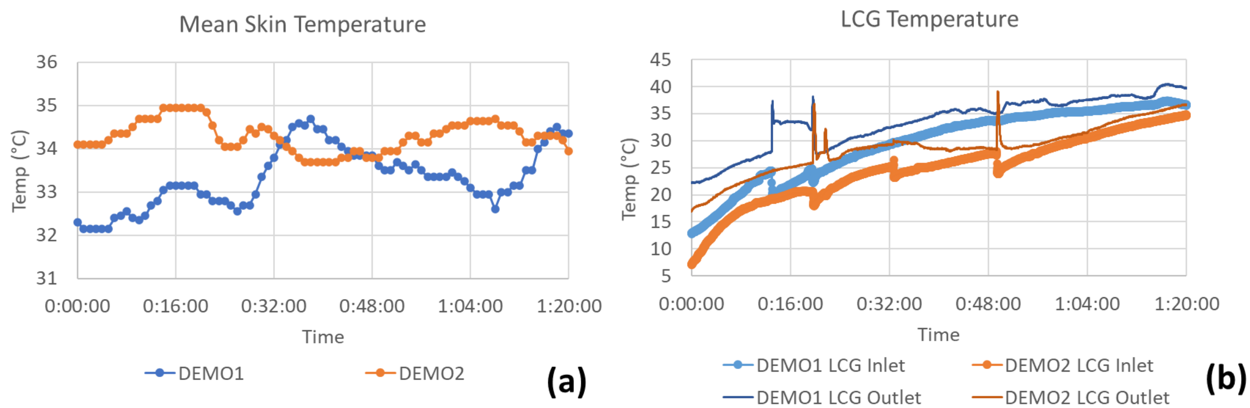


Figure 6. Example thermal series data during two simulated EVA (DEMO1 and DEMO2) with the HS3. *(a) Mean skin temperature over time during simulated EVA tasks. The values for mean skin temperature remained stable from heat offloading with the LCG. (b) Inlet and outlet LCG temperature during simulated EVAs showed a gradual increase as the simulated EVA progressed due to the feedwater being pre-chilled prior to HS3 donning but not chilled during operation.*

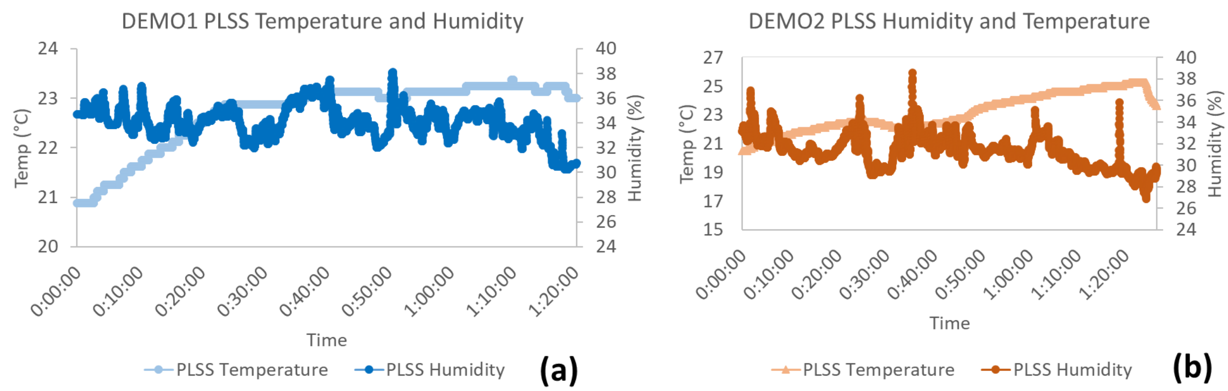


Figure 7. HS3 PLSS temperature and humidity during two simulated EVAs (DEMO1 and DEMO2). *(a) Temperature and humidity for DEMO1 remained stable at room temperature with humidity between 30 and 38 % in the PLSS housing. (b) DEMO2 showed similar stability in PLSS humidity but showed an increase in PLSS temperature.*

C. Metabolic Rate and Heart Rate Analysis Outputs

During the simulated EVAs, tasks were binned into general exploration EVA task categories consistent with those used for physical workload assessments in other ground analogs.[11,12] Average metabolic rate and heart rate (displayed as a percent of HR_{max}) were calculated over each task category (Table 5). Similar to other simulated EVA analog testing, such as ARGOS offloaded suited testing,[12] the highest metabolic driver during the simulated EVA with HS3 was the translation walking task. Likewise, object relocation tasks that involve both translating and carrying objects increased metabolic rates for both subjects (Table 5). The HS3 configuration allowed for the EVA simulated tasks to be completed and observed in binned task analysis for heart rate and metabolic rate (Figure 8). This type of EVA task timeline will be continued to further characterize the HS3 system by allowing the grouping of tasks to observe the effectiveness and fidelity of each subsystem.

Table 5 EVA task category and associated mean percent of maximum heart rate and metabolic rate

Category	DEMO1		DEMO2	
	Percent of HR_{max}	Avg Metabolic Rate (BTU/hr)	Percent of HR_{max}	Avg Metabolic Rate (BTU/hr)
Translation (Walking)	65% ± 8	2124 ± 549	77% ± 8	2269 ± 717
Translation (Carrying objects)	59% ± 2	1563 ± 215	71% ± 1	1723 ± 262

Trenching (Kneeling)	56% ± 2	1108 ± 221	73% ± 1	1597 ± 149
Chip Sampling (Kneeling)	56% ± 3	1092 ± 170	77% ± 2	1881 ± 272
Cable Routing (Standing)	51% ± 5	1268 ± 241	70% ± 4	1870 ± 289
Raking (Standing)	58% ± 3	1379 ± 216	73% ± 2	1724 ± 153
Pause (Resting, Standing)	49% ± 6	836 ± 327	60% ± 7	869 ± 203

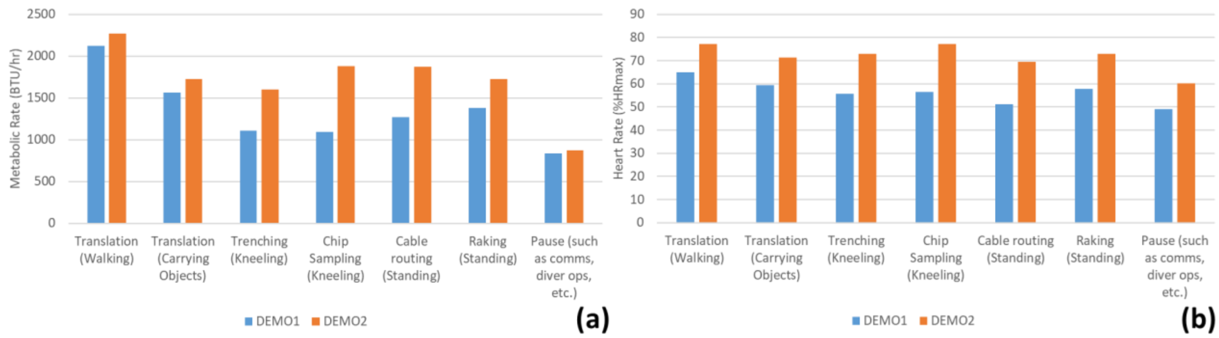


Figure 8. EVA Task category and associated metabolic rate and heart rate. *(a) Average metabolic rate for each various task categories including translating, carrying objects, chip sampling, raking, and trenching, and (b) average heart rate (percent of maximum heart rate) for each task category during DEMO1 and DEMO2.*

V. Conclusion & Future Work

Here we present the HS3, a modular space suit simulator with an integrated suite of human physiology sensors as a new capability and research tool for ground-based EVA simulation and evaluation. In this initial assessment of the HS3, metabolic rate, heart rate, gait kinematics, mean skin temperature, and suit thermal metrics were successfully collected using the integrated sensor platform during 3-hour simulated EVAs. HS3 represents a new research tool enabling customizable, modular use of a space suit simulator to address study specific aims while providing physical and cognitive workload and immersion during simulated EVA.

Future work will focus on characterizing the physical and cognitive workload simulation during HS3 EVA simulation for a larger cohort of subjects in the 1-g APACHE environment, provide a baseline assessment of HS3's operational capacity/characteristics (e.g., communication, power, and thermal), and investigate additional measures including core temperature, ROM, FOV, alteration of biomechanics, immersion, physical and cognitive workload. The suit simulator would then used in computational EVA simulations, where further software testing and quality assurance procedures would be carried out. H-3PO is planning on inviting subjects with pressured-suit experience to comment on HS3's simulation characteristics when compared to other analog suit simulators. This study is expected to finish testing in 2023. Additional studies focus on comparing the relevancy of HS3 to existing analog space suits (and comparison to previous datasets of spacesuit testing in a simulated reduced environment) and the applicability of HS3 configurations for different EVA scenarios will follow in the subsequent years.

Acknowledgments

We thank NASA Exploration Capabilities for funding this work. We would like to thank Dr. Kyoung Jae Kim for his support in reviewing and editing this paper. We also thank James Stoffel for initial design and implementation of the HS3.

References

[1]Abercromby, A. F., Bekdash, O., Cupples, J. S., Dunn, J. T., Dillon, E. L., Garbino, A., *et al.*, "Crew Health and Performance Extravehicular Activity Roadmap: 2020," NASA/TP-20205007604, 2020.

[2]Akin, D., "Development and Testing of a Next-Generation Spacesuit Simulator for Analog Field Tests," *International Conference on Environmental Systems*, Charleston, South Carolina, 2017, pp. 1-14.

[3]Akin, D., Saripalli, S., Di Capua, M., Hodges, K., Davis, K., and Younge, K., "Field Analogue Simulations Investigating EVA/Robotic Collaboration in Lunar Exploration," *International Conference on Environmental Systems,* Portland, Oregon, 2011,

pp. 1-11.

[4]Groemer, G., and Ozdemir, S., "Planetary Analog Field Operations as a Learning Tool," *Frontiers in Astronomy and Space Sciences*, Vol. **7**, No. 32, 2020, pp. 1-6.

[5]Soucek, A., Ostkamp, L., and Paternesi, R., "Suited versus Unsuited Analog Astronaut Performance using the Aouda.X Space Suit Simulator: The DELTA Experiment of MARS2013," *Astrobiology*, Vol. 15, No. 14, 2015, pp. 283-290.

[6]Swarmer, T., Akin, D. L., and Davis, K. P., "Suit Simulators for Analog Sites: Lessons Learned from HI-SEAS Testing," *International Conference on Environmental Systems*, Bellevue, Washington, 2015, pp. 1-15.

[7]Baughman, A. J., Kim, K. J., Suri, K., and Abercromby, A. F., "Assessments of Physiology And Cognition in Hybrid-reality Environments (APACHE)–Physical Workload Approximation," *International Conference on Environmental Systems*, St. Paul, Minnesota, 2022, pp. 1-12.

[8]Atlas Devices, EXploration CONop (EXCON) Suit, URL: https://atlasdevices.com/products/atlas-devices-excon

[9]Tejral, Z., "Testing the Exploration Conops (Excon) Mockup Suit in Lunar Analog Environments in 2022," *International Conference on Environmental Systems*, Calgary, Canada, 2023 (accepted).

[10]Davis, K., and Meginnis, I., "Testing of the NASA Exploration Extravehicular Mobility Unit Demonstration (xEMU Demo) Architecture at the Neutral Buoyancy Laboratory," *International Conference on Environmental Systems*, Boston, Massachusetts, 2019, pp. 1-16.

[11]Bekdash, O., Dunn, J. T., Garbino, A., Welsh, L. D., Norcross, J. R., and Abercromby, A. F., "Physical and Cognitive Exploration Simulations: Development and Testing of Exploration Activity Modules," *International Conference on Environmental Systems*, Lisbon, Portugal, 2020, pp. 1-12.

[12]Schlotman, T. E., Cox, L. I., McGrath, T. M., Baughman, A. J., Estep, P. N., Siders, B. A., et al., "A Preliminary Assessment Of Physical Demand During Simulated Lunar Surface Extravehicular Activities," *IEEE Aerospace Conference*, Big Sky, Montana, 2023 (accepted).

[13]Tanaka, H., Monahan, K. D., and Seals, D. R., "Age-predicted Maximal Heart Rate Revisited," *Journal of the American College of Cardiology*, Vol. 37, No. 1, 2001, pp. 153-156.

[14]Schlader, Z. J., Johnson, B. D., Pryor, R. R., Stooks, J., Clemency, B. M., and Hostler, D., "Human Thermoregulation during Prolonged Exposure to Warm and Extremely Humid Environments Expected to Occur in Disabled Submarine Scenarios. *American Journal of Physiology-Regulatory, Integrative and Comparative Physiology*, Vol. 318, 2020, pp. R950-R960.

[15]Hart, S. G., "NASA-Task Load Index (NASA-TLX); 20 Years Later," *Proceeding of the Human Factors and Ergonomics Society*, Vol. 50, No. 9, 2006, pp. 904-908.

[16]Péronnet, F. and D. Massicotte, *Table of nonprotein respiratory quotient: an update.* Can J Sport Sci, 1991. **16**(1): p. 23-9.

[17]Hoffmann, B., Schlotman, T., Cox, L., Garbino, A., Estep, P., Abercromby, A., Somers, J., "Human Thermal Analysis of Traverse and Geology Tasks During Simulated Lunar Extravehicular Activity," *IEEE Aerospace Conference*, Big Sky, Montana, 2023 (accepted).

[18]Mitchell, D., and Wyndham, C., "Comparison of Weighting Formulas for Calculating Mean Skin Temperature," *Journal of Applied Physiology*, Vol. 26, No. 5, 1969, pp. 616-622.

[19]Bekdash, O., Valle, P., Kim, K. J., Jarvis, S., Dunn, J., Norcross, J., Abercromby, A., "Development and Evaluation of the Active Response Gravity Offload System as a Lunar and Martian EVA Simulation Environment," *International Conference on Environmental Systems*, Lisbon, Portugal, 2020, pp. 1-12.

[20]Smith, M., Craig, D., Herrmann, N., Mahoney, E., Krezel, J., McIntyre, N., et al., "The Artemis Program: An Overview of NASA's Activities to Return Humans to the Moon," *IEEE Aerospace Conference*, Big Sky, Montana, 2020, pp. 1-10.

[21] D. Coan, "Exploration EVA System Concept of Operations," EVA-EXP-0042, Oct. 2020.