Development and Evaluation of the Active Response Gravity Offload System as a Lunar and Martian EVA Simulation Environment

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In preparation for future exploration missions, NASA seeks the ability to simulate partial-gravity operations for use in ground-based research, crew training, and engineering design evaluations. The Active Response Gravity Offload System (ARGOS) at the Johnson Space Center (JSC) is designed to simulate reduced gravity environments, such as lunar, Martian, or microgravity, using a robotic system similar to an overhead bridge crane. ARGOS continuously offloads a portion of a suited human's weight during all dynamic motions within the test facility, which can include basic functional movements such as walking, running, and jumping, as well as a wide range of planetary surface activities. This system will be used as part of a metabolic-rate task characterization study to determine the workload associated with partial-gravity extravehicular activity (EVA). Pilot testing was conducted using the MKIII prototype planetary space suit and two gimbal designs to determine the ability of the ARGOS test environment to simulate planetary EVA operations. This paper will describe the lessons learned from the feasibility testing, simulation-environment mockup design, and the results from the pilot tests and their influence into the final study design. Being able to effectively simulate partial-gravity environments and characterize the performance of crewmembers will have an impact on multiple domains including suit design, task design, thermal models, and life-support-system capacity verification plans, among others.

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Nomenclature

ARES	=	Astromaterials Research and Exploration Science
ARGOS	=	Active Response Gravity Offload System
CG	=	Center of Gravity
DOF	=	Degrees of Freedom
EMU	=	Extravehicular Mobility Unit
EV	=	Extravehicular
EVA	=	Extravehicular Activity
H-3PO	=	Human Physiology, Performance, Protection, and Operations
IMU	=	Inertial Measurement Unit
IV	=	Intravehicular
JSC	=	Johnson Space Center
MKIII	=	Mark III Prototype Spacesuit
MCC	=	Mission Control Center
NASA	=	National Aeronautics and Space Administration
NBL	=	Neutral Buoyancy Laboratory
PACES	=	Physical and Cognitive Exploration Simulations
PSIA	=	Pounds per Square Inch Absolute
PSID	=	Pounds per Square Inch Differential
POGO	=	Partial Gravity Simulator
SME	=	Subject Matter Expert
xEMU	=	Exploration Extravehicular Mobility Unit

I. Introduction

AS NASA prepares for exploration missions to the moon and Mars, there is an immediate need to establish facilities that can support ground-based partial gravity operations research, crew training, and hardware evaluations. Accurately and effectively simulating partial gravity relies on understanding the usability and limitations of the partial-gravity analog environment. While no single analog can fully simulate the partial gravity experienced in space, several different simulation environments have been developed by NASA. Some of these have included the partial-gravity simulator (POGO), underwater simulations at the Neutral Buoyancy Laboratory (NBL), and parabolic flights. Each of these carry different limitations on freedom of movement, size of work volume, or method of simulating reduced gravity. The POGO only allowed two (Y, Z) degrees of freedom (DOF) and had significant overhead inertia from the lifting mechanism and passive horizontal translation resulting in direct impacts to subject task performance[1]. Parabolic flight improves upon the DOF available and offloads the subject with the greatest simulation quality, however, the volume to perform tasks and the duration of the parabolas (~30 s) limit the quality and type of data that can be collected[2]. Lastly, underwater partial gravity analogs, which typically provide the largest work and mockup volume and also allow full DOF, place significant water drag on the subject during dynamic movements (e.g., gross translations)[3]. While the Active Response Gravity Offload System (ARGOS) does not resolve all of these limitations, it does provide full X, Y, Z translational DOF (vertical system in Z, horizontal system in X-Y), a precise control of the offload, and active control of all translational axes to reduce the system inertial effects on the subject. ARGOS is designed to simulate reduced gravity environments, such as lunar, Martian, or microgravity, using a robotic system similar to an overhead bridge crane.

The ARGOS attaches to a human or payload using a gimbal. The active ARGOS robot provides the three translational degrees of freedom while the passive gimbal provides the three remaining rotational DOF. For the current testing with the Mark III spacesuit (MKIII), two gimbals have been used, both of which attach via the Mark III waist ring donning-stand interface and have a wide range of center of gravity (CG) alignment adjustment. Both gimbals feature continuous yaw rotation through a bearing connection to the lifting cable, limited roll rotation (approximately 30 degrees) via the parallelogram design, and continuous pitch rotation (limited by subject interference with the gimbal structure). The first gimbal, known as the "claw gimbal", is a fully metallic gimbal that weighs approximately 105 pounds. The second, known as the "EMU/MkIII adapted gimbal", uses a spreader bar with polyester lifting straps to reduce weight, and weighs approximately 53 pounds, and was modified from the gimbal used to support the extravehicular mobility unit (EMU) space suit in microgravity. Figure 1 below shows the claw and modified EMU gimbals, and a close up of the rotational element and lift point adjustment.

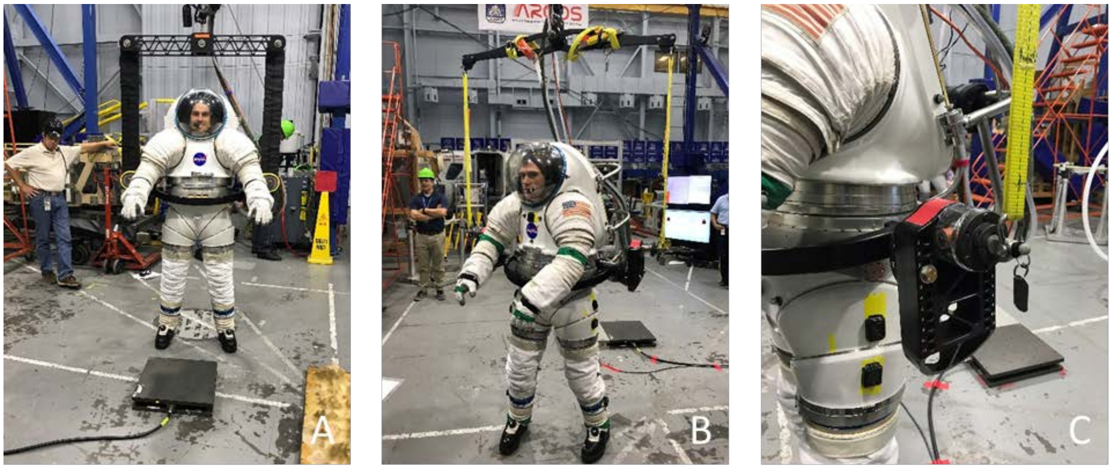

Figure 1. (A) Claw gimbal; (B) EMU/MkIII adapted gimbal; (C) Lift point adjustment and rotation is the same between both gimbal configurations.

Historically, ARGOS suited testing has been primarily focused on functional movement or hardware evaluations in microgravity[4-6]. However, there is now a need to use the facility as an end-to-end EVA simulation environment where a subject can perform all components of an EVA following realistic EVA timelines. This type of EVA simulation facility will enable better, in-context characterization of human suited performance that includes both the physical and cognitive workload that will be present in flight. Specifically, the NASA JSC Human Performance, Physiology, Protection, and Operations (H-3PO) laboratory is preparing to conduct a study to characterize planetary EVA metabolic rates in exploration class spacesuit prototypes. This paper will describe work to: (1) assess the ARGOS partial gravity simulation quality for enabling performance of exploration EVA tasks; and (2) demonstrate the ARGOS test facility as an end-to-end EVA simulation environment, including definition and pilot testing of performance metrics, data collection hardware, and analysis methods for future studies.

II. Methods

A. Subjective and Objective Measures for Characterizing ARGOS Simulation Environment

This feasibility test series worked to develop metrics and methodologies that could be used unobtrusively to characterize the ARGOS and suited performance outcomes. In the tests with the claw gimbal, two subjects were used, both of whom had significant prior experience in the MKIII and would thus be able to differentiate between expected suit limitations and those resulting from being attached to the ARGOS system. Following an initial checkout of the ARGOS system using this gimbal, testing of the ARGOS as an EVA simulation environment was performed in the EMU/MKIII adapted gimbal using three test subjects. One of the subjects is a geologist and could best evaluate the simulation quality of bringing real-world geologic fieldwork into the ARGOS volume. The remaining two subjects were current astronauts that have completed geologic science training but were also part of prior tests with the MKIII in other partial gravity environments (POGO and/or C-9 flights) and could extrapolate from a flight operations and simulation perspective on the acceptability of the ARGOS testing environment.

In addition, a key requirement for execution of an immersive exploration simulation is that breaks in simulation for data collection are kept to a minimum. The measures presented here were pilot tested in this effort to determine best methods for unobtrusive integration during an ARGOS test. This included subjective assessments of simulation quality, ARGOS configuration acceptability, and objective measures such as metabolic expenditure, functional movements, and gait. Several of these measures still are being evaluated for their efficacy in meeting future study objectives and this paper will describe the current state of implementation and forward work.

All testing was performed with the MKIII prototype spacesuit pressurized to 4.3psid (19 psia). The MKIII is a rear-entry hybrid space suit configuration composed of a hard upper torso and brief, and soft components around the elbows and knees for mobility.

1. Simulation Quality

The simulation quality ratings provided by the subjects (Figure 2), reflect the extent to which the ARGOS was able to provide an accurate simulation of a partial-gravity environment. Subjects were asked to rate the simulation quality with respect to the ARGOS offload and the subject's gimbal awareness, taking into consideration the ability to: stand stationary in their preferred posture, ambulate, perform weight transfer tasks, use desired range of upper and/or full body motion, and to support various EVA simulation tasks.

Scale Rating	Criteria
1	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.
2	Some simulation limitations or anomalies encountered, but minimal impact to the validity of test data.
3	Simulation limitations or anomalies made test data marginally adequate to provide meaningful evaluation of test objectives (please describe).
4	Significant simulation limitations or anomalies precluded meaningful evaluation of major test objectives (please describe).
5	Major simulation limitations or anomalies precluded meaningful evaluation of all test objectives (please describe).

Figure 2. Simulation quality ratings scale.

2. Acceptability

The acceptability rating scale (Figure 3) is a 10-point Likert scale ranging from totally acceptable to totally unacceptable. In addition to simulation quality subjects were asked to rate the acceptability of the ARGOS gimbal to enable performance of the various functional tasks and EVA simulation activities. Subjects were specifically instructed to evaluate the *task acceptability* of the ARGOS gimbal and work environment to 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. Ratings of 3 or greater required subject comment of the specific improvements to improve the gimbal interaction with the spacesuit, or the ARGOS testing environment to increase their level of acceptability to best support the exploration activities.

Totally Acceptable		Acceptable		Borderline		Unacceptable		Totally Unacceptable		No Rating
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 deficiencies		Unable to assess capability
1	2	3	4	5	6	7	8	9	10	NR

Figure 3. Acceptability ratings scale.

3. Functional Mobility

During both the functional task battery and exploration simulation activities, a portion of the testing data were collected to automatically determine the feasibility of characterizing the postures and activities of the subjects using wireless inertial measurement units (IMUs). Seven Opal^{TM} (APDM, OR, USA) IMUs were attached to the spacesuit: one on the chest, left and right upper hip bearing, left and right mid-hip bearing, and left and right ankle bearing (Figure 4). Postures and activities evaluated with the IMUs included ambulating, standing, bending over, and kneeling. Future work will aim to refine and verify the IMU data processing algorithm (publication of the specific signal analysis method is in work). A Vicon MX motion-capture system simultaneously tracked key landmarks on the suit and gimbal to capture overall suited motion. Work is underway to understand the best methods for reporting these data and how they can be used to understand subject performance and EVA simulation execution consistency. Future work also will focus on repeated data sessions at varying gimbal settings, which is expected to inform how gimbal artifacts may be affecting functional mobility in addition to improving the functional movement analysis algorithm.

Figure 4. Wireless IMUs attached to the outside of the MKIII (top left: center of HUT, top right: upper and lower hip bearing, bottom: ankle bearing)

4. Gait Assessment

As subjects performed walking tasks, the same IMUs used for the functional mobility analysis also were used to assess gait performance and to quantify relevant gait kinematics (e.g., upper body tilt, gait phase, gait parameters). Future work aims to determine if the gimbal and/or ARGOS offload affects subject gait performance.

5. Metabolic Expenditure

Understanding metabolic workload associated with partial-gravity EVAs is an integral part of mission planning, crew safety, and spacesuit system design. This feasibility testing series worked to determine optimal methods for integration of the H-3PO metabolic-rate measurement system with the MKIII spacesuit. The system is placed on the back of the suit, with a tubing line attached to an Apollo style fitting ahead of the backpressure relief valve. The positive pressure of the suit drives the flow to the sensor and flow rate is controlled via a fixed orifice fitting. Figure 5 shows the miniaturized system on the back of the MKIII. The current setup records data locally, however, future work will integrate this with a larger data recording system for real time display, syncing with timeline tracking software, and rapid data post-test data processing.

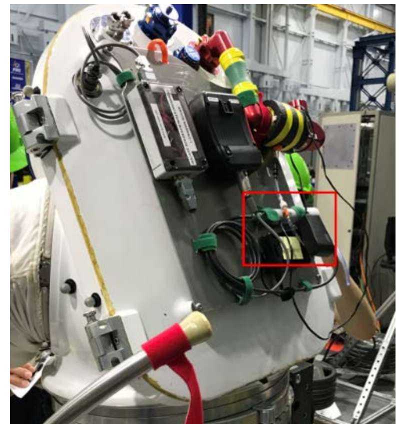

Figure 5. Rear hatch of the MKIII spacesuit with the metabolic-rate measurement hardware outlined in red.

B. Functional Movement Tasks

An initial set of functional-movement tasks was identified for feasibility testing. These tasks were distilled from a task analysis of the proposed surface EVAs on the moon and Mars describe in the EVA-EXP-0042 Document: Extravehicular Activity Office Exploration EVA System Concept of Operations.[7] Tasks primarily were intended to drive out issues associated with the ARGOS partial-gravity offload and determine if functionally a subject can acceptably perform the tasks that would be included in the EVA simulation portion of the testing. Functional tasks were selected to determine if the gimbal and settings chosen for a specific subject were providing adequate simulation quality and that the ARGOS configuration was not assisting or preventing subjects from performing expected suited operations. These tasks are described in Table 1.

Table 1. Functional movement task battery for assessment of gimbal settings impact on subject capability.

Functional Movement Task	Description
Ambulation	~60 ft. ambulation (back and forth required in ARGOS volume)
Ambulation w/ a 30-lb load	~30 ft. ambulation while carrying a 30-lb bag (back and forth required in ARGOS volume)
Kneel and recover	Single knee kneel and recover
Prone and recover	Subject lays down on flat surface and recovers to a standing posture
Object pickup	Subject picks up a tennis ball from the ground
Treadmill 0% grade walking profile	Subject walks at speeds from 1-4 mph in intervals of 0.5 mph
Treadmill incline/decline walking profile	Subject walks at fixed 1.5 mph with grades varying between -10% to +30% at 10% intervals.

C. Surface EVA Simulations

In addition to the functional task battery, two exploration EVA simulations were pilot tested to demonstrate ARGOS as an EVA simulation facility: a science payload deployment activity derived from the Apollo 16 geophone deployment EVAs and a scientific traverse around a simulated geologic site of interest. For this introductory paper, only the scientific traverse is described. Each of these simulations were first scoped under the H-3PO Physical and Cognitive Exploration Simulations (PACES) project to include all tasks expected during actual lunar EVAs under ideal (i.e., lunar surface) conditions and then modified for what was able to be simulated in the ARGOS environment[8]. For example, in the current ARGOS configuration, only single EV crewmember operations are supported. Therefore EVA timelines and tasks, which nominally require two EV crewmembers to complete, were modified for all tasks to be performed by a single EV. While that may not be representative of flight, the primary objective of demonstrating ARGOS as a possible end-to-end EVA simulation environment could still be met. Execution of these simulations also included direct science IV to EV crewmember communication, contextual EVA overhead (e.g., suit status checks), use of high fidelity tools where possible, and simulation of camera views that could be present on the lunar surface. The simulation task timelines and ARGOS mockup configuration for each activity are shown in Figure 6 respectively. For the geologic science simulation, large bins filled with varying types of sand and small boulders were emplaced, along with large boulders on which X-ray fluoroscopy (XRF) measurements and chisel samples could be taken. Safe operation within the ARGOS structure places restrictions on mockup design and size because room must always be available for safety equipment to enter the workspace. Hence, why multiple small, easily moveable bins were used for this testing. While it is preferred to have a single large workspace, understanding the level of simulation quality and acceptability under these ARGOS facility constraints is essential to determine how well end-to-end EVAs can be simulated there.

1. Subsite Traverse and Geologic Sampling EVA Simulation

The geologic science traverse performed in this feasibility testing looked at translating a notional field site on the lunar surface into the ARGOS workspace. The simulation assumes the EVA crewmember has arrived at the center of a site of interest on the lunar surface that is approximately 30 meters in diameter. This size of region is a reasonable estimate based on consultation with terrestrial and planetary geologists. Multiple sites of interest may be explored during a single EVA traverse or surface mission. In this simulation, two subsite stations, within the site of interest, were tested. In each, the crewmember will perform a terrain survey traverse, relay observations of terrain, geomorphology, contact lines, photo-documentation of region, and proposed sampling strategies back to the mission control center (MCC) before performing sampling activities. The EVA simulation timeline is shown in Figure 6. This timeline was adapted from a notional lunar surface EVA where two crewmembers are exploring the site of interest. To complete this simulation in the ARGOS facility, two major changes were made. First, all tasks needed to be performed by a single crewmember, so any dual crew tasks were reduced into single crew tasks and shortened to maintain the same total workload while still performing all anticipated surface tasks. Second, because the traverse distance (15 meters) between subsite stations was greater than the ARGOS area, these were accomplished by walking back and forth in the ARGOS volume. Ideally, a volume large enough to meet the required site survey area is available, however, because the primary aim in the future is to understand metabolic workload, as long as the correct total distance was achieved this was viewed as acceptable by the study team with subjects providing ratings on the size and volume of ARGOS to evaluate this assumption.

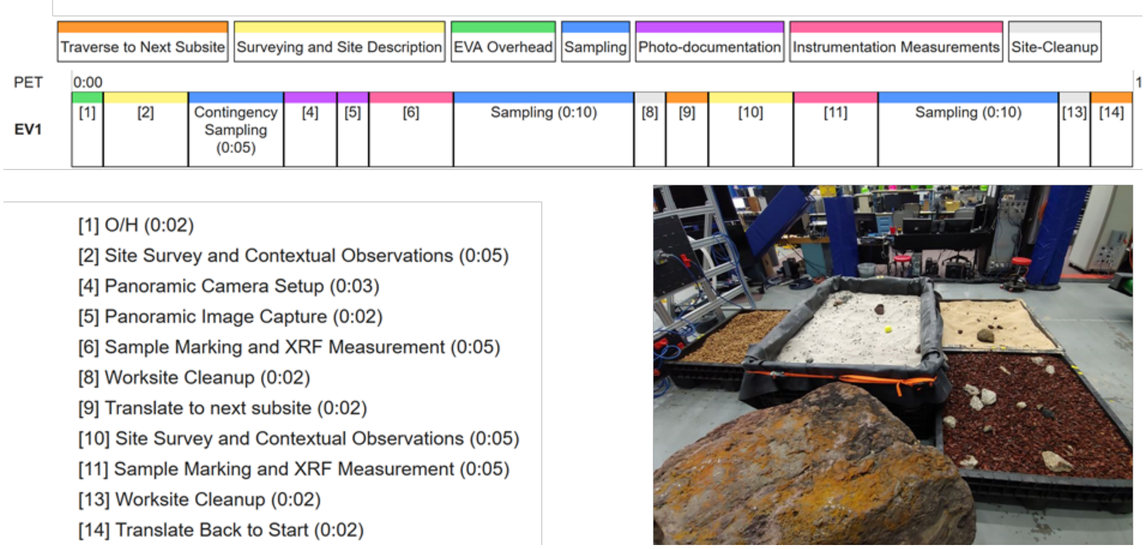

Figure 6. Subsite traverse and geology sampling EVA simulation timeline and the ARGOS layout.

Tasks were selected based on analysis of the EVAs performed during Apollo missions, review of the latest NASA EVA-EXP-0042 document, and consultation with subject matter experts (SMEs) from the NASA JSC Astromaterials Research and Exploration (ARES) group. These included providing a description of the immediately visible area (to simulate this, a screen with a lunar landscape was shown to the subject) identifying geologic features of interest, contact lines, and possible areas for sampling. Following the contextual survey and documentation, subjects set up a panoramic camera, and then performed a contingency sample. During all sampling activities, subjects performed audio and photo documentation of the samples and communicating with a member of a simulated science backroom team on sampling targets of interest. Some geologic features then were selected by the scientist “on the ground” for further analysis and in-situ XRF measurement. Sampling strategies were largely at the discretion of the subject, including which tool they deemed most appropriately to retrieve the sample with minimal contamination (Figure 7). In some cases, where a secondary objective also was to evaluate tool design, the backroom scientist would recommend a specific tool for a specific sample. Sampling at a given site was performed for 10 minutes before the subject was tasked with site cleanup and traverse to the next subsite where the activities were repeated a second time. Full duration of the simulation was approximately 1 hour.

Figure 7. A subject performing geologic sampling activities in the simulated field environment.

Following completion of the simulation activities, the subjects were asked to answer questions related to the simulation quality and acceptability of the exploration activities performed and of the mockups and tools that were used. In addition to these subjective measures, the functional movements required to complete the tasks (e.g., time spent kneeling, standing, ambulating, etc.) and the metabolic rate also were collected.

III. Feasibility Testing Results

A. Functional Task Battery

Initial tests were performed using the claw gimbal, with the assumption that once the lighter EMU/MkIII adapted gimbal was available that testing would continue with that as the primary option. The claw is designed with the vertical supports very close to the suit to reduce inertia. However, this was found to have the unfortunate side effect of severely limiting arm motion during ambulation and some upper body EVA tasks. Subjects reported they were unable to ambulate on the treadmill at speeds above 2 mph without significant interference with the preferred walking style, resulting in an arms forward posture and discomfort from maintaining that posture.

The reduction of mass in the EMU/MkIII adapted gimbal improved the simulation, as there are less artifacts of the gimbal in the subject's motion. An additional benefit of the EMU/MkIII adapted gimbal beyond the mass and inertia savings is that because of the existing spreader bar sizing, the straps connecting the spreader bar to the lower portion of the gimbal connecting to the suit are moved further out to the sides, giving the subject more freedom of arm motion. During treadmill translations, both gimbals, due to their attachment below the waist bearing of the Mark III suit, rotate with the subject's hips during walking or running motions. This exacerbates the interference with the subject's arms, as the gimbal is "spun" into their arms during a normal walk or twist. All subjects reported that their preferred walking form was altered and resulted in discomfort at their shoulders and arms from holding them out of the way of the gimbal over long-distance ambulation.

Overall simulation quality ratings for the adapted gimbal and ARGOS were 3 or greater, indicating that an adequate simulation with limited deficiencies was achieved. For all functional tasks except the treadmill profile crew subjects reported that the ARGOS offload method was "probably flight-like", with simulation quality ratings ranging from 2 to 3 (some simulation limitations with limited impacts to validity of test data). Additional comments included limited range of motion when performing object pick up tasks, with elbows hitting the gimbal because of limited clearance. During the treadmill ambulation task, subjects reported that there was some unknown inertia to the system that was difficult to attribute to the suit or ARGOS specifically, in addition to similar issues with arm posture in relation to the gimbal that was seen with the first tests using the claw gimbal. Future testing will specifically question subjects on this to more precisely determine where the "unknown inertia" stems from and if it is simply a function of managing the spacesuit mass effectively or an actual artifact of the ARGOS offload.

In addition to the simulation quality ratings, subjects were asked to rate the acceptability of performing these tasks in the as -tested MKIII suit + gimbal configuration. Ratings were similar between subjects 1 and 3; however, subject 2 reported that the prone to recover, ambulation with the load, and object pickup were unacceptable. This subject found that it was difficult to grip a heavy load in front of the suit while walking and recommended that there be some way of affixing these to the suit directly. Subjects also commented that it was difficult to get the suit into a full squatting position in lunar-G offload and that when required to go down on both knees, there is a tendency to fall forward and rotate within the gimbal. It was not possible to determine if this was specifically attributable to an ARGOS gimbal artifact or the 1/6-G operations. Overall, subjects found that performing functional movements in the ARGOS is acceptable for future testing and would enable performance of exploration tasks.

A summary of the simulation quality and acceptability ratings is shown in Table 2. Because of the low number of subjects in this initial testing, the individual data is reported.

Table 2. Simulation quality and acceptability ratings for performing functional movements in the EMU/MKIII adapted gimbal configuration

Functional Task	Simulation Quality			Acceptability		
	S1	S2	S3	S1	S2	S3
Ambulation	2	2	2	3	4	3
Ambulation w/ a load (30lb)	2	2	2	3	7	3
Kneel & recover	2	2	2	2	4	2
Prone & recover	2	2	2	3	7	2
Object pickup	3	2	2	4	6	3
Treadmill 0% Grade Profile	3	3	2	3	2	3
Treadmill Variable Grade Profile	3	3	2	3	2	3
Overall Offload & Gimbal	2	2	2	2	4	3

B. EVA Simulation Execution and Subject Feedback

1. Subsite Traverse and Geologic Sampling EVA Simulation

Overall, the subjects found that the geologic simulation quality was sufficient and that the ARGOS facility for performing these types of activities was acceptable. Ratings for simulation quality ranged from 2 (some simulation limitations with minimal impact to data) to 3 (simulation limitations made test data marginally adequate). Simulation limitations reported included some motion limitations from the gimbal when wanting to turn left or right, an ability to "sit back" into the suit while being supported by the gimbal, and that the gimbal is likely providing more stability than actual reduced gravity. All subjects also commented that the space constraints in the ARGOS work volume, the simplicity of the mockups, and the simulated regolith (to protect suit components, several bins were filled with rubber mulch or cork) were all of marginal simulation quality. While limiting in simulation fidelity, subjects reported that the overall motion and offload was adequate to support these geologic science tasks.

With respect to acceptability of the operations performed in the simulation, and the ARGOS gimbal and volume to support them ratings were consistent between subjects, with all reporting that these features were acceptable with no or minor improvements desired. Areas that received improvements warranted or borderline ratings included overall volume in the ARGOS space, the work envelope in the gimbal, the mockups, and some of the geologic procedures. Subjects reported that the area limited ability to include a variety of geologic features in which to perform science and the mockups were too simplistic for fully performing geologic science tasks that would occur in the field but for a short-duration test the facility is acceptable to perform EVA simulations. All also reported that from a task, tool, and science instrument training perspective, this facility is well able to prepare future astronauts for work on the moon or Mars. A summary of the simulation quality and acceptability ratings is shown in Table 3.

Table 3. Simulation quality and acceptability ratings following the surface geologic simulation activity. *The questions asked of the subjects were expanded following the first subject's run.

Subsite Traverse and Geology Sampling EVA Simulation	Simulation Quality Ratings			Acceptability Ratings		
	S1*	S2	S3	S1*	S2	S3
Offload & gimbal overall (repeat for geophone and geology)	2	2	2	2	4	3
Work envelope within gimbal	3	2	2	5	3	2
Ability to position body as needed within gimbal	-	2	2	-	3	2
Ability to orient body as needed within gimbal	-	2	2	-	3	2
Vertical offload velocity/acceleration	-	2	2	-	3	2
Horizontal velocity/acceleration	-	2	2	-	3	3
Stability (e.g. not providing artificial stability)	-	3	2	-	3	3
Geology task mockups	2	3	3	4	4	3
Geology task tools	3	2	2	4	3	3
Overall volume to perform geology module tasks	3	3	3	5	3	3
Overall layout to perform geology module tasks	2	3	2	3	3	3
Overall task design and order of operations	2	3	2	3	3	2
Overall execution of geology tasks (e.g., shoveling, trenching, XRF)	-	3	2	-	3	2
Executing geology operations without an EV2 present	2	2	2	3	3	2
Procedures and science operations	2	3	2	3	5	3
IV ↔ EV communication	2	2	2	2	3	2
Overall procedure delivery (IV ↔ EV dictation)	2	2	2	2	2	2

C. Measurement Hardware Integration and Analysis Methods

Feasibility testing aimed to understand methods for integration of sensor hardware and data streams into the ARGOS environment for data capture during testing without interfering with the EVA simulation activities. Additionally, work was started to develop methods for analysis and reporting of data to meet stakeholder objectives.

1. Subjective Measures Survey

Integration of subjective measures was tested in two ways. For the first subject, questions were asked over the communication loop while the subject was still in the spacesuit and offloaded on ARGOS. The test conductor transcribed responses dictated by the subject and provided them with a paper copy of the scales for reference. This method was not preferred for anything beyond the subject providing a single rating value without comment as the poor audio quality between the suit and ARGOS system, the difficulty of rapidly transcribing subject response, and the excess use of pressurized suit time made accurate recording of data difficult. For the remaining two subjects, all subjective measures were collected following completion of the simulation activity with the subject fully egressed from the MKIII. Subjects were isolated from the test team/environment and given dedicated time to directly input their own responses on a survey application. This was the preferred method by both subjects and test team operators as the subject could provide more detailed responses without a time or transcription constraint.

2. Functional Movement Characterization

The functional movement characterization was performed by analyzing the IMU data for discrete signal patterns representative of functional movements being categorized. For this first round of feasibility testing periods of standing, ambulating, and kneeling (single and both knees) including torso bent forward were evaluated as a capability demonstration and to provide pilot data to begin data analysis product definition. Figure 8 shows examples of these postures and activities.

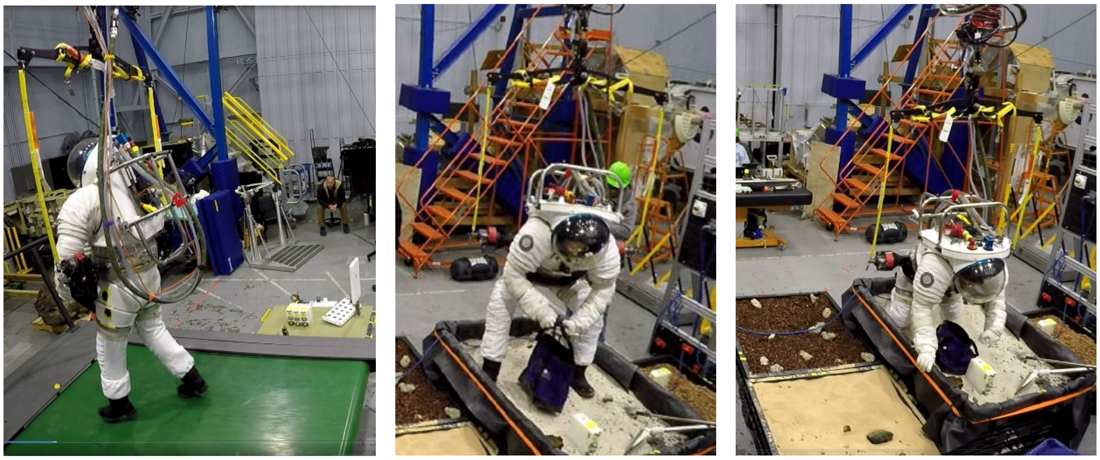

Figure 8. Examples of postures and activities: walking on the treadmill (left); standing with torso bent forward (middle), kneeling with both knees (right)

Integration of the IMUs with the MKIII consisted of simply adhering them to the outside of the spacesuit. Future work will examine the number and location of IMUs that are required and if they can be reduced to save on set up time (which is already minimal). Data are collected continuously during the run with no input required from test execution personnel. Following each run, data were analyzed to produce a breakdown of the total time a subject was in a certain posture. This could have implications – such as understanding injury risk, suit joint cycles, dust mitigation and suit contact with the surface – for a variety of stakeholders or optimizing task completion strategies training for crew. An example report from this data collection is shown in Figure 9.

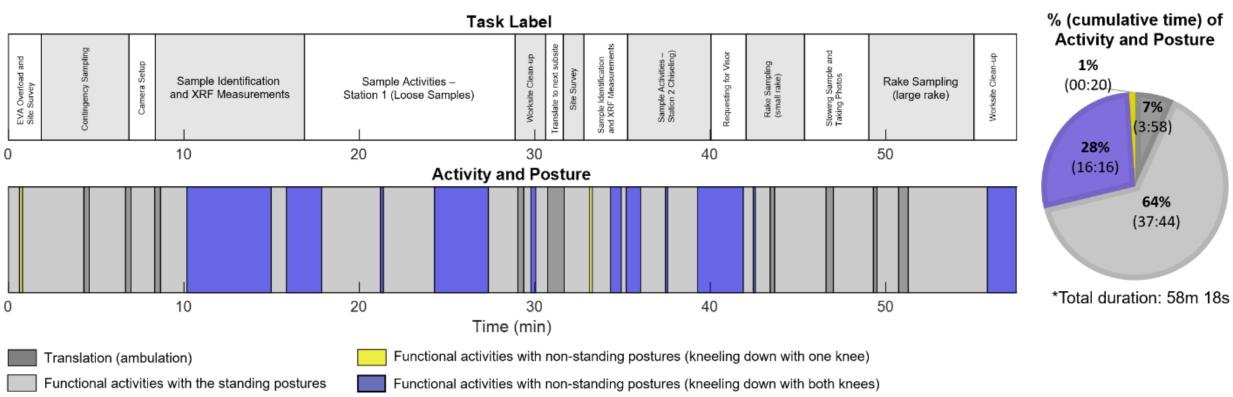

Figure 9. Example data representation of periods of functional movements performed by the subject at various stages of the geologic simulation.

3. Gait Measurement

Subject gait kinematics also were able to be measured from the IMUs on the exterior of the spacesuit and analyzed to determine how the gimbal and offload affected them. At ARGOS, subjects displayed more erect upper bodies and shortened initial swing phases that may be the result of the offloading system and/or the treadmill. In a comparison of 1-G unsuited walking with 1/6-G offloaded, the same proportion of swing versus stance phases was observed. In previous work with POGO, an unsuited subject in simulated 1/6-G offload displayed a shorter stance phase than that in 1-G offload which may indicate that subject was able to rely on the vertical offload system to assist their upward movement and reduce their need to produce the necessary propulsive forces in the forward direction[2]. With this data we also are able to begin to compare ARGOS performance with other analog environments such as the NBL. Figure 10 shows a comparison of percentage of gait cycle for each phase between ARGOS (suited in the MKIII), NBL (SCUBA configuration), and 1-G ambulation (shirtsleeve). Data were taken from different subjects in the environments as using the same subjects, while preferred, was not possible. Future testing will aim to test the same subject across environments to further reduce sources of variability. For this first phase of testing the goal was primarily to develop evaluation methods and collect initial data to inform future testing. The percentages of swing and stance phases on the 1-G ground and 1/6-G suited ARGOS were the same (50% each). At ARGOS, the mid-swing point (initial swing) was 10% earlier than the normal ground walking, the reason for which is still being investigated. At the NBL the gait characteristics in the water (e.g., forward trunk lean, increased swing phase) is different with both ground and ARGOS walking due to the water resistance indicating that any tasks that may require gross translations be performed in ARGOS versus NBL.

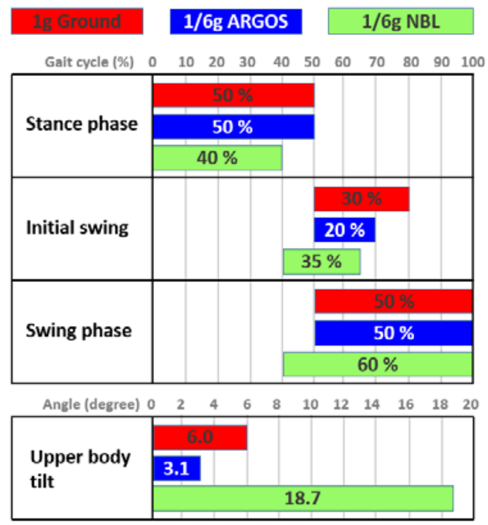

Figure 10. Comparison of walking parameters between analog testing environments.

4. Metabolic Rate Measurement

The metabolic rate measurement system was integrated into the back plate of the MKIII and measured expired CO_2 to calculate metabolic rate throughout the run. Overall, this proved straightforward and data were able to be successfully collected with minimal intervention on behalf of the test team and were confirmed to be within reasonable estimations for the tasks being performed. These data also were used to pilot develop data visualizations and summary products for stakeholders. Because this is ongoing work and testing described in this paper is from a limited set of subjects, metabolic rate data are not shown.

IV. Conclusions and Forward Work

Overall, these first attempts at using ARGOS as an EVA simulation environment were successful with positive feedback from both subjects and test operators. To accurately understand energy expenditure and suited crewmember performance, it is necessary to understand how well analog environments simulate flight operations and what improvements are needed to reach the level of fidelity required to provide reliable and actionable data.

Following this testing series several recommendations were made to the gimbal design resulting in the decision to build a new gimbal. To reduce the negative simulation effects because of arm interference with the gimbal vertical supports, the ARGOS team is currently working on a new gimbal design that will minimize arm interference. The new gimbal is based on a gimbal that is used for shirtsleeve (i.e., unsuited) lunar-G testing, and features a single vertical support column behind the subject that then wraps around their sides and attaches to the back of the suit. This gimbal also will be compatible with both the Mark III and future exploration EMU (xEMU) space suits, allowing for one gimbal to be used across different tests with different suits. While this gimbal may be heavier than the EMU/MkIII adapted gimbal and add some artifacts from the increased mass, it is expected that the simulation will still be improved by removing sources of interference with the subject's arms. By connecting above the waist bearing of the suit, it also will not couple negatively with the subject's walking motion.

Work is continuing on further developing the simulation environment to add fidelity with respect to operational volume and mockups, procedures, and task design to include more flight-like operations, and to incorporate tasks that are most currently representative of Artemis lunar mission EVAs. The limited ARGOS work volume will continue to be a constraint on performing long-duration EVA simulation activities; however, a larger ARGOS facility may be available in the future. In the near term studies are being planned to use this analog environment facility with the MKIII (until an xEMU prototype becomes available) including the partial-gravity metabolic-rate characterization study, an impaired crewmember first EVA on Mars study, and evaluations of the spacesuit mass and cgty acceptability, among others.

Acknowledgments

The authors would like to thank the JSC Advanced Suit Laboratory for their support throughout testing and for their flexibility in quickly preparing suit hardware to meet the study needs. We also would like to thank the ARGOS test operators and facility personnel for their support in ensuring safe and efficient tests.

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