Assessments of Physiology And Cognition in Hybrid-reality Environments (APACHE) – Physical Workload Approximation

Alexander J. Baughman, M.S.[1]
GeoControl Systems, Houston, TX, 77054

Kyoung Jae Kim, Ph.D.[2], Kadambari Suri, M.S.[3]
KBR, Houston, TX, 77058

and

Andrew F. J. Abercromby, Ph.D.[4]
NASA Johnson Space Center, Houston, TX, 77058

The Human Physiology, Performance, Protection & Operations Laboratory (H-3PO) at NASA Johnson Space Center (JSC) is developing a hybrid reality exploration surface analog, "Assessments of Physiology And Cognition in Hybrid-reality Environments" (APACHE). The goal of APACHE is to create a planetary extravehicular activity (EVA) simulation environment that provides a representative physical and cognitive workload approximation using a combination of virtual reality (VR), physical reality, and hybrid reality (HR) techniques. To develop and characterize the physical workload approximation within the APACHE environment, a two-part approach was implemented. In part 1, baseline physical workload during ambulation within APACHE was evaluated and compared with that in other planetary EVA analog environments and with existing data sets from Apollo planetary EVAs and reduced gravity testing of prototype planetary spacesuits. For this evaluation, 10 subjects were asked to ambulate in three surface analog environments: a passive treadmill in APACHE, natural terrain in an outdoor field environment, and a standard motorized treadmill. Subjects' heart rate and metabolic rate (VO_2/VCO_2) were measured and compared among the different test conditions and existing data sets. Gait parameters were also collected to compare with suited mechanics and to understand the role of gait kinematics in physical workload. In part 2, the aim is to evaluate the addition of a custom weighted body suit to the aforementioned surface analog environments and the ability to titrate the suit configuration to provide the best possible physical workload approximation for simulation of lunar and Martian EVAs.

Nomenclature

ARGOS	=	Active Response Gravity Offload System
APACHE	=	Assessments of Physiology And Cognition in Hybrid-reality Environments
COTS	=	Commercial off-the-shelf
EVA	=	Extravehicular Activity
H-3PO	=	Human Physiology, Performance, Protection & Operations
HR	=	Hybrid Reality
IV	=	Intravehicular
JSC	=	Johnson Space Center

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[1] Human Performance Engineer, H-3PO Lab, NASA JSC, 2101 E NASA Pkwy., Houston, TX 77058
[2] Human Performance Data Engineer, H-3PO Lab, NASA JSC, Houston, TX.
[3] Integration Engineer, H-3PO Lab, NASA JSC, Houston, TX.
[4] H-3PO Lab Lead, H-3PO Lab, NASA JSC, Houston, TX.

NASA	=	National Aeronautics and Space Administration
PACES	=	Physical And Cognitive Exploration Simulations
VR	=	Virtual Reality

I. Background

NASA is planning to return to the Moon in the mid-2020s as a stepping stone to Mars missions in the 2030s. Spacewalks, or extravehicular activities (EVAs), performed on Mars will differ in a variety of ways from those that have been performed for decades in low earth orbit and during the Apollo lunar surface missions, bringing unique challenges to a new spacesuit design and concepts of operation. The consequences of losing situational awareness, missing a step in a procedure, or making the wrong decision during an EVA can be catastrophic, which is why procedures and flight rules exist for almost every aspect of an EVA. EVAs performed on the International Space Station (ISS) can be planned and practiced extensively because the entire structure was created by humans, and the exact location of every nut, bolt, hand-rail and tether point is known. During the Apollo missions, the limited number and duration of EVAs meant that every minute of every EVA was planned in advance based on precursor information, closely monitored by Mission Control throughout, and had limited opportunity for astronauts to deviate from the plans and flight rules.

The distance between Earth and Mars is such that Earth-Mars communications will be delayed by a minimum of four minutes and as much as 22 minutes in each direction. This unavoidable communications latency will require that many of the support, monitoring, commanding, and control functions currently provided by the large team of flight controllers in Mission Control will have to be performed instead by astronauts and their spacecraft or spacesuit. Furthermore, the nature of scientific exploration requires flexibility to respond to new information and discoveries while maintaining the operational discipline and situation awareness necessary to manage the considerable risks and complexity.

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 spacesuits 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 spacesuits 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.

This paper describes the initial steps in the development and validation of a hybrid-reality environment in which both the physiological and cognitive demands of performing exploration EVAs are simulated, and performance of operationally relevant tasks is quantified. This environment, also known as the "Assessments of Physiology And Cognition in Hybrid-reality Environments," or APACHE, is broadly defined here, and this paper will focus on the physical workload characterization and follow-on efforts to approximate the physical workloads in APACHE to those expected within a prototype spacesuit in a simulated reduced-gravity environment.

II. Development

A hybrid-reality environment was selected for APACHE because the cognitive demands of an EVA can be simulated through high fidelity VR simulations and the physical demands can be approximated through the integration of a treadmill and other physical assets to create an immersive hybrid reality (HR) environment for exploration EVAs. The EVA tasks in APACHE have been iteratively developed with the Physical and Cognitive Exploration Simulations (PACES) methodology[2] which aims to develop a battery of tasks, procedures, information systems, and standard measures to assess physical and cognitive workloads during operational exploration EVAs.

The APACHE environment was implemented at NASA Johnson Space Center through a collaboration between multiple organizations and projects. The HR EVA environment was created by the JSC Engineering Directorate powered by the Unreal Engine (UE4.27.2, Epic Games Inc., Cary, NC), using an HTC Vive Pro Eye virtual reality system (HTC Corporation, Taiwan). The APACHE environment, pictured in Figure 1, is roughly a 6.1 m x 4.6 m space. The space is surrounded by a 0.3m (12") tall lined sandbox and filled roughly 0.1m (3") deep

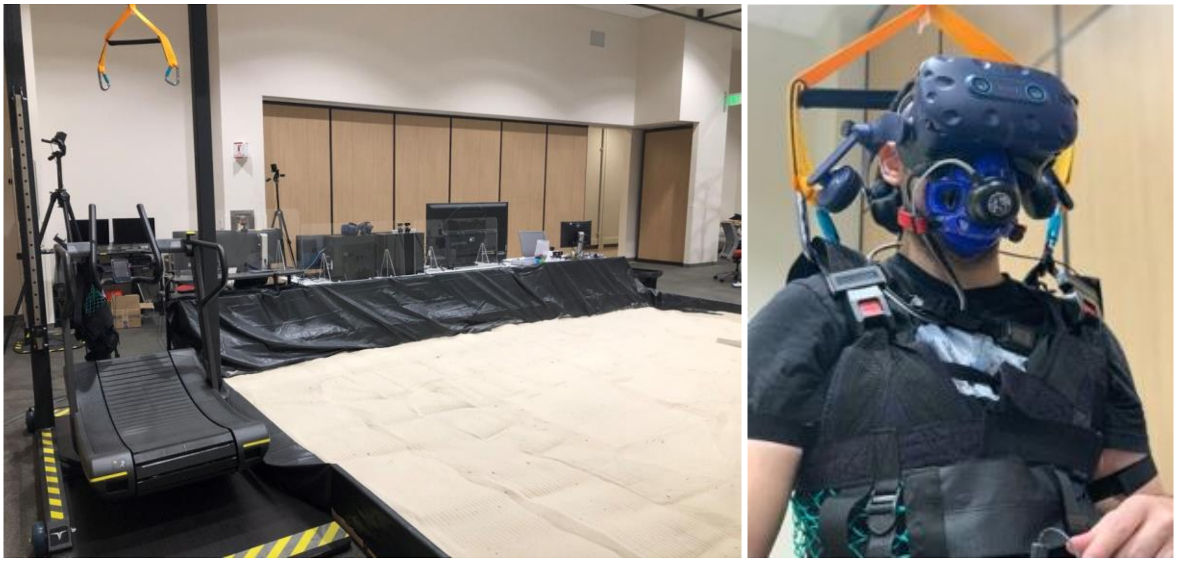

Figure 1. APACHE space (left) and subject wearing VR headset and portable metabolic rate analyzer (right). *Passive treadmill (left) enables the exploration of large virtual environments while the sandbox allows for more detailed, operationally relevant surface EVA tasks. A mobile metabolic rate analyzer (Cosmed K5) is used to measure physical workload from subjects during testing.*

with lunar regolith simulant. APACHE can support multiple EV crewmembers in the HR environment, working in tandem. Additionally, a computer workstation is located nearby and supports an IV crewmember as part of the simulation. The IV crewmember has direct video and audio communication with the EV crew in VR, and steps them through their EVA procedures as well as provide operational support. Future iterations of APACHE will also aim to support cognitive workload evaluations of the IV crewmember as exploration EVAs transition to greater crew autonomy.

There are two virtual environments that subjects can explore within APACHE, a lunar and martian surface. The virtual lunar surface was created from lunar LIDAR data of the shackleton crater to create roughly 16 sq km of explorable terrain. The virtual martian surface was developed in partnership with Buendea and their custom developed UE5 editor (Mars 2030, FMG Labs, Florida), and contains roughly 40 sq km of explorable terrain derived from Mars Reconaissance Orbiter (MRO) LIDAR data of the Jezero crater. In addition to the virtual environments, APACHE includes numerous models and assets including: a lander vehicle, a controllable planetary rover, photorealistic rocks, and models of surface experiments from the Apollo Lunar Surface Experiments Package (ALSEP).

A curved, self-powered treadmill (Skillmill Connect, Technogym, Italy) with a custom fall protection harness (Tuff Tread, Texas) is located next to the sandbox to enable exploration of these large virtual environments while also imposing the physical demands and representative timelines required to traverse these distances during an EVA. This is accomplished by placing two Vive Tracker pucks on the the ankles of subjects such that their physical steps on the treadmill translate to movement in the virtual environment. Direction is changed using a “point-and-click” method which aligns the straightline walking path with the direction of the hand-held motion controller. In addition to this novel approach, APACHE recently acquired a commercial, omnidirectional VR treadmill and will have this system integrated in 2022 for future testing and evaluations.

Additional physical elements were integrated into the hybrid environment for increased immersion and to evaluate specific tasks outlined in the PACES task modules. These include physical and virtual mockups of an umbilical interface assembly (UIA) panel, a wearable spacesuit display and control unit (DCU), and experimental surface packages. These HR objects are integrated within the environment, such that changes to the physical asset, like flipping a switch, are also reflected in the virtual world. New mockups can easily be added to support specific test or research objectives.

Physical performance in APACHE is primarily quantified by a user’s heart rate and/or metabolic rate.[2] A user’s physical workload can be manipulated with the treadmill resistance setting (1-10) and/or through the addition of a weighted suit.[8]

The cognitive demand of a planetary EVA is simulated through a series of EVA-relevant tasks performed in the immersive VR environment, with high fidelity visual and auditory representations of a lunar and/or martian surface.

Additionally, a computer model of a spacesuit PLSS displays select simulated suit data to the VR HMD for active monitoring by the EV crew and added cognitive demand. Future iterations of APACHE will include biosensor driven informatics, such as real time heart rate monitoring and/or derived values from crew state physiologic models. To objectively quantify the cognitive workload of subjects within APACHE, performance measures are used and compared with other validated methods such as subjective questionnaires and psychophysiometrics. Task-specific performance measures include time to completion, accuracy, and error rates. Additional embedded performance tasks incorporated throughout the entire EVA consist of response times to system alerts, resource management (simulated O_2 consumption vs spacesuit performance and timeline constraints), memory recall, and navigational situation awareness. Various psychophysiological sensors have been tested in the APACHE environment and are still being evaluated for future use.[10]

III. Objectives

The primary goal of APACHE is to create a physically and cognitively realistic planetary EVA simulation environment using a combination of virtual reality (VR), physical reality, and hybrid reality (HR). More specifically, APACHE seeks to approximate the physical workloads of an operator ambulating in a pressurized spacesuit at lunar and martian gravity levels, ideally matching unsuited APACHE metabolic rates to suited metabolic rates to within 10%. To accomplish this, a physical workload validation was conducted and separated into two phases: 1) a baseline characterization of APACHE metabolic rates, and 2) the evaluation of a weighted suit simulator.

A. Baseline Characterization

The primary focus of this paper is to characterize the voluntary metabolic rate during ambulation on a passive treadmill in APACHE in comparison to other planetary analog environments, like the JSC rock yard. The goal for this characterization was to define the physical workload during ambulation in the 1g, unsuited APACHE environment and compare this to the workloads from previous datasets of spacesuit testing in a simulated reduced environment.

B. Weighted Suit Simulator

The follow-on to the above will aim to characterize the physical workload during ambulation on a passive treadmill in APACHE while wearing a weighted suit simulator in various configurations. The study will seek to provide a recommendation on possible weighted suit configurations such that a subject ambulating in 1g APACHE has comparable workloads to that in a spacesuit at reduced gravity. This study is expected to finish testing in 2022.

IV. Methods – Baseline Characterization

This study was focused on the comparison of metabolic rate and human gait characteristics when ambulating in different planetary analog environments. Some of the strategies to adapt to walking environments (uneven terrain, obstacles, etc.) may affect the gait kinematics measured from a wireless inertial measurement unit (IMU) sensor and the related metabolic cost. The three analog environments of interest were the JSC rock yard, ARGOS (Active Response Gravity Offload System), and the APACHE test environment. These analog environments can be further defined as a comparison between rocky/natural terrain, a motorized treadmill, and a self-powered passive treadmill. Workload was manipulated in the rock yard by defining the path one traversed and whether to include hills, craters, and other obstacles. The workload on a motorized treadmill was affected by the speed and slope grade. And lastly, the passive treadmill in APACHE has different resistance settings which could potentially affect workload. For this test, subjects walked in each environment at varying test conditions (terrain, resistance, speed/grade) for 10-15 minutes each such that steady state was reached. Metabolic rate, heart rate, and gait were collected and analyzed. The goal was to determine if differences exist in workload and gait and what corrections can be made to normalize across analog environments.

A. Subjects

This study was approved by the NASA IRB, study #223. Ten subjects (mean ± stdev; Sex = 6M / 4F, Age = 45 ± 5 yrs, Weight = 65 ± 5 kg) were then recruited to participate.

B. Independent Variables and Environments

The goal was to reproduce similar workloads across the analog environments at JSC: the rock yard, APACHE, and ARGOS. These analog environments define the study's three variables of interest: rocky/natural terrain, a self-powered passive treadmill, and a motorized treadmill, and to understand their effect on physical workload and gait. These parameters and resulting test conditions are described here and outlined in Table 1.

The rock yard at JSC, pictured in Figure 2, is an analog environment commonly used to test objectives and technologies related to science and exploration EVAs. The rock yard contains different geographical structures such as hills, craters, ridges, and contains different surface and sedimentary features similar to the Moon and Mars. The addition or exemption of these features in a pre-planned walking path is thought to impact the workload a subject will exert when navigating the rock yard. The maximum rock yard slope was measured to be ~15° (~27% grade).

The treadmill used in APACHE is a curved, self-powered treadmill and was used for the passive treadmill condition. There are incremental treadmill resistance settings ranging from 0-10 that can be used to manipulate how hard it is to walk on the treadmill. Because this treadmill is commonly used in APACHE, subjects also wore a VR headset and ankle trackers for some test conditions. This is described in more detail below.

Lastly, a standard, powered treadmill (Quinton Q55) was used for the motorized treadmill condition. Testing within the ARGOS facility at JSC is costly and was not practical for this evaluation, so instead it was assumed that differences between flat, motorized treadmills were negligible and results from H-3PO's exercise treadmill would be similar to 1g on the ARGOS treadmill. The motorized treadmill can change walking speed (0-10mph (0-4.47 m/s)) and slope grade percentage (0-25%).

Figure 2. A subject ambulates through the JSC rock yard (left) and an aerial view of the rock yard (right). *The "Mars Yard" portion of the rock yard, pictured left, was used for the flat with obstacles condition (R3).*

C. Dependent Variables and Equipment

This study collected metabolic rate (VO_2/VCO_2), heart rate (bpm), and gait kinematics (dynamic upper body mediolateral (ML) sway displacement (cm)).[3,4] The equipment used to collect these metrics was: the Cosmed K5 portable metabolic analyzer (COSMED, Rome, Italy) for metabolic rate, a Polar H10 heart rate strap (Polar Electro, Kempele, Poland) for heart rate, and an APDM Opal (APDM Wearable Technologies Inc., Portland, OR) inertial measurement unit (IMU) strategically placed on the chest for monitoring dynamic upper body sway during walking. Specifically, the maximum range a subject swayed from side to side during walking was measured and used as a metric. An increase in the metric can indicate that terrain becomes more complex or a subject needs greater body sway to maintain stability control. Additionally, because speed was recorded from both treadmill environments and was likely to have a significant effect on workload, walking speed was also included and collected as part of this study. For the rock yard, this was collected using the GPS sensors within the Cosmed K5 system.

D. Protocol

All three environments were tested on the same day with each testing environment taking no more than one hour, for a total test duration of roughly 3 hours per subject. The order of environments and the conditions within each were randomized. On the test day, subjects were briefed and consented before they donned all the sensors and hardware. Subjects were instructed to walk at a comfortable pace, with the exception of the motorized treadmill conditions. Subjects would then ambulate in the assigned environment and condition until a steady state heart rate was reached. Once steady state was determined, a 30-second timer was started and this window of data was used to determine the

Walking Environment	Manipulated Parameter(s)	Test Condition	Test Code
Rock Yard	Terrain	Generally flat walking path, no obstacles	R1
		Mixed terrain walking path	R2
		Generally flat walking path, with obstacles	R3
Passive Treadmill	Resistance setting	Resistance setting = 1, No VR	P1
		Resistance setting = 3, No VR	P2
		Resistance setting = 6, No VR	P3
		Resistance setting = 9, No VR	P4
		Resistance setting = 3, with VR	P5
		Resistance setting = 6, with VR	P6
Motorized Treadmill	• Grade curve • Walking Speed	Walking speed = 1.5mph, Grade = 0%	M1
		Walking speed = 1.5mph, Grade = 10%	M2
		Walking speed = 1.5mph, Grade = 20%	M3
		Walking speed = 3mph, Grade = 0%	M4
		Walking speed = 3mph, Grade = 10%	M5
		Walking speed = 3mph, Grade = 20%	M6

Table 1. Treadmill comparison testing conditions. *A summary of the three environments tested and the independent parameters investigated within each environment.*

average steady state values for each test condition. Subjects walked a maximum of 15 minutes if steady state could not be reached. Following each trial were 5-minutes of prescribed rest.

For the rock yard, there were three conditions tested: 1) a generally flat walking path, 2) a mixed terrain walking path, and 3) a generally flat walking path with obstacles. The flat walking path still had subjects walk on gravel and loose sand but tried to remain as flat as possible. This was intended to represent the low workload condition. The mixed terrain walking path incorporated more variability by including hills, craters, and other obstacles found at the rock yard. This served as the high workload condition. The generally flat with obstacles path contained a mixture of geographical objects ranging in size from a few centimeters across to roughly one meter wide objects. This was the medium workload condition.

There were six conditions tested on the passive treadmill. The first four test conditions had the subject walk at their own pace with varying treadmill resistance settings: 1, 3, 6, and 9. Because this treadmill is used in APACHE VR simulations, two additional tests were performed in VR. For these test conditions, subjects wore the HTC Vive Pro Eye headset and VIVE tracker pucks on their ankles. This would allow subjects to translate in the lunar VR environment. The VR test configurations represent how the passive treadmill is used in APACHE and walking in VR may impact speed, gait, and potentially metabolic rate. To limit any learning effects, there was a short training period prior to the first VR test condition to ensure the subject was familiar and comfortable with walking on the treadmill while in VR.[11]

The motorized treadmill also had six test conditions. The first three were all set at a walking speed of 1.5 mph (0.67 m/s) with varying grade percentages of 0%, 10%, and 20%. The other three were set at a walking speed of 3.0 mph (1.34 m/s) with the same grade curve progression.

V. Results – Baseline Characterization

The Cosmed K5 collected VO_2 and VCO_2 (both in mL/min) from subjects during ambulation in the three environments. This was then normalized by subject weight and converted to energy expenditure[5,7] to produce steady state metabolic rates (mL/kg·min) for each environment across all test conditions. These workloads are shown in Figure 3 while descriptive statistics for each condition can be found in Table 2. With a sample size of N = 10, parametric statistics were used and the model assumptions for a repeated measures ANOVA were found to be met (normality, homoscedasticity, independence) for each environment dataset. Post-hoc comparisons were done with the Tukey method and a Bonferonni correction.

For the rock yard, a one-way repeated measures ANOVA found that the rock yard terrain had a significant effect on a subject's steady state metabolic rate ($F(2,18) = 74.07$, $p < 0.0001$). Tukey pairwise comparisons revealed the mixed terrain (R2) produced significantly higher workloads than both flat ground conditions ($p_{R1\text{-}R2} < 0.0001$, $p_{R2\text{-}R3} < 0.0001$). No difference was found between flat (R1) and flat with obstacles (R3).

Test code	Metabolic Rate (mL/kg·min)	Heart Rate (bpm)	Upper Body ML Displacement (cm)
R1	16.6 (±3.4)	110 (±11)	15.39 (±3.58)
R2	25.0 (±5.0)	134 (±17)	26.18 (±7.68)
R3	16.1 (±3.6)	109 (±11)	24.28 (±5.53)
P1	26.2 (±4.5)	129 (±15)	12.09 (±2.62)
P2	25.5 (±4.7)	131 (±17)	14.38 (±4.00)
P3	29.7 (±5.7)	141 (±14)	18.41 (±4.46)
P4	26.1 (±4.1)	137 (±13)	25.58 (±9.03)
P5	26.1 (±4.4)	133 (±15)	11.38 (±2.11)
P6	28.8 (±4.0)	141 (±12)	14.62 (±2.27)
M1	12.2 (±2.1)	100 (±9)	14.85 (±4.58)
M2	17.5 (±2.4)	114 (±13)	18.16 (±5.76)
M3	24.1 (±2.8)	130 (±14)	22.28 (±7.86)
M4	15.4 (±1.3)	105 (±7)	12.45 (±3.03)
M5	27.7 (±1.7)	140 (±12)	17.21 (±4.93)
M6	40.2 (±3.5)	164 (±10)	18.17 (±3.16)

Table 2. Summary statistics for all test conditions. *Descriptive statistics are presented as mean (±stdev) for the rock yard (red), APACHE passive treadmill (no VR blue; VR dark blue), and motorized treadmill (green). Additional gait parameters were collected and analyzed but only the ML displacement is shown here for brevity.*

For the passive treadmill in APACHE, when comparing the non-VR conditions to the VR conditions (P2-3 vs. P5-6), no significant effect was found ($p = 0.139$). When looking only at the non-VR conditions (P1-4), no significant effect was found for the one-way repeated measures ANOVA with treadmill resistance as the main effect ($p = 0.40$). However, when performing a one-way ANCOVA with treadmill resistance as the main effect and the average walking speed as a covariate, a statistical difference was found for the adjusted model means ($F(3,35) = 5.49$, $p = 0.003$). The interaction effect was found to be insignificant ($p = 0.98$). The adjusted model means, after accounting for the effect of average walking speed, for treadmill resistances 1, 3, 6, and 9, were 21.3(±2.0), 21.4(±1.8), 30.3(±1.3), 34.4(±2.8) mL/(kg·min), respectively. Pairwise comparisons of the adjusted model means revealed that resistances 1 and 3 produced lower workloads than at resistances 6 and 9 (1-6, p_{adj}=0.006; 1-9, p_{adj}=0.027, 3-6, p_{adj}=0.003; 3-9, p_{adj}=0.018). No differences were found between resistance 1 and 3, and resistances 6 and 9.

And lastly, for the motorized treadmill a two-way repeated measures ANOVA with interaction effects found that all factors had significant effects on steady state metabolic rate: grade percentage ($F(1,47) = 1360$, $p < 0.0001$), walking speed ($F(1,47) = 583$, $p < 0.0001$), and the interaction term ($F(1,47) = 166$, $p < 0.0001$). When looking only at the effect of grade percentage, Tukey pairwise comparisons revealed that all conditions were different from each other ($p_{0\text{-}10} < 0.0001$, $p_{0\text{-}20} < 0.0001$, $p_{10\text{-}20} < 0.0001$). When looking only at the effect of walking speed, pairwise comparisons revealed that a walking speed of 1.5mph (0.67 m/s), conditions M1-M3, had significantly lower steady state metabolic rates than those found when walking at 3.0mph (1.34 m/s), conditions M4-M6 ($p_{1.5\text{-}3}<0.0001$).

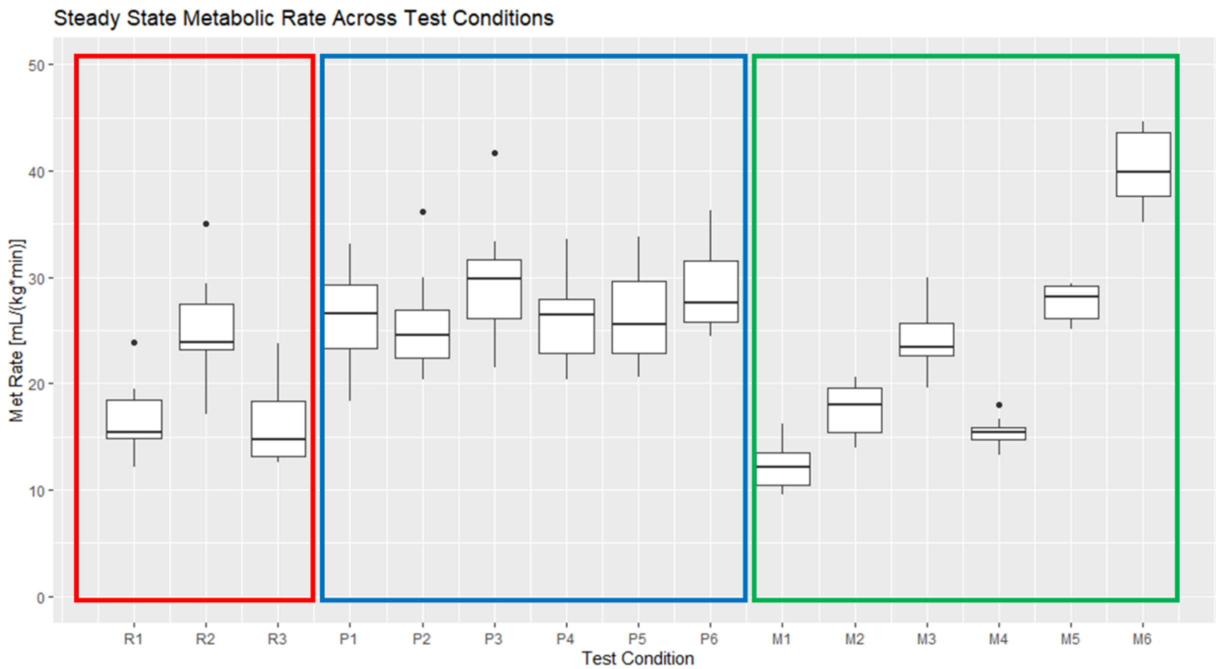

Figure 3. Steady state workloads for each of the three environments tested in the baseline characterization study. *Steady state metabolic rates [mL/(kg·min)] of 10 subjects after ambulating in the JSC rock yard (red), APACHE passive treadmill (blue), and a standard motorized treadmill (green) under various environmental conditions.*

Another variable of interest was whether the gait kinematics changed significantly between environments. The gait related variable used for this study was upper body mediolateral sway displacement (cm). Parametric statistics were used as the model assumptions were found to be met (normality, homoscedasticity, independence). Repeated measures ANOVA models were then fit to the gait metric for comparison against environmental conditions (terrain, resistance, grade/speed). Post hoc comparisons using the Tukey HSD test were also carried out. The upper body ML displacement was plotted for all test conditions and is shown in Figure 4 while descriptive statistics are listed in Table 2.

For the rock yard, a one-way repeated measures ANOVA showed a significant difference between conditions in the upper body ML sway displacement ($F(2,18) = 11.79$, $p < 0.001$). Tukey's HSD Test for multiple comparisons found that the mean value of the upper body ML sway displacement was significantly different between R1 and R2 ($p_{R1\text{-}R2} < 0.001$) and between R1 and R3 ($p_{R1\text{-}R3} = 0.008$).

For the passive treadmill in APACHE, a comparison of VR vs. non-VR conditions revealed a significant difference for upper body ML displacement ($F(1,38) = 22.45$, $p < 0.001$). Only looking at the non-VR conditions (P1-P4), a one-way repeated measures ANOVA revealed a significant effect and positive correlation with treadmill resistance and upper body ML displacement ($F(3,36) = 11$, $p < 0.001$). Post hoc comparisons using the Tukey test found that treadmill resistance 9 (P4) had a significantly larger upper body ML displacement than all other non-VR conditions ($p_{P1\text{-}P4} < 0.001$, $p_{P2\text{-}P4} = 0.005$, $p_{P3\text{-}P4} = 0.044$).

For the motorized treadmill, a two-way repeated measures ANOVA found the upper body ML sway displacement was significantly effected by treadmill grade ($F(1,47) = 11$, $p < 0.001$), but not by treadmill speed ($p = 0.097$). Post-hoc comparisons using the Tukey test found significant differences between three conditions ($p_{M1\text{-}M3} = 0.032$, $p_{M4\text{-}M5} = 0.025$, $p_{M4\text{-}M6} = 0.007$).

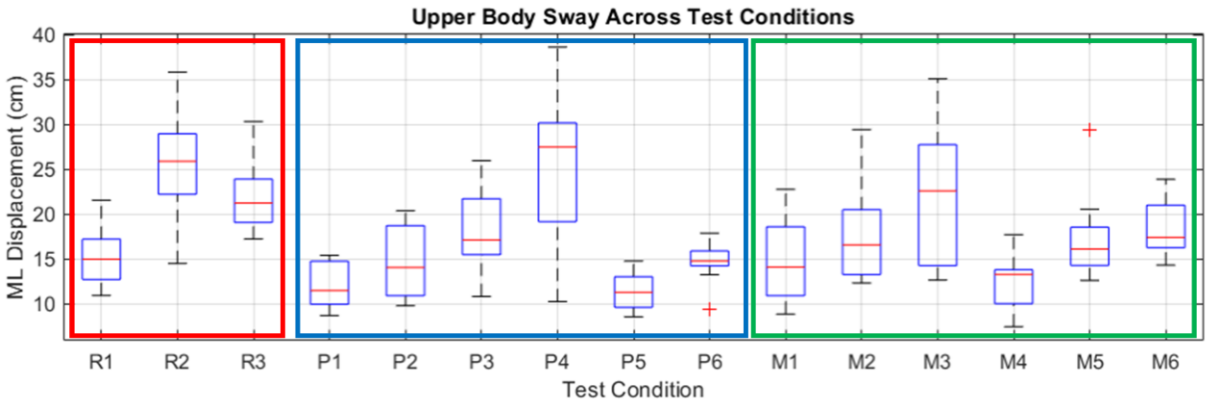

Figure 4. Upper body sway for each of the three environments tested in the baseline characterization study. *Upper body mediolateral (ML) sway displacement (cm) of 10 subjects after ambulating in the JSC rock yard (red), APACHE passive treadmill (blue), and a standard motorized treadmill (green) under various environmental conditions.*

VI. Discussion

A. Baseline Characterization

With a sample size of N=10, we can begin to characterize the steady state metabolic rate in each environment by looking at Figure 3. For the rock yard, steady state metabolic rates in both flat ground conditions (R1/R3) were significantly different than the mixed terrain condition (R2), as expected. In comparison, conditions R1 and R3 metabolic rates were similar to each other indicating that the flat path was no different than the flat with obstacles. Interestingly, the upper body ML displacement was sensitive to these subtle changes in terrain and was able to distinguish differences between conditions R1 and R3. It is thought that the increase in gait kinematics (e.g. upper body ML displacement) is associated with an increase in metabolic cost as the subject has to significantly change the way they navigate the natural terrain. And in this case, the obstacles present in condition R3, although significant enough to increase the upper body ML displacement, were not enough of a hindrance to significantly impact the subject's physical workload.

The motorized treadmill showed clear trends between both walking speed and grade for both steady state metabolic rate and upper body ML displacement. The motorized treadmill was also able to produce the smallest and largest workloads out of any of the three environments tested. Compared to the rock yard, motorized conditions M3 and M5 were most similar to the mixed terrain condition, R2, with respect to steady state metabolic rates. Likewise, these conditions were also similar to all passive treadmill conditions (P1-4).

With regards to APACHE and the passive treadmill, no differences were found in workload between the non-VR conditions (P2-3) and the VR conditions (P5-6). There was a concern that subjects may walk slower in VR and thus experience lower *voluntary* workloads than if they were not in VR, which may have added uncertainty when applying the passive treadmill models to APACHE because they were built from the non-VR conditions. When looking at the gait, particularly the upper body ML sway displacement, the VR conditions had significantly less displacement. This was thought to be due to the overhead safety harness and the small tactile feedback it provides users while walking in VR may produce this observed effect. Additionally, a positive trend was seen between the upper body ML displacement and the treadmill resistance which may suggest it was harder for the subject to walk on the treadmill, even though the steady state metabolic rates did not reflect this.

The observed physical workloads in APACHE ranged from 18.34 to 41.69 mL/(kg·min) with a mean steady state metabolic rate of 26.9 (±4.9) mL/(kg·min). The relatively constant workloads for each treadmill resistance was thought to be caused by the self-paced nature of the treadmill, e.g. at higher resistances, subjects slowed themselves to maintain a manageable workload. Looking at the passive treadmill ANCOVA model which accounts for the effect of average walking speed, the adjusted model means revealed a different trend (21.3(±2.0), 21.4(±1.8), 30.3(±1.3), 34.4(±2.8) mL/(kg·min) for conditions P1-4 respectively) and conditions P1-2 had significantly lower workloads than conditions P3-4. While this isn't easily seen in Figure 3, when adjusting for walking speed, the predicted steady state metabolic rates were significantly higher with increasing treadmill resistance, as one would expect. In practice however, the passive treadmill is a self-regulated device and specific walking speeds cannot be accurately prescribed, especially while a subject is in VR and cannot see the moving tread beneath them. More so, the walking speeds required to achieve these higher workloads are not physically possible without using the front hand rails to help push against. This is also not desirable for APACHE as VR hand controllers are frequently used while ambulating on the treadmill to respond to various system alerts. In actuality, the data showed that during voluntary ambulation on the passive treadmill, subjects decreased walking speed (3.4(±0.5), 3.3(±0.4), 2.4(±0.5), 1.0 (±0.2) mph) with increasing treadmill resistance, but remained at a relatively constant workload for each (26.9 (±4.9) mL/kg·min). Because of this coupling between treadmill resistance and walking speed, and no significant effect on metabolic rate from treadmill resistance only, it was concluded that the baseline physical workload characterization for ambulation in APACHE was 26.9 (±4.9) mL/kg·min, with minimal controls from the treadmill to increase or decrease this value to match a desired workload.

It may be difficult to compare metabolic rates in APACHE to lower workload activities in other analog environments, such as flat ground walking in the field, because there are limited ways to reach these desired workloads within APACHE. The subject can be artificially paced in APACHE through simulated suit consumable depletion rates and ensure they maintain a pace that doesn't lead to elevated suit temperatures or CO_2 levels, but the slower walking speeds needed to reach these lower workloads may not be practical for operations. It is possible to increase metabolic rate in APACHE, such as adding weight to the subject and this will be further investigated in Part II of the Physical Workload Approximation efforts. However, because the treadmill in APACHE is not motorized and rather powered by the subject, it is thought that this treadmill has inherently higher workloads than a flat motorized treadmill[9] and lower workloads may not be achievable, even at lower speeds.

With APACHE broadly characterized, the baseline unsuited workloads were further evaluated against workloads seen in other planetary analogs and against historical Apollo data from lunar EVAs. For example, recent scientific EVA field test analogs saw participants (N=3) with workloads ranging up to 32 mL/(kg·min) during 2-3 hour simulated EVAs while wearing roughly 60 lbs (27.2 kg) of gear. An analysis of Apollo metabolic data during lunar EVAs[6] found workloads >2000 BTU/hr, or >21 mL/(kg·min) for an 80kg person, which would be on the lower end of workloads during voluntary ambulation in APACHE. This is achievable for APACHE if subjects are given the proper pacing constraints, but there is still uncertainty about how low a workload one can achieve during ambulation in APACHE and still maintaining operational relevance.

On the opposite side of the spectrum, unpublished suited metabolic rates collected during ambulation in a simulated Martian gravity environment at 3.4 mph (1.5 m/s) ranged up to 45 mL/(kg·min). This is significantly higher than the unsuited workloads measured in the rock yard or in APACHE and requires a different strategy than increasing speed to obtain these higher, Martian-like suited workloads. Phase II of the Physical Workload Approximation efforts will attempt to resolve this question by investigating a weighted suit at different carrying loads and its effect on a user's physical workload. The hope is that through the addition of a weighted suit simulator, APACHE will be able to achieve the higher workloads seen in a suited Martian environment and provide recommendations to future APACHE studies on the configuration necessary to approximate a desired workload to within 10%.

B. Future Work

Future work within APACHE would like to validate both physical and cognitive workloads of a complete end-to-end simulated planetary EVA. Once validated, future applications of APACHE are expected to include assessment of heads-up displays, biofeedback algorithms, caution and warning systems, and other decision support systems that may be implemented on spacesuits, inside the spacecraft with the IV crewmembers, and/or in Mission Control.

With the recent commercial interest in VR technologies, multiple systems have been developed to help a user physically explore their virtual world without teleporting or other controller-type mechanisms. One of these systems is an omni-directional treadmill which allows subjects to walk in any direction using a specialized treadmill platform. The H-3PO lab has recently purchased one of these omni-directional treadmills and will integrate the system into APACHE simulations in 2022. A similar analysis will be done with this treadmill to compare with the current straightline, passive treadmill. Besides adding the capability for a second EV crewmember, the hope is that the new VR treadmill will allow for a more natural gait and immersive experience, and to accommodate lower physical workloads than what is currently achievable with the passive treadmill.

In addition to the physical workload approximation efforts, the initial APACHE development and validation will focus on a subset of Design Reference EVA timelines to prove out operational concepts, with mission-like timelines based on data collected from previous analog field tests in combination with exploration mission architectural analyses and assumptions.[1,2] Specific tasks will include continual monitoring of several functions being performed by a computer simulation of a spacesuit's portable life support system (PLSS); maintain temporal awareness of progress relative to the detailed EVA timeline; maintain spatial awareness of location relative to other simulated EVA crewmembers, vehicles, and topographical hazards; respond appropriately to simulated anomalies; accurately perform and report completion of complex EVA procedures; communicate accurately and promptly with other simulated EVA and intravehicular (IV) crewmembers; and make appropriate decisions based on multiple information sources. Performance on simulated cognitive tasks will be measured using a combination of subjective measures, explicit queries, psychophysiological sensors, and implicit performance measures such as task completion times, error rates, and deviation rates. One of these identified tasks, an experimental package deployment, will serve as the operational timeline to be evaluated in an upcoming cognitive workload study in 2022. New measures of cognitive performance will also be assessed and implemented to support research objectives.

Other upcoming testing will focus on test-retest reliability of performance measures and comparison of APACHE EVA-relevant performance measures against existing validated cognitive performance measures; as well as evaluating performance, both physical and cognitive, during a simulated contingency walkback at varying levels of elevated CO_2.

VII. Conclusion

The main goals of the physical workload approximation were to 1) characterize the voluntary metabolic rate during EVA-like traverses in different analog environments (natural terrain at the JSC rock yard, a passive treadmill used in APACHE, and a motorized treadmill similar to one used in ARGOS) and 2) develop strategies to match metabolic rate across environments or apply correction factors to adjust for differences. The first objective was met with the baseline characterization study presented here.

A total of ten subjects were tested in the three different environments. Steady state metabolic rate, heart rate, and gait kinematics were collected in order to meet this objective. With a sample size of N=10, voluntary metabolic rates and multiple gait parameters were able to define an initial characterization of physical workload in APACHE, as well as the JSC rock yard and a motorized treadmill. It was determined that the passive treadmill's resistance setting did not have a significant effect on the voluntary metabolic rates of subjects ($p=0.40$). Instead, the observed physical workloads in APACHE ranged from 18.34 to 41.69 mL/(kg·min) with a mean steady state metabolic rate of 26.9 (±4.9) mL/(kg·min).

Comparisons were made to physical workloads observed from field test analogs, Apollo EVA data, and prototype spacesuit testing in a simulated Martian gravity. It is desired to approximate these workloads in the unsuited 1-g APACHE to within 10%. The results from this analysis begin to address the second objective, but a more effective strategy is needed than simply changing the treadmill resistance settings.

In comparison to flat ground walking at the JSC rock yard and on a motorized treadmill, both were found to have significantly lower steady state metabolic rates than every condition tested in APACHE. Additionally, Apollo lunar metabolic rates were found to be on the lower end of possible workloads within APACHE. This presents a possible limitation to APACHE because of the inability to achieve relatively lower physical workloads while ambulating without significantly controlling a subject's walking speed, and potentially losing operational relevance and cognitive demand. A flat, VR omnidirectional treadmill will be integrated into APACHE in 2022 and the treadmill will undergo a similar analysis, with the idea that it will allow for lower physical workloads because it is powered and actively controlling the tread. For workloads higher than those observed on the passive treadmill in APACHE, like those measured in simulated Martian gravity testing of a prototype spacesuit, a follow-on study will investigate the effect of a weighted suit simulator on a user's workload; with the goal of effectively increasing metabolic rate while in APACHE.

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