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**THE WALKBACK test: a study to
evaluate suit and life support
system performance
requirements for a 10 kilometer
traverse in a planetary suit**

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Abstract

As planetary suit and planetary life support systems develop, specific design inputs for each system relate to a presently unanswered question concerning operational concepts: What distance can be considered a safe walking distance for a suited EVA crew member exploring the surface of the Moon to 'walk-back' to the habitat in the event of a rover breakdown, taking into consideration the planned EVA tasks as well as the possible traverse back to the habitat? It has been assumed, based on Apollo program experience, that 10 kilometers (6.2 mi) will be the maximum EVA excursion distance from the lander or habitat to ensure the crew member's safe return to the habitat in the event of a rover failure. To investigate the feasibility of performing a suited 10 km Walkback, NASA-JSC assembled a multi-disciplinary team to design and implement the 'Lunar Walkback Test'. The test was designed not only to determine the feasibility of a 10 km excursion, but also to collect human performance, biomedical, and biomechanical data relevant to optimizing space suit design and life support system sizing. These data will also be used to develop follow-on studies to understand interrelationships of such key parameters as suit mass, inertia, suit pressure, and center of gravity (CG), and the respective influences of each on human performance.

Introduction

As planetary suit and planetary life support systems develop, specific design inputs for each system relate to a presently unanswered question concerning operational concepts: What distance can be considered a safe walking distance for a suited Extravehicular Activity (EVA) crew member exploring the surface of the Moon to ‘walk-back’ to the habitat in the event of a rover breakdown, taking into consideration the planned EVA tasks as well as the possible traverse back to the habitat? It has been assumed, based on Apollo program experience, that 10 kilometers (6.2 mi) will be the maximum EVA excursion distance from the lander or habitat to ensure the crew member’s safe return to the habitat in the event of a rover failure.

To investigate the feasibility of performing a suited 10 km traverse, NASA-JSC assembled a multi-disciplinary team to design and implement the ‘Lunar Walkback Test’. The test was designed not only to determine the feasibility of a 10 km excursion, but also to collect human performance, biomedical, and biomechanical data relevant to optimizing space suit design and life support system sizing for the targeted operational environment. These data will also be used to develop follow-on studies to understand interrelationships of such key parameters as suit mass, inertia, suit pressure, and center of gravity, and the respective influences of each on human performance.

The basic approach was to have each test subject perform each test point both suited and ‘shirt sleeve’ to allow for the quantification of the specific biomedical, metabolic, and biomechanical costs attributed to the suit across a range of gravity levels and ambulation speeds.

Test Objectives

Primary Objective: To collect biomedical and human performance data on crew subjects conducting a suited planetary traverse and produce a crew consensus regarding the feasibility of performing a suited 10 km ‘Walkback’ in lunar gravity.

Secondary Objectives:

- 1) Understand the specific biomedical and human performance limitations of the suit by comparing the suited data to the matched unsuited controls
- 2) Collect metabolic and ground-reaction force data to aid in the development of an EVA simulator to be used on future pre-breathe protocol verification tests
- 3) Provide biomedical and human performance data for use in suit and portable life support system (PLSS) design
- 4) Assess the cardiovascular and resistance exercise associated with partial-gravity EVA for planning and designing appropriate exploration exercise countermeasures.
- 5) Collect data to support the development and execution of follow-on studies to understand interrelationships of such key parameters as suit mass, inertia, suit pressure, and center of gravity, and their respective influences on human performance.

Test Hardware

Partial Gravity Simulator

All data collection sessions were performed on the partial gravity simulator (also known as the 'POGO') in the Space Vehicle Mock-up Facility (SVMF) at Johnson Space Center. The POGO uses a pneumatic cylinder servo mounted to a 40ft air baring (frictionless) rail to create a constant lift (or offloading) force to simulate a reduced-gravity environment throughout the subject's range of motion in the forward, aft, up, and down directions. The vertical servo system consists of the vertical servo assembly, strain gauge, pneumatic cylinder assembly, and the piston rod assembly. A gimbal support structure attached to the end of the lifting actuator supports (or off-loads) a suited subject and allows for the pitch, roll, and yaw rotational degrees-of-freedom during movement. During unsuited (or shirt sleeve) testing, a separate spreader bar and harness assembly off-loads the suspended subjects.

It should be noted that before the test trials began, an assessment of the dynamics of the pneumatic servo system was conducted to verify that for known initial forces and velocities, the resulting trajectories were consistent with the theoretical models for each gravity level (as described in the Partial Gravity Simulator Characterization section).

During the shirt-sleeve (unsuited) trials, the POGO was adjusted to completely offset the weight of the harness and spreader bar, while the subject's weight was offset to the appropriate gravity level. For the suited trials, the combined weight of the subject, liquid cooling garment (LCG), pressure garment (MKIII suit) and PLSS mockup, and gimbal support structure were offset to the appropriate gravity level. This was done because the 135-pound combined weight of the PLSS mock-up (40 lbs) and the gimbal support system (95 lbs) very closely simulates the actual weight of the current PLSS. These configurations were designed to create realistic lunar and martian weights for the respective unsuited and suited conditions.

Mark III Advanced Space Suit Technology Demonstrator & Spider-Gimbal System

For the suited trials, the subjects wore NASA's Mark III Advanced Space Suit Technology Demonstrator (a.k.a. the MK III). The MK III suit is essentially a "test bed" for advanced space suit technologies. It is currently configured to represent a conceptual planetary suit design that accommodates the dynamic ranges of motion required to effectively perform a wide variety of planetary EVA tasks while minimizing any suit-induced changes to the crewmember's natural movement patterns.

The MK III is a hybrid suit, composed of some hard elements (e.g., upper torso and hips), and some soft elements (e.g., elbows and knees). The scye and hip bearing positions allow for optimal suited ranges of motion in multi-axial joints (like the shoulder and hip), which are important for planetary EVA. It also has bearings that allow for additional degrees of freedom in the upper arm, wrist, waist, upper thigh, and ankle. The MK III is a rear-entry suit, meaning it is donned in one piece (with the exception of the gloves) through a hatch on the backside of the

hard upper torso (HUT). The hatch also serves as the interface for the PLSS mock-up for test purposes.

The suited test subjects are held in place inside the suit via a shoulder restraint system. The subjects also have the option of using a waist belt in concert with the harness system to transfer some of the weight of suit to the hips during 1-G ops. Foam padding can also be placed inside the HUT for comfort.

The MK III weighs about 54 kg (120 lbs), and has modular leg, arm, and glove soft goods components and metal sizing rings that allow for individualized sizing adjustments. The boots on the MK III are modified commercial work boots with flexible soles for walking and a convoluted ankle for joint mobility. The large HUT and hip section provide for an acceptable suit-fit in most of male astronaut population, however a smaller HUT and hip sections would be necessary to accommodate proper suit-sizing for most of the female astronaut population.

The MK III is designed for an optimal operating pressure of 4.3 psig. The maximum operating pressure for most of the suit components, including the HUT, is 8 psig. All suited tests were performed at 4.3 psig with certified breathing air at the standard flow rate of 6.0 acfm. Each subject wore a Liquid Cooling Garment (LCG) under the suit, through which chilled water mixture was continuously pumped a rate of approximately 120 lb/hr. Communication between the test team and the suited test subject was available via a system comprised of 9 wireless head sets and 2 hardwire head sets.



Figure 1: MK III Advanced Space Suit Technology Demonstrator

**Subsequent references in this report to the “MK III suit” include the pressure garment and combined mockup backpack and gimbal support structure.*



The Spider-Gimbal System provides the interface between the suited subject and the Partial Gravity Simulator.

Figure 2: MK Suit and Spider-Gimbal System Test Set Up

The Spider-Gimbal System (the large aluminum structure shown in image above) connects the MK III suit to the POGO. Its purpose is to offload weight from the suited subject in a manner that allows him to move in the roll, pitch, and yaw planes of motion while attached to the POGO (i.e., avoid the “marionette” effect of hanging from or being pulled upward by the POGO).

The spider-gimbal system has some CG adjustment capability, in that the position of the main load-bearing components can be adjusted such that the suited subject’s total weight is perfectly balanced, slightly forward, or slightly aft when offloaded to a specific gravity level (e.g. lunar). However, the “dial-in” capability is somewhat limited because there is difficulty in determining the correct settings for each subject (due to cross-coupling of the dependent variables – subject weight, height, and body weight distribution - in the system), and the resulting CG for each setting is currently defined only by the subject’s interpretation (subjective), which is 1) difficult to measure or define with a small number of subjects, and 2) inconsistent between subjects. The entire Spider-Gimbal System weighs approximately 40.8 kgs (90 lbs).

It should be noted that, for this test, the CG adjustability was sufficient but less than ideal because the team was not able to know the exact location of the CG, or what effect the resulting weight distribution (forward, aft, etc.) may have had on each subject’s metabolic rate or biomechanics. For future tests, a model of the system will be developed (with height and weight inputs) and used to standardize the settings for a specific CG location for each suited subject.

Challenger Treadmill

The treadmill used for this test was a commercial off-the-shelf (COTS) Challenger model 5.0. It had a sufficient (although not optimal) walking surface area of 27”x 72”, and allowed for speeds ranging from 0.1 to 10.0 mph with resolutions of 0.1 mph. The test team outfitted the treadmill with four AMTI force plates positioned beneath each ‘leg’ of the treadmill (as described under Data Collection Techniques).

It should be noted that although the Challenger treadmill offered a sufficient but less than ideal walking surface (tread width and length), speed control, and no incline/decline capability, using it allowed the test team to gain both data and experience to help define the treadmill specifications and capabilities required for future suited planetary traverse testing. Upon completion of the Walkback test, the team concluded that a much larger walking surface area is required to avoid suited gait alterations due to the tread width and length, as well as force plates imbedded in the deck to distinctly quantify the ground reaction forces of each foot strike. A stronger motor, a more user-friendly control/display panel, and incline/decline capability are also desired.

Methods

Subject Selection

All subjects were recruited from either a pool of personnel who typically perform EVA-related suited studies for the Engineering Directorate or from a group of astronauts selected to support exploration EVA studies. Due to the projected completion time of the 10 km test and the potential medical safety issues associated with improper suit fit in an active long-duration test, only those with optimal suit fit in the MK III were selected for inclusion in this study. Once this distinction had been made, 6 male astronaut subjects (Table 1) participated in the data collection phases of the study, including the 10 km portion.

Table 1. Summary of AWT Subject Characteristics

		Maximum	Mean ± STDEV	Minimum
Gender:	6 males			
Subject Age (yrs)		51	46.8 ± 4.3	40
Weight (lb)		197	179.5 ± 17.3	157
Height (inches)		74	71 ± 2.0	69
VO ₂ peak (ml/kg/min)		55.6	48.7 ± 5.7	40.8

All subjects successfully passed the modified Air Force Class III Physical or equivalent examination. Each subject was provided verbal and written explanations of the testing protocols and the potential risks and hazards involved in the testing and signed NASA JSC Human Research documentation indicating their understanding and consent. All testing protocols were reviewed and approved by NASA JSC's Committee for the Protection of Human Subjects and the appropriate test readiness review boards.

Partial Gravity System Characterization

The POGO is essentially a servo control system that provides a relatively constant weight offloading (or lift) force to the subject as he ambulates while attached to the piston, which allows for the simulation of his ambulatory dynamics at lunar or martian gravity. Time series motion analysis and ground-reaction force (GRF) data were used to provide an independent assessment of the POGO system performance. Two subjects performed submaximal treadmill translation on a level treadmill (0% grade) at 1/6G and 3/8G in a shirt sleeve condition using the POGO system. The total-body center of mass (COM) trajectory was calculated from time series motion analysis for 3 different speeds for each subject in each gravity level. The measured downward acceleration was then derived from the maximum displacement of the COM until the point of foot-strike with the treadmill. Table 2 depicts the measured versus theoretical downward acceleration and the percent error for each subject. The percentage error between the theoretical and measured accelerations showed some variation with speed and gravity level, but averaged within 5% for both subjects. This suggested that the POGO was performing within acceptable limits and was appropriate for simulating lunar and martian gravity levels in this study.

Table 2. Measured versus theoretical downward accelerations

Subject	Speed (m/s)	Speed (mph)	Gravity Level	Actual Acceleration (m/s)	Theoretical Acceleration (m/s)	% Error
3	1.6765	3.75	Lunar	1.76	1.64	7
3	2.1236	4.75	Lunar	1.84	1.64	13
3	2.5662	5.74	Lunar	1.67	1.64	2
4	1.5692	3.51	Lunar	1.55	1.64	5
4	2.0118	4.5	Lunar	1.59	1.64	3
4	2.4499	5.48	Lunar	1.48	1.64	10
3	1.9939	4.46	Mars	3.65	3.68	1
3	2.4321	5.44	Mars	3.59	3.68	2
3	2.8791	6.44	Mars	3.58	3.68	3
4	2.1191	4.74	Mars	3.58	3.68	3
4	2.5796	5.77	Mars	3.43	3.68	7
4	3.0088	6.73	Mars	3.75	3.68	2

Testing Protocols

VO₂ Peak Test

To compare energy expenditure across the different conditions planned for this test, subjects performed a graded treadmill exercise test to determine their aerobic capacity/peak oxygen consumption, or VO₂pk. The test began with three stages lasting 3 minutes each on a level surface, with the speed increased 1 mph at the start of each new stage. After the third stage, the speed remained the same and the incline (or grade) on the treadmill surface was increased 3% at the start of each subsequent minute, per the protocols described by the following references: Lee, et al., 1997; Watenpaugh, et al., 2000. The subject continued exercising through these stages as long as possible, to maximal effort. VO₂pk and peak heart rate were determined by standard exercise testing criteria. From the VO₂pk, measured levels of energy expenditure during subsequent test sessions can be evaluated as percentages of VO₂pk to ensure subject safety and allow valid relative comparisons among subjects.

Unsuited “Energy-Velocity” Tests

Part 1: Preferred Transition Speed Determination

To establish accurate baseline metabolic and biomechanical data for a range of walking and running speeds, it was first necessary to determine the walk-to-run transition speed, or the Preferred Transition Speed (PTS), for each subject at both 1/6G and 3/8G. This was determined subjectively and confirmed quantitatively via the following protocol: The subject (wearing shirt-sleeve test attire), mounted the treadmill and the speed was set so the subject was clearly walking (i.e., at least one foot was in contact with the treadmill at all times). Once a steady gait was achieved, the treadmill speed was increased slightly. The subject would then achieve a steady gait at the new speed, and the preceding steps repeated until a speed was reached at which the subject freely chose to switch his gait from a walk to a run. Subsequently the treadmill speed was adjusted to find the exact speed where 1) the subject remained walking, but had to exert increased effort to do so 2) the subject exerted significant effort to avoid drifting rearward on the treadmill, and 3) the subject indicated that he would prefer to slowly jog at that speed if required to do so for an extended length of time. The speed at which all 3 criteria were met was noted as the subject’s PTS. Then, each subject would walk at a specified speed above and below the identified PTS while his or her metabolic data was collected. Because walking at a true running speed is more metabolically costly than running at that speed (and vice-versa), the met rate data could quantitatively confirm the subject’s PTS.

Once the PTS for each subject was determined for each gravity level, 3 walking and 3 running velocities were assigned (per the protocol shown in Table 3) as the official data collection velocities to allow investigators to understand the shape of the metabolic curve in both the walking and running ranges. The PTS (and the immediate ranges above and below it) were intentionally avoided to ensure the subject would be able to maintain a steady gait during data collection at his or her assigned velocities and to avoid confounding influences on metabolic rate (a dependent variable in this study).

Table 3. Determination of Velocities Used for the Energy-Velocity Tests

Speeds Used for the Energy-Velocity Tests:		
Stage	Speed	Comments
1	X minus 1.1 mph	Subtract 0.3 mph per stage; need smaller increments for walking
2	X minus 0.8 mph	
3	X minus 0.5 mph	Subtract 0.5 mph to assure walking out of transition zone
PTS = X		No data collected in transition zone
4	X plus 0.5 mph	Add 0.5 mph to assure running out of transition zone
5	X plus 1.5 mph	Add 1.0 mph to distinguish metabolic/biomechanical differences at running speeds
6	X plus 2.5 mph	

Part 2: Unsuiting (Shirt-Sleeve) Energy-Velocity Testing

During the subsequent unsuited energy velocity tests, each subject performed submaximal locomotion on a level treadmill (0% grade) for 3 minutes at each of the 6 different (assigned) velocities determined for each of the 3 gravity levels (1G, 1/6G, and 3/8G). Simulations of 1/6G and 3/8G were accomplished by having subjects wear a waist/hip harness that allowed the POGO to offload a percentage of the subject’s weight to simulate his weight at the desired gravity level.



Instrumented subject performs unsuited energy-velocity test while partially suspended from POGO overhead.

Figure 3: Shirt-Sleeve Test Set Up

Subjects completed a total of 5 trials during this session, 3 trials using true ‘unsuited’ weight relief and 2 in which the subject’s weight was adjusted to match his total suited weight (including the MK III suit and the spider/gimbal interface with the POGO). This approach was used to provide weight-matched controls that, when compared to later suited tests, allowed for the assessment of the specific metabolic and biomechanical costs of the suit (i.e., the combined effects of inertial mass, pressure-volume work, and kinematic constraints). The trials are described below:

Trial 1: Earth gravity (1-g), wearing harness	}	Referred to as the ‘unsuited’ condition
Trial 2: Moon gravity (1/6-g), wearing harness		
Trial 3: Mars gravity (3/8-g), wearing harness		
Trial 4: Moon gravity (1/6-g), wearing harness <u>with</u> simulated weight	}	Referred to as the ‘weighted’ condition
Trial 5: Mars gravity (3/8-g), wearing harness <u>with</u> simulated weight		

Each subject initially performed Trial 1 and then the order of subsequent trials was varied systematically such that half the subjects completed the 1/6G condition (Trial 2) first and half completed the 3/8G condition (Trial 3) first to address test order and learning bias.

Suited Energy-Velocity Tests

Each subject performed suited submaximal treadmill translation on a level treadmill (0% grade) in 1/6G and 3/8G. Translation speeds (3 walking, 3 running) and durations (3 minutes/stage) for each individual were set to be identical to those used during the unsuited tests for walking, however running velocity increments were set at half those of the unsuited trials (0.5 mph vs. 1.0 mph, respectively) due to the difficulty of moving the MKIII suit at higher speeds. This practice ensured that 2 of the 3 running speeds would be identical to unsuited trials for comparison across gravity levels for each subject. Gravity levels were applied in the same manner as during the unsuited tests. At the end of the 1/6G trial, each subject was asked to identify the velocity at which they expected they would want to perform the 10 km Walkback session.

Note: Suited or shirt sleeve “weighted” conditions for the 1G gravity level were not performed because the combined mass of the suit and the spider-gimbal system make traversing in 1G nearly impossible and most definitely unsafe to attempt.



Suited subject performs treadmill locomotion while partially suspended from Pogo overhead.

Figure 4: Subject Performing 10 km Translation in MK III Suit in Lunar Gravity

Suited 10 km ‘Walkback’ Test

On a later date (after completing the portions of the test described above), each subject again donned the LCG and MKIII suit for the full-up Walkback Test. In addition to the set-up for the suited energy-velocity tests (described above), subjects were outfitted with a wireless ECG system that delivered a 3-lead ECG signal to the medical monitor console, a core-temperature measuring device, and skin temperatures sensors. Subjects were also provided a low-profile 32 oz in-suit drink bag from which water could be consumed as needed during the test.

The testing scenario described the subject to be 10 km from a lunar habitat, having completed approximately 4 hours of surface activities when his or her rover breaks down. The subjects were reminded of the test termination criteria (Appendix A) and ground rules (Appendix B) and given the following basic instructions:

1. Attempt to translate 10 km at any speed you desire. Speed can be increased or decreased whenever you request; there is no time requirement. You may stop and rest at any time you wish. You may also request the test be stopped at any time, for any reason.
2. You will be prompted every 15 minutes for ratings of exertion, controllability, and discomfort. If at any time you experience discomfort, please tell the test team regardless whether it occurs at the designated interval.
3. Because of the potential for injury, do not press through excessive levels of discomfort. Should you need to stop the test before reaching 10 km, calculations based upon the completed portion of the test can allow the team to extrapolate nominal expected time to completion and associated data.

Data Collection Techniques

Metabolic Data Collection

During the $\text{VO}_{2\text{pk}}$ and unsuited tests, energy expenditure (ie, metabolic rate) was determined from the continuous measurement of VO_2 , carbon dioxide (CO_2) production, and expiratory volume (V_E) using a headset/mouthpiece connected to a True One 2400 metabolic cart (Parvo Medics, Provo, UT). Heart rate during the $\text{VO}_{2\text{pk}}$ test was monitored from 12-lead electrocardiogram (ECG) recordings, and during submaximal tests from a 3-lead ECG or Polar Heart Rate Monitor.

During exercise in the MK III suit, energy expenditure was based on measured suit ventilation rate, expired CO_2 concentration in the exhaust umbilical (CD-3A Infrared Carbon Dioxide Analyzer, AEI Technologies, Pittsburgh, PA) and the regression between VCO_2 and VO_2 as measured during the VO_2 peak test. This technique and hardware were identical to those currently used during suited NBL tests.

Thermoregulatory demand was measured only during the 10 km sessions from measures for body core and skin surface temperatures. Core temperature was determined using a radio frequency capsule while skin temperatures were measured using thermocouple sensors, all transmitted to a wireless VitalSense® physiological monitor (Mini Mitter Company, Inc., Bend, OR). Standardized equations were used to calculate body heat storage.

Biomechanical Data Collection

Biomechanical data were collected using a 12-camera motion analysis system (120 Hz; Vicon, Oxford, UK) and 4 strain gauge force plates then processed and analyzed using customized MATLAB computer programs. Data were sampled during 20 full, consistent strides during each stage of testing; however during the 10 km session, data were sampled for 20 strides every 5 minutes. Ground reaction forces were collected using 46.2 x 50.8 cm force plates, mounted to each corner support structure of the treadmill. Ground reaction force variables of interest included the peak impact force during ground contact and loading rates. The motion analysis system was used to record 3-dimensional (3-D) trajectories of reflective markers, 51 in total, attached to each body segment of the subjects. Post-test analyses were performed on the

kinematic variables of interest that included hip, knee, and ankle range of motion, stride frequency, and vertical excursion of the body during the exercise. The results of the time series motion analysis will be combined with suit engineering data on joint forces and torques (and published at later date) to estimate the magnitude and degree of resistive exercise associated with walking EVAs in partial-gravity.

Subjective Data Collection

For the unsuited and suited energy-velocity test sessions the Rating of Perceived Exertion (RPE; Borg, 1982) and Cooper-Harper (Cooper, 1957; Cooper & Harper, 1969) ratings were recorded at the end of each stage. The RPE is used to gauge how much effort a person feels they must exert to perform a task, particularly exercise, on a scale of 6 to 20. The scale roughly correlates with heart rate such that a subject's RPE should be about 1/10 of his or her actual HR during exercise (e.g., if HR = 120, the subject's RPE is expected to be ~12). The Cooper-Harper rating, on a scale of 1 to 10, is used to determine the level of compensation a person feels is necessary to maintain body control. The original Cooper-Harper scale was developed for pilot controllability of an aircraft, but was later modified to apply to control of the human body.

Before beginning the 10 km test, subjects completed the first phase of the NASA Task Load Index (TLX) questionnaire (Hart and Staveland, 1988) that measures the perceived physical and mental workload necessary to perform a given task. The subject then donned the suit and, once operating pressure was reached, was asked to complete a target tracking task as quickly as possible. The task consisted of tracking targets on a touchpad and time to completion was measured to see if there was any degradation between the pre- and post-tests. During the test, subjects were prompted for RPE and Cooper-Harper ratings every 15 minutes. At the same interval, they used a discomfort (0 to 10) scale to rate discomfort on any and all portion(s) of the body (Corlett and Bishop, 1976). At the end of the 10 km Walkback session, subjects completed final RPE and NASA TLX workload ratings as well as a final target tracking task to measure any pre- to post-test degradations in task completion time. Scales used for these measurements are depicted in Appendix C.

Imaging

Photographic data also were collected after completion of each testing run if human-suit interactions were unfavorable or resulted in skin or musculoskeletal abnormalities. This information will be provided as feedback to Space Medicine and the suit designers. During all suited tests 2 Sony digital video cameras captured lateral (side) and anterior (front) video as well as auditory comments of the crewmember and test team, except during time periods declared to be private medical conferences by the medical officer.

Summary of Preliminary Results

All subjects completed the 10 km “Walkback” translation without difficulty. The average time to completion was 95.8 minutes at an average velocity of 3.94 mph with an average metabolic rate of 2374 BTU/hr (or ~10 kcal/min) for the 6 subjects. Prior to the test, it was believed that suit fit issues, boot discomfort in particular, would limit the ability of crewmembers to withstand that much time or number of gait cycles in the suit. It was furthermore expected that subjects would need in excess of 3 hours to complete the task. Most subjects started at relatively slow pace (< 4 mph) and worked up to slightly faster steady-state pace to perform the 10K translation. One subject performed it in a more “interval” type manner, as shown in Figure 1 below, most likely due to suit fit

The maximum 15 minute average metabolic rate was 2617 BTU/hr. Both the average and 15 minute peak metabolic rates exceed the Apollo and EMU cooling capabilities. All of the test subjects mentioned that they would have liked to ambulate at higher speeds, but were not able to because of cooling limitations. However, it should be noted that the suit’s portable cooling system was not capable of operating at the nominal flow rate for the LCG design worn by the subjects during the test.

Preliminary data from the energy-velocity tests indicate that the transport costs ($\text{mlO}_2/\text{kg-km}$) become more efficient at higher ambulation speeds in Lunar Gravity, which may be inherent to the design of the hip and waist components as well as the inertial mass of the MK III suit. More testing and analysis is being performed to better understand how inertial mass, suit mobility, CG location, and gravity level affect the transport cost of the suit, but these preliminary data suggest that improvements to space suit cooling systems will be necessary to exploit the increased transport efficiency at higher ambulation speeds for various EVA contingencies ranging from emergency “Walkback” scenarios to suit leaks.

Note: The above information is preliminary data as described in NASA’s EVA Walkback Test (EWT) Quicklook Report (released Jan 2007). Further analysis and discussion of the results with respect to the metabolic and transport costs of the suit as determined by the energy velocity tests, the biomechanics associated with Lunar translation in the MK III suit, and all associated subjective data will be published at a later date.

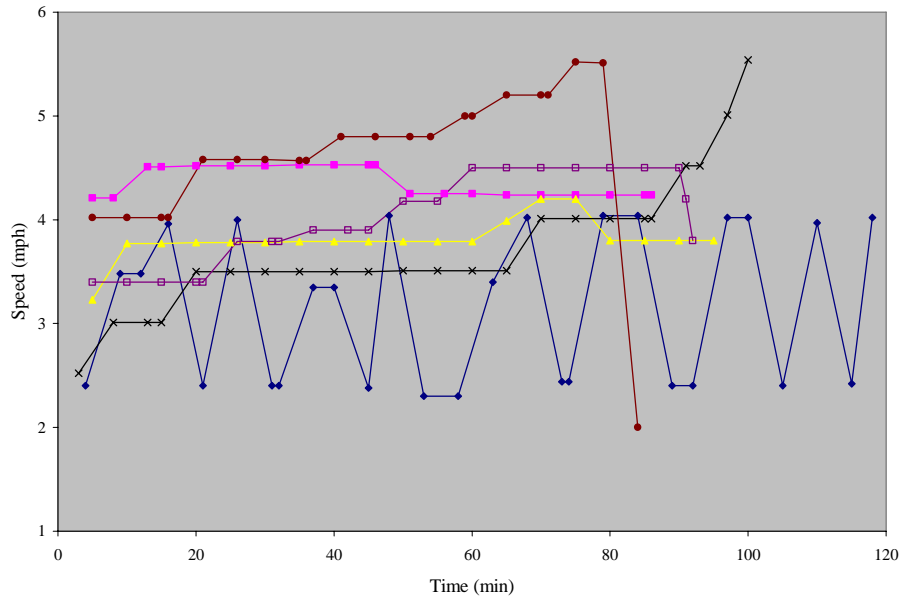


Figure 5: 10 km Walkback Strategy as Speed vs. Time for All Subjects

Consumables are an important consideration for EVA excursions, and the 10 km Walkback provided some insight into hydration and nutritional requirements for a task of similar duration or intensity. All subjects were provided 32 oz of water in an in-suit drink bag affixed with Velcro to the sternum area of the inner suit torso, with a bite valve placed near the crew-member’s mouth. This configuration was a special accommodation for this test because of the expected duration of the exercise, as the MK III suit is not currently configured to contain a drink bag. As a result, the fit of the drink bag was better for some subjects than others. The subjects generally consumed between 50% to 100% of the water provided, and 1 subject would have preferred to have another 20% available.

At the energy expenditure rates found in this study, caloric supplements may be desirable for lunar missions dependent upon the planned EVA operations. Under the assumptions of this test, subjects would have been on EVA for 4 hrs, driving the rover to the work site and performing the nominal tasks of the day, prior to a rover failure. Based upon Apollo surface EVA data, this would equate to the consumption of approximately 1000 kilocalories (kcal) before beginning the excursion back to the habitat (Waligora & Horrigan, 1977). The 10 km Walkback required an average of 944 kcal total, or 10 kcal/min. Thus the total energy needs for a sample EVA with this Walkback-type contingency would approach 2000 kcal, which is approximately 2/3 of the recommended daily energy intake (3000 kcal/day) for a 70 kg male on NASA Exploration missions (NASA-JSC, 2005), indicating a possible need for caloric supplements beyond the additional 50 kcal on EVA days currently advised. In addition, all subjects felt that a nutritional item, either food such as a bar or energy gel, or flavored electrolyte drink may improve performance and/or endurance.

Conclusions

This series of tests established the feasibility of performing a lunar 10 km Walkback, and provided objective data to support Constellation Program Lunar Architecture decisions.

Analysis of transport costs identified that cooling system improvements will be required to exploit the increased transport efficiency associated with higher ambulation velocities. These data also provide the basis for sizing the PLSS and consumables usage in conjunction with evolving operational concepts. Another important product of this test was the development and refinement of data analysis methods that will form a set of ‘standard measures’ for future studies that look at effects of suit weight, mass, pressure, CG, and kinematic constraints for both ambulation and exploration tasks. Tools resulting from the Walkback test include analysis software to rapidly post-process motion data to determine the number of cycles on any joint of the suit as a function of time and velocity. These analysis tools will be effective for developing suit cycle requirements and will provide significant cost savings during suit certification compared the conventional methods of manual video tape review.

The results of this study provided an initial assessment of the cardiovascular effort associated with ambulatory EVA in Lunar gravity. Future tests involving other suits and exercise conditions, including varying suit mass and CG location, will add to this data set and also will permit assessments of the resistive exercise associated with EVA. The resulting estimates of cardiovascular and resistive exercise associated with EVA will allow NASA to optimize their countermeasures in conjunction with EVA.

In summary, the Walkback test not only answered the primary objective of the study, but provided an entry into the systematic assessment of the complex interrelationships of the human-suit system in a partial-gravity environment. All of the data, analysis tools and lessons learned from this study will be used to refine NASA’s understanding of the various parameters pertinent to performing suited exploration EVA tasks. Ultimately, these studies will provide information to the EVA community for making evidence-based recommendations to optimize suit design for the targeted operational environment and crew anthropometric range.

Study Limitations

This study was undertaken as a pilot experiment because of the complexity of integrating personnel and facilities from various JSC organizations and because the testing protocols were the first of their kind (i.e., different than methods employed during the Apollo era). As a result, caution must be used when interpreting and generalizing the findings of this study. Most notably, trials in this study were performed on a smooth, firm treadmill surface while a portion of the subject’s weight was lifted by a servo-controlled device which limited movement degrees of freedom. Development of simulators which permit more realistic ambulation on planetary surfaces is required.

The key areas involving study limitations and lessons learned include hardware, test set up, and study design. As mentioned previously, the Challenger treadmill was used for this test despite known shortcomings. The team suspected the that treadmill belt was not wide enough for

subjects to ambulate in 1/6G or suited conditions without stepping off the belt, but tests conducted during the Pogo characterization determined that this treadmill was acceptable for the test purposes. During the test, subjects only occasionally stepped off the belt with either a toe or heel, but this did not significantly impact their gait. However, several subjects did report that they consciously modified their gait with the belt width in mind. Having learned from the Walkback test, NASA has invested in a new treadmill with a much larger tread (5' x 8') to ensure that true gait biomechanics are not compromised. The new treadmill also has 4 force plates (the same kind that were used with the Challenger treadmill in this test) imbedded in the treadmill deck, which is a much more optimal set up than what was used for this test (as previously described in the Test Equipment section).

A significant limitation of the existing unsuited harness and the suited gimbal system was the inability to precisely control or accurately set the center of gravity. Standard procedures were used to configure the systems such that the subject was suspended in a neutral posture. Although these settings were recorded for future analysis, the analytical tools for determining the actual CG were not available at the time of this test and therefore the CG settings may have been inconsistent across test subjects and test conditions. NASA has begun to improve the designs of the harness and gimbal systems for future testing to allow for precise and consistent application and systematic variation of CG locations for each test activity.

Several issues with study design, such as the insufficient thermal data during suited trials, will be addressed in future investigations. There is also the possibility of learning effects associated with ambulation using the Pogo system. The 10 km Walkback will be analyzed against the shorter energy velocity tests and as a function of time during the 10 km Walkback to assess the magnitude of any learning effects. If it is determined that there are significant learning effects, future tests will be designed to incorporate longer familiarization sessions.

Appendix A: Submaximal Test Termination Criteria

Test Termination Criteria for All Submaximal Testing –

1. Subject request to stop at any time
2. Subject's heart rate or measured VO_2 at level $> 85\% \text{VO}_{2\text{pk}}$ for 2 min or more
3. Failure of PGCS/Pogo hardware and/or treadmill system

ADDITIONAL Test Termination Criteria for **Suited** Submaximal and 10 km Testing -

1. Expired CO_2 levels greater than 5%
2. If subject reports discomfort rating ≥ 7 (on 10-point scale) for two consecutive recording periods, subject will be asked to terminate the test. If subject asks to continue, they will be allowed to continue until they meet condition 3
3. Discomfort rating ≥ 7 for 3 recording periods (may be non-consecutive) or severe pressure point
4. Engineering hardware failure such as in suit or suit environmental control (These standard/approved engineering termination criteria were described in the detailed test plan (CTSD_AHL_0009) and addressed in the test readiness review (TRR).

Appendix B: 10 km Ground Rules

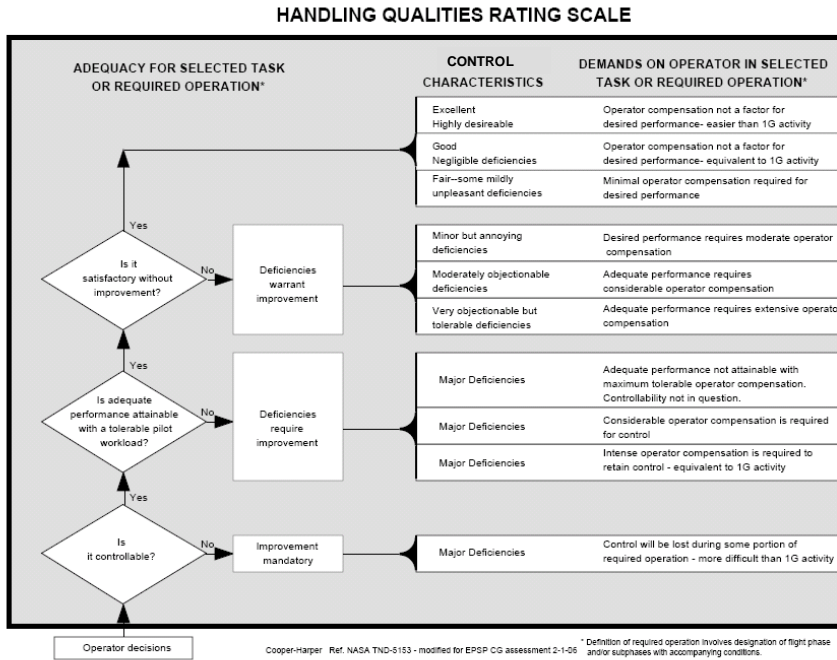
Ground Rules for the 10 km Walkback session:

1. Operation of all engineering systems and equipment to record metabolic rate (met rate), ground-reaction force vectors (GRF), and motion analysis must be nominal to start each test. Skin and core temperatures and LCVG delta temperature, heart rate (HR) and electrocardiogram (ECG) are desired, but not required for test start.
2. Up to 60 min into the test (excluding trouble shooting time), the operating procedure is to stop the test and trouble shoot any required issue for up to 20 min. If the problem cannot be fixed, then proceed to terminate the test.
3. At any time beyond 60 min into the test (excluding trouble shooting time), the operating procedure is to stop the test and trouble shoot up to an additional 20 minutes (total of 40 min for the entire test) for loss of critical engineering systems or met rate, GRF, or motion analysis. If met rate, GRF or motion analysis is not fixable in that timeframe, then continue the test until 10 km is achieved or other test termination criteria have been met.
4. Multiple critical systems are involved in this test, and failure of any of these may result in termination of the test within the guidelines set forth in the previous paragraph. A test termination condition may be initiated by the test director, test subject, medical officer, test safety officer, suit technician, treadmill technician, facility representative, or test team member. This is done to ensure the safety of the test subject and investigators, minimize damage to hardware and facilities in use, and assure the quality of the scientific data collected. Specific criteria for these systems are outlined in the detailed test plan.

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Appendix C: Ratings Scales for Subjective Measures

Modified Cooper-Harper Scale



Borg Rating of Perceived Exertion Scale (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	Maximal exertion

Corlett & Bishop Discomfort Scale

Front of Participant

Discomfort Scale

0	Nothing at All
0.5	Extremely Low Discomfort
1	Very Low Discomfort
2	Low Discomfort
3	Moderate Discomfort
4	
5	High Discomfort
6	
7	Very High Discomfort
8	
9	
10	Extremely High Discomfort

Back of Participant

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