Integrated Suit Test 1 - A Study to Evaluate Effects of Suit Weight, Pressure, and Kinematics on Human Performance During Lunar Ambulation

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ABSTRACT

In an effort to design the next generation Lunar suit, NASA has initiated a series of tests aimed at understanding the human physiological and biomechanical affects of space suits under a variety of conditions. The first of these tests was the EVA Walkback Test (ICES 2007-01-3133). NASA-JSC assembled a multi-disciplinary team to conduct the second test of the series, titled Integrated Suit Test 1 (IST-1), from March 6 through July 24, 2007. Similar to the Walkback Test, this study was performed with the Mark III (MKIII) EVA Technology Demonstrator suit, a treadmill, and the Partial Gravity Simulator in the Space Vehicle Mock-Up Facility at Johnson Space Center. The data collected for IST-1 included metabolic rates, ground reaction forces, biomechanics, and subjective workload and controllability feedback on both suited and unsuited (shirt-sleeve) astronaut subjects. For IST-1 the center of gravity was controlled to a nearly perfect position while the weight, pressure and biomechanics (waist locked vs. unlocked) were varied individually to evaluate the effects of each on the ability to perform level (0 degree incline) ambulation in simulated Lunar gravity. The detailed test methodology and preliminary key findings of IST-1 are summarized in this report

INTRODUCTION

Current understanding of suited human performance in reduced gravity environments includes limited observations from Apollo Lunar surface EVAs and from a few previous studies conducted in partial gravity simulation environments. NASA is in the process of enhancing the design of the next generation space suit and have initiated a series of tests aimed at understanding suited human performance under a variety of simulated Lunar EVA conditions. These studies include matched unsuited controls, so that the specific metabolic costs and biomechanics of the suit can be understood. The results of entire test series will provide evidence-based recommendations for suit design parameters to optimize human performance in partial gravity environments.

The first of these studies, the EVA Walkback Test was conducted using the Partial Gravity Simulator (Pogo) in the Space Vehicle Mock-Up Facility (SVMF, Building 9) and the Mark III (MKIII) EVA Technology Demonstrator suit. Results from the Walkback Test quantified the total metabolic cost and biomechanics of suited locomotion for a 10 kilometer “walkback” scenario on the Moon (1/6-g). For IST-1, the center of gravity location was held constant while the weight, pressure, and suit kinematic constraints (waist locked out) were varied to determine their individual effects on Lunar ambulation.

This is a preliminary report providing a high-level overview of some of the key findings of IST-1 based on the data that has been analyzed to date. Further results with respect to the effects of suit inertial mass, kinematics, and transports costs of the MK III suit during Lunar translation, will be published at a later date.

TEST OBJECTIVES

The objectives of IST-1 discussed in this paper include quantifying the effects of varied weight, varied pressure, and suit kinematic constraints (waist locked vs. unlocked) on human performance (measured via metabolic rate, joint mobility, and subjective assessments) during suited translation in a simulated Lunar environment (1/6g).

METHODS

Subjects were recruited from a pool of personnel who typically perform EVA suited studies for the Engineering Directorate and from a group of astronauts selected to support exploration EVA studies. Only those subjects who had good suit fit were considered for inclusion in this study due to potential medical safety issues. From this pool, 6 male astronaut subjects (Table 1) participated in the data collection phases of the study. At time of test, no available female astronauts properly fit in the MK III suit. All subjects successfully passed the modified Air Force Class III Physical or equivalent examination.

Table 1: Subject Characteristics

n=6	Height (cm)	Body Mass (kg)	Age (years)	VO2pk (ml/min/kg)
Avg	179.1	80.7	44.8	50.8
St. Dev.	4.8	8.5	6.9	6.7
Max	185.9	86.4	52.0	60.7
Min	174.6	68.2	37.0	42.6

TEST HARDWARE

Partial Gravity Simulator (Pogo)

All IST-1 data collection sessions were performed using the Space Vehicle Mock-up Facility (SVMF) Pogo system to provide simulated partial-gravity conditions. The Pogo uses a pneumatic cylinder servo controlled to a strain gauge to result in a constant gravitational offloading throughout the subject's range of motion. The vertical servo system consists of the vertical servo assembly, strain gauge, pneumatic cylinder assembly and the piston rod assembly (ref. drawing JSC-26802-4). A gimbal support structure attached to the end of the lifting actuator supports a suited subject and allows for the pitch, roll, and yaw rotational degrees-of-freedom during movement. During unsuited testing, a separate spreader bar and harness assembly provided support to the suspended subjects.

For the unsuited trials the Pogo system was adjusted to completely offset the weight of the harness and spreader bar, while the subject's weight was offset to the appropriate level. For suited trials, the combined weight of the subject, liquid cooling garment (LCG), pressure garment (MKIII) and portable life support system (PLSS) volumetric mockup, and gimbal support structure were offset to the appropriate gravity level. The combined 59 kg weight of the PLSS backpack mock-up (18 kg) and the gimbal support system (41 kg) very closely simulates the current 61 kg EMU PLSS weight. These configurations were designed to create realistic configurations for the respective unsuited and suited conditions.

Mark III Advanced Space Suit Technology Demonstrator EVA suit

The MK III suit is a prototype suit that provides dynamic ranges of motion considered necessary for a wide variety of planetary EVA tasks and is a valid test bed from which design requirements for future suit development can be derived. The MKIII is a hybrid space suit configuration composed of hard elements, such as a hard upper torso and brief section, and of soft components such as fabric elbows and knees that are designed to handle operating pressures of up to 55.0 kPa (8.0 psi). Another feature of the suit is the use of bearings in multi-axial mobility joint systems including the shoulder, upper arm, waist, upper hip, mid hip, upper leg (3 bearing hip), and ankle joints. The suit is entered through a hatch on the backside of the hard upper torso (rear entry suit) that also accommodates integration of a backpack. Suit subjects are integrated to and supported in the suit by a waist belt weight relief system and shoulder straps. The boots are modified commercial work boots with flexible soles for walking and a convoluted ankle joint for mobility. The 54.5 kg MKIII has modular leg, arm, and boot soft goods components that allow individualized sizing adjustments with sizing rings. Foam padding also is used to improve fit and to avoid pressure or rubbing spots.

Figure 1: Mark III Advanced Space Suit Technology Demonstrator EVA Suit

During testing sessions certified breathing air was provided by a compressed air source (a tube trailer) at an approximate flow rate of 4.2 l/s (9.0 cubic feet per minute) Internal suit cooling was provided via a closed water loop that circulates through an ice/water chiller to cool the test subject's Liquid Cooling Garment (LCG). The system is powered by an external pump (~109 kg/hr) and can deliver a minimum suit inlet temperature of 4º C or a maximum of 28º C when the chiller bypass valve is activated. Communication with the suited test subject was available via a system comprised of 9 wireless head sets and 2 hardwire head sets.

For the purposes of this report, "suit" refers to the pressure garment, combined mockup backpack, and gimbal support structure.

VacuMed Oversized Treadmill

The treadmill used for testing was a customized VacuMed model #13610 large research treadmill owned by the EVA & Spacesuit Systems Branch (Figure 2). With a walking surface 1.5 meters wide and 2.4 meters in length, it allows speeds from 0.16 to 45 km/h with speed resolutions of 0.16 km/h and grades from 10% decline to 30% incline. The treadmill was instrumented with four force plates (AMTI Model #OR6-5-2000) placed under the deck and belt of the treadmill.

Figure 2 - *VacuMed Research T*readmill

TESTING PROTOCOLS

Peak Oxygen Consumption (VO2pk) 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. Refer to ICES paper 2007-01-3133 for details on the VO2pk test protocol. 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.

Establishment of Individualized Preferred Transition Speed (PTS)

Similar to the Walkback Test, an accurate range of walking and running speeds for individuals of different size and stride length was established by determining the PTS for each subject at Lunar gravity (1/6-g). Refer to ICES paper 2007-01-3133 for details on the PTS determination protocol.

Table 2 - Speeds Used for Data Collection

Stage	Speed	Comments
1	PTS minus 2.4 km/h	Subtract 0.8 km/h per stage; need smaller increments for walking
2	PTS minus 1.6 km/h	
3	PTS minus 0.8 km/h	Subtract 0.8 km/h to assure walking out of transition zone
Preferred Transition Speed		No data collected in transition zone
4	PTS plus 0.8 km/h	Add 0.8 km/h to assure running out of transition zone
5	PTS plus 2.4 km/h	Add 1.6 km/h to distinguish metabolic/biomechanical differences at running speeds
6	PTS plus 4.0 km/h	

Once the PTS was determined, three walking and three running velocities were assigned such that the PTS and immediate range above and below it were avoided during data collection (Table 2). This was to maintain a steady gait and to avoid confounding influences on metabolic rate derivation. Three speeds were selected for data collection to allow investigators to understand the shape of the metabolic curve in both the walking and running ranges.

Pogo Off-loading

Prior to the beginning of any trial, the target weight for the subject was verified with the integrated force plates in the treadmill to ± 0.5 kg (1 lb). Due to subject discomfort during unsuited testing, the target weight was adjusted to ± 1.4 kg (3 lb).

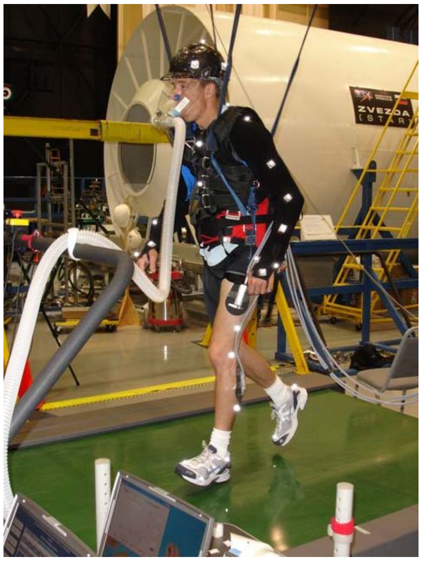

Figure 3 - Instrumented unsuited subject performs treadmill locomotion while partially suspended from Pogo overhead

Varied Pressure Test (Suited)

Each subject donned the MKIII suit and was initially pressurized to 29.6 kPa (4.3 psi) Each subject then translated on a level treadmill (0% grade) for three minutes at each of the six prescribed velocities (three walking, three running) while the Pogo system provided partial weight relief to simulate Lunar gravity (Figure 4). Subjects completed the ambulation trials at each of 5 different suit pressures: 6.9, 20.7, 29.6, 34.5, and 44.8 kPa (1.0, 3.0, 4.3, 5.0 and 6.5 psi). Suit weight and mass were held constant at 121 kg in these trials.

Figure 4 - Suited subject performs treadmill locomotion while partially suspended from Pogo overhead

Varied Weight Test (Unsuited and Suited)

Ambulation at the same 6 speeds used in the Varied Pressure condition was repeated in both suited and unsuited conditions at a range of simulated suit weights while holding mass (121 kg) and suit pressure (29.6 kPa (4.3 psi)) constant. Pogo off-loading force was adjusted for suit weights of approximately 63, 121, 186, 247 and 308 kg. These varied weight conditions can also be interpreted as varied gravity levels of 0.12-g, 0.167-g, 0.22-g, 0.27-g and 0.32-g.

DATA COLLECTION AND ANALYSIS

Metabolic Rate

During the VO2pk and unsuited tests, metabolic rate was determined from the continuous measurement of VO2, carbon dioxide (CO2) production, and expiratory volume (VE) using a headset/mouthpiece connected to a True One 2400 metabolic cart (Parvo Medics, Provo, UT). Heart rate during the VO2pk test was monitored from 12-lead electrocardiogram (ECG) recordings, and during sub-maximal tests from a Polar Heart Rate Monitor.

During exercise in the MKIII suit, metabolic rate was based on measured suit ventilation rate, expired CO2 concentration in the exhaust umbilical (CD-3A Infrared Carbon Dioxide Analyzer, AEI Technologies, Pittsburgh, PA) and the regression between VCO2 and VO2 as measured during the VO2 peak test. This technique and hardware were also used for the Walkback Test and are identical to those currently used during suited NBL tests at JSC.

The metabolic rates represent the highest one-minute average during each of the 3-minute walking or running stages. Metabolic rate was defined as ml of O2 consumed per kg of the subject’s body mass, per minute (ml·kg-1·min-1). Transport cost was defined as ml of O2 consumed per kg of the subject’s body mass per km traveled (ml·kg-1·km-1). Second order polynomials were used to represent metabolic rate variation with respect to speed.

Significant Metabolic Differences

Due to the limited sample size (n=6), inferential statistics were not used, therefore statistical significance was not calculated. For these analyses a metabolic rate of 3.5 ml·kg-1·min-1 was chosen for practical significance. This is equivalent to resting metabolic rate and 10% of the VO2pk in a subject with a VO2pk 35 ml·kg-1·min-1 who would be representative of a slightly deconditioned crewmember. The average ISS crewmember has a pre-flight VO2pk of 43.7 ± 6.1 ml·kg-1·min-1 (NASA Exercise Physiology Lab Database).

Biomechanical Data Collection and Analysis

Three-dimensional forces and moments under feet were recorded during walking and running on a VacuMed treadmill instrumented with four 46.2 x 50.8 cm strain gauge force-plates (AMTI, Watertown, MA USA). The signal was collected at 1000 Hz over thirty gait cycles at varying speeds, pressures, and simulated suit weights and then stored for subsequent analysis. The vertical components of each of the four force-plates were resolved into one vertical component for each of the thirty gait cycles. For all trials, in each of the conditions, an ensemble average was calculated over the thirty gait cycles after which the peak vertical force was determined using customized computer code (MATLAB, Natick, MA, USA). A second order polynomial fit was generated examining the relationship between the independent and dependent variables using basic curve fitting capabilities available in MATLAB.

Three-dimensional trajectories of retro-reflective markers placed at approximate anatomical landmarks on the MKIII suit were collected at 100 Hz (Vicon, Oxford, UK) to determine the displacement of the segments of the suit. These trajectories were then filtered, processed, and reduced to the three-dimensional angular displacement of the three lower extremity joints during locomotion using customized computer code. This information was used for subsequent analysis to describe the kinematics of the MKIII suit during treadmill ambulation at varying suit pressures and suit weights.

Subjective Data Collection and Analysis

The following subjective ratings were recorded at the end of each testing condition:

- Ratings of Perceived Exertion (RPE; Borg, 1982) were used to gauge how much effort subjects felt they must exert to complete each condition.
- A modified version of the Cooper-Harper rating (Cooper, 1957; Cooper & Harper, 1969) on a scale of 1 to 10 was 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.
- The Corlett & Bishop Body Part Discomfort Scale was used to characterize discomfort at different body locations (Corlett & Bishop, 1976).
- Thermal comfort was assessed for two reasons: to determine the subjective thermal comfort of the subject and to determine whether any changes were necessary to improve the thermal comfort of the subject during testing. Thermal comfort was assessed using the Bedford scale (Bedford, 1936).

Imaging

During all suited tests a digital video camera captured video of the subject in the sagittal plane as well as auditory comments of the subject and test team. During all unsuited tests video was captured without the audio

PRELIMINARY RESULTS AND DISCUSSION

Varied Pressure - Metabolic Rate Findings

Variation in suit pressure at simulated Lunar gravity did not significantly affect metabolic rate (see Figures 5 and 6). The largest difference was between 6.9 kPa (1.0 psi) and 34.5 kPa (5.0 psi) with the difference ranging from 0 to 3.0 ml·kg-1·min-1 across the range of speeds.

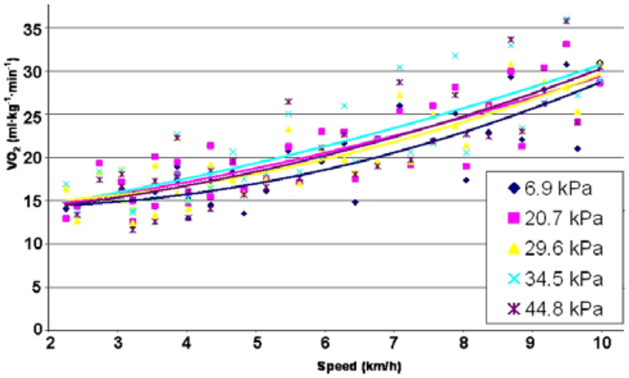

Figure 5: Metabolic rate versus speed at different suit pressures during suited locomotion at Lunar gravity.

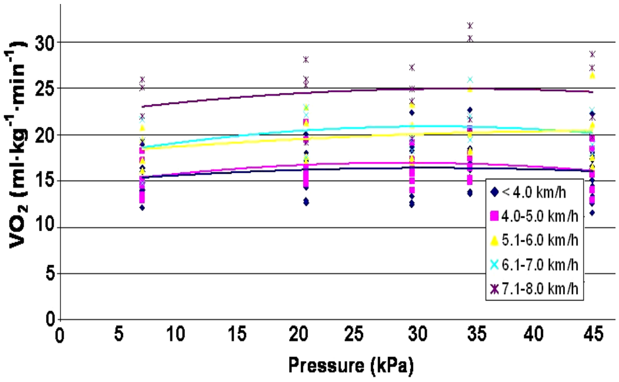

Figure 6: Metabolic rates within speeds at different suit pressures for suited locomotion at the 121 kg suit weight at Lunar gravity.

Figure 6 shows there is very little variation in the metabolic cost as a function of pressure for five different ambulation speeds, suggesting that metabolic costs not directly effected by changes in suit pressure.

In summary, suit pressure has a minimal influence on the metabolic rate for the group as a whole. It is important to note that this test was limited to ambulation and does not imply that suit pressure would not have a significant effect on crewmembers performing upper body and hand intensive exploration tasks.

Varied Pressure - Subjective Findings

Subjective findings showed similar trends to the metabolic rate. There was very little variation in either RPE or the modified Cooper-Harper ratings between different suit pressures as shown in Figure 7 and Figure 8, respectively. RPE increased with speed as expected. Modified Cooper-Harper ratings had a trend towards increasing with speed, but were generally in the acceptable range of ~ 3 in the expected nominal ambulation speeds of < 5 km/hr.

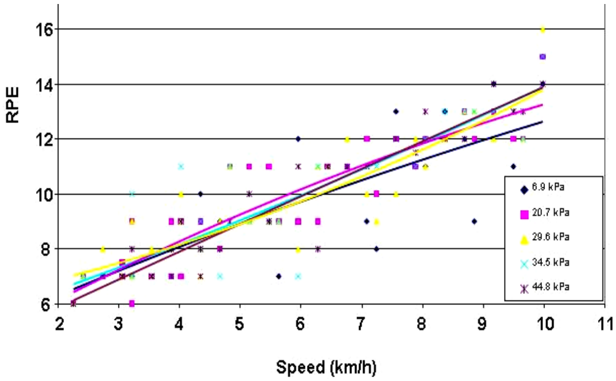

Figure 7: Figure 7 - RPE at varied pressures for suited locomotion at the 121 kg suit weight in Lunar gravity

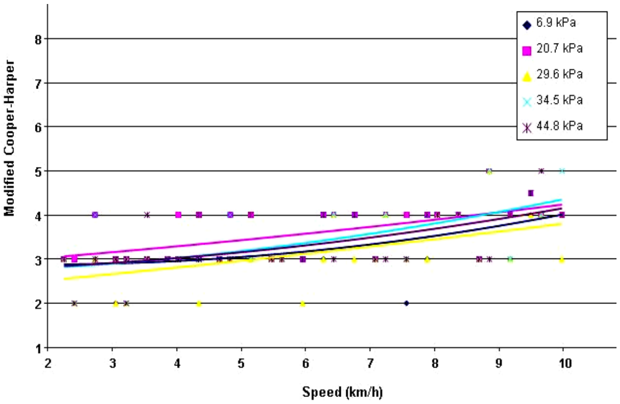

Figure 8: Modified Cooper-Harper ratings at varied pressures for suited locomotion at the 121 kg suit weight in Lunar gravity.

Varied Pressure - Biomechanics Findings

Similar to metabolic rate, most of the biomechanics variables showed little variation with changes in suit pressure. The ground reaction force (GRF) is a result of the human interacting with the ground. During locomotion, the individual is acted upon by the GRF at the same time the individual pushes against the ground. The magnitude of the GRF varies as a function of locomotion speed, increasing with increasing speed. In earth walking, the vertical component of the GRF has a maximum value of 1 to 1.2 "times body weight" (BW) and in earth running, the maximum or peak can be as high as 3 to 5 BW. Mean peak GRF did not change with suit pressure. Gait parameters including stance time, stride length and cadence also did not vary. Suit joint motion indices including waist, hip and knee average angular velocity showed a trend to decrease with increased pressure as shown in Figures 9-11.

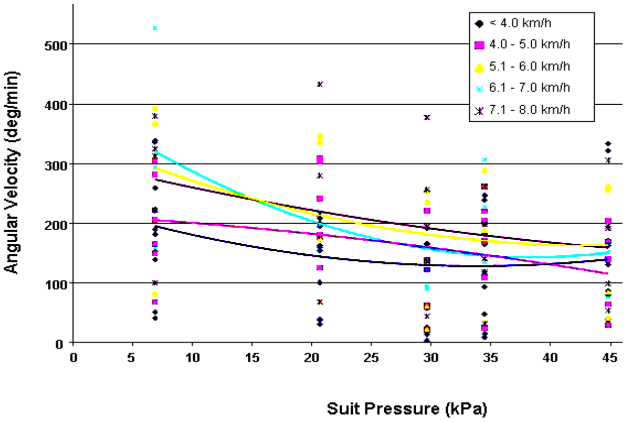

Figure 9: Waist average angular velocity versus suit pressure for suited locomotion at the 121 kg suit weight in Lunar gravity

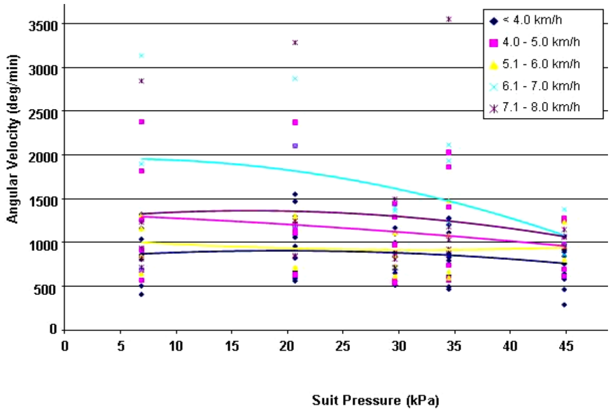

Figure 10: Knee average angular velocity versus suit pressure for suited locomotion at the 121 kg suit weight in Lunar gravity

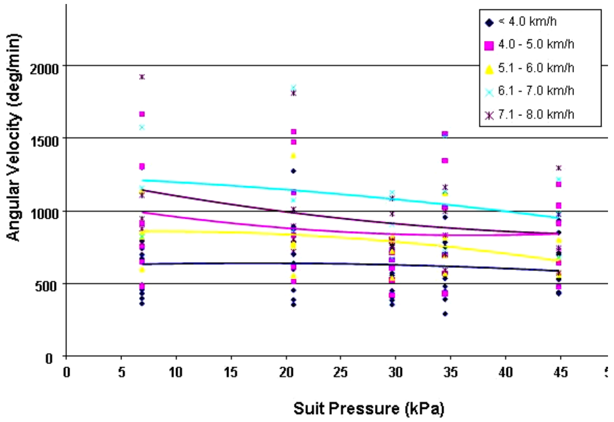

Figure 11: Hip average angular velocity versus suit pressure for suited locomotion at the 121 kg suit weight in Lunar gravity

Varied Weight (Suited and Unsuited) - Metabolic Findings

Figure 12 shows the relationship between metabolic rate and ambulation speeds for earth suit weights ranging from 63 kg to 308 kg. At speeds less than 4.0 km/h, the difference in average metabolic rate between the lightest and the heaviest suit weight was 2.85 ml·kg-1·min-1, which is not significant (≤ 3.5 ml·kg-1·min-1). At speeds above 4 km/hr the differences in suit weight became significant. The difference between the lowest and the highest suit weight varies from ~ 6 ml·kg-1·min-1 at speeds between 4.0-5.0 km/h up to ~ 15 ml·kg-1·min-1 at speeds between 6.1-8.0 km/h.

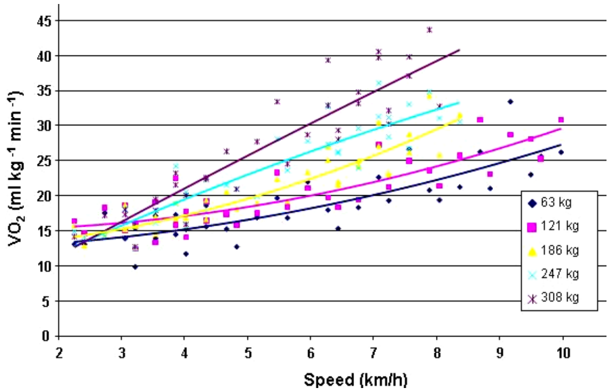

Figure 12: Metabolic rate versus speed for different 1-g equivalent suit weights during suited locomotion at Lunar gravity with constant suit pressure (29.6 kPa)

To better understand the suit related factors that cause an increase in metabolic rate with increasing suit weight, we compared the suited metabolic rates to the metabolic rates of weight matched unsuited subjects. To calculate the metabolic cost of the suit independent of weight, the metabolic rates of the unsuited weight-matched controls were subtracted from the metabolic rates of the suited trials. Figure 13 is a plot of the difference in metabolic rate between suited and unsuited subjects, as a function of earth suit weight. This delta metabolic cost was not significant for suit weights between 63 and 186 kg, but began to increase significantly at suit weights greater than 186 kg. This increase in metabolic rate at suit weights greater than 186 kg might be related to an increase in the average joint rotational velocities as shown in Figures 17-19.

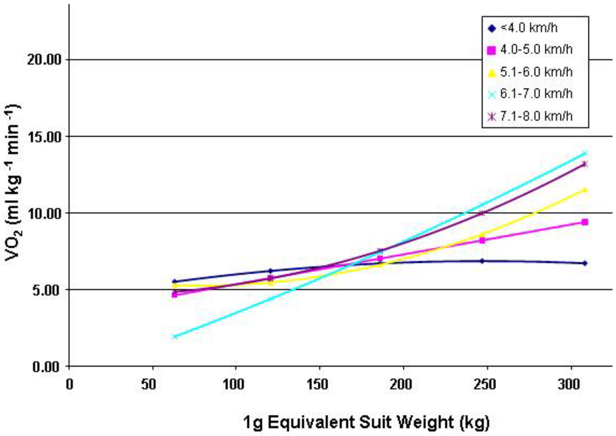

Figure 13: - Metabolic cost of the suit not related to weight versus 1-g equivalent suit weight for suited locomotion at Lunar gravity at a suit pressure of 29.6 kPa

Varied Weight (Suited and Unsuited) - Subjective Findings

Subjective findings showed similar trends to the metabolic rate. The general trend as seen in Figure 14 was that RPE increased as suit weight increased. The difference in RPE between suit weights also increased as speed increased. Figure 15 shows that modified Cooper-Harper ratings were very similar for suit weights of 186 kg and below. The two heavier weights averaged a modified Cooper-Harper rating that was higher by 1-2 levels. For all subjects at all speeds, suit weights of 186 kg or less had modified Cooper-Harper ratings ≤ 5, with most in the acceptable range of ≤ 4. In many cases, the heavier suit weights were also acceptable, but there were several ratings ≥ 6, especially at higher speeds.

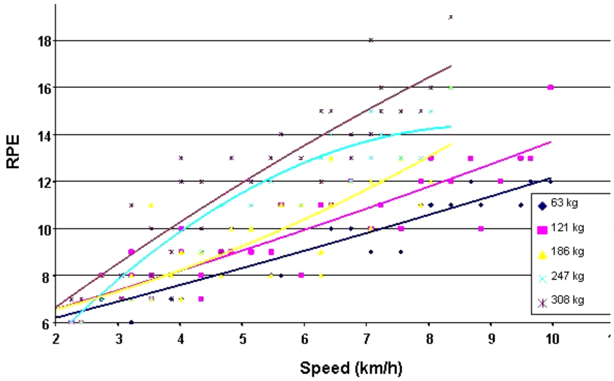

Figure 14: RPE versus speed for different 1-g equivalent suit weights during suited locomotion at Lunar gravity with constant suit pressure (29.6 kPa)

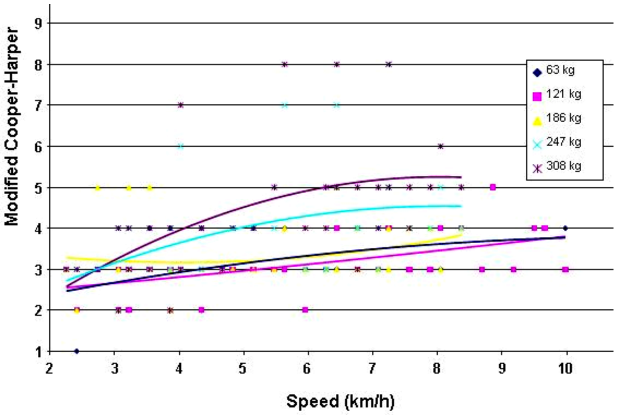

Figure 15: Modified Cooper-Harper versus speed for different 1-g equivalent suit weights during suited locomotion at Lunar gravity with constant suit pressure (29.6 kPa)

Varied Weight (Suited and Unsuited) - Biomechanics Findings

The mean vertical peak GRF data showed a trend unlike varying the suit pressure. In this case, there appeared to be a general trend of increasing vertical peak GRF with increasing suit weight (Figure 16). For suit weights less than 186 kg there was a minimal difference in vertical peak GRF in at nominal ambulation speeds of ≤ 5 km/hr. This finding could be due to the fact that all subjects exhibited less of a "bounding or loping" type gait and instead adopted more of a terrestrial earth type gait as suit weight increased.

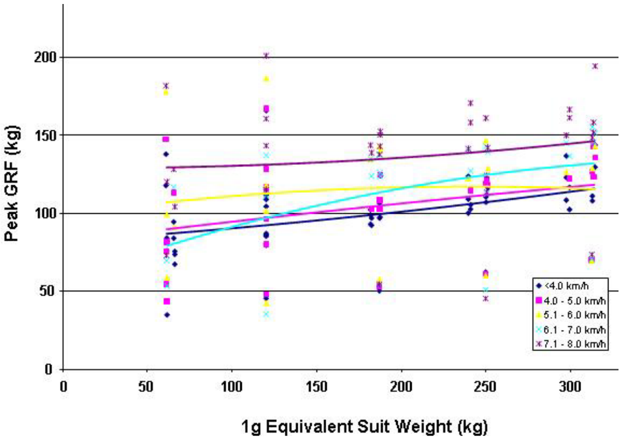

Figure 16: Peak GRF rate versus 1-g equivalent suit weight during suited locomotion at Lunar gravity with a constant pressure (29.6 kPa)

Figures 17-19 show that with increased suit weight there was a general trend of increased average angular velocity of the waist, hip and knee joints.

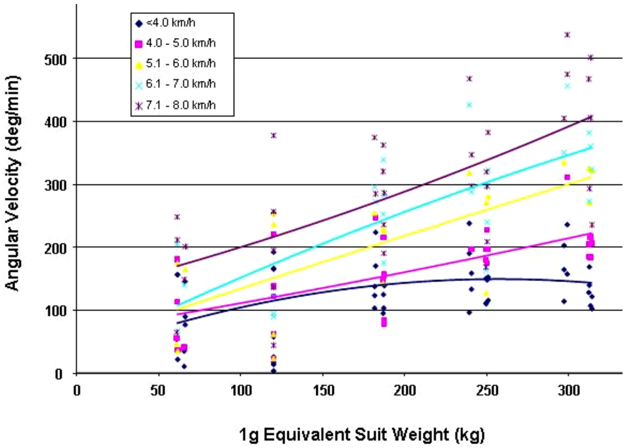

Figure 17: Waist average angular velocity versus 1-g equivalent suit weight during suited locomotion at Lunar gravity with a constant pressure (29.6 kPa)

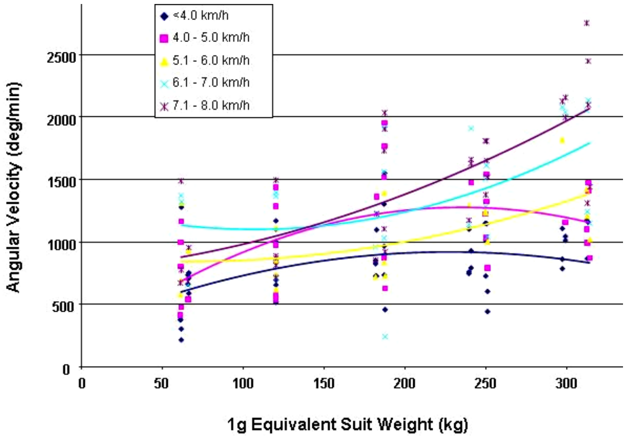

Figure 18: Knee average angular velocity versus 1-g equivalent suit weight during suited locomotion at Lunar gravity with a constant pressure (29.6 kPa)

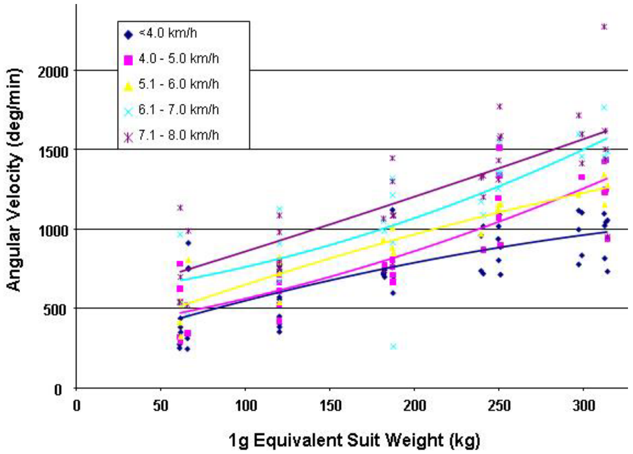

Figure 19: Hip average angular velocity versus 1-g equivalent suit weight during suited locomotion at Lunar gravity with a constant pressure (29.6 kPa)

Varied Suit Kinematics - Waist-Locked vs Unlocked Locomotion

To evaluate the effect of the mobility provided by the waist bearing during Lunar ambulation, the waist joint of the MK III was locked out at the nominal configuration of 121 kg, 29.6 kPa (4.3 psi) and 1/6-g. The data indicates that locking the waist joint does not affect the metabolic cost of level ground ambulation (Figure 20).

While the metabolic rate was not different between nominal and waist-locked conditions, the subjective ratings did differ. The average RPE and modified Cooper-Harper values were approximately one rating higher than nominal (waist-unlocked) operations.

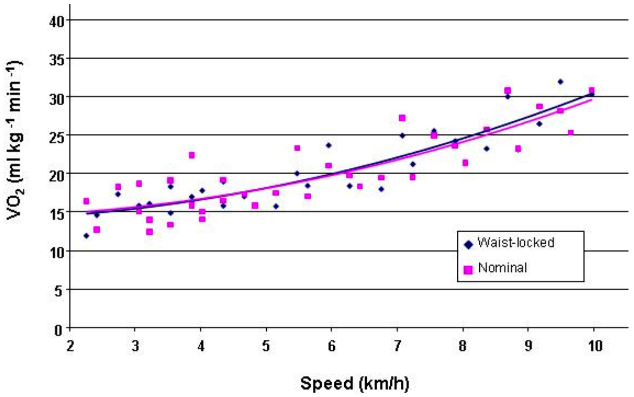

Figure 20: Locomotion with the waist locked compared to nominal suit configuration at Lunar gravity with suit weight of 121 kg and suit pressure of 29.6 kPa (4.3 psi)

STUDY LIMITATIONS

1. Because this test was a continuation of the Walkback Test, a comparison of data from this test and the Walkback test was done. IST-1 had 3 subjects who had also participated in the Walkback Test (3 subjects were new to this test). To look at the test-to-test variability, only the 3 returning subjects were compared. The only two carry-over conditions were suited at Lunar gravity and 29.6 kPa (4.3 psi) and the unsuited weight-matched control trial. Figure 21 shows the comparison of these two test conditions. When comparing the results, the metabolic rates from IST-1 were consistently lower than the Walkback Test. Proposed reasons for this variation include increased subject familiarization with partial gravity ambulation, a larger treadmill walking surface, and improved weigh-out procedures which required that each subject's weight on the ground be measured to within 1.4 kg of the target weight. Previous weight-out procedures relied only on a load cell measuring Pogo off-loading force.

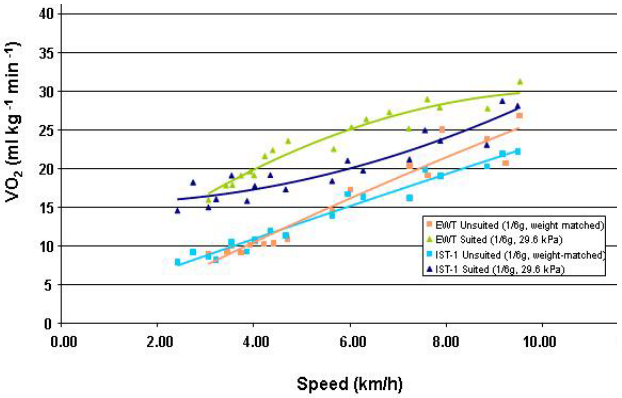

Figure 21: Lunar locomotion comparison of repeat subjects from both the Walkback Test and IST-1.

2. Although weight was varied, inertial mass was not varied. All varied weights occurred at a suit mass of 121 kg. Without mass matching these conditions or characterizing the effects of varied mass, the results of the varied weight section have to be viewed as preliminary.

3. Due to limited time and resources, the subject pool was limited to six male astronauts with limited anthropometric variability. Also, at time of test there were no available female astronauts available who properly fit in the MK III suit. Ideally, future tests will include female subjects and male subjects with different anthropometrics.

4. Another consideration is that during the reduced-gravity trials the subjects' arms and legs still operated in a 1-g field. Because the weight of the limbs was not reduced, it is possible that the metabolic and biomechanical data may not accurately simulate that which would occur in true reduced gravity environments. However it is not felt that these effects were substantial given the relatively small amount of total body weight comprised in the limbs, and in a constant gravity field the energetics of the pendular upswing and downswing would generally be offsetting. Additionally a limited cross over test on C-9 parabolic flights showed close agreement with the results of the Pogo based tests.

CONCLUSIONS

Initial findings suggest that – for level ground ambulation – suit pressure has a minimal influence on metabolic rate or on subjective assessments of exertion and operator compensation for the group as a whole.

Interestingly, biomechanical analysis revealed decreases in average angular velocities of the waist, hip and knee with increased pressure, which other data suggests would normally lower the metabolic rate. The observation that metabolic rate was essentially unchanged by suit pressure suggests a more complex relationship involving both energy consuming and energy recovery elements that balance each other to result in little net effect in the MKIII suit. Different suit designs with different joint designs and sequencing might be affected differently by suit pressure. These observations are limited to ambulation and do not imply that suit pressure would not have a significant effect on subjects performing upper body and hand intensive exploration tasks.

Suit weight (63kg – 308 kg) did not affect average metabolic rate at locomotion speeds below 4.0 km/h. At speeds above 4 km/hr the differences became significant, reaching up to ~15 ml·kg-1·min-1 at speeds between 6.1 and 8.0 km/h.

The metabolic cost of the suit unrelated to weight was not significant for suit weights between 63 and 186 kg, but began to increase significantly at suit weights greater than 186 kg, probably because there is more energy expended in the rotation of the torso at higher suit weights. These observations suggest a compound relationship between mass and weight, and that a reduction in the mass of the rotating components on the suit might result in a reduction in suited metabolic rates.

Perceived exertion increased as suit weight increased and the increase in exertion with speed was greater in heavier suits. For all subjects at all speeds, suit weights of 186 kg or less had operator compensation ratings (modified Cooper-Harper) ≤ 5, with most in the acceptable range of ≤ 4. In many cases, the heavier suit weights were also acceptable, but there were several ratings ≥ 6, especially at higher speeds.

Metabolic data indicates that locking the waist-joint does not affect the metabolic cost of level ambulation. However, subjective ratings did differ between conditions, with the average exertion and modified Cooper-Harper ratings being approximately one rating higher in the waist-locked condition than in nominal (waist unlocked) operations.

Futher analysis and future tests will be conducted to evaluate the individual contributions of the inertial mass, suit kinematics and stability as well as examine the various inter-relationships and coupling factors present in untested combinations of these variables. By understanding these individual factors, NASA will be able to enhance EVA space suit designs, and improve upon EVA mission planning and overall consumables packaging.

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