NASA/TP-2010-216125

Metabolic Costs and Biomechanics of Inclined Ambulation and Exploration Tasks in a Planetary Suit

Jason R. Norcross[1], Kurt G. Clowers[2], Tim Clark[2], Lauren Harvill[3], Richard M. Morency[4], Leah C. Stroud[5], Lena Desantis[3], Jessica R. Vos[4], Michael L. Gernhardt[4]

[1]Wyle Integrated Science & Engineering Group, Houston

[2]MEI Technologies, Inc., Houston

[3]Lockheed Martin, Houston

[4]NASA Johnson Space Center, Houston

[5]Rice University, Houston

June 2010

THE NASA STI PROGRAM OFFICE . . . IN PROFILE

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) Program Office plays a key part in helping NASA maintain this important role.

The NASA STI Program Office is operated by Langley Research Center, the lead center for NASA's scientific and technical information. The NASA STI Program Office provides access to the NASA STI Database, the largest collection of aeronautical and space science STI in the world. The Program Office is also NASA's institutional mechanism for disseminating the results of its research and development activities. These results are published by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA's counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.
- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, eg, quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.
- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.
- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or cosponsored by NASA.
- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and mission, often concerned with subjects having substantial public interest.
- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services that complement the STI Program Office's diverse offerings include creating custom thesauri, building customized databases, organizing and publishing research results . . . even providing videos.

For more information about the NASA STI Program Office, see the following:

- Access the NASA STI Program Home Page at http://www.sti.nasa.gov
- E-mail your question via the Internet to help@sti.nasa.gov
- Fax your question to the NASA Access Help Desk at (301) 621-0134
- Telephone the NASA Access Help Desk at (301) 621-0390
- Write to:
  NASA Access Help Desk
  NASA Center for AeroSpace Information
  7115 Standard
  HANOVER, MD 21076-1320

NASA/TP-2010-216125

Metabolic Costs and Biomechanics of Inclined Ambulation and Exploration Tasks in a Planetary Suit

Jason R. Norcross[1], Kurt G. Clowers[2], Tim Clark[2], Lauren Harvill[3], Richard M. Morency[4], Leah C. Stroud[5], Lena Desantis[3], Jessica R. Vos[4], Michael L. Gernhardt[4]

[1]Wyle Integrated Science & Engineering Group, Houston

[2]MEI Technologies, Inc., Houston

[3]Lockheed Martin, Houston

[4]NASA Johnson Space Center, Houston

[5]Rice University, Houston

June 2010

Available from:

NASA Center for AeroSpace Information
7115 Standard Drive
Hanover, MD 21076-1320
301-621-0390

National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
703-605-6000

This report is also available in electronic form at http://ston.jsc.nasa.gov/collections/TRS/

Prepared by:

Jason Norcross

Jason Norcross (Wyle), Project Science Coordinator
EVA Physiology, Systems and Performance Project

2/9/10
Date

Technical Review by:

Amy Ross for Lindsay Aitchison

Lindsay Aitchison (NASA), Configuration 2 Lead
Constellation Space Suit Element Pressure Garment System

4/21/10
Date

Kurt Clowers, Ph.D. (MEI Technologies), Lead Engineer
Anthropometry and Biomechanics Facility

2/11/10
Date

Lena DeSantis

Lena Desantis (Lockheed-Martin), Senior Human Factors Design Engineer
Usability Testing and Analysis Facility

2/11/10
Date

John De Witt, Ph.D. (Wyle), Lead Biomechanist
Exercise Physiology and Countermeasures Project

2/11/10
Date

Heather Paul

Heather Paul (NASA), Ventilation Subsystem Lead
Constellation Space Suit Element Portable Life Support Systems

2/19/10
Date

Jessica Vos

Jessica Vos (NASA), Integrated Test Lead
Constellation EVA Systems Project Office

2/22/10
Date

James M Wessel

James Wessel III (Wyle), Scientist
Environmental Physiology Laboratory

2/9/10
Date

Approved by:

Michael Gernhardt, Ph.D. (NASA), Principal Investigator
EVA Physiology, Systems and Performance Project

2/12/10
Date

Richard Morency (NASA), Technical Monitor
Anthropometry and Biomechanics Facility

2/16/10
Date

Jeff Patrick

Jeff Patrick (NASA), Testing and Facilities Manager
Constellation EVA Systems Project Office

4/21/10
Date

Contents

1 Introduction 1
1.1 Test Objectives 2
1.2 Secondary Test Objectives 2

2 Methods 2
2.1 Subjects 2
2.2 Test Hardware 3
2.2.1 Mark III advanced spacesuit technology demonstrator 3
2.2.2 Busy board 5
2.3 Testing Protocols 5
2.3.1 Inclined ambulation 5
2.3.2 Exploration tasks 5
2.3.3 Weight carry 7
2.4 Testing Sessions 7
2.4.1 Weight/mass/offload/gravity terminology 7
2.4.2 Varied mass (unsuited) 8
2.4.3 Varied pressure (suited) 9
2.4.4 Varied weight test (suited and unsuited) 10
2.5 POGO Off-loading 10
2.6 Metabolic Data Collection and Analysis 10
2.6.1 Calculating contributions of weight, mass, pressure, and suit kinematics to the overall metabolic cost of the MKIII suit 11
2.6.2 Significant metabolic differences 11
2.6.3 Earth Shirtsleeve Performance Index 11
2.7 Biomechanical Data Collection and Analysis 12
2.8 Subjective Data Collection and Analysis 16
2.9 Imaging 17

3 Results and Discussion 17
3.1 Test Objective 1: Contributions of Weight, Mass, Pressure, and Suit Kinematics to Metabolic Cost of MKIII Suit in POGO Configuration 17
3.2 Test Objective 2: Quantification of the Effects of Specific Factors on Suited and/or Unsuited Metabolic Rate, Biomechanics, and Subjective Ratings During Inclined Ambulation and Exploration Tasks 21
3.2.1 Effect of varied suit pressure at constant offload (weight), mass, and CG 21
3.2.2 Effect of varied mass (unsuited) 35
3.2.3 Effect of varied weight (suited and unsuited) 37
3.3 Test Objective 3: Compare MKIII at POGO Configuration to the MKIII at POGO Configuration with the Waist Bearing Locked 65
3.4 Test Objective 4: Predictive Models of Metabolic Rates, Subjective Assessments, and Suit Kinematics 69
3.4.1 Predictive models for metabolic rate 69
3.4.2 Predictive model for metabolic rate based on subjective ratings 72
3.4.3 Predictive model for suit kinematics 73

3.5 Secondary Test Objectives 73
3.5.1 Define standard measures and protocols for evaluating exploration suits and requirements verification 73
3.5.2 Understand the specific human performance limitations of a suit compared to matched shirtsleeve controls 74
3.5.3 Collect metabolic and ground reaction force data to develop an extravehicular activity simulator for use on future prebreathe protocol verification tests 77
3.5.4 Provide data to estimate consumables usage for input to suit and Portable Life Support System design 77
3.5.5 Assess the cardiovascular and resistance exercise associated with partial-gravity extravehicular activity for planning appropriate exploration exercise countermeasures 77
3.6 Study Limitations 77
3.7 Lessons Learned 80

4 Conclusions 82
4.1 Contributions of Weight, Mass, Pressure, and Suit Kinematics to Metabolic Cost of MKIII in POGO Configuration 82
4.2 Effects of Varied Weight, Mass, and Pressure on Suited Human Performance 83
4.3 Comparison of the MKIII at POGO configuration to MKIII with the Waist Bearing Locked 84
4.4 Development of Predictive Models for Metabolic Rate and Suit Kinematics 84
4.5 Secondary Objectives 84
4.6 Summary 85

5 Works Cited 85

Appendix A: Submaximal Test Termination Criteria 87
Appendix B: Ratings Scales for Subjective Measures 88

Acknowledgements 90

Figures

1 Mark III advanced spacesuit technology demonstrator 4
2 Busy board included handrail removal/installation and several quick-disconnect stations 5
3 Description of forces acting on the system mass and the resultant forces 8
4 Instrumented unsuited subject wearing an X-Vest and performing shoveling task (metabolic emphasis) 9
5 Suited subject performs inclined treadmill locomotion 9
6 Four force plates (red boxes) were mounted to each corner support structure of the treadmill underneath the treadmill belt 12
7 Anterior view of Plug-in Gait marker set 13
8 Posterior view of Plug-in Gait marker set 13
9 Medio-lateral and anterior-posterior center of pressure for the left foot and right foot, and the total for a small rock pickup trial 15
10 Visualization of how the medio-lateral and anterior-posterior center-of-pressure total was compared to the base of support for a small rock pickup trial.... 15
11 Percentage of metabolic cost for individual factors performing suited inclined ambulation 18
12 Percentage of metabolic cost for individual factors performing suited exploration tasks 19
13 Metabolic cost of individual components for suited incline walking 19
14 Metabolic cost of individual components for suited exploration tasks 20
15 Metabolic rate vs. suit pressure for exploration tasks with 121-kg suit mass at lunar gravity 22
16 Metabolic rate vs. suit pressure for inclined walking with 121-kg suit mass at lunar gravity 22
17 Rating of perceived exertion at varied pressures for suited incline locomotion at the 121-kg suit mass in lunar gravity 23
18 Gravity compensation and performance scale ratings at varied pressures for suited locomotion at the 121-kg suit mass in lunar gravity 23
19 Rating of perceived exertion for exploration tasks at varied pressures with a constant 121-kg suit mass 24
20 Gravity compensation and performance scale ratings for exploration tasks at varied pressures with a constant 121-kg suit mass 25
21 Peak vertical ground reaction force normalized to body weight for all subjects at varying suit pressures during treadmill walking at 10%, 20%, and 30% grades at lunar gravity 26
22 Average cadence for all subjects at different pressures during incline treadmill walking with constant suit mass (121 kg) at lunar gravity 27
23 Schematic of hip flexion and extension 28
24 Theoretical plot of a joint angle vs. time 28
25 Mean hip angle vs. time normalized to the gait cycle for all subjects at different pressures during suited incline treadmill walking 29
26 Knee-joint kinematics for varying pressure conditions while walking at 10%, 20%, and 30% grades 29

27 Knee initial contact (IC) and toe-off (TO) for all subjects at varying pressures during inclined treadmill walking 30
28 Knee initial contact and toe-off averaged over all subjects at varying pressures during suited inclined treadmill walking.. 31
29 Ankle joint kinematics for varying suit pressures while walking at 10%, 20%, and 30% grades 31
30 A 3-dimensional visualization of the mean three lower-extremity joint ranges of motion vs. pressure and incline during suited incline treadmill ambulation 32
31 Waist-bearing cycles for all subjects at different suit pressures during suited inclined treadmill ambulation.. 33
32 Linear travel of the waist bearing for all subjects at different suit pressures during treadmill walking at 10%, 20%, and 30% grades 34
33 Mean absolute relative phase for the interacting segments of the hip and knee and the ankle and knee for suited location at all inclines 35
34 Metabolic rate vs. added mass during unsuited but weight-matched (121-kg) inclined ambulation at lunar gravity.. 36
35 Metabolic cost vs. added mass during unsuited but weight-matched (121-kg) exploration tasks at lunar gravity 36
36 Metabolic rate vs. grade for different gravity profiles during suited walking at lunar gravity with constant suit pressure (29.6 kPa) 37
37 Metabolic rate vs. gravity level during suited inclined ambulation at lunar gravity with a constant pressure (29.6 kPa) 38
38 Metabolic rate vs. total gravity adjusted weight during unsuited inclined ambulation at varied offloads 38
39 Metabolic rate for incline walking at different suited and unsuited conditions 39
40 Postural differences for inclined walking among the 1-g environment, a predicted 1/6-g environment, and the POGO 1/6-g environment 40
41 Metabolic cost for exploration tasks at different gravity levels but constant pressure (29.6 kPa) and suit mass (121 kg).. 40
42 Metabolic rate and time to completion for the busy board task at varied weights... 41
43 Metabolic rate and time to completion for the rock transfer task at varied weights.. 41
44 Metabolic rate and rock mass for the shoveling task at varied weights 42
45 Rating of perceived exertion during incline walking for different gravity levels at a constant pressure (29.6 kPa) and suit mass (121 kg)....................................... 44
46 Gravity compensation and performance scale during incline walking for different gravity levels or total gravity adjusted weights at a constant pressure (29.6 kPa) and suit mass (121 kg) 44
47 Rating of perceived exertion during exploration tasks at different gravity levels at a constant pressure (29.6 kPa) and suit mass (121 kg)....................................... 45
48 Gravity compensation and performance scale during exploration tasks at different gravity levels at a constant pressure (29.6 kPa) and suit mass (121 kg) ... 45
49 Rating of perceived exertion for exploration tasks at all shirtsleeve conditions...... 46
50 Gravity compensation and performance scale for all exploration tasks at all shirtsleeve conditions 47

51 Peak vertical ground reaction force normalized to body weight for all subjects at varying suit weights during suited inclined treadmill walking 48
52 Average cadence for all subjects at different suit weights during suited inclined treadmill walking 49
53 Mean hip angle vs. time normalized to the gait cycle for all subjects at different suit weights during suited inclined treadmill walking 49
54 Knee-joint kinematics for varying suit weight conditions during suited inclined treadmill walking 50
55 Knee initial contact and toe-off for all subjects at varying weights while walking at 10%, 20%, and 30% grades 50
56 Knee initial contact and toe-off averaged over all subjects at varying weights while walking at 10%, 20%, and 30% grades 51
57 Ankle joint kinematics for varying suit weights while walking at 10%, 15%, 20%, and 30% grades 52
58 Three-dimensional visualization of the mean three lower-extremity joint ranges of motion vs. suit weight and incline 52
59 Waist-bearing cycles for all subjects at different gravities during treadmill walking at 10%, 15%, 20%, and 30% grades 53
60 Linear travel of the waist bearing for all subjects at different suit weights during suited inclined treadmill walking 54
61 Mean absolute relative phase for the interacting segments of the hip and knee and the ankle and knee at different suit weights during inclined treadmill walking 55
62 Percentage of trials with observed stable vs. unstable foot placement during rock pickup task. Subjects were rated on consistency of foot contact with force platforms. DNC (did not complete) Task: subject completely lost contact with force platforms, fell over, reported a gravity compensation and performance scale rating of 10, or used assistance (ie, leaned on nearby equipment) during the task 56
63 Hand involvement during large and small rock pickup tasks 56
64 Interaction between upper and lower extremities when performing rock pick-up tasks. Subjects either leaned to the left, leaned to the right, or bent straight down (not favoring either left or right side) when picking up the rock 57
65 Comparison of two main strategies (“stand up” and “jump up”) with varying weighted conditions for the kneel-and-recover task.. 58
66 Percentage of “stand-up” and “jump-up” strategies across varying operating pressure conditions at the 121-kg weight condition for the kneel-and-recover task.. 60
67 Percentage of observed stable vs. unstable foot placement during shoveling task. Subjects were rated on consistency of foot contact with force platforms. DNC (did not complete) Task: subject completely lost contact with force platforms, fell over, reported a gravity compensation and performance scale rating of 10, or used assistance (ie, leaned on nearby equipment) during the task...................... 61
68 Percentage of center of pressure outside the base of support for the small rock pickup task for all trials for all subjects 63

69 Percentage of center of pressure outside the base of support for the large rock pickup task for all trials for all subjects 63
70 Percentage of center of pressure outside the base of support for the shoveling task for all trials for all subjects 64
71 Percentage of performed trials for the rock pickup task, including both small and large for all subjects 67
72 Hand involvement for the rock pickup task comparing waist locked to waist unlocked for all subjects 68
73 Average percent center of pressure outside the base of support comparing waist locked to waist unlocked for all subjects for the small rock pickup task 68
74 Average percent center of pressure outside the base of support comparing waist locked to waist unlocked for all subjects for the large rock pickup task 69
75 Model-predicted metabolic rate for suited incline ambulation vs. actual data 71
76 Inclined ambulation model-predicted VO_2 (red) and observed VO_2 (blue) with respect to rating of perceived exertion 72
77 Exploration task model-predicted VO_2 (red) and observed VO_2 (blue) with respect to rating of perceived exertion 73
78 Earth Shirtsleeve Performance Index for suited exploration tasks at lunar gravity with MKIII at POGO configuration (121-kg suit mass at 29.6 kPa) 75
79 Earth Shirtsleeve Performance Index for suited inclined walking at lunar gravity with MKIII at POGO configuration (121-kg suit mass at 29.6 kPa) 75
80 Metabolic rate vs. load carried both suited (POGO configuration) and shirtsleeve at lunar gravity ($n = 5$) 76
81 Example of the current difficulties with studying how the suit affects human movement (a possible suit knee angle is shown in red and a possible human knee angle is shown in black) 76

Tables

1 Subject Characteristics 3
2 Shirtsleeve Metabolic Cost of Exploration Tasks 43
3 Average Workload Scores for Suited Conditions 65
4 Average Workload for Unsuited Conditions 65
5 Nominal vs. Waist-locked Configuration at 121-kg Suit Mass and 29.6 kPa 66
6 Learning Effect for Exploration Task Metabolic Rate 66
7 Range of Experimental Conditions on which the Preliminary Model Is Based 71

Acronyms

a-p	anterior-posterior
ABF	Anthropometry and Biomechanics Facility
BOS	base of support
BW	body weight
cfm	cubic feet per minute
CG	center of gravity
CO_2	carbon dioxide
COM	center of mass
COP	center of pressure
CxP	Constellation Program
DNC	did not complete
EPSP	EVA Physiology, Systems, and Performance [Project]
ESPO	EVA Systems Project Office
ESSPI	Earth Shirtsleeve Performance Index
EVA	extravehicular activity
EWT	EVA Walkback Test
GCPS	gravity compensation and performance scale
GRF	ground reaction force
IC	initial contact
IST-1	Integrated Suit Test-1
JSC	Johnson Space Center
LCG	liquid cooling garment
m-l	medio-lateral
MKIII	Mark III Advanced Spacesuit Technology Demonstrator
O_2	oxygen
PLSS	Portable Life Support System
POGO	Nickname for B.9 Partial Gravity Simulator
PTS	preferred transition speed
QD	quick disconnect
ROM	range of motion
RPE	rating of perceived exertion
SVMF	Space Vehicle Mock-up Facility
TGAW	total gravity adjusted weight
TLX	task load index
TO	toe-off
TRR	test readiness review
V_E	rate of expiratory ventilation
VCO_2	rate of carbon dioxide production
VO_2	rate of oxygen consumption
VO_2pk	peak rate of oxygen consumption

1 Introduction

Our current understanding of suited human performance in reduced-gravity planetary environments includes limited observations from Apollo lunar surface extravehicular activities (EVAs) and from a few previous studies conducted in partial-gravity simulation environments (1) (2) (3) (4). The Constellation Program (CxP) EVA Systems Project Office (ESPO), which is developing design requirements for the next-generation lunar EVA suit, initiated a series of tests, working with the EVA Physiology, Systems, and Performance (EPSP) Project and the Anthropometry and Biomechanics Facility (ABF) aimed at understanding human performance and suit kinematics under a variety of simulated lunar EVA conditions. These studies included matched unsuited controls in an attempt to identify the specific metabolic costs and biomechanics of the prototype Mark III Advanced Spacesuit Technology Demonstrator (MKIII). A primary goal of the overall test series is to provide evidence-based recommendations for suit mass, center of gravity (CG), pressure, and suit kinematic constraints that optimize human performance in partial-gravity environments. Results of this test series will also be combined with studies in other lunar analogs to evaluate the effectiveness and limitations of these environments.

The two previous tests in the series, the EVA Walkback Test (EWT) and the Integrated Suit Test-1 (IST-1), were conducted using the partial-gravity simulator (nicknamed: POGO) in the Space Vehicle Mock-up Facility (SVMF, Building 9) and the MKIII. The study described in this report, Integrated Suit Test-2 (IST-2), was conducted in the SVMF using the MKIII suit because the MKIII is the only planetary suit prototype in NASA’s inventory that is compatible with the POGO. The MKIII also has the most variable operational pressure range of the available prototype suits. IST-2, the companion test to IST-1 (2), had identical objectives and similar test conditions but different test points. Whereas IST-1 focused on level-ground ambulation, IST-2 focused on exploration tasks and inclined ambulation.

To evaluate the human performance effects of changes in any parameter of interest, only that parameter was changed while all other controlled test variables were held constant. For instance, when the effect of weight was varied by applying changes to the POGO offload, the suit pressure, suit mass, and suit CG were all held constant (as much as possible). Wherever possible, these changes were also evaluated in both suited and unsuited (shirtsleeve) tests. The terms unsuited and shirtsleeve will be used interchangeably throughout this document. Due to limitations, this study did not test all possible combinations of the variables of interest but, rather, focused on the most likely operationally relevant zones from which to vary parameters. As our understanding of suited human performance matures, different combinations of these variables can be evaluated to determine whether significant interactions exist between these parameters.

This report provides an overview of the key findings of IST-2. As future tests are completed, focusing on other suit factors, analog environments, or different suits, the results of this study will be continually combined and reevaluated. The series of tests comprising IST-2 was conducted from June 13, 2007 through October 24, 2007.

1.1 Primary Test Objectives

The purpose of IST-2 was to move beyond level-ground locomotion and evaluate suited human performance during exploration-type tasks and inclined locomotion. Specifically, the primary objectives of this test were to

1. Identify the individual contributions of weight, mass, pressure, and suit kinematics to the overall metabolic cost of the MKIII suit in its 121-kg (265-lb.) POGO configuration, including the mass of the Portable Life Support System (PLSS) mock-up and gimbal, which is 29.6 kPa (4.3 psi) during inclined ambulation and exploration tasks in 1/6-g.
2. Quantify the effects of the following factors on suited and/or unsuited metabolic rate, biomechanics, and subjective ratings during exploration tasks and inclined ambulation:
   a. Suited – varied suit pressure at constant offload, mass, and CG
   b. Suited – varied suit offload (weight) at constant pressure, mass, and CG
   c. Unsuited – varied offload (weight) at constant mass and CG
   d. Unsuited – varied mass at constant offload and CG
3. Compare the MKIII at POGO configuration to the MKIII at POGO configuration with the waist bearing locked.
4. Develop predictive models of metabolic rate, subjective ratings, and suit kinematics based on measurable suit, task, and subject parameters.

1.2 Secondary Test Objectives

The secondary objectives of IST-2 did not determine the test protocol. Rather, they are other expected ways for which these data could be applied. Secondary objectives include the following:

1. Define standard measures and protocols for objectively evaluating future exploration suit candidates and requirements verification of the flight suit.
2. Understand specific human performance limitations of the suit compared to matched shirt-sleeve controls.
3. Collect metabolic and ground-reaction force data to develop an EVA simulator for use on future prebreathe protocol verification tests.
4. Provide data to estimate consumables usage for input to suit and PLSS design.
5. Assess the cardiovascular and resistance exercise associated with partial-gravity EVA for planning appropriate exploration exercise countermeasures.

2 Methods

2.1 Subjects

Subjects were recruited from two different pools of personnel – those who typically perform EVA suited studies for the Johnson Space Center (JSC) Engineering Directorate and a group of astronauts, many of whom have previous in-space EVA experience, selected to support exploration EVA studies. Suit fit-checks in the MKIII suit were performed on a range of subjects, and only those who had good suit fit were considered for inclusion in this study due to potential medical and safety issues. From this list, six male astronaut subjects (Table 1) participated in the data-collection phases of the study. All subjects had also participated in IST-1 and had significant experience with both the MKIII and the POGO. At this time, no available female astronauts properly fit in the MKIII suit.

Table 1. Subject Characteristics

n=6	Height (cm)	Body Mass (kg)	Age (yr)	VO_2pk* (mL/min/kg)	Leg Length (cm)
Average	179.1	80.7	44.8	50.8	104.0
St. Dev.	4.8	8.5	6.9	6.7	3.8
Max	185.9	86.4	52.0	60.7	109.2
Min	174.6	68.2	37.0	42.6	100.2

*VO_2pk = peak rate of oxygen (O_2) consumption.

All subjects successfully passed the modified Air Force Class III physical or equivalent examination. Each subject was provided verbal and written explanations of both the testing protocols and the potential risks and hazards involved in the testing and signed NASA JSC human research documentation indicating his understanding and consent. All testing protocols were reviewed and approved by NASA JSC Committee for the Protection of Human Subjects, and appropriate test readiness reviews were conducted before testing.

2.2 Test Hardware

Test hardware used for IST-2 included the POGO, MKIII gimbal support structure, shirtsleeve harness, X-Vest, and VacuMed (Ventura, Calif.) treadmill. These pieces of hardware, which were previously described in the test hardware section of the EWT (1) and IST-1 report (2), will not be discussed in this report.

2.2.1 Mark III Advanced Spacesuit Technology Demonstrator (MKIII)

For suited testing, the MKIII suit (Figure 1) was used as it represents a suit concept that provides the dynamic ranges of motion considered necessary for a wide variety of planetary EVA tasks within today's technology level given other constraints that must be considered in pressure garment design. The MKIII also had an existing method to integrate with the POGO and allowed for varied pressure testing. Thus, the MKIII provides a valid testbed from which attainable requirements for future suit development can be derived. The MKIII is a hybrid spacesuit configuration composed of hard elements (e.g., a hard upper torso and brief section) and soft components (e.g., fabric elbows and knees designed to handle operating pressures of up to 55.0 kPa [8.0 psi]). Another feature of the suit is the use of convolutes and bearings allowing multi-axial mobility joint systems The shoulder is a rolling convolute with scye and upper arm bearing. At the waist, both a bearing and a rolling convolute are used to allow for flexion, extension, and rotation. Multiple bearings and convolutes at the hip and thigh allow abduction, adduction, flexion, and extension. 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 PLSS. Suit subjects are stabilized in the suit by shoulder straps. The boots are modified commercial work boots with flexible soles for walking and a convoluted ankle joint for mobility. The MKIII has modular leg, arm, and boot soft goods components that allow individualized sizing adjustments with metal sizing rings. Foam padding is also used to improve fit and avoid pressure or rubbing spots.

Different hard components materials can be used, depending on test objectives. The MKIII, as tested in IST-2, used the following components: PLSS mock-up, aluminum hatch, aluminum hard upper torso, composite brief, and medium-profile waist bearing. The gloves used during the ambulation trials (non-hand-intensive) were a few generic-sized pairs of series 4000 because they were readily available from the Advanced Suit Laboratory and rated for use at higher pressures. During exploration tasks, each crew member wore specifically sized Phase VI gloves because of the need for increased tactility and custom fit to complete the tasks. As these gloves were rated for use up to 29.6 kPa (4.3 psi), they therefore prevented the exploration tasks from being tested at the higher pressures.

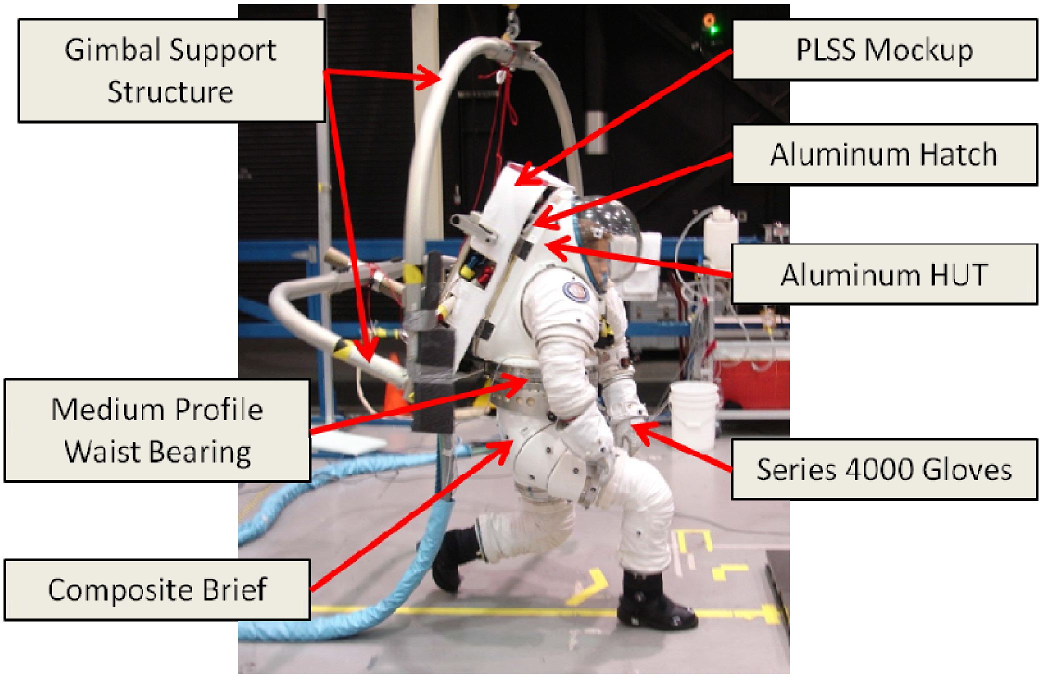


Figure 1. Mark III Advanced Spacesuit Technology Demonstrator.

During testing sessions, certified breathing air was provided by a compressed breathing air tube trailer at an average standard flow rate of 4.2 L/s (9.0 cubic feet per minute [cfm]) through a manifold and transfer hoses and reduced to the appropriate pressure of interest between 6.9 and 44.8 kPa (1.0 and 6.5 psi). Internal suit cooling was provided via a closed water loop that circulates through an ice/water chiller to cool the test subject's Class III modified shuttle liquid cooling garment (LCG). The system, which is powered by an external pump (~109 kg/hr), can deliver a minimum suit inlet temperature of 4ºC or a maximum of 28ºC when the chiller bypass valve is activated. Communication with the suited test subject was available via a system comprised of hardwire head sets.

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

2.2.2 Busy board

To simulate construction-type tasks and tool use, we used a custom-built “busy board” with several different quick-disconnect (QD) hoses and a removable handrail (Figure 2). Only the components on the top half of the board were completed. A portable power drill was provided for handrail removal and reinstallation.

Figure 2. Busy board included handrail removal/installation and several quick-disconnect stations.

2.3 Testing Protocols

2.3.1 Inclined ambulation

Each subject walked on an inclined treadmill for 3 minutes at his lowest walking speed as determined previously from IST-1 during the preferred transition speed (PTS) establishment (2). This lowest walking speed was the PTS minus 0.7 $m \cdot s^{-1}$. Grades tested were primarily 10%, 20%, and 30%. Initially, the grades tested were to be 10%, 15%, and 20% at the three heaviest weight (lowest offload) conditions, but it quickly became apparent that 10%, 20%, and 30% grade could be used throughout the test. Two subjects performed the test at 10%, 15%, and 20%, while the remaining four subjects completed every condition at 10%, 20%, and 30% grade.

This testing protocol was performed during all suited and shirtsleeve configurations.

2.3.2 Exploration tasks

Each subject performed a battery of tasks representing typical activities expected during lunar EVA performance. Tasks included, in the order of performance, are described as follows:

1. Small rock pickup – Subjects stepped onto two force plates and bent down to pick up a 1-kg weight and then stood up completely. Subjects then returned the weight to the starting point, stood back up. and stepped off the force plates. Due to interactions and limited mobility with the POGO gimbal interface to the MKIII, the weight was elevated on a surface 50 cm from the top of the force plates. This was repeated three times for each condition.
2. Large rock pickup – Subjects stepped onto two force plates and bent down to pick up a 5-kg weight and then stood up completely. Subjects then returned the weight to the starting point, stood back up, and stepped off the force plates. Again, due to interactions and limited mobility with the POGO gimbal interface to the MKIII, the weight was elevated on a surface 50 cm from the top of the force plates. This was repeated three times for each condition.
3. Shoveling (biomechanics emphasis) – Subjects were provided a shovel before beginning this task. Subjects then stepped onto two force plates and proceeded to move a single shovelful of lava rocks from the rock box to the collection bucket. Once the single shovelful was transferred, the subjects stepped off the force plate. Due to interactions and limited mobility with the POGO gimbal interface to the MKIII, the rock box and collection bucket were placed on the treadmill, which was 40 cm from the top of the force plates. This was repeated three times for each condition.
4. Shoveling (metabolic emphasis) – Subjects were provided a shovel before beginning this task. Subjects then proceeded to shovel lava rocks from the rock box to the collection bucket until either the rock box was empty or 3 minutes had elapsed. Due to interactions and limited mobility with the POGO gimbal interface to the MKIII, the rock box and the collection bucket were placed on the treadmill, which was 50 cm off the floor. The difference in heights for the rocks on the different shoveling tasks was due to the removal of the force plates for the shoveling with metabolic emphasis.
5. Kneel and recover – Subjects kneeled on one knee and returned to a standing position. Subjects were instructed to kneel on the same knee for each trial. This was repeated three times for each condition.
6. Rock transfer – Eight different weights were placed on a platform 40 cm off the ground (equivalent to the height of the treadmill surface) and 2.5 m from the treadmill. Starting from the treadmill, subjects proceeded to move all weights from the platform to the treadmill one at a time and then return the weights one at a time back to the platform.
7. Hammering – Subjects were provided a rubber mallet and were instructed to hammer six different spots on the rock. The rock was placed on a platform 40 cm above the ground.
8. Ladder placement – Subjects were handed a 10-ft ladder at waist level parallel to the ground. Subjects then rotated the ladder into the upright position and placed the top rung over a preset marker on a stand. Once the ladder was upright and secure, subjects removed the ladder and returned it to waist level.
9. Busy board – Subjects stood on two force plates in front of a vertically mounted busy board. This board (
10.) contained several different types of QD tasks and involved the removal and reinstallation of a handrail using a handheld power drill. Subjects completed all tasks on the board twice.

This testing protocol was performed during all suited and shirtsleeve configurations except for the two suited conditions at 34.5 kPa (5.0 psi) and 44.8 kPa (6.5 psi). These higher-pressure conditions were not tested because subjects used the Phase VI gloves with the MKIII suit, which were believed to provide better manual dexterity but were only rated to 29.6 kPa (4.3 psi).

2.3.3 Weight carry

Each subject walked on a level treadmill for 3 minutes at his lowest walking speed while carrying a weighted load in front of him. Each subject completed three different loads of 4.5, 9.1, and 13.6 kg (10, 20, and 30 lb) for 3 minutes apiece. The 4.5- and 13.6-kg loads were round rubber medicine balls, and the 9.1-kg load was a rectangular sandbag.

This testing protocol was performed at the POGO suited configuration of 29.6 kPa (4.3 psi), 121-kg suit mass, and lunar gravity. It was also completed during the shirtsleeve configuration at lunar gravity.

2.4 Testing Sessions

Subjects participated in four separate test sessions: [1] unsuited inclined ambulation; [2] unsuited exploration tasks; [3] suited inclined ambulation, and [4] suited exploration tasks. Session order, which was not controlled, was a by-product of the facility schedule, facility setup, and subject schedule. Task order was controlled and done in the same order for each trial to make valid comparisons across configurations.

For inclined ambulation test sessions, subjects started at the lowest incline and proceeded to the highest incline (10%, 20%, and 30%). For the two configurations that included the weight carry, the 13.6-kg load carry was performed first, followed by 10%, 20%, and 30% incline conditions; the 9.1-kg load carry and 4.5-kg load carry were performed last. For exploration task test sessions, the task order was done in the order in which the tasks were described previously.

Testing configuration order was balanced within each test session to minimize fatigue and familiarization issues. The only exception to this was that the 1-g unsuited trial was always done first on the unsuited testing days, and the suited trials with the waist locked were always performed last. For the suited exploration task test session, a full familiarization session was included at lunar gravity in the POGO configuration.

2.4.1 Weight/mass/offload/gravity terminology

To prevent confusion with the terminology used throughout the report, Figure 3 describes the way in which terminology is used throughout this document. System mass is defined as the sum of the gimbal support structure, PLSS mockup, MKIII, and subject masses with kilograms as the defining unit. Total gravity adjusted weight (TGAW) is the resultant weight on the ground after the POGO offloading force has been applied to the system mass. TGAW is described with units of force such as Newtons or pounds. TGAW is calculated by multiplying the system mass by the gravity level. Offload is the upward vertical force applied to the system mass, and gravity is the downward vertical force applied to the system mass. On Earth, gravity is a constant at 9.81 $m \cdot s^{-2}$, so the only way to alter the effect of gravity is to apply offload to the system mass to slow the acceleration the system mass returns to the ground. This also alters the TGAW, which can be plainly referred to as "weight."

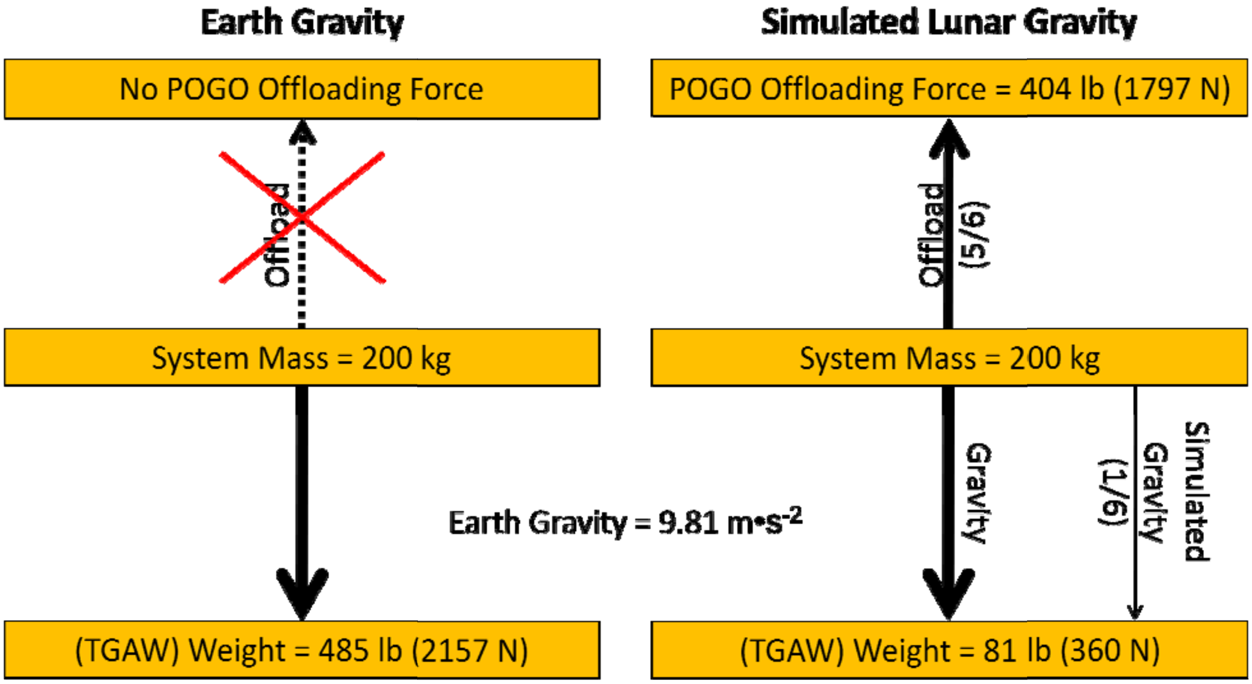


Figure 3. Description of forces acting on the system mass and the resultant forces.

With Earth gravity (1-g), the POGO does not apply any offload force and only gravity acts on the system mass, which means all 200 kg of the system mass are falling back towards the ground and the TGAW is 2157 N (485 lb). Taking that same mass but applying an offload force to simulate lunar gravity (0.17-g) means that two independent forces are acting on the mass. It is important to note that the simulated gravity is the resultant force of a large offload forces countering an even larger gravitational force. The responsiveness and consistency of the offload force determines the quality of the simulated-gravity environment. To interpret the results and discussion, here are some key points:

- TGAW = weight
    - In cases in which it is critical to discuss weight and mass together, TGAW may be used to prevent confusion, but weight is an equally appropriate term
- Changing offload = changing gravity = changing weight
- Increasing offload = decreasing gravity = decreasing weight

2.4.2 Varied mass (unsuited)

To evaluate the effect of varied mass on human performance, subjects completed inclined ambulation and exploration tasks four times with each trial set at a different mass but with constant weight. Masses of 0, 11.4, 22.7, and 34 kg (0, 25, 50, and 75 lb) were evenly distributed across the torso using a commercial weighted training vest (X-Vest), while each subject's overall weight was kept constant by increasing the POGO offloading force to offset the added mass in each condition (Figure 4).

Figure 4. Instrumented unsuited subject wearing an X-Vest and performing shoveling task (metabolic emphasis).

2.4.3 Varied pressure (suited)

To evaluate the effect of varied suit pressure on human performance, each subject donned the MKIII suit with an initial pressure of 29.6 kPa (4.3 psi) and an in-suit O_2 concentration of 21% provided via certified breathing air, as is customary during EVA test operations with the MKIII (Figure 5). Each subject completed the inclined ambulation trials at each of five 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) and the exploration tasks at each of three different suit pressures: 6.9, 20.7, and 29.6 kPa (1.0, 3.0, and 4.3 psi). Suit mass (121 kg) was held constant during these trials.

Figure 5. Suited subject performs inclined treadmill locomotion.

2.4.4 Varied weight test (unsuited and suited)

Inclined ambulation and exploration tasks used in the varied pressure and varied mass conditions were repeated in both suited and unsuited conditions at a range of simulated suit weights while holding constant mass (121 kg) and suit pressure (29.6 kPa [4.3 psi]). For suited testing, POGO offloading force was adjusted to different gravity levels of 0.12-g, 0.17-g, 0.22-g, 0.27-g, and 0.32-g. For these trials, the mean TGAW (calculated using mean subject mass of 80.7 kg) was 53, 75, 97, 119, and 141 lb. TGAW did vary slightly from these mean levels, depending on how an individual subject's body mass differed from the mean.

By using a constant mass suit, neither the inertial properties nor the mass distribution was changed. Because suits of varied mass were unavailable and current POGO hardware does not provide the lift capability of adding significant mass, the closest comparison we could make to understanding how a change in suit mass affects human performance was to simulate a change in mass by varying the offload level to see how a constant mass suit affected human performance at a different TGAW. Assuming our mean subject mass of 80.7 kg and true lunar gravity, it would require a suit mass of approximately 63, 121, 186, 247, or 308 kg to achieve the same TGAWs as were tested in IST-2. A combination of the unsuited varied mass testing in this study as well as future suited and/or unsuited varied mass and weight testing will be required to understand how mass properties of the suit affect performance.

Unsuited testing was performed at 1-g, 0.17-g, and weight-matched conditions in which the TGAW of an unsuited subject was matched to the same TGAW as in the suited condition for 0.12-g, 0.17-g, and 0.22-g.

2.5 POGO Off-loading

Before beginning any trial, the target weight for the subject was verified with the integrated force plates in the treadmill. For all tests, the target weight was adjusted to ± 1.4 kg (3 lb). This allowed for much quicker adjustments and minimized the overall time a subject was actually suspended by the POGO as compared to previous tests with a ± 0.5-kg (1-lb.) zone for target weight.

2.6 Metabolic Data Collection and Analysis

During unsuited tests, the metabolic rate was determined from continuous measurement of the rate of oxygen consumption (VO_2), rate of carbon dioxide (CO_2) production (VCO_2), and expiratory volume (V_E) using an oronasal mask and COSMED K4b2 (COSMED USA Inc., Chicago, Ill.). Heart rate was monitored from a chest strap monitor (Polar S-810i, Lake Success, N.Y.).

During exercise in the MKIII suit, metabolic rate was based on measured suit ventilation rate, expired CO_2 concentration in the exhaust umbilical (CD-3A Infrared Carbon Dioxide Analyzer, AEI Technologies, Pittsburgh, Penn.) and the regression between VCO_2 and VO_2 as measured during the subject's most recent VO_2pk test. This technique and hardware were identical to those currently used during suited Neutral Buoyancy Laboratory tests and in IST-1 and the EWT.

The metabolic rates for inclined ambulation represent the highest 1-minute average VO_2 during each of the 3-minute walking stages. Metabolic rate was defined as milliliters of O_2 consumed per kilogram of the subject's body mass, per minute ($mL•kg^{-1}•min^{-1}$). Transport cost was defined as milliliters of O_2 consumed per kilogram of the subject's body mass per km traveled ($mL•kg^{-1}•km^{-1}$).

For exploration tasks, metabolic cost was used because the workload cannot be controlled; therefore, there cannot be a clear steady-state metabolic rate to compare between subjects and conditions. We define metabolic cost as the total O_2 consumed during completion of the task.

For all metabolic data, the best second-order polynomial fit was used for displaying trend lines.

2.6.1 Calculating contributions of weight, mass, pressure, and suit kinematics to the overall metabolic cost of the MKIII suit

Individual contributions to the total metabolic cost of the MKIII suit were based on a second-order polynomial regression model combining suited and unsuited data from this test. The unsuited baseline metabolic rate and the suited metabolic rate were calculated by using the regression equation relating speed to metabolic rate. The total metabolic cost of the suit was determined by subtracting unsuited trials from suited trials. Two different models exist due to different methods of calculating the cost of weight. In the unsuited weight cost model, the metabolic cost of weight was determined by calculating the difference between unsuited and unsuited weight-matched trials. In the suited weight cost model, the cost of weight was determined by extrapolating regression equations back to a 0.0-N suit weight and calculating the difference between 0.0 and 1,187 N (121 kg). Models pertaining to treadmill ambulation used the unsuited weight cost model whereas models pertaining to exploration tasks used the suited weight cost model. The cost of suit pressure was determined by extrapolating regression equations back to 0.0 kPa and determining the difference between 0.0 and 29.6 kPa (4.3 psi). The last component, titled "other suit/system factors," is a large mix of factors including suit factors such as mass, kinematic constraints, and stability as well as system-level components such as harnessing differences between unsuited and suited conditions and possibly differences due to different metabolic collection systems. There may also be other factors of which we are unaware. This "other suit/system factors" category was calculated by subtracting the metabolic cost of pressure and weight from the total metabolic cost of the suit.

2.6.2 Significant metabolic differences

In comparing the metabolic costs of different suited conditions, it is important to define some level of metabolic rate that is deemed significant. 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. Rationale for this choice was described in the IST-1 final report (2). In absolute terms, 3.5 $mL•kg^{-1}•min^{-1}$ would be equivalent to 0.30 $L•min^{-1}$ assuming an average subject body mass of 82 kg (180 lb), which is typical of the current male astronaut population.

2.6.3 Earth Shirtsleeve Performance Index

It would be desirable to develop an EVA suit that required no more effort to perform a task than a person performing that same task on Earth without a suit would exert. The Earth Shirtsleeve Performance Index (ESSPI) is defined as the metabolic cost of a suited task at partial gravity divided by the metabolic cost of performing the same task under Earth shirt-sleeved conditions. A full 1-g data set was collected for this study, allowing for exact calculation of the ESSPI.

Knowing the 1-g metabolic cost of an activity creates a reference point, and the ESSPI provides an index to identify the suited tasks that may require the most improvement.

2.7 Biomechanical Data Collection and Analysis

During ambulation, biomechanical data were collected using a 12-camera motion analysis system (Vicon MX hardware, Vicon Nexus software [Vicon, Oxford Metrics, Oxford, U.K.]) and four strain-gauge force plates (AMTI, Watertown, Mass.). The force data were then processed and analyzed using customized MATLAB (The MathWorks™, Natick, Mass.) computer programs. Data were sampled during 30 full, consistent strides throughout each stage of testing.

Ground reaction forces were collected using four 46.2×50.8-cm force plates, mounted to each corner inside the treadmill underneath the treadmill belt support plate (Figure 6). The signal was collected at 1,000 Hz over 30 gait cycles at varying speeds, pressures, and simulated suit weights and was 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 30 gait cycles. For all trials, in each of the conditions, the peak vertical force was calculated over the 30 gait cycles and averaged over the trial using customized computer code (i.e., MATLAB).

Three-dimensional trajectories of retroreflective markers placed at approximate anatomical landmarks on the MKIII suit were collected at 100 Hz (Vicon, Oxford, U.K.) 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 weights.

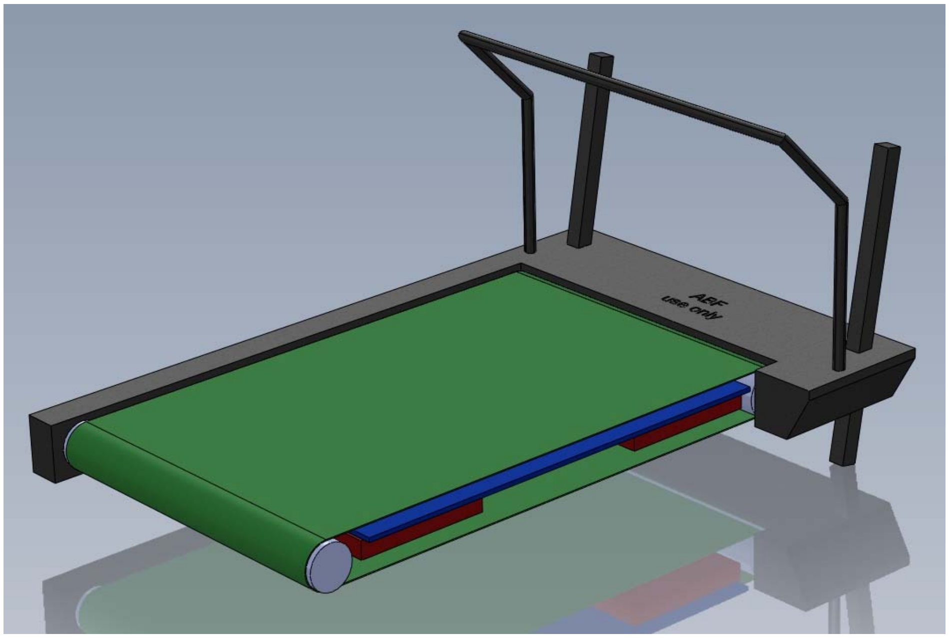


Figure 6. Four force plates (red boxes) were mounted to each corner support structure of the treadmill underneath the treadmill belt.

The motion analysis system was used to record 3-dimensional trajectories of reflective markers, 51 in total, which was a modified Plug-in Gait (VICON, Oxford Metrics, Oxford, U.K.) marker set (Figure 7 and Figure 8), attached to each body segment of the subjects. The 3-dimensional trajectory data were reduced and analyzed using customized MATLAB computer programs to provide selected kinematic and temporal spatial characteristics of suited human locomotion.

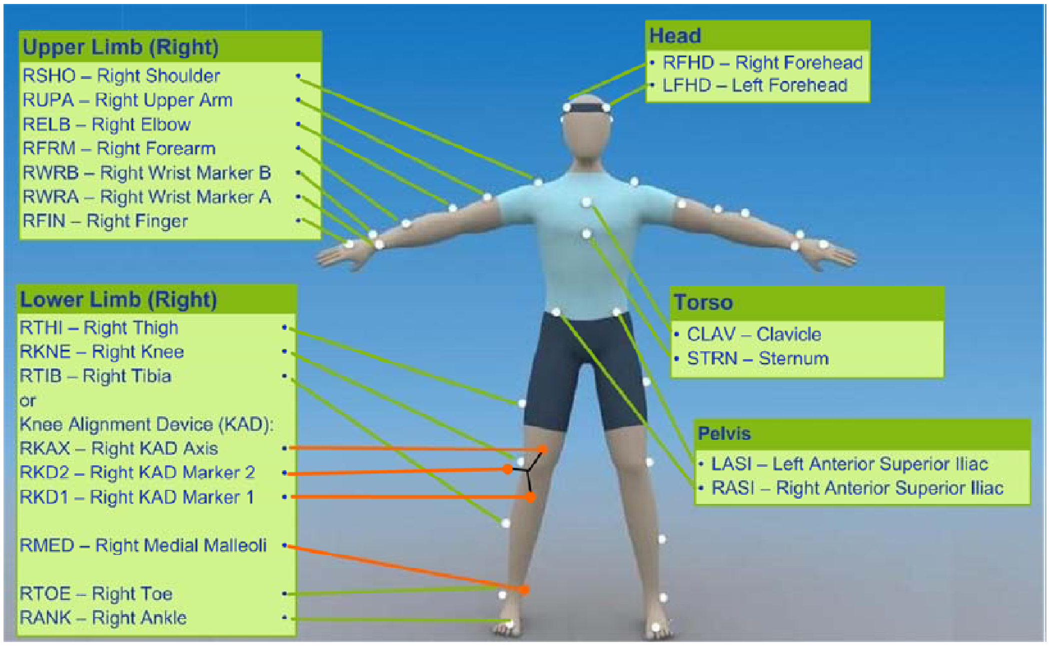


Figure 7. Anterior view of Plug-in Gait marker set.

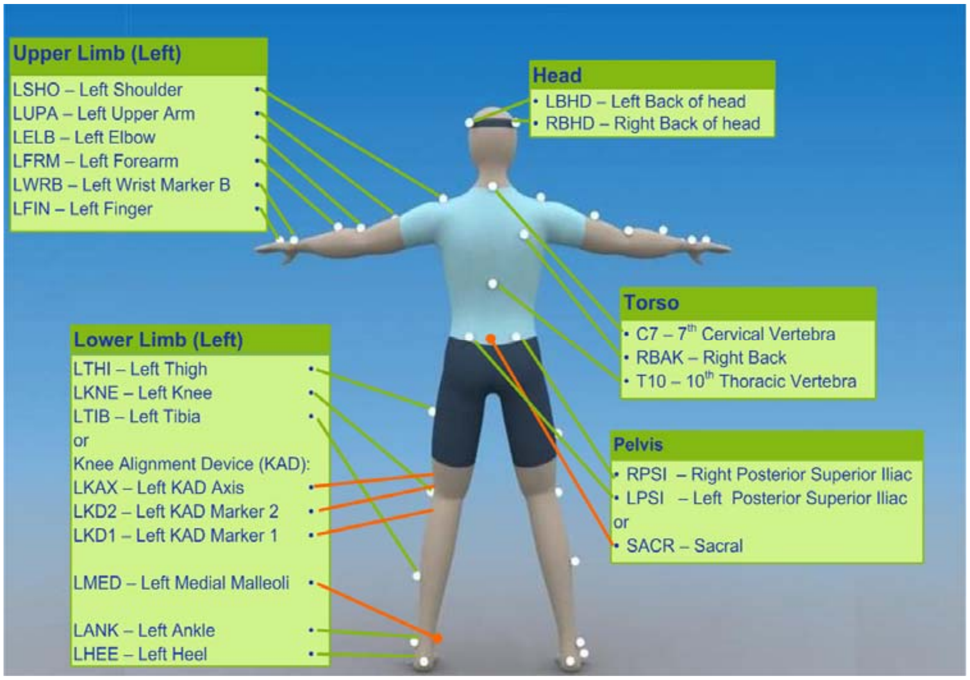


Figure 8. Posterior view of Plug-in Gait marker set.

In movements such as locomotion, the motions of the segments are cyclic in nature. More specifically, walking is the periodic movement of each foot from one position of support to the next. For walking, one stride (or cycle) is defined as the distance traveled by a person from one heel strike to the next heel strike on the same side. For analysis, each trial was subdivided into gait cycles. Information from each gait cycle was extracted and averaged, assuming constant gait was maintained.

Two methods were used to analyze exploration data. As each subject adopted a different strategy to complete the various exploration tasks with which he was presented, analysis of movement during trial performance began with examination of qualitative measures (ie, observation). This method was selected to provide meaningful interpretation of exploration task data, given the difficulty inherent in generalizing kinematic analyses of variable adopted movement strategies to a population. For instance, production of a movement in the suit can be the result of a simple motion about a single joint when executed by a particular subject. However, another subject may necessitate the coordination of several suit joints to accomplish the same task, which prevents the direct comparison between subjects when performing various tasks. Additionally, break points of the suit joints do not necessarily coincide (line up) with anatomical joint centers of rotation. This does not allow for a truly accurate representation of human motion inside the suit, and likely induces constraints that determine movement strategies adopted by the subjects when performing the various tasks. The analysis technique used was unique to the three exploration tasks (rock pickup, kneel and recover, and shoveling) and is discussed in detail in the results section for each task.

The second method used to analyze the exploration tasks was the examination of center of pressure (COP). Typically, COP is used by researchers, clinicians, and engineers to examine postural stability or other neurovestibular measures. From the cornucopia of research available on COP, it is universally understood that if the COP falls outside a person's base of support (BOS), that person will have to take measures to realign the COP within the BOS. For example, if when standing still a person's COP falls outside his BOS, that person will either pick up his feet to readjust his BOS or will lose his balance. It is this concept that was employed to examine the task of large and small rock pickup. It was hypothesized by the ABF that during a rock pickup task, the varying suit weights may perturb the subject's CG, thus altering the COP and resulting in either a change in the subject's BOS or the subject falling over.

The COP analysis was a multistep process performed in customized code (MATLAB, MathWorks™, Natick, Mass.) written by the ABF. The first step in the COP analysis was to determine the BOS for each frame of data collected. Typically, the BOS was a box that is formed by the right and left foot on the ground. More specifically, while the right and left foot is on the ground, the BOS would be a box surrounding the outermost edges of the feet and connecting the two. This BOS was determined by using the *x*, *y*, and *z* coordinates for the feet from the kinematic data. Next, for each frame of data collected, the COP was calculated for each foot using the 3-dimensional forces and moments from the force plates. The COPs for the left and right foot were combined to determine the COP total (Figure 9). For each frame, the COP total was compared to the BOS to determine whether the COP fell outside the BOS (Figure 10). Since for each trial and each subject the time of the trial differed, the percentage of frames that the COP total was outside the BOS was determined. The BOS was formed for frame ***k***, and the anterior-posterior (a-p) and medio-lateral (m-l) coordinates for the COP for frame ***k*** were compared to the BOS at the same frame. If the COP in either direction fell outside this boundary, a value of one was assigned to that frame and stored in an array. The array was then summed and divided by the total number of frames for that trial to determine a percentage. Hence, a value of 50% means that for half of that trial the subject's COP was outside his BOS. Conversely, a value of 0% means the subject performed the entire trial without the COP falling outside of the BOS. This measure was used in subsequent analyses to determine whether varying suit weights affected the stability of the subject.

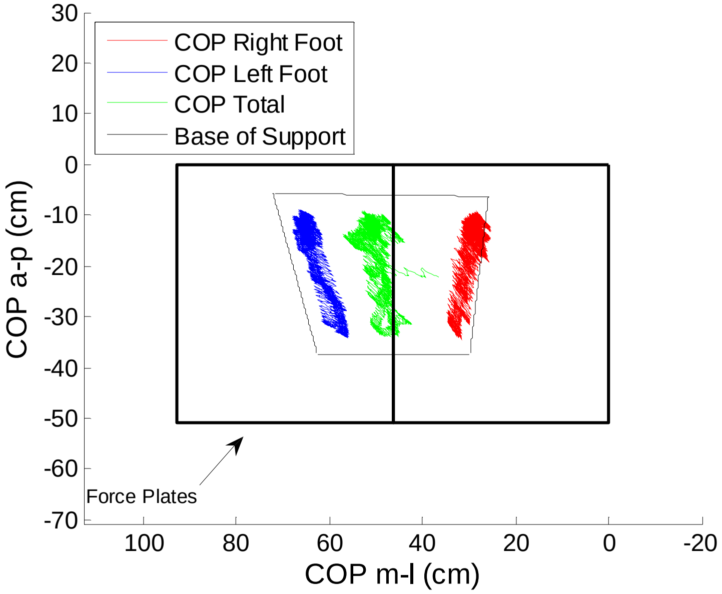


Figure 9. Medio-lateral and anterior-posterior center of pressure for the left foot and right foot, and the total for a small rock pickup trial.

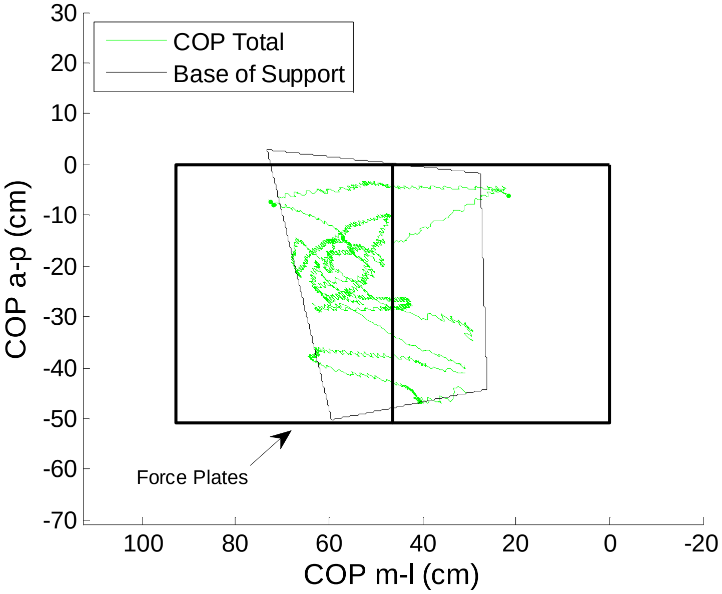


Figure 10. Visualization of how the medio-lateral and anterior-posterior center-of-pressure total was compared to the base of support for a small rock pickup trial.

2.8 Subjective Data Collection and Analysis

The following subjective ratings were recorded at various times throughout the test:

- The gravity compensation and performance scale (GCPS) was used to determine the level of compensation a person feels is necessary to maintain performance as compared to his performance unsuited in 1-g (1). Significant differences in GCPS are discussed in the IST-1 final report (2).
- Ratings of perceived exertion (RPE) (5) were used to gauge how much effort subjects felt they must exert to complete each condition. RPE was collected during the last minute of the inclined ambulation and load carry tasks. It was collected on completion of the metabolic shoveling, rock transfer, and busy board exploration tasks. Significant differences in RPE are discussed in the IST-1 final report (2).
- The Corlett & Bishop body part discomfort scale was used to characterize discomfort at different body locations (6). Discomfort ratings were collected during the last minutes of inclined ambulation and load carry task and at the completion of the series of exploration tasks.
- Thermal comfort was assessed for two reasons: [1] to determine the subjective thermal comfort of the subject, and [2] to determine whether any changes were necessary to improve the thermal comfort of the subject during testing. Thermal comfort, which was assessed using the Bedford scale (7), was collected during the last minute of inclined ambulation and load carry tasks and at the completion of the series of exploration tasks.
- Thermal preference was assessed at the same time as thermal comfort. It was collected to determine what changes, if any, were necessary to improve the subject's thermal comfort.
- The NASA task load index (TLX) was developed by Hart & Staveland in 1988 (8). It uses six factors to assess workload for a task: mental demand, physical demand, temporal demand, effort, performance, and frustration. Subjects are asked to complete a pair-wise comparison of the six factors, selecting which factor was the greatest source of workload. The pair-wise comparison of the six factors contributing to workload determines the weighting factor used to calculate the total workload index. Each factor is then rated on a 0 to 100 scale as to how much it contributed to the workload. Each factor is rated such that 0 is the lowest and 100 is the highest, with the exception of performance in which 0 is excellent. The definitions of each factor, as presented to the subjects, were as follows:
  Mental demand – how much mental and perceptual activity was required?
  Physical demand – how much physical activity was required?
  Temporal demand – how much time pressure did the subject feel?
  Effort – how hard did the subject have to work (mental and physical)?
  Frustration – how insecure, discouraged, irritated, and annoyed did the subject feel?
  Performance – how well did the subject think [he/she] did; lower score is better, as in golf.

For IST-2, at the end of the first condition the subjects were asked to complete the pair-wise comparisons and then rate each factor. For subsequent test conditions, the subjects were asked whether their pair-wise comparisons changed and were also asked to rate each factor.

The following is the equation used to calculate the workload score:

$$\text{TLX} = [\text{sum (weights} \bullet \text{rating)}]/15$$

Additional information on each of these scales is included in Appendix B. RPE will also be used in conjunction with GCPS to develop predictive models for metabolic rate to ensure that these subjective factors can be used in other lunar analog environments, such as underwater analogs and parabolic flight, in which direct measures of metabolic rate are currently not possible. Discomfort and thermal comfort were both primarily used for test termination criteria as well as to provide feedback to the test team about test hardware, conditions, and length of trials. Discomfort and thermal data will not be discussed in this report.

2.9 Imaging

Photographic data were collected after the completion of each testing run if trauma or irritations due to human-suit interactions were present. This information will be provided as feedback to the Space Medicine Division and EVA suit engineers. During all suited tests, a digital video camera captured video of the subject in the sagittal plane as well as auditory comments made by the test subject and test team members. During all unsuited tests, video was captured without the audio. The imaging data, which were kept in reserve, will not be discussed throughout this report other than a few pictures used to provide background information.

3 Results and Discussion

The results of IST-2 and their implications are discussed in this section. As these results are based on one suit architecture using the POGO with a limited number of male astronaut test subjects, they should be considered preliminary and in need of further validation. The section is separated into subsections corresponding to the test objectives. For each test objective, the results of analyses performed to date are described; the potential implications of these preliminary results are discussed with respect to EVA suit design requirements and concepts of operations; and the plan for completing these analyses and meeting the test objectives are described. Unless otherwise noted, all results and corresponding figures are based on analysis from all six subjects.

Results and discussion of preferred transition speed and the location of the system CG in relation to the gimbal axes of rotation can be found in the IST-1 report (2).

3.1 Test Objective 1: Contributions of Weight, Mass, Pressure, and Suit Kinematics to Metabolic Cost of MKIII Suit in POGO Configuration

Test Objective 1 was “[to] identify the individual contributions of weight, inertial mass, pressure, and suit kinematics to the overall metabolic cost of the MKIII suit in its POGO configuration (121 kg [265 lb] including mass of PLSS mockup and gimbal, 29.6 kPa [4.3 psi]) during inclined locomotion and exploration tasks in lunar gravity.”

The individual contributions of weight (specifically increased ground reaction force [GRF] with greater TGAW), pressure, and the other suit/system factors are shown as a percentage of overall metabolic cost for the MKIII suit in its POGO configuration in Figure 11 for inclined walking and in Figure 12 for exploration tasks. The methods for calculating the individual contributions are described in Section 2.6.1 of this document. For inclined walking, shirtsleeve baseline costs and the cost of additional weight account for most of the energy cost; the percentage contribution from both of these factors increased as grade increased. For exploration tasks, the shirtsleeve baseline costs were also present, but weight actually had the opposite effect and acted to decrease metabolic rate. Our assumption is that the added mass of the suit helps by increasing the GRF and; therefore, stability for the subject, but it also hinders performance because of the inertia effects. The component contributing most to the suited metabolic cost of exploration tasks was the "other suit/system factors," which includes (but is not limited to) suit kinematic constraints, stability, mass, system-level differences between unsuited and suited subjects, POGO/gimbal/suit system interactions, imperfect suit fit, subject fatigue, and the lack of familiarization with the tasks. Suit pressure was a minor component of inclined walking metabolic cost and an insignificant contributor to the exploration tasks evaluated. The limited contribution of pressure to metabolic cost in the MKIII suit may be because most joints are either constant volume or nearly constant volume. The higher pressures (34.5 and 44.8 kPa) also were not tested in the exploration tasks; thus, the regression model was less robust for the pressure component of the exploration task metabolic cost model. At this point, we have no clear explanation as to why the metabolic cost of pressure would decrease as incline increases or why the effect of pressure changes depending on the exploration task tested.

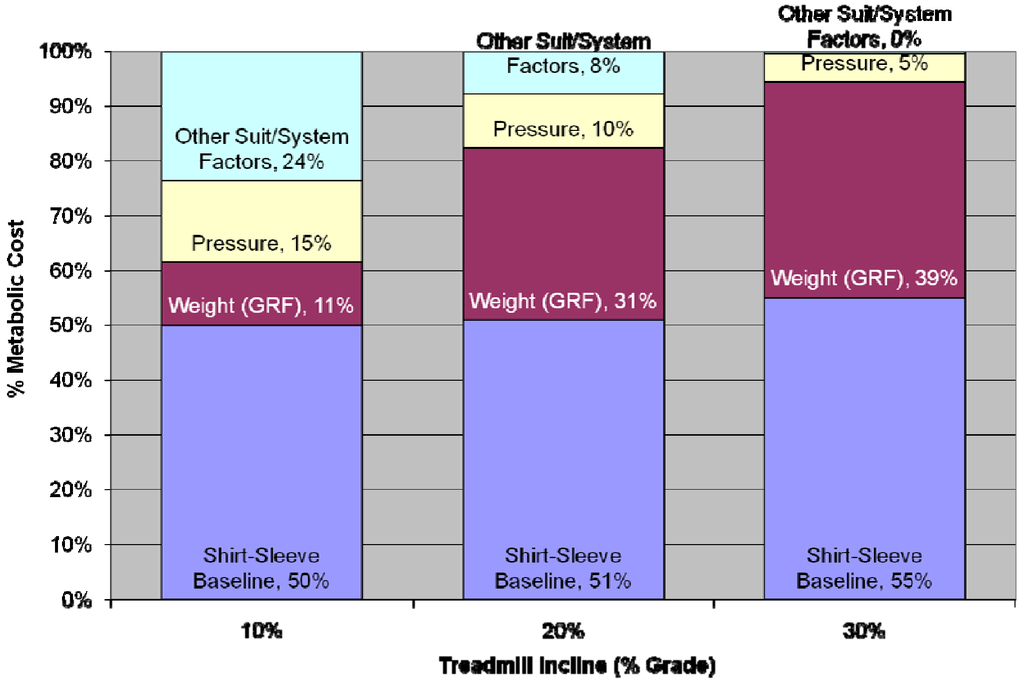


Figure 11. Percentage of metabolic cost for individual factors performing suited inclined ambulation.

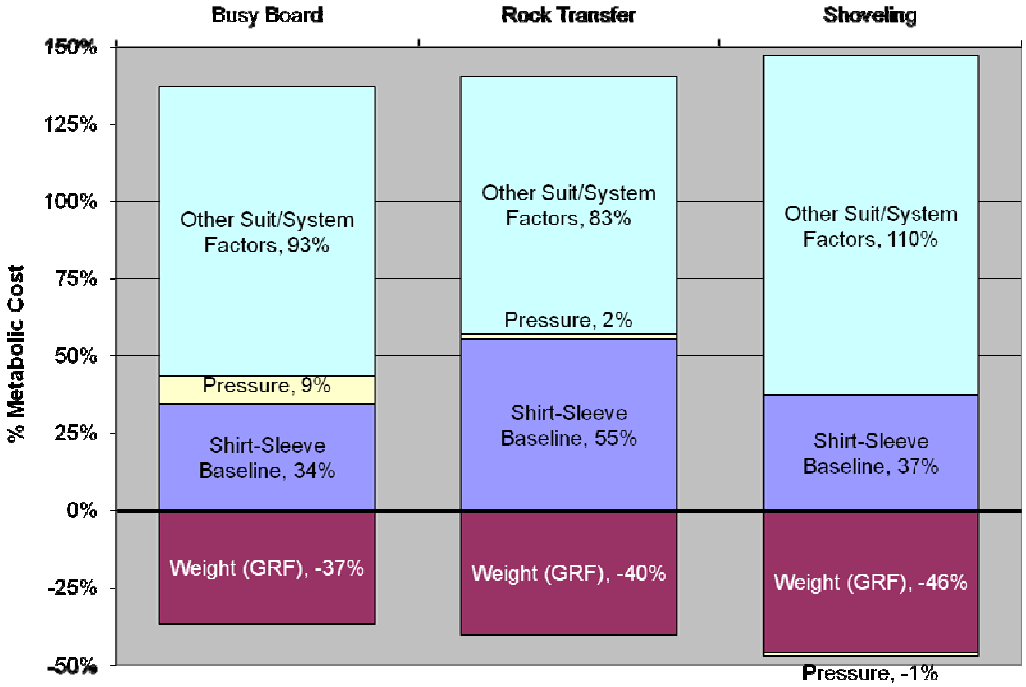


Figure 12. Percentage of metabolic cost for individual factors performing suited exploration tasks.

Figure 13 and Figure 14 show the metabolic data for inclined walking and exploration tasks; these data are broken down into the individual component metabolic rate contributions summing into the average metabolic rate for the task across the six subjects.

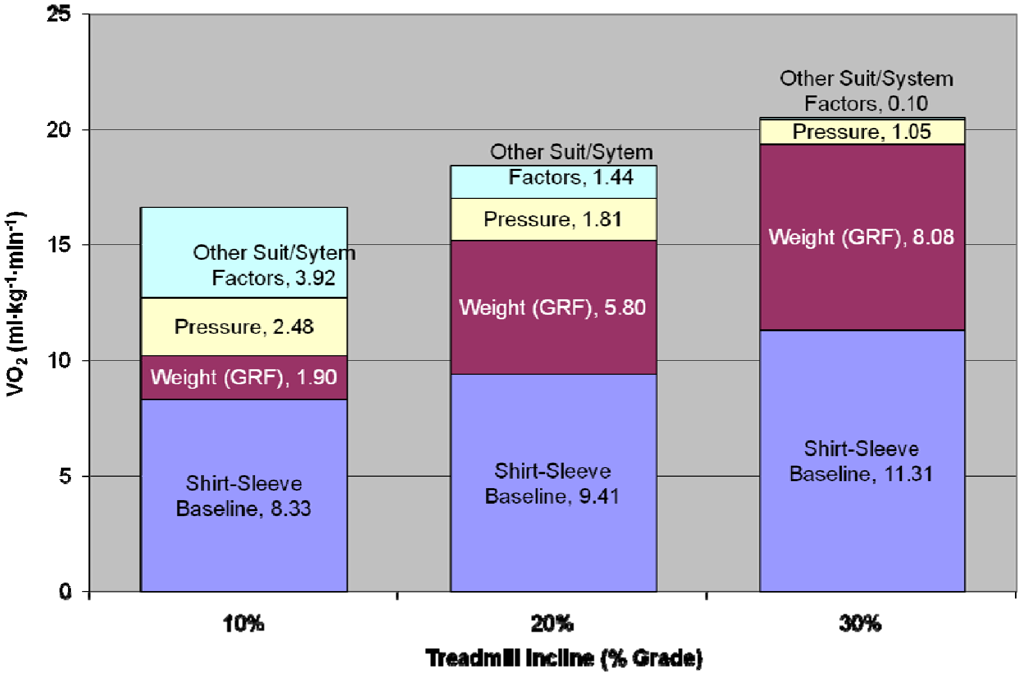


Figure 13. Metabolic cost of individual components for suited incline walking.

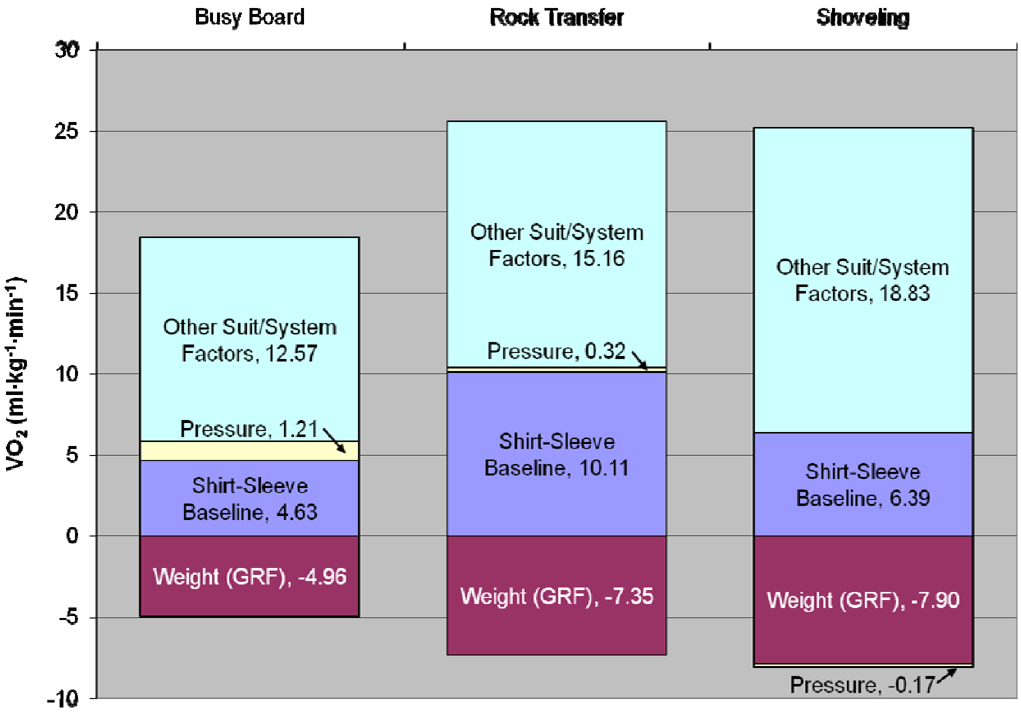


Figure 14. Metabolic cost of individual components for suited exploration tasks.

Comparing suited human performance to unsuited human performance is a complex problem involving many different factors. The estimate of the metabolic cost of the suit was based on the assumption that we could directly compare across suited and unsuited conditions. Although the systems in place for IST-2 allowed subjects to conduct identical tasks with identical magnitudes of offloading, the suspension methods between suited and unsuited conditions differs greatly as does the equipment used to collect the metabolic data. Each suspension method and data collection system will have some inherent error, so the metabolic cost of the suit results as shown (specifically compared to the shirtsleeve metabolic results) have extremely limited applicability and scientific inference for future suit design requirements at this time. To have confidence in this type of comparison, an improved gimbal support system that suspended suited and unsuited subjects in the same way would be required. Improvements to the suited metabolic data collection system to measure O_2 consumption directly rather than inferring VO_2 from CO_2 production would also improve the model.

Even with these noted limitations, individual task performance was clearly affected in different ways by different factors. Because of this, lunar operational concepts will drive out the key factors to optimize performance across a series of EVAs over a mission. As more data are collected, the EPSP Project intends to generate EVA performance models based on statistical algorithms to define metabolic rate, joint cycles, joint displacements, and consumable usage for a given operational scenario. The goal of these models is to help provide data to optimize EVA suits for complete EVA performance rather than focusing on a specific task or hardware performance.

If designed properly, future tests could potentially both drive out the individual contributions of these remaining components as well as examine various interrelationships and coupling factors present in untested combinations of these variables. By understanding these individual factors, the EPSP Project hopes to provide specific recommendations for suit design requirements, EVA mission planning, and overall consumables packaging.

3.2 Test Objective 2: Quantification of the Effects of Specific Factors on Suited and/or Unsuited Metabolic Rate, Biomechanics, and Subjective Ratings During Inclined Ambulation and Exploration Tasks

Test Objective 2 is intended to quantify the effects of the following specific factors on suited and/or unsuited metabolic rate, biomechanics, and subjective ratings during inclined ambulation and exploration tasks:

a. Suited – varied suit pressure at constant offload (weight), mass, and CG
b. Suited – varied suit offload (weight) at constant pressure, mass, and CG
c. Unsuited – varied offload (weight) at constant mass and CG
d. Unsuited – varied mass at constant offload and CG

3.2.1 Effect of varied suit pressure at constant offload (weight), mass, and CG

Metabolic Rate Findings

For accurate metabolic rate comparisons across the different conditions, nonstandard metrics were required. Unlike treadmill ambulation in which workload can be accurately controlled and a steady-state metabolic rate can be sampled, exploration tasks were completed in varying amounts of time and with different strategies. For example, one subject may choose to complete the task slowly at a lower metabolic rate and another may choose a more aggressive approach and finish in less time, but at a higher metabolic rate. Therefore, results for average metabolic rates or time to completion did not allow for direct comparison. To alleviate this problem, we selected total metabolic cost defined as total liters of O_2 consumed to complete the task (liters/task) for the busy board and rock transfer tasks. For the shoveling task, we selected milliliters of O_2 consumed per kilograms of rock shoveled (mL/kg rock) for metabolic rate comparison.

Variation in suit pressure at simulated lunar gravity did not significantly affect metabolic rate with either exploration tasks (Figure 15) or inclined walking (Figure 16). Task type and the walking grade primarily determined metabolic cost. Although there was little to no variation from changing suit pressure, it is important to note that exploration tasks did not test at the higher pressures of 34.5 or 44.8 kPa. Moreover, while the tasks often involved gripping and hand use, no task was extremely hand-intensive for long periods of time. Because hand fatigue and glove-related trauma are relatively common complaints from EVA, we recommend further evaluation of suit pressure and glove function using higher pressures and more hand-intensive tasks.

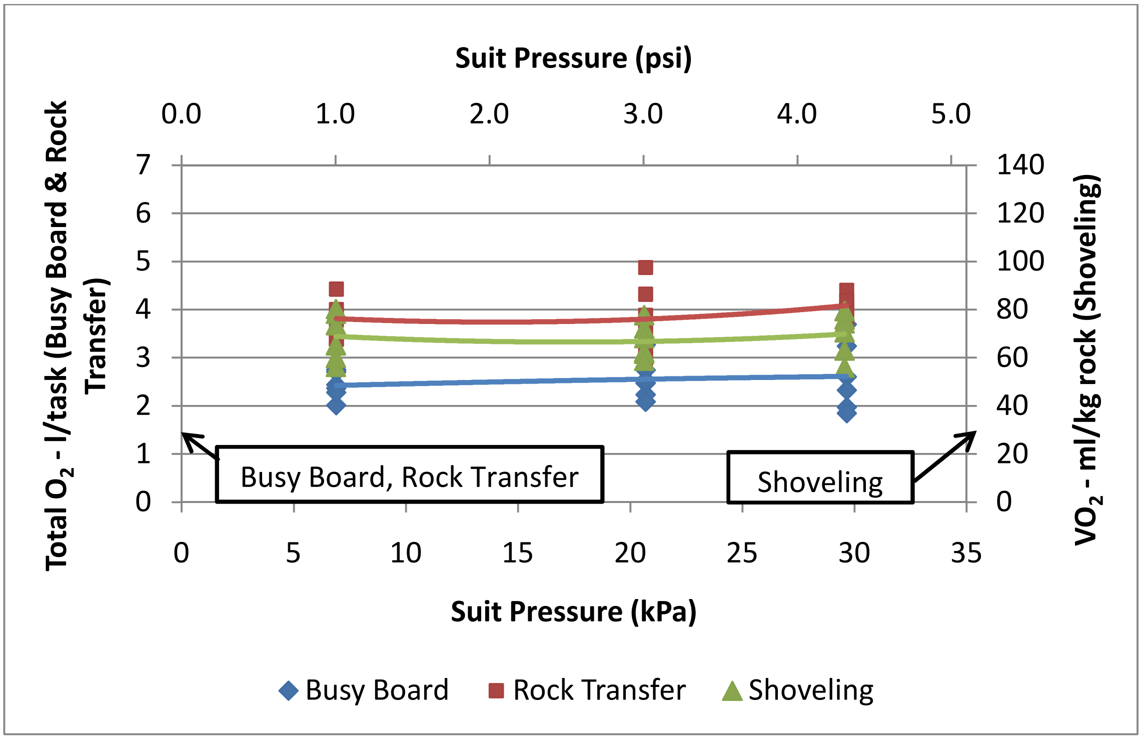


Figure 15. Metabolic rate vs. suit pressure for exploration tasks with 121-kg suit mass at lunar gravity.

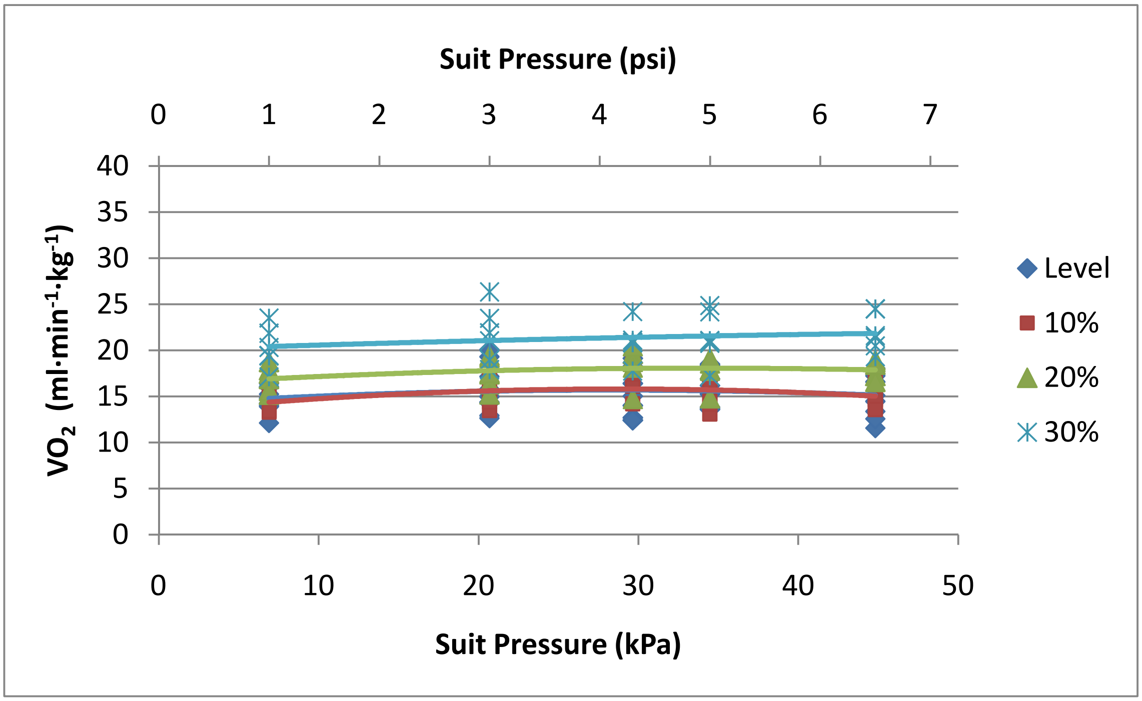


Figure 16. Metabolic rate vs. suit pressure for inclined walking with 121-kg suit mass at lunar gravity.

Subjective Findings

The trends in the subjective findings were similar to those of the metabolic rate. Very little variation in either RPE or GCPS ratings was noted between different suit pressures during inclined walking, as shown in Figure 17 and Figure 18, respectively. RPE increased with grade as expected. GCPS had a trend towards increasing with grade, but to a lesser extent than RPE. RPE ratings tended to rate the exertion level as light to somewhat hard, and GCPS ratings typically indicated that the compensation required for inclined locomotion in the suit was either ideal (GCPS ≤ 3), acceptable (GCPS of 4), or the modifications warrant improvement (GCPS of 5 to 6).

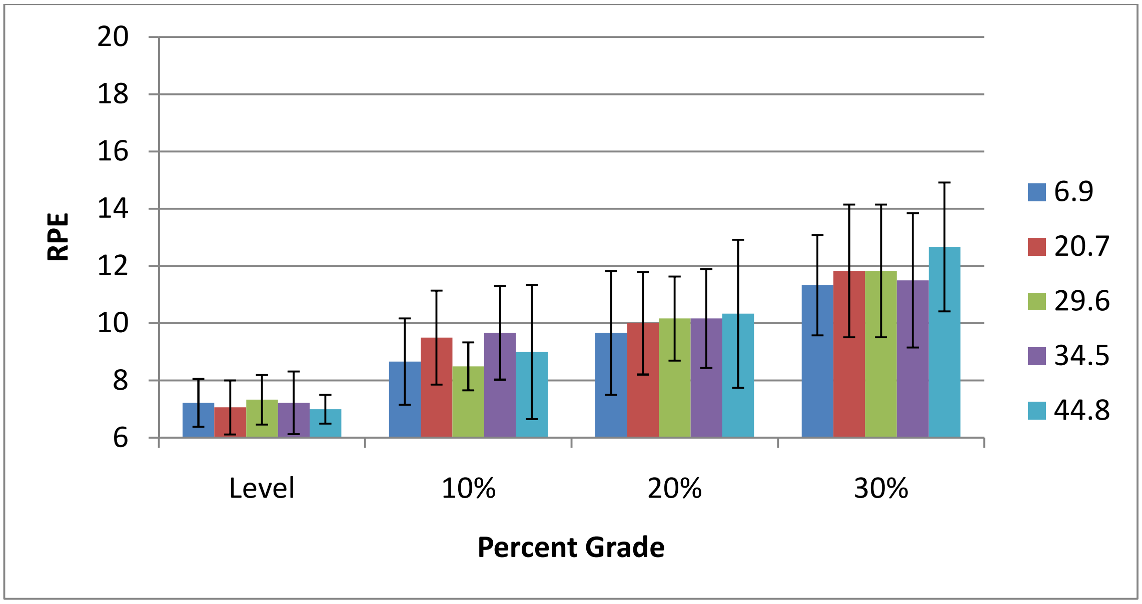


Figure 17. Rating of perceived exertion at varied pressures for suited incline locomotion at the 121-kg suit mass in lunar gravity.

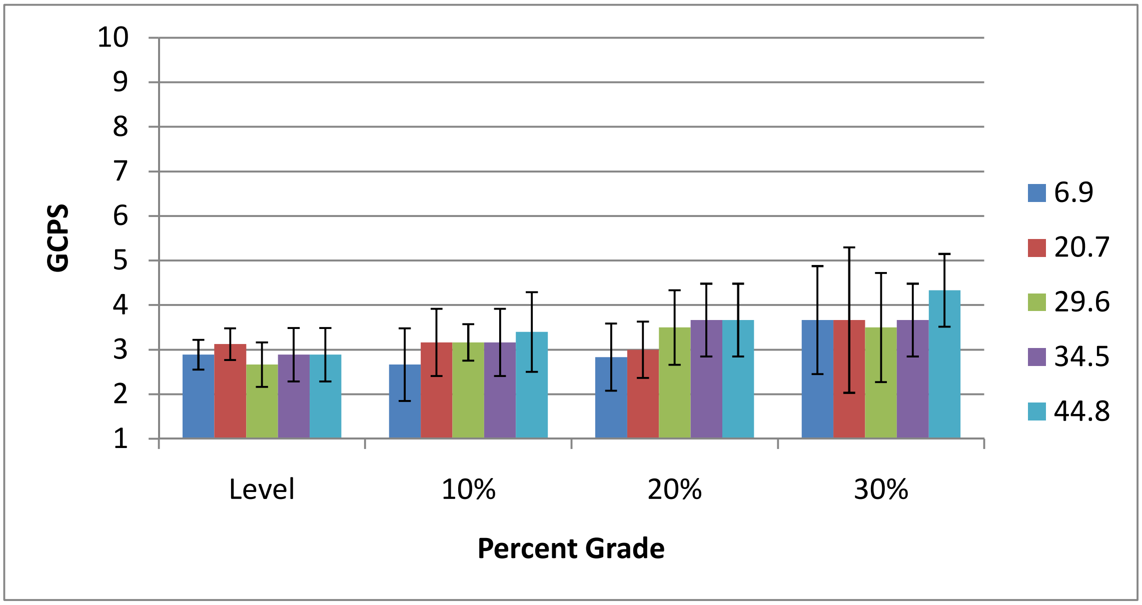


Figure 18. Gravity compensation and performance scale ratings at varied pressures for suited locomotion at the 121-kg suit mass in lunar gravity.

On completion of the varied pressure trials using inclined locomotion, subjects were asked to provide a rank order of the conditions considering all factors that they experienced. For varied pressures and inclined walking, the rank order preference from favorite to least favorite was typically from lowest to highest pressure, although this was not the case for every subject.

Due to hardware limitations, exploration task performance was only tested at suit pressures ≤ 29.6 kPa. Phase VI gloves were used by all subjects to provide the best possible fit with the MKIII suit. The general trend for both RPE and GCPS (Figure 19 and Figure 20) was that 29.6 kPa was the condition that produced the highest ratings, although only slightly higher than the other two pressures tested, which were about equal. Again, all of the tasks were relatively short in duration, and no task was hand-intensive; therefore, although varying pressure little affected the subjective ratings for the tasks tested, other issues that this test did not address in regard to hand fatigue and/or glove performance may be related to varied pressure.

At the conclusion of the varied pressure trials for exploration tasks, subjects were asked to rank their preference for the different conditions based on their complete experience. Subject rank order preference from favorite to least favorite was 6.9, 20.5, and 29.6 kPa, respectively. Five of six subjects ranked 29.6 last, and only two subjects chose 20.5 kPa as their favorite.

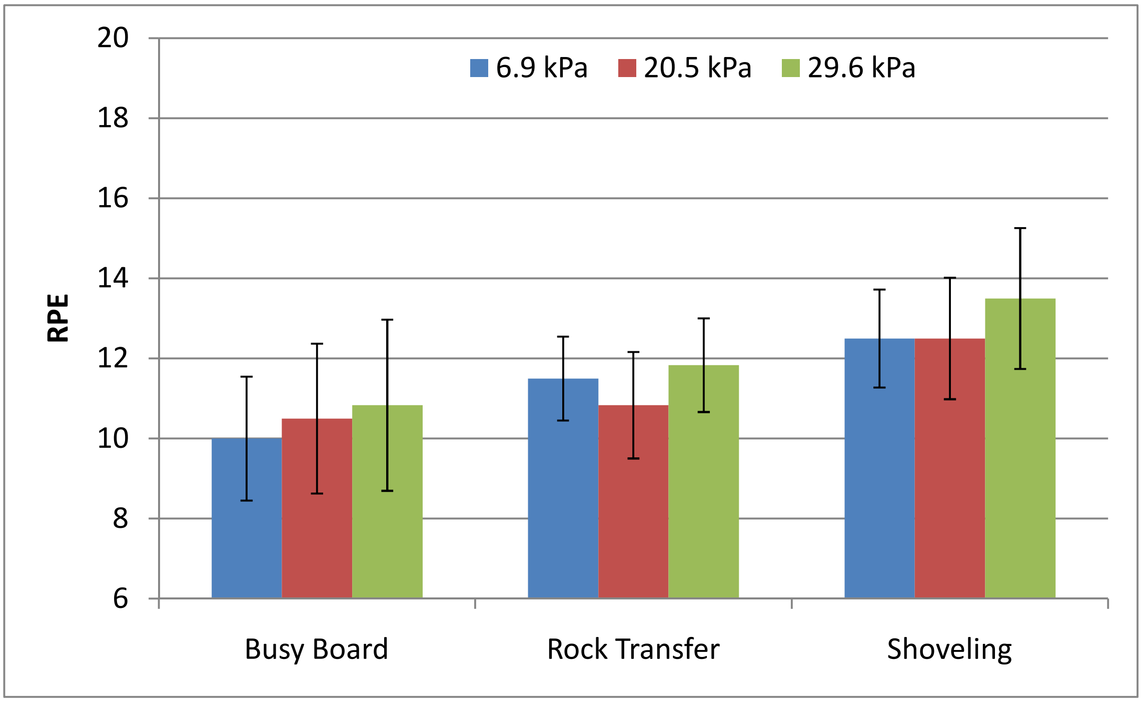


Figure 19. Rating of perceived exertion for exploration tasks at varied pressures with a constant 121-kg suit mass.

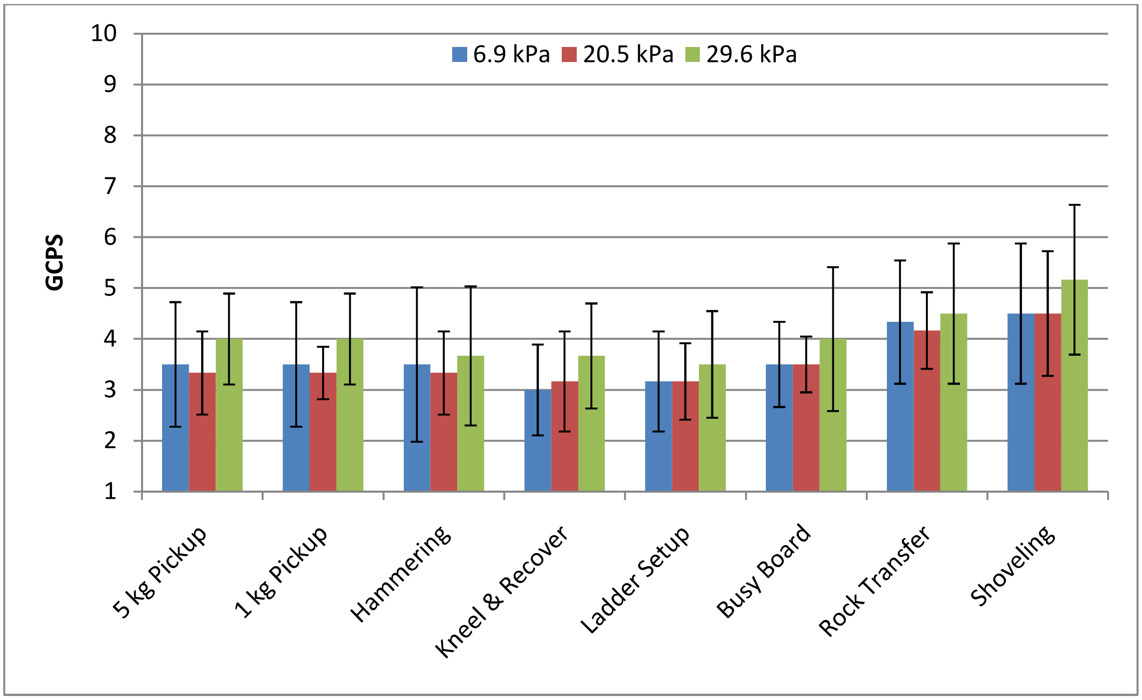


Figure 20. Gravity compensation and performance scale ratings for exploration tasks at varied pressures with a constant 121-kg suit mass.

Biomechanics Findings

Treadmill results

Kinetics

Typically, vertical GRF data have been shown as the peak GRF in Newtons. To date, representing the GRF in this format has revealed just the obvious trends (2). Analysis performed on the incline treadmill ambulation data stops short of revealing significant trends.

Representing the GRF data in this format, when comparing across subjects, often obscures valuable information. For example, if a crew member has a body mass of 80 kg and another crew member has a body mass of 100 kg, naturally the peak vertical GRF force would be greater for the heavier crew member. However, if we normalize the crew members to their respective body weights, a direct comparison can be made between subjects. Normalizing the GRF data to each crew member's unsuited body mass allows the following:

- Results can be compared to 1-g bodyweight for countermeasure development.
- Consistent comparisons may be made across different gravity conditions.

This normalization provides a baseline from which to make comparisons, especially as one of the specific aims of this test is to evaluate the effect of different suit weights on gait parameters.

During Earth terrestrial over-ground walking, typical GRFs are about 1.0 to 1.5 times body weight (BW); and during over-ground running, the GRFs can range from 2.0 to 5.0 times BW (9). Figure 21 depicts the peak GRF normalized BW at different suit pressures while walking at different inclines for all subjects. This method reveals that with varying suit pressures, the subject was exposed to peak GRF loads as great as 1.1 times BW. Subjects generally experienced peak

GRF loads in the range of 0.5 to 1.1 times BW, regardless of suit pressure conditions or walking surface incline.

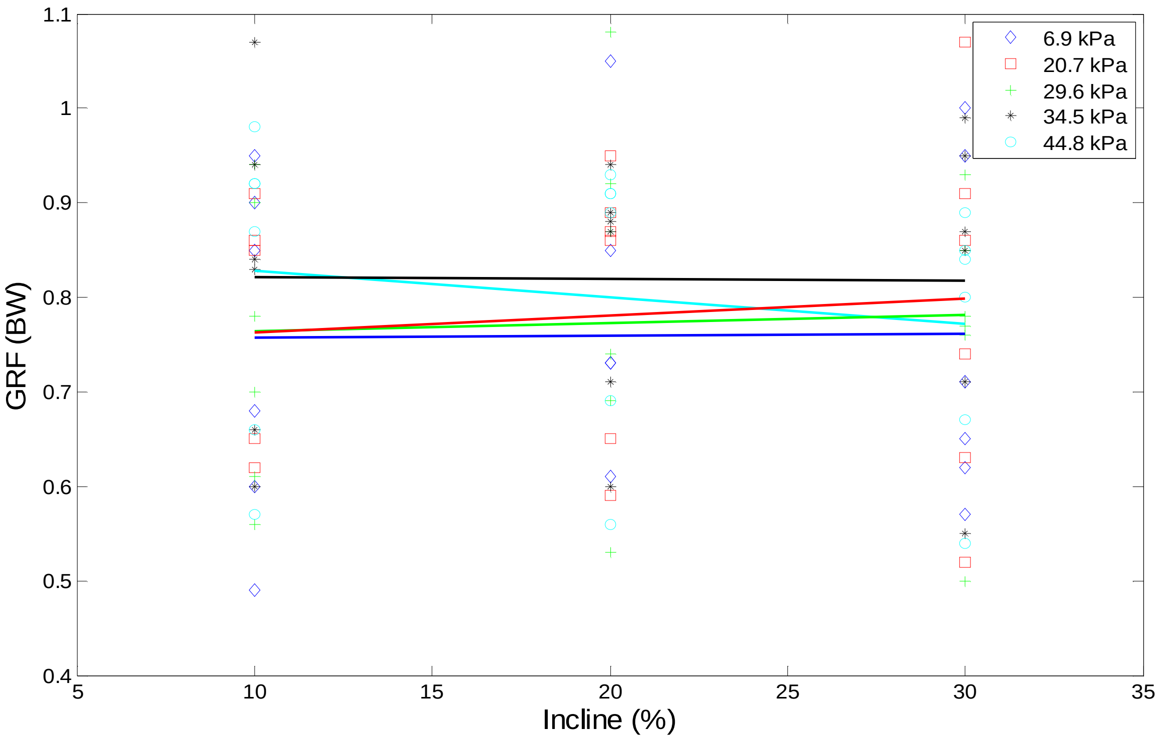


Figure 21. Peak vertical ground reaction force normalized to body weight for all subjects at varying suit pressures during treadmill walking at 10%, 20%, and 30% grades at lunar gravity.

Because the moon is at 1/6-g, it is unlikely that the lunar GRF would be in the same range for an unsuited subject, but the additional mass of an EVA suit will increase overall loading to the body during ambulation. If a similar GRF was seen between a suited ambulation on the moon and an unsuited 1-g ambulation, this would create significant implications for the exercise countermeasure requirements for future lunar explorers.

Temporo-spatial Characteristics

Figure 22 shows that as the incline increased, there was no observable trend for cadence regardless of suit pressure. One possible explanation for the difference is the subjects were wearing a 121-kg EVA suit that was offloaded to simulate lunar gravity. While, in fact, the subjects may have weighed less, the mass and inertia characteristics of the subject and suit remained unchanged. This is much like a swimmer in the pool who “weighs” less, due to buoyant forces, but still has the same mass and inertial properties. The swimmer in water is still required to accelerate, decelerate, and translate the same mass, as if on dry land, despite the lower weight. Even with the offloaded weight, the suited subjects for IST-2 must still move the combined mass of the suit and their own mass while also compensating for the amount of resistance to change in velocity (eg, inertia). Hence, the subjects may have taken more frequent, shorter steps compared to those they would have taken in 1-g to compensate for the mass and inertia factors associated with suited conditions.

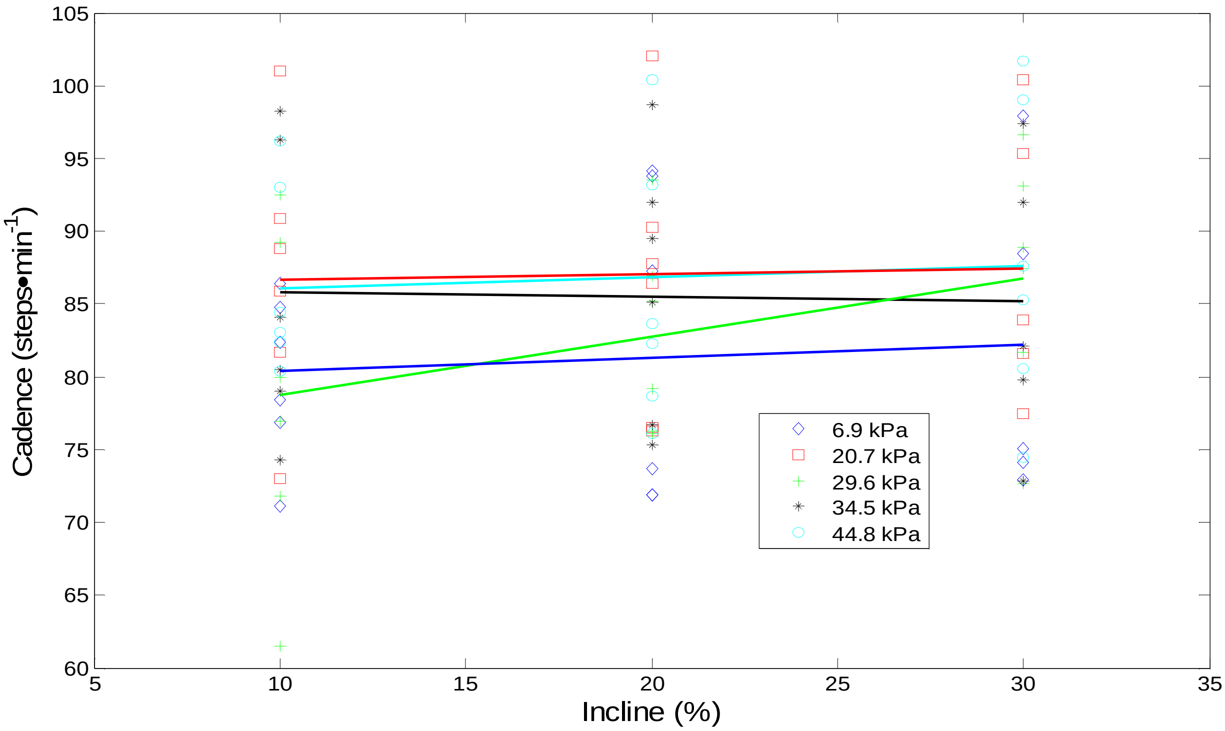


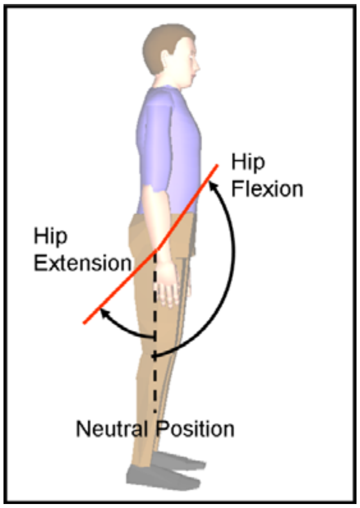
Figure 22. Average cadence for all subjects at different pressures during incline treadmill walking with constant suit mass (121 kg) at lunar gravity.

Joint Kinematics

Walking on an incline compared to walking on the horizontal can be distinguished by the following factors: the requirements to raise or lower the body's center of mass (COM), vertical displacement during each stride, and foot clearance. The following paragraphs address these factors.

First, it is important to define some of the terminology used to describe joint kinematics in the following discussion. The term flexion describes a decrease in relative angles between segments, and extension is an increase in relative angles between segments. This is not to be confused with an isolated joint range of motion (ROM). For example, an isolated hip flexion has a clearly defined starting and stopping point, namely the thigh segment moves from a neutral position of 0 deg, achieves some value of Θ, and returns to the neutral position of 0 deg (Figure 23 and Figure 24). However, during gait, given the dynamic nature of the movement, the subject may never achieve a neutral position. More specifically, gait is not a series of isolated movements; numerous concurrent actions are taking place during walking.

Figure 24 shows a theoretical plot of some joint angle ***x*** vs. time. In the first plot, the joint is flexing and extending but never crosses the neutral position of 0 deg. This is most often the case observed in laboratories, and is a direct result of the simultaneous flexion and extension of other joints during the motion. The second plot depicts the joint angle returning to the neutral position and extending beyond 0 deg, which is less commonly seen. Therefore, an accepted method of reporting joint angles is in terms of increases in relative angles between segments (extension) or decreases in relative angles between segments (flexion).



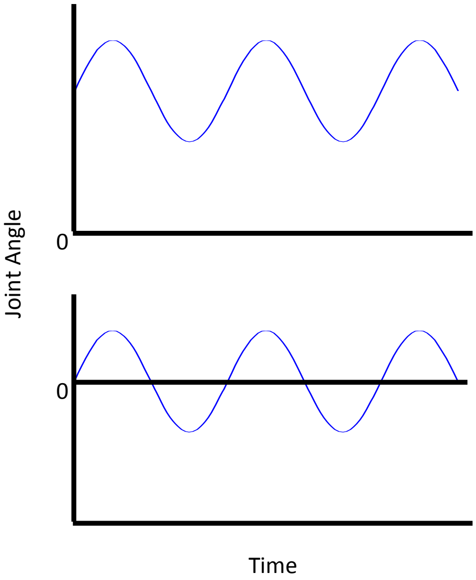


Figure 23. Schematic of hip flexion and extension. **Figure 24. Theoretical plot of a joint angle vs. time.**

During the gait cycle, it is customary to call the onset of the stance phase *heel strike*, although the heel of a crew member within an EVA suit may never contact the ground or may do so much later in the cycle. Thus, to avoid this area of confusion, the generic term *initial contact* will be used to describe the instant at which the EVA boot just touches the floor. The joint positions at this time determine the limb's loading response pattern. Conversely, at toe-off, an abrupt unloading of the limb occurs and the joint positions relate to the foot clearance of the floor and advancement of the limb.

Numerous studies have demonstrated that the angle of incline is a factor influencing hip, knee, and ankle angles (10) (11) (12) (13). These studies concluded that the governing factor regarding the effect of incline on lower-extremity joint angle may be the orientation of the COM of the upper body during these tasks. Hence, any decrease in ROM experienced by any of these lower joints must be accompanied by an increased ROM in the other joints to maintain the upper body center-of-mass orientation associated with the subject's adopted gait pattern.

Results from the inclined treadmill ambulation phase showed a general increase in the hip ROM as incline increased (Figure 25) for varying pressure conditions.

The mean knee-joint kinematics were time-normalized over the gait cycle for all subjects at varying pressures; these are displayed in Figure 26. Due to the variability among subjects, the only discernable trend is that, with increasing inclines, there was an increase in the knee-joint angle at initial contact.

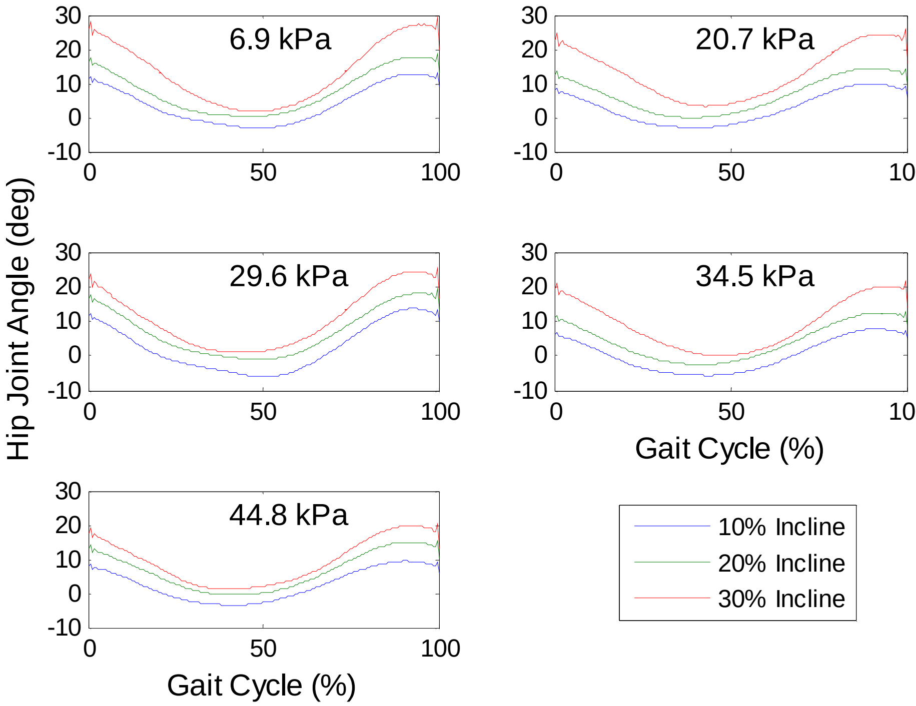


Figure 25. Mean hip angle vs. time normalized to the gait cycle for all subjects at different pressures during suited incline treadmill walking.

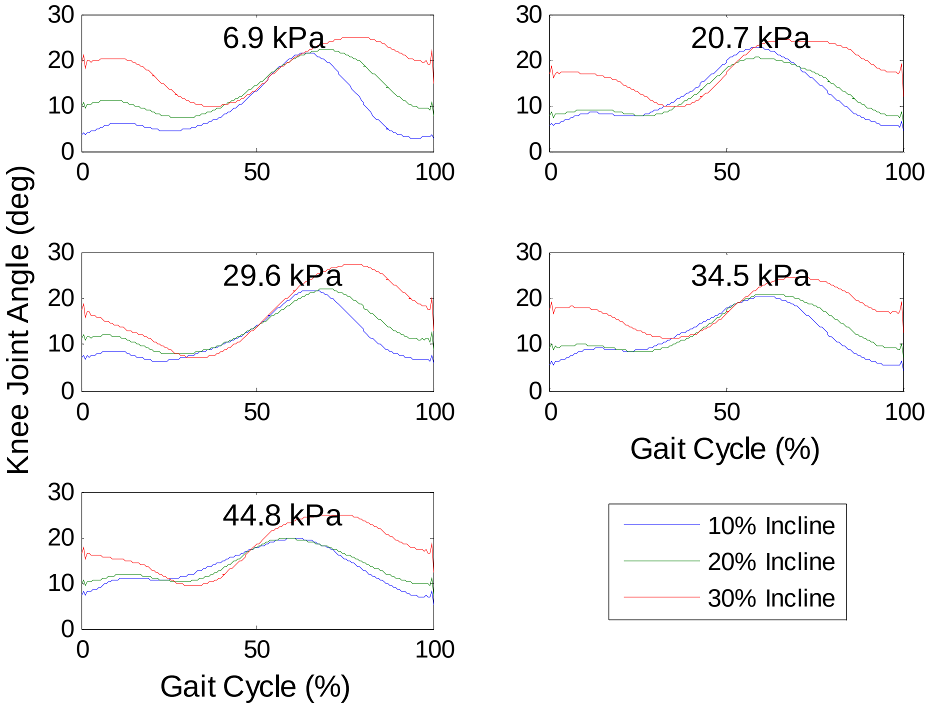


Figure 26. Knee-joint kinematics for varying pressure conditions while walking at 10%, 20%, and 30% grades.

It was postulated that with increasing inclines of treadmill walking, there would be a change in the position of the knee angle at initial contact and toe-off. One of our hypotheses was that the knee-joint angle may change with the increasing demand for the foot to clear the floor and move the leg forward to prevent falling during ambulation at steeper grades. Thus, the average knee-joint angle at initial contact and toe-off for each pressure was determined. Plotting the joint position data against incline on the independent axis revealed no observable trends for changing suit pressure (Figure 27).

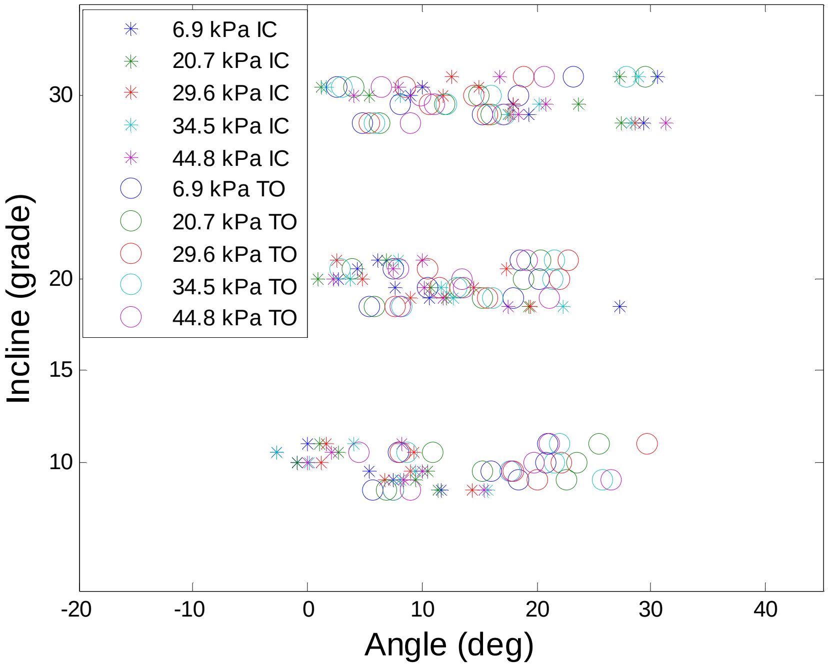


Figure 27. Knee initial contact (IC) and toe-off (TO) for all subjects at varying pressures during inclined treadmill walking.

Averaged data across all subjects demonstrate that the initial contact knee angle increases and the toe-off knee angle decreases with increases in incline (Figure 28). However, the data should be taken generally as the calculated standard deviation varies as much as 16 deg. Since 10% incline is similar to level walking, it stands to reason that the knee angle at initial contact is less than that at toe-off because initial contact occurs when the knee is extending forward. When the incline increases to a 20% grade, the knee angle difference between initial contact and toe-off decreases as the subject has to place the foot higher on the incline. At 30% incline, the knee begins to bend more at initial contact and straightens more at toe-off to push the body upward. No discernable trends were observed across the varying pressure conditions.

As the angle of incline increased, the ankle angle at initial contact increased for varying pressure conditions (Figure 29).

Often not all data are intuitively represented with a 2-dimension plot, and much information is best revealed with 3-dimension techniques, including many results from this test. It is difficult to determine the relationship of pressure, incline, and a variable ***x*** with a 2-dimension plot. Thus, the three lower-extremity joint ROMs using 3-dimension plots were examined to determine the effects of pressure and incline.

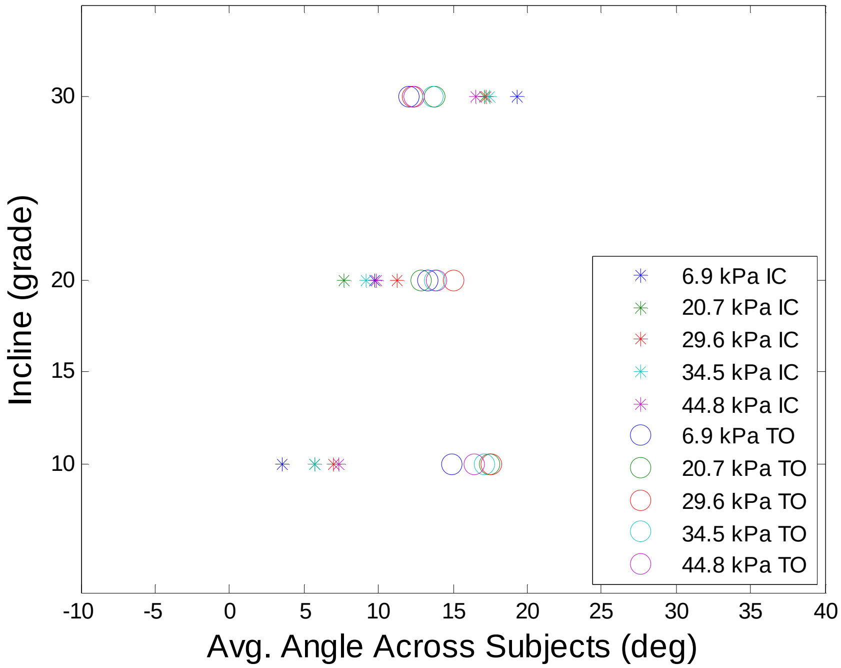


Figure 28. Knee initial contact and toe-off averaged over all subjects at varying pressures during suited inclined treadmill walking.

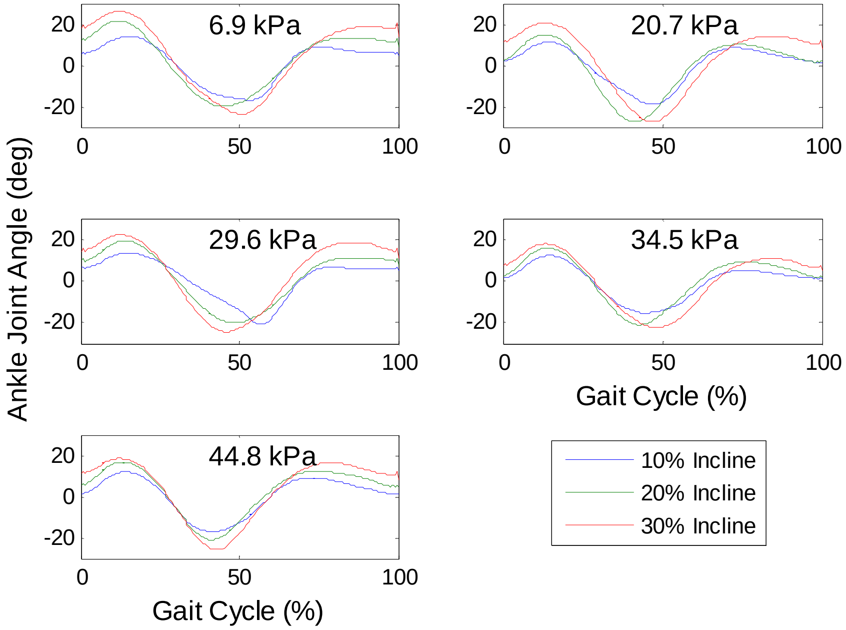
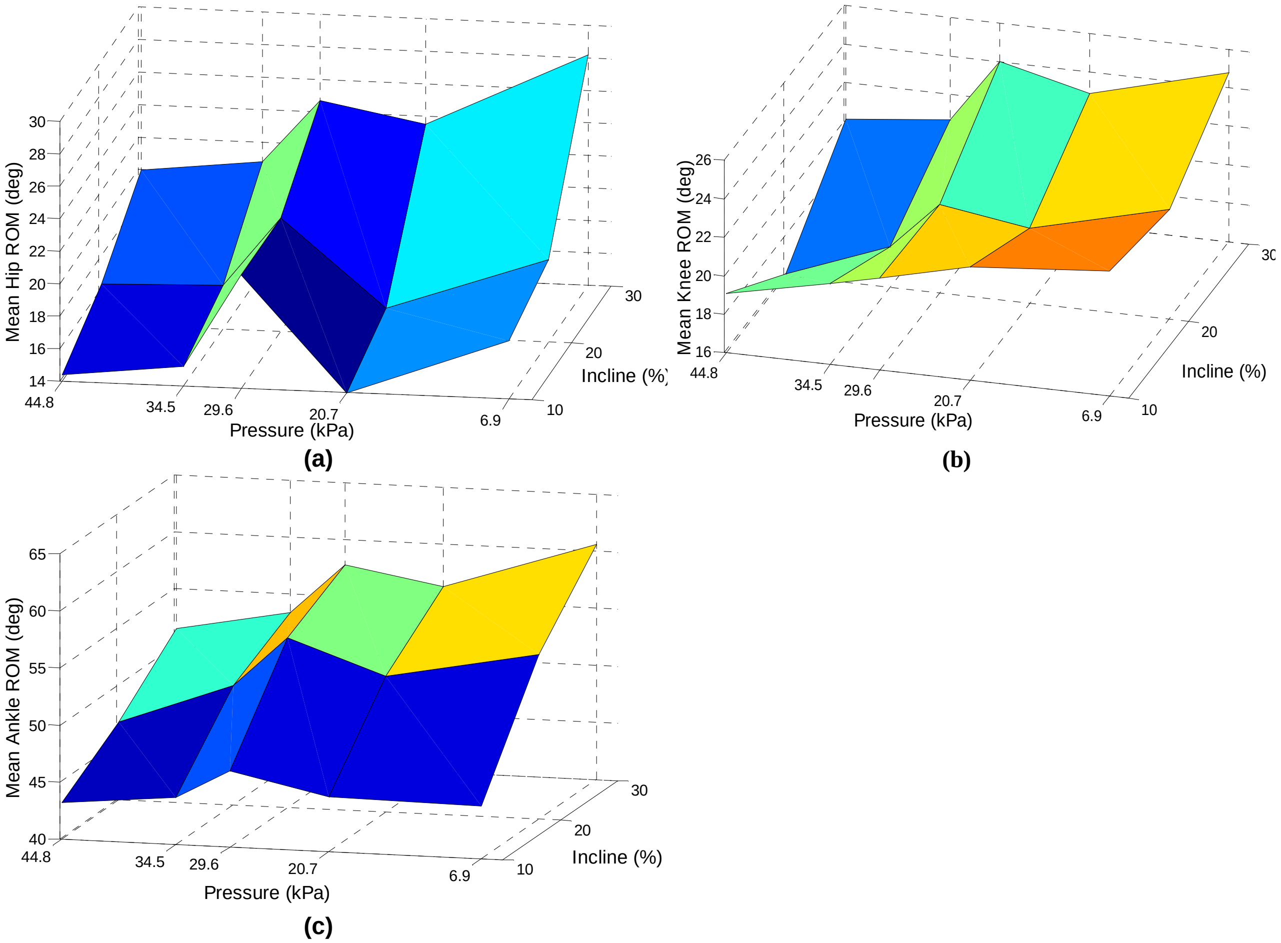


Figure 29. Ankle joint kinematics for varying suit pressures while walking at 10%, 20%, and 30% grades.

Figure 30 shows the mean three lower-extremity joint ROMs vs. pressure and incline. With the data represented 3-dimensionally, the effects of pressure and incline on the joint ROM can be readily seen. The greatest hip ROM was observed at the highest incline with a low-pressure suit (Figure 30a). The knee-joint ROM for varying pressure is not as easily seen as with the hip ROM but there is still a clear trend that with a lower pressure suit and higher incline there was a greater amount of knee ROM required (Figure 30b). The ankle joint ROM shows similar patterns as the hip and knee: with a high incline and a low pressure suit there is an increase in the joint ROM required to complete the task (Figure 30c).



(a)

(b)

(c)

Figure 30. A 3-dimensional visualization of the mean three lower-extremity joint ranges of motion vs. pressure and incline during suited incline treadmill ambulation.

The joint kinematic results from this study showed that walking on an incline required greater hip, knee, and ankle ROMs with increasing surface inclines. This trend follows the logical estimates of what should occur as the rise over run increases, requiring greater hip and knee flexion and ankle dorsiflexion as well as plantar flexion. Further, there is a "ridge" present for all three lower-extremity joint ROMs at 29.6 kPa. This finding suggests that this operating pressure may alter gait kinematics. Further study is warranted. These findings are relevant for all interested in determining the requirements for developing a suit for lunar sorties. These data have implications for suit designers in that a planetary exploration suit with designs structured similarly to the MKIII joints and patterned convolutes must be equipped to accommodate the three lower-extremity joint ROMs reported from this study. Further, results from this study demonstrate that a low-pressure suit will require increased joint ROM capabilities to perform incline locomotion tasks, especially in a soft joint. This finding may be different in a suit using primarily hard joints.

Additional Kinematic Measures

Figure 31 depicts the waist-bearing cycles for all subjects at different pressures.

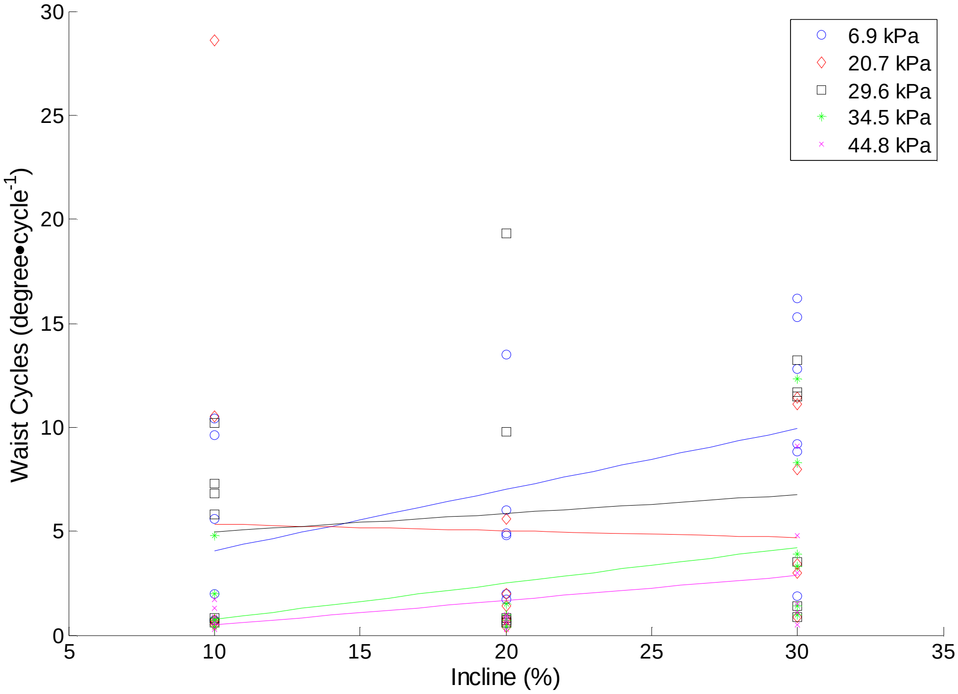


Figure 31. Waist-bearing cycles for all subjects at different suit pressures during suited inclined treadmill ambulation.

As demonstrated above, there appears to be an unclear relationship between waist cycles (presented as degrees per cycle) and varying suit pressures (Figure 31) during ambulation on a treadmill at varying gradients. Much like the GRF data, when waist-bearing data are presented in the traditional format of degrees per cycle, the data do not allow for any clear inferences or conclusions to be drawn due to the large variation in their spread.

Another way to look at the waist-bearing data is the linear distance the bearing travels per gait cycle. The “ball race diameter” (ie, the ball center-line diameter) of the MKIII suit is 39.4 cm. The circumference of the circle was divided by 360 deg to obtain a conversion factor. This conversion factor, multiplied by the waist-bearing cycles, yields the linear travel of the bearing for one cycle. The data represented in this format can quantify the total linear travel of the bearing and help quantify a major component causing wear to the bearing.

Figure 32 represents the linear travel of the waist bearing per cycle for all subjects at different suit pressures during treadmill walking separated by 10%, 20%, and 30% inclines. This figure demonstrates that as pressure increased, there appears to be a general trend of decreased linear travel by the waist bearing.

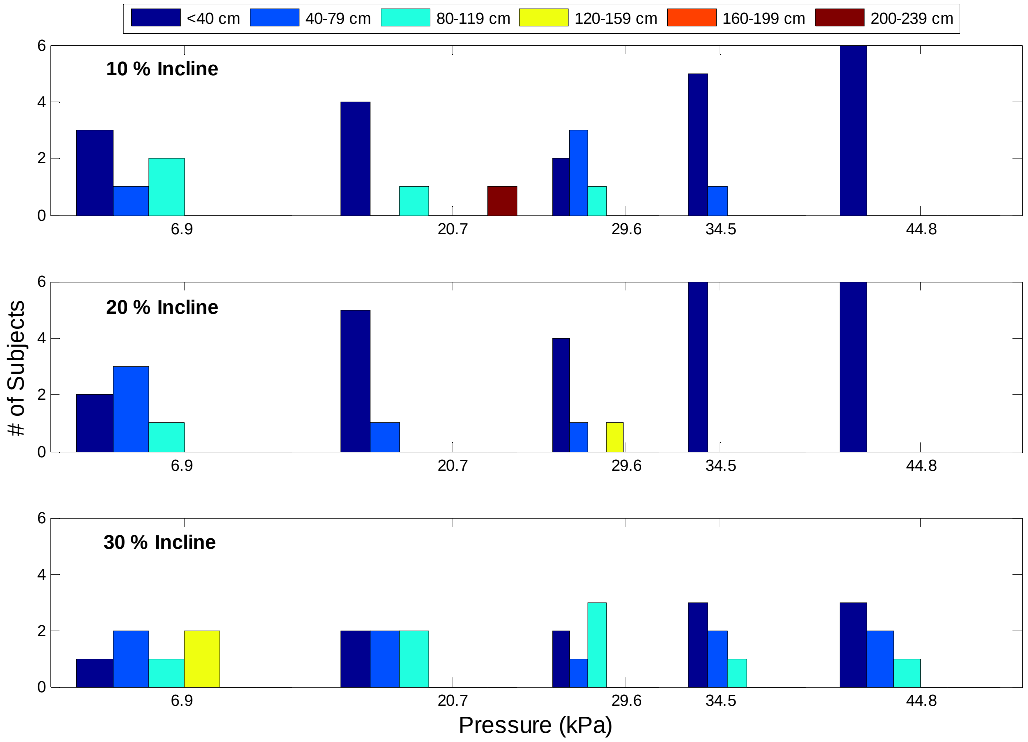
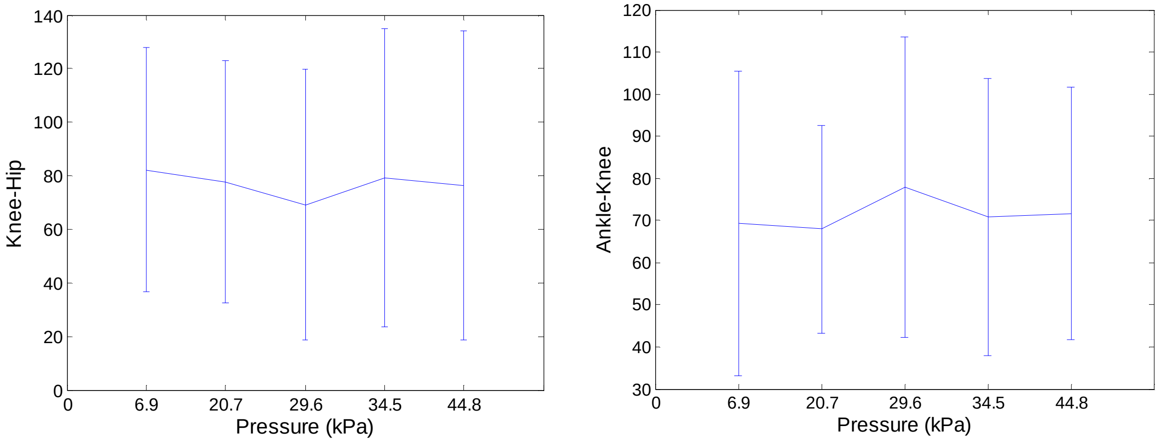


Figure 32. Linear travel of the waist bearing for all subjects at different suit pressures during treadmill walking at 10%, 20%, and 30% grades.

Several factors may contribute to the observed decrease in waist-bearing travel as pressure increases. One possible explanation is that the subject must change his gait kinematics to maintain CG to keep from falling down. This notion is supported by the increase in cadence (Figure 22) and the decrease in the lower-extremity joint ROM as pressure increases (Figure 30). As pressure increases, the subject was taking more frequent steps using less ROM to compensate for the increase in pressure. However, this phenomenon may be a result of the interaction between pressure and incline. Future tests are warranted to better understand this interaction.

Phase portrait is a new technique applied to gait analysis to determine a qualitative picture of the organization of the neuromuscular system. It provides initial insight into the control mechanisms of gait. The phase angle of the phase portrait trajectory is used to quantify the behavior of the neuromuscular system during gait (eg, the lower-extremity segments). The trajectories of the phase portrait are transformed from Cartesian to polar coordinates. The angle formed by the radius and the horizontal axis is the phase angle of the trajectory. This phase angle is used to calculate the relative phase that provides a measure of the interaction between (coordination of) the two segments during the gait cycle. The relative phase is determined by subtracting the phase angle of the proximal segment from that of the distal segment for each *i*th data point of the time-normalized gait cycle. Relative phase values approaching 0 deg suggest that the two oscillating segments are in phase, while relative phase angles approaching 180 deg are considered out of phase. A negative relative phase indicates that the proximal segment is ahead of the distal segment in phase space while a positive relative phase suggests that the distal segment is ahead of the proximal segment in phase space. To quantify differences between relative phase curves, the mean absolute relative phase is used to determine whether the interacting segments display an in-phase or out-of-phase pattern during gait.

The mean absolute relative phase for the knee-hip and ankle-knee segments is displayed in Figure 33. These data show that the knee and hip joints were more in phase for a suit with a pressure of 29.6 kPa, whereas the ankle and knee joints were more in phase with the 20.7-kPa suit pressure. However, the graphs also display the confidence level (via error bars) of the data. The error bars spanned a large range for all plots, suggesting a large amount of variability among subjects. Future tests, including more familiarization time and possibly even more control over the subjects' gait, would reduce the variability observed in this test.



(a) **(b)**

Figure 33. Mean absolute relative phase for the interacting segments of the hip and knee and the ankle and knee for suited location at all inclines.

Exploration Task Results

Examination of the exploration tasks showed little variation with different pressures, but this was not the case for the varied weight series. Overall results and discussion of the exploration task biomechanics findings can be found in Section 3.2.3

3.2.2 Effect of varied mass (unsuited): metabolic rate findings

Variation in added mass did not clearly affect metabolic rate for either incline walking or exploration tasks for unsuited testing. The most likely reason for this lack of variation was the small increments between varied mass conditions (11.3 kg). Although not proven, it would be expected that larger increments more similar to the variations seen with the varied weight testing would be expected to lead to more variation in metabolic rate, especially in weight-supporting and frequent change-of-direction activities such as ambulation and the rock transfer task. Future studies are planned that will use large incremental changes in mass in both unsuited and suited conditions to evaluate the effect on varied inertial mass. Figure 34 describes the lack of metabolic rate variation seen when mass was changed in 11.3-kg increments. Although there is a subtle trend for an increase in metabolic rate with increased mass at a constant weight, this trend was not significant. Figure 35 also shows the same lack of metabolic rate variation within the exploration tasks when mass was changed.

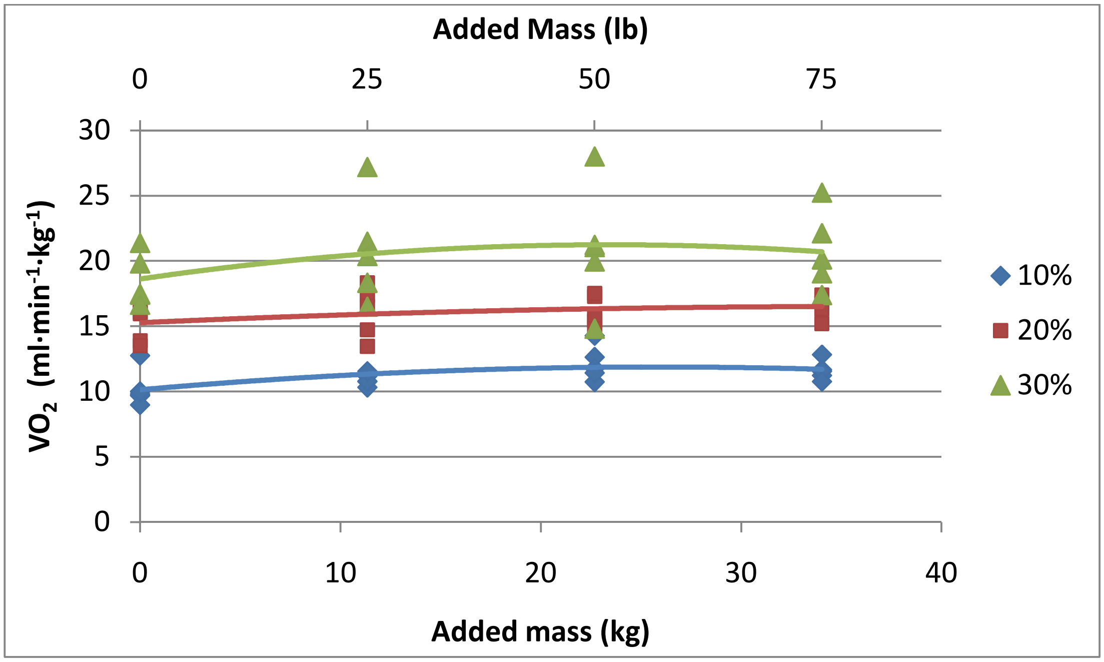


Figure 34. Metabolic rate vs. added mass during unsuited but weight-matched (121-kg) inclined ambulation at lunar gravity.

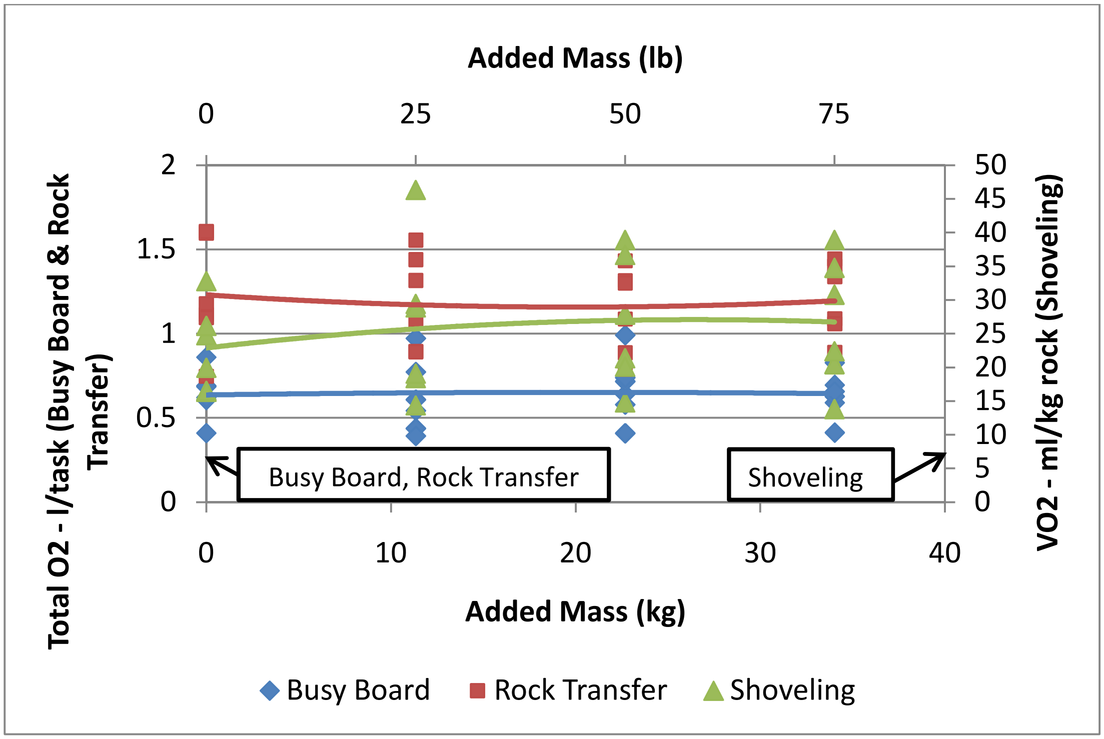


Figure 35. Metabolic cost vs. added mass during unsuited but weight-matched (121-kg) exploration tasks at lunar gravity.

3.2.3 Effect of varied weight (suited and unsuited)

Metabolic Findings

Figure 36 shows the relationship between suited metabolic rate and treadmill incline at a constant mass but at different gravity levels leading to different total gravity-adjusted weights. Level data from IST-1 are also included (2). At 0% and 10% grade, the mean difference between the highest and the lowest weight conditions was 1.9 mL•kg^{-1}•min^{-1}and 3.5 mL•kg^{-1}•min^{-1}, respectively, neither exceeding our criteria for significance (>3.5 mL•kg^{-1}•min^{-1}). However, as the grade increased to 20% and 30%, this difference increased to 8.7 and 17.0 mL•kg^{-1}•min^{-1}, respectively.

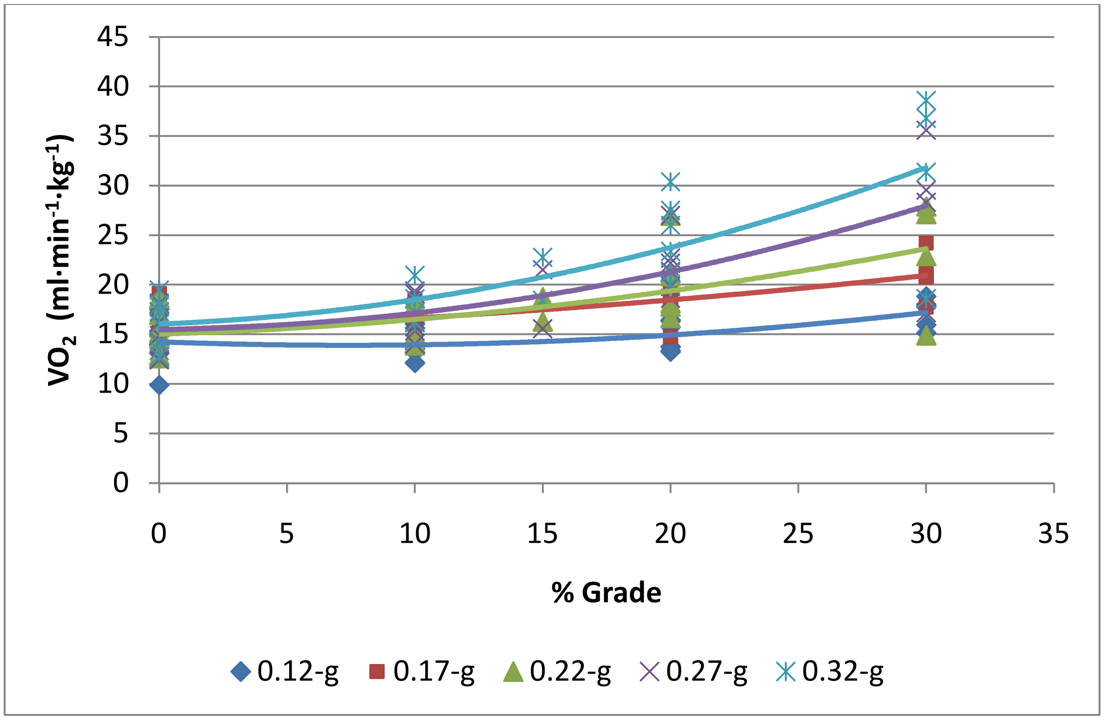


Figure 36. Metabolic rate vs. grade for different gravity profiles during suited walking at lunar gravity with constant suit pressure (29.6 kPa).

To more effectively see the effect of weight, Figure 37 plots metabolic rate vs. gravity level and TGAW. The slope for the 0% and 10% grade lines was minimal, indicating that weight alone had little effect at this slow walking speed. However, the slopes of the 20% and 30% plots were much more aggressive and indicate that wearing a heavier suit would require a higher metabolic rate on steeper slopes. Results of IST-1 showed similar results with speed, i.e., as speed increased, the metabolic rate increased to a greater extent with heavier weights (2).

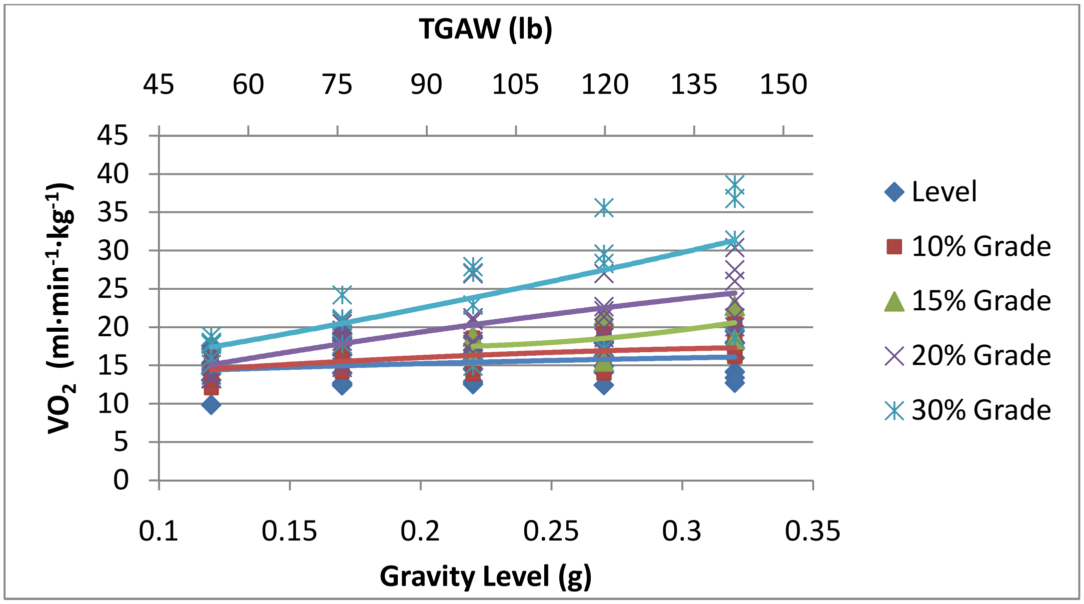


Figure 37. Metabolic rate vs. gravity level during suited inclined ambulation at lunar gravity with a constant pressure (29.6 kPa).

Figure 38 describes the effect of increased weight on unsuited inclined ambulation. In this figure, the trend for 10% and 20% was similar to the suited results, but 30% showed a less aggressive slope.

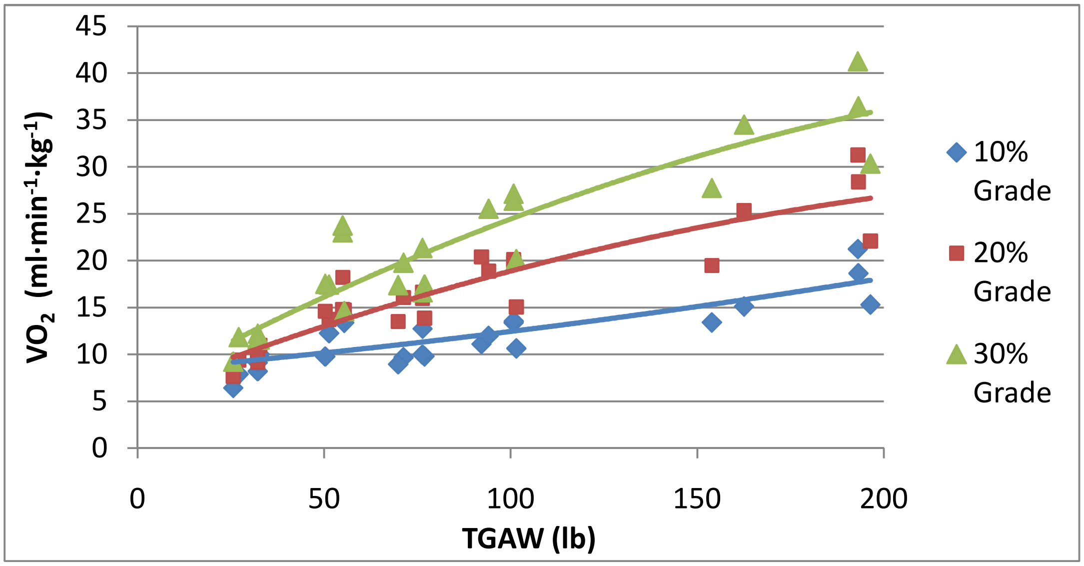


Figure 38. Metabolic rate vs. total gravity adjusted weight during unsuited inclined ambulation at varied offloads.

To pull the shirtsleeve and suited trends together, Figure 39 plots the data for four different conditions. Lunar shirtsleeve represents pure, unsuited performance on the moon; lunar suited represents suited performance; lunar shirtsleeve weight-matched represents the performance of an unsuited subject weighing the same as if that subject were wearing a suit; and the 1-g shirt-sleeve, which represents Earth performance, is provided for reference only. The difference between the two lunar shirtsleeve conditions represents the metabolic cost associated with increased weight only. The difference between the suited and shirtsleeve weight-matched conditions accounts for the increased metabolic costs of the suit unrelated to weight; ie, factors such as mass, pressure, kinematic constraints, and different harnessing and offloading mechanics between suited and unsuited conditions.

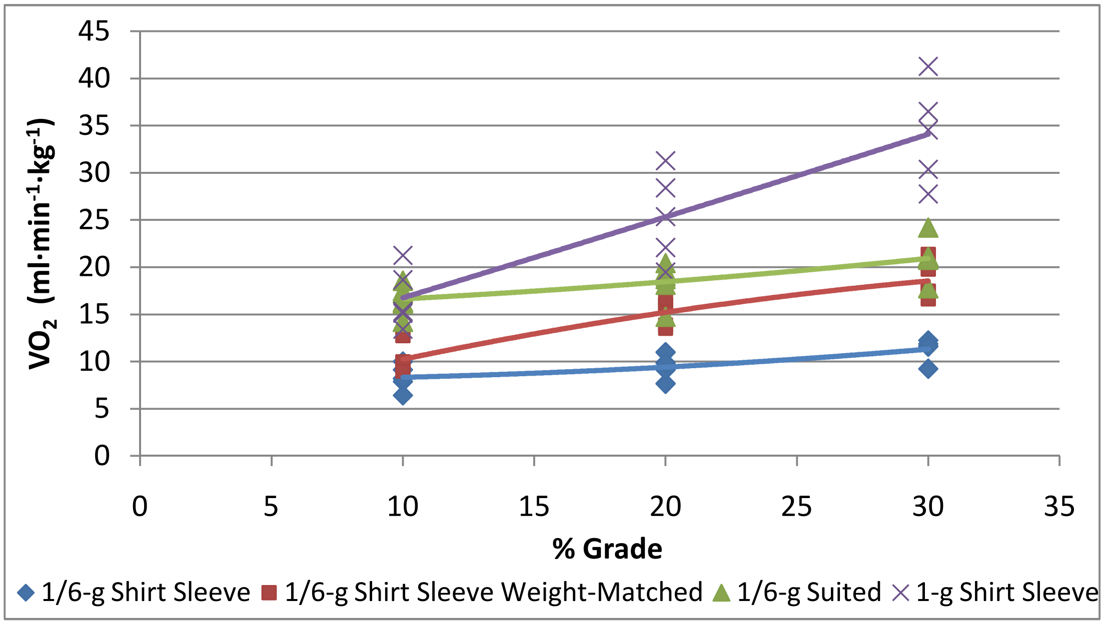


Figure 39. Metabolic rate for incline walking at different suited and unsuited conditions.

The metabolic cost of weight increased with grade, as would be expected. However, the metabolic costs unrelated to weight decreased with increasing grade. In all of our previous studies on suited ambulation, the shirtsleeve weight-matched metabolic rate was always less than the suited metabolic rate at similar speeds, and the slope of the suited lines was always more aggressive (1) (2). For inclined ambulation, this was not always the case, as demonstrated by the convergence of the two lines at 30% grade. Although mean VO_2 was still higher in the suited condition, this was not the case for one of the five subjects. These findings indicate there was some compensation mechanism in place for suited incline locomotion allowing subjects to either recover energy more effectively from the suit or get artificial assistance from the POGO system. We believe that it is primarily the latter.

Normally when walking up an incline, the torso is shifted forward to compensate for the change in mechanics and help put the COM over the COP, allowing forward progression (see Figure 40A). Theoretically, in a lunar environment this shifting of the COM would be exaggerated to allow for the same forward progression (see Figure 40B). However, what was observed in the POGO environment was just the opposite, with the subject's trunk held upright while walking the incline (see Figure 40C). This posture while walking on an incline would not normally be possible without the POGO system supporting the subject.

Unlike ambulation trends, which have generally indicated a lighter suit may offer better performance, we found heavier weights were often associated with lower metabolic rates during exploration task performance. Figure 41 shows that the best performance (lowest metabolic rate) was associated with the three heaviest weights and the worst performance was seen at the lightest weight.

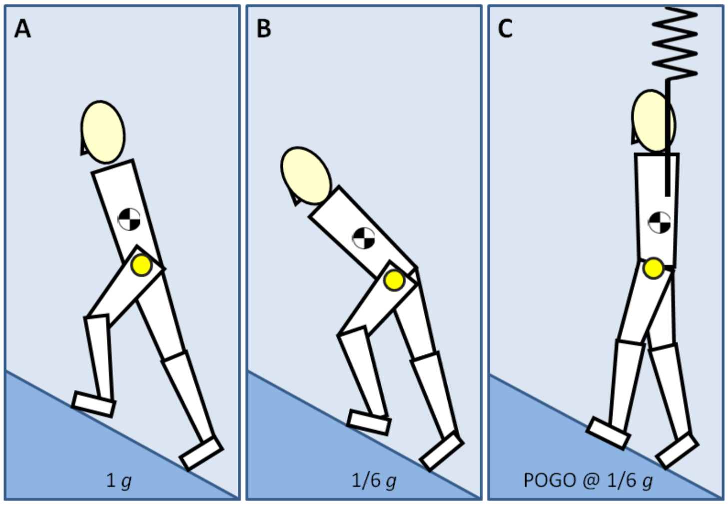


Figure 40. Postural differences for inclined walking among the 1-g environment, a predicted 1/6-g environment, and the POGO 1/6-g environment.

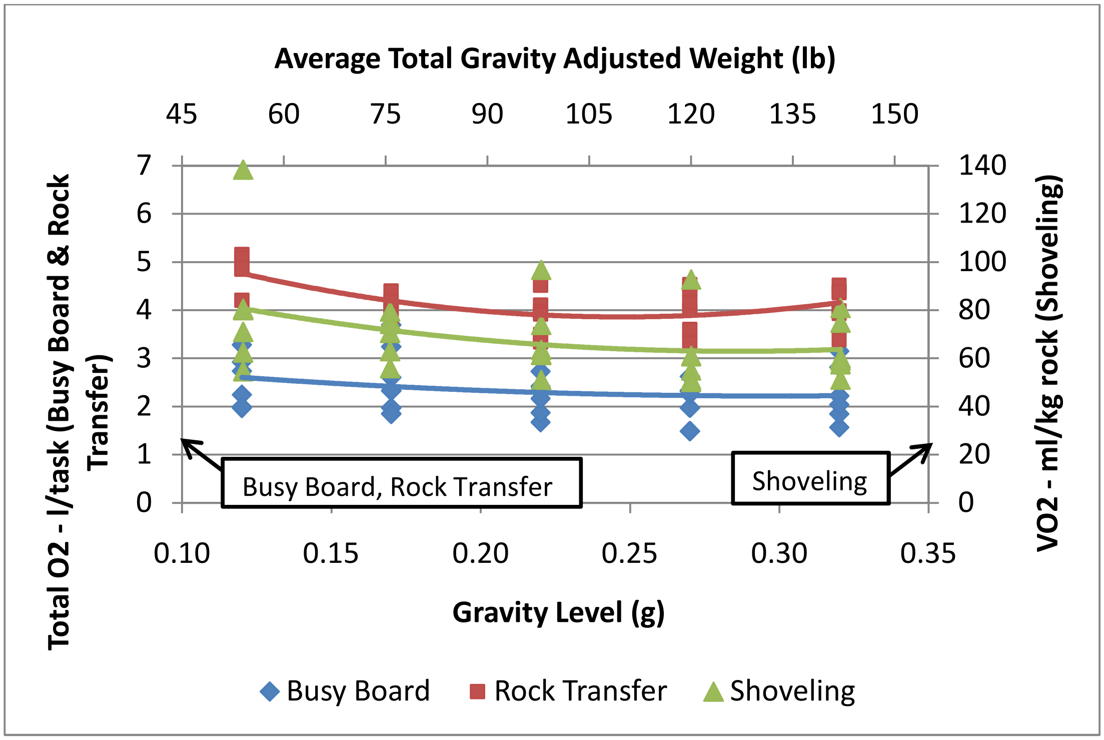


Figure 41. Metabolic cost for exploration tasks at different gravity levels but constant pressure (29.6 kPa) and suit mass (121 kg).

What is unclear from Figure 41 is whether the variation in metabolic cost occurred because the subjects were working at different metabolic rates and similar task completion times or at similar metabolic rates but different completion times, or whether some combination of both of those factors was true. Figure 42 and Figure 43 show where the variation in overall metabolic cost originates, by differentiating between metabolic rate and time to completion. In these cases, the greater variation was seen in time to completion. Figure 44 shows similar information but uses metabolic rate and total rock mass shoveled over a 3-minute period instead of time. Similarly, the greater variation was seen in rock mass rather than average metabolic rate.

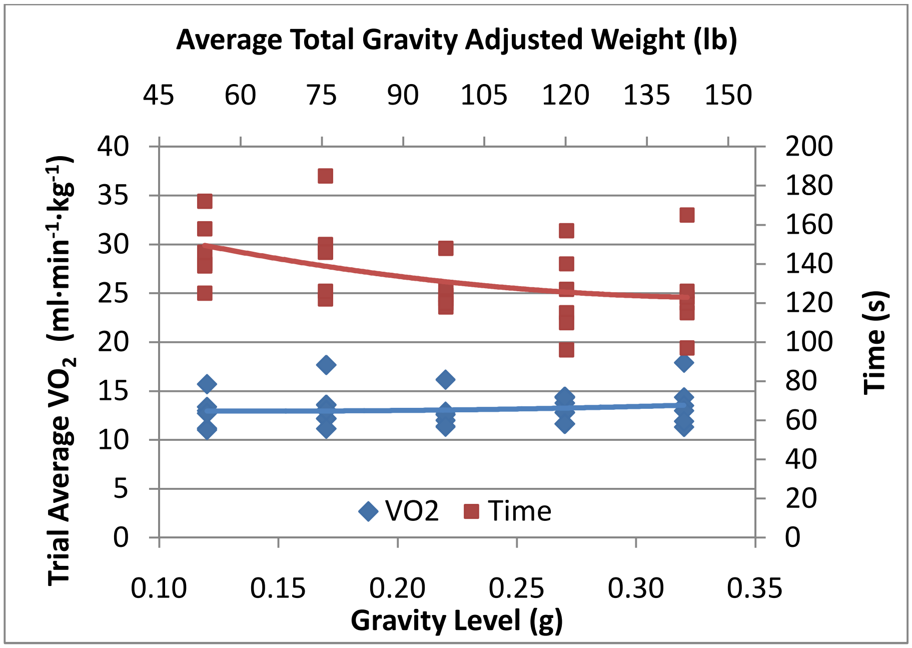


Figure 42. Metabolic rate and time to completion for the busy board task at varied weights.

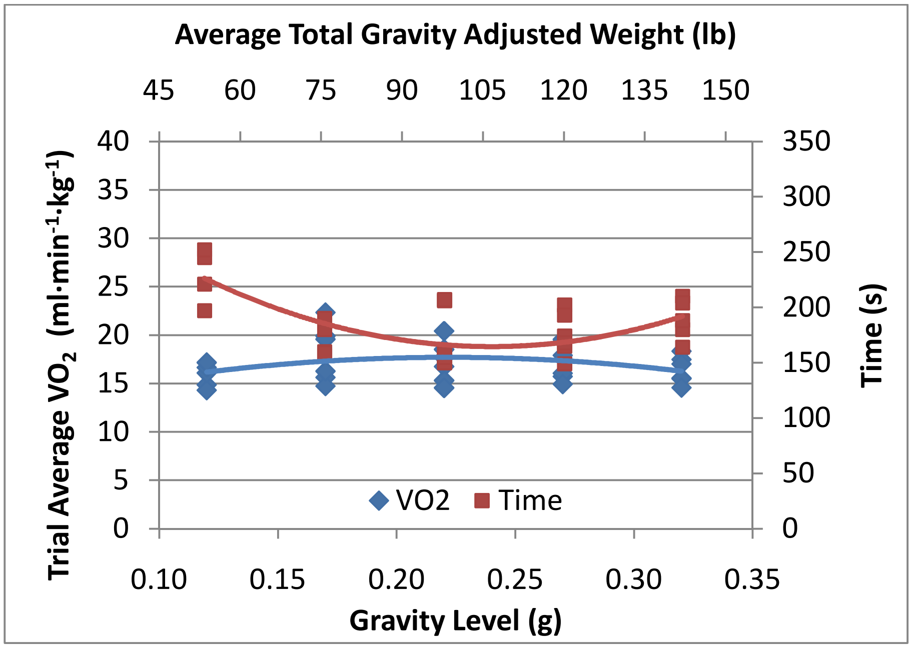


Figure 43. Metabolic rate and time to completion for the rock transfer task at varied weights.

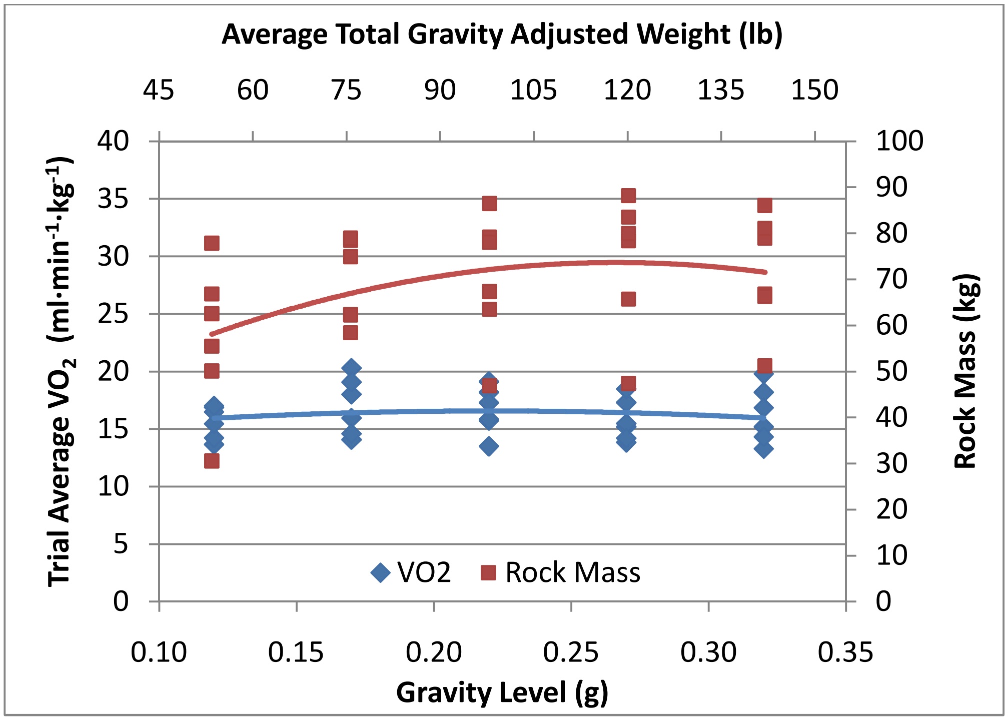


Figure 44. Metabolic rate and rock mass for the shoveling task at varied weights.

Although there was some variation in average metabolic rate between different weight conditions, the greater change occurred in either task completion time or mass of rock shoveled. In all three tasks, the average metabolic rate was below, and often well below, 50% of VO_2pk. This finding seems to indicate that crew members are likely to choose to work at a comfortable intensity level, and the time spent to complete the task will likely be the component that varies with differences in suit parameters.

While variation in exploration task metabolic cost was clearly seen within the suited conditions, it was not apparent in the unsuited conditions. Results of all shirtsleeve conditions, including varied weight and varied mass, are summarized in Table 2. The only clear difference seen among all unsuited conditions was a lower metabolic cost for the rock transfer task during 1-g conditions (1.32 ± 0.37 L/task) as compared to the average of all reduced-gravity conditions (2.15 ± 0.39 L/task). For reduced-gravity conditions, the average metabolic cost for the rock transfer ranged from 2.03 ± 0.36 to 2.27 ± 0.30 L/task. The average busy board metabolic cost ranged from 0.82 ± 0.26 to 0.96 ± 0.60 L/task for all unsuited conditions. The average shoveling metabolic cost for all reduced-gravity conditions ranged from 22.8 ± 6.37 to 28.5 ± 13.88 mL/kg rock shoveled.

Table 2. Shirtsleeve Metabolic Cost of Exploration Tasks

Unsuited Condition	Average TGAW (lb)	Busy Board (l/task)	Rock Transfer (l/task)	Shoveling (ml/kg rock)
1-g baseline	180	0.87 ± 0.22	1.32 ± 0.37	24.19 ± 8.19
0.17-g shirtsleeve baseline	30	0.83 ± 0.32	2.14 ± 0.36	28.53 ± 13.88
0.12-g weight-matched	53	0.82 ± 0.26	2.17 ± 0.60	23.49 ± 8.17
0.17-g weight-matched	76	0.90 ± 0.22	2.27 ± 0.30	22.78 ± 6.37
+ 11.3 kg added mass	76	0.96 ± 0.59	2.10 ± 0.44	26.11 ± 11.59
+ 22.7 kg added mass	76	0.84 ± 0.28	2.03 ± 0.34	26.64 ± 9.61
+ 34.1 kg added mass	76	0.80 ± 0.21	2.20 ± 0.33	26.88 ± 9.51
0.22-g weight-matched	98	0.92 ± 0.32	2.17 ± 0.42	23.88 ± 7.55

The lack of variation in metabolic cost for exploration tasks among all shirtsleeve conditions was surprising. Normally, mass and weight notably affect performance. One possible reason for the similarity may be because the subjects had freedom to move their arms and legs as they normally do with only minor limitations due to the spreader bar and harness assembly. Subjects could move and use their arms and hands without having the potential kinematic constraints of the suit or gloves. This may suggest that if a suited subject had control and mobility similar to shirtsleeve conditions, suit factors such as weight and pressure might not make as much difference in performance as they currently do, although this remains just a theory because the actual reason of the lack of variation is not well understood. Another contrary explanation is that the gimbal/harness restricted key movements such as pitch and roll in such a way that subjects were forced to use the same strategies and methods to complete the tasks independent of weight or mass, which might explain the differences seen in the rock transfer between 1-g and all other conditions.

Subjective Findings

Subjective findings showed similar trends to the metabolic rate for inclined treadmill walking. The general trend, as seen in Figure 45, was that RPE increased both as weight increased and as grade increased. Figure 46 shows that GCPS also followed a similar trend to RPE and metabolic rate with respect to increasing as weight increased, but that GCPS was not significantly changed by grade. Although individual results varied, most conditions, except for the highest grades at the higher gravity levels, had mean GCPS ratings of ≤ 4, indicating acceptable performance or better.

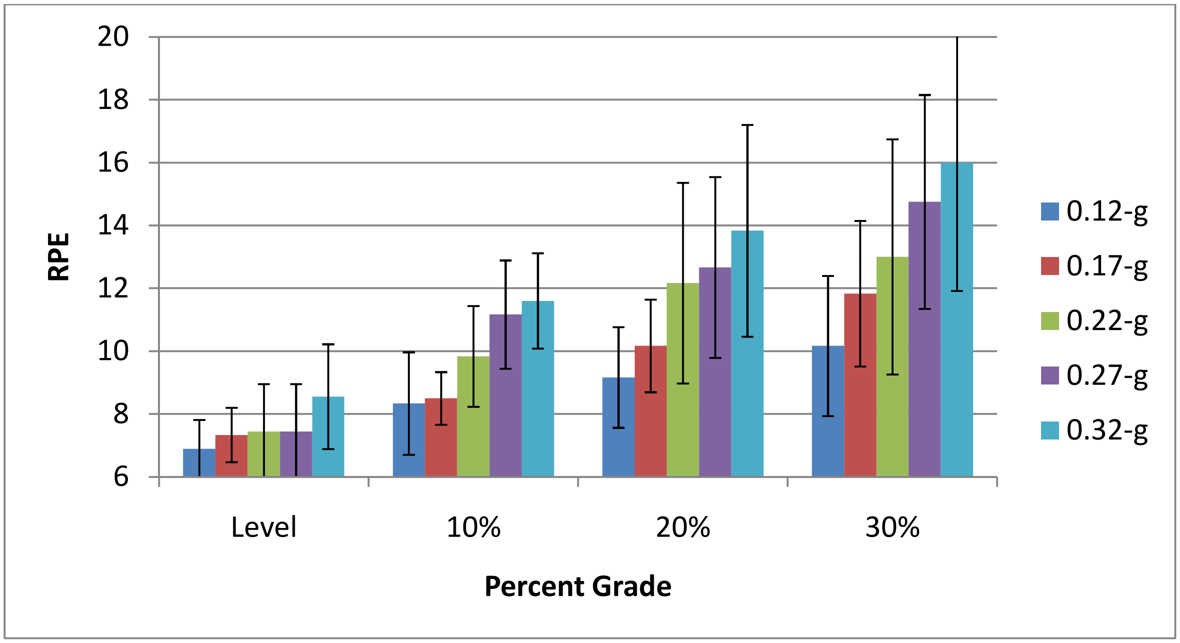


Figure 45. Rating of perceived exertion during incline walking for different gravity levels at a constant pressure (29.6 kPa) and suit mass (121 kg).

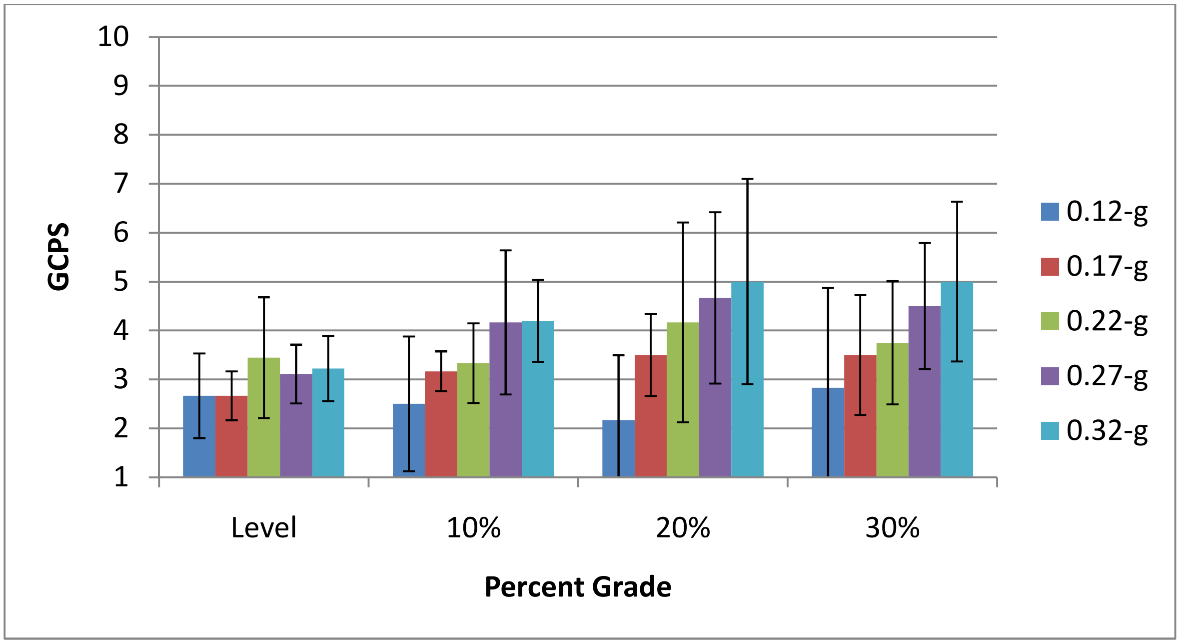


Figure 46. Gravity compensation and performance scale during incline walking for different gravity levels or total gravity adjusted weights at a constant pressure (29.6 kPa) and suit mass (121 kg).

For exploration tasks, there was little difference in RPE ratings for the shoveling task (Figure 47). The average RPE rating was higher for the 0.12-g condition for both the busy board and the rock transfer task. There was little to no difference in the RPE for the other conditions evaluated for the busy board and rock transfer tasks. Figure 48 shows the average GCPS ratings for all exploration tasks. The primary finding was that the 0.12-g condition consistently had the highest GCPS ratings. Subjects consistently reported that they felt more stable as the gravity level increased. The 0.17-g condition was only slightly higher than the three heaviest suit weights, which were approximately equal.

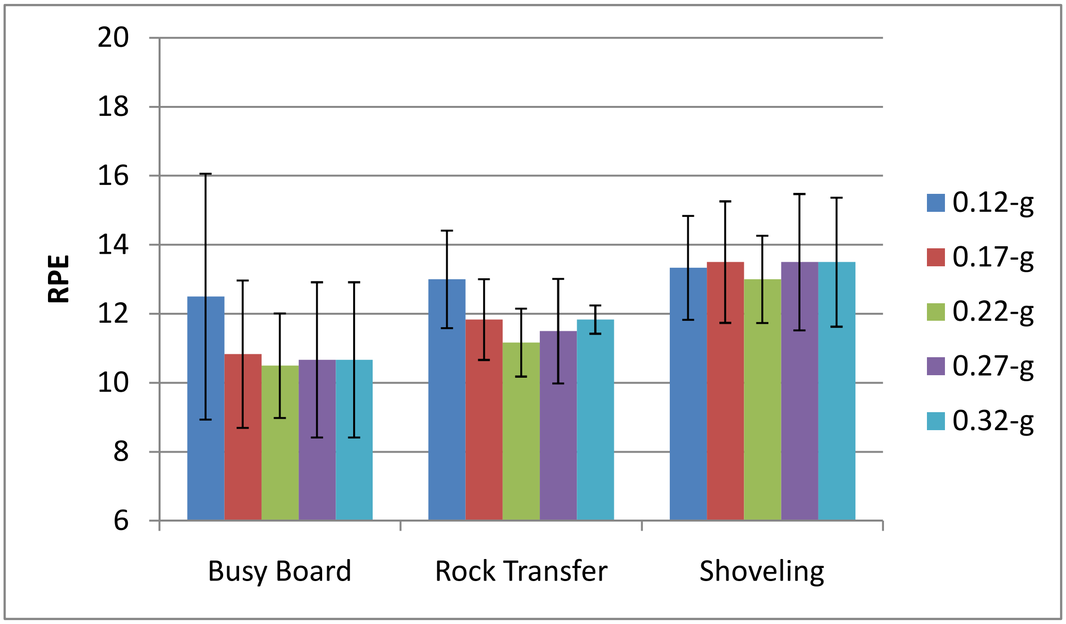


Figure 47. Rating of perceived exertion during exploration tasks at different gravity levels at a constant pressure (29.6 kPa) and suit mass (121 kg).

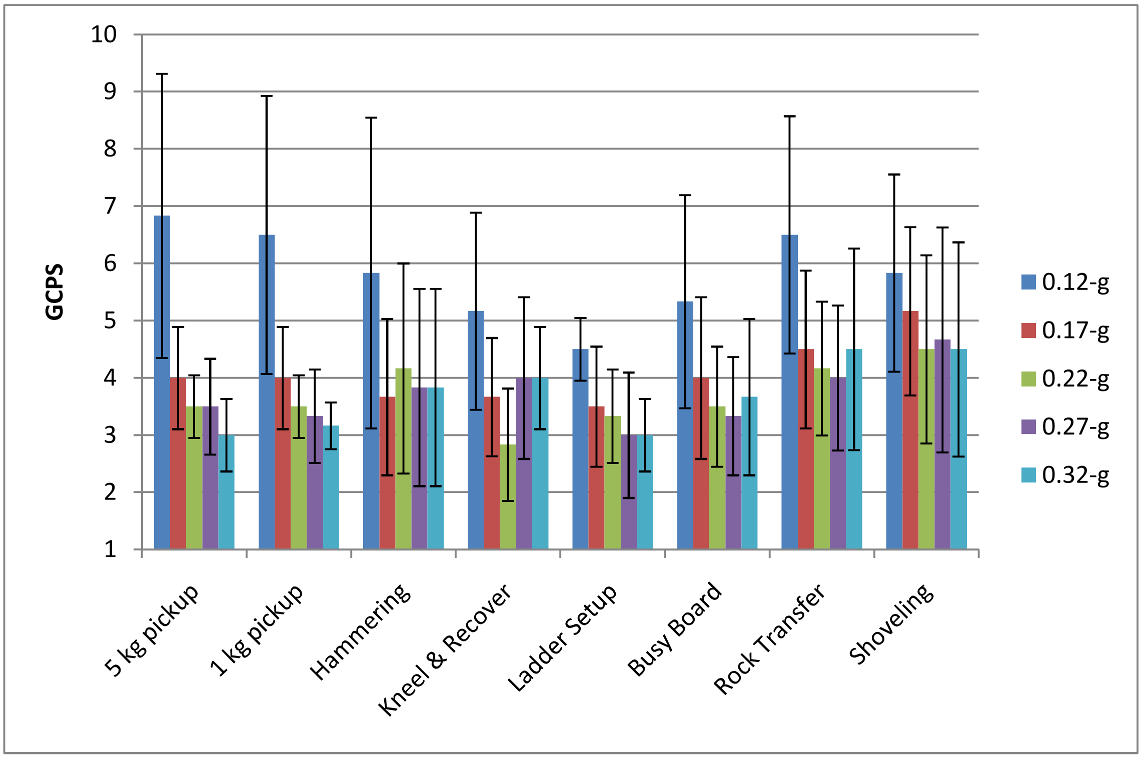


Figure 48. Gravity compensation and performance scale during exploration tasks at different gravity levels at a constant pressure (29.6 kPa) and suit mass (121 kg).

In addition to the measured subjective ratings, all subjects were asked to provide a rank order preference of the different weight conditions for both inclined walking and exploration tasks. For inclined walking, subjects preferred the 0.12-g and 0.17-g conditions equally as their favorite, followed by 0.22-g as a close third and then ranked the two highest gravities in fourth and fifth place. For exploration tasks, results showed two consistent trends. All subjects ranked the 0.22-g condition as their favorite, although one subject stated that 0.22-g and 0.17-g were tied as his favorite. All subjects also ranked the 0.12-g condition in last place. The 0.27-g condition was always second or third, and 0.32-g was always third or fourth. The 0.17-g condition had the greatest range where it was tied for first with one subject, but also was distributed among second, third, and fourth place. It is important to note that several subjects stated that all conditions but the 0.12-g condition were acceptable.

Shirtsleeve RPE (Figure 49) and GCPS (Figure 50) ratings were similar to the metabolic rate showing little difference between reduced gravity and varied mass conditions. Mean RPE ratings at 1-g were the lowest for all three tasks, and GCPS ratings for 1-g are not shown because they rate a “2” by definition on the scale.

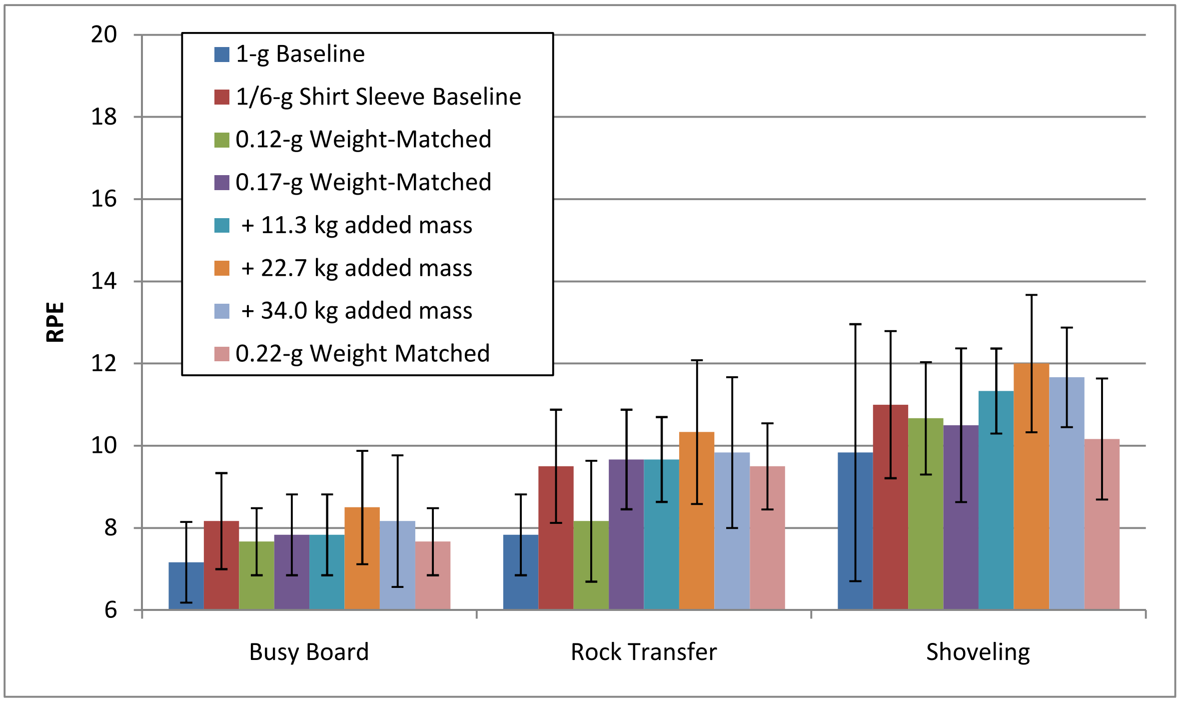


Figure 49. Rating of perceived exertion for exploration tasks at all shirtsleeve conditions.

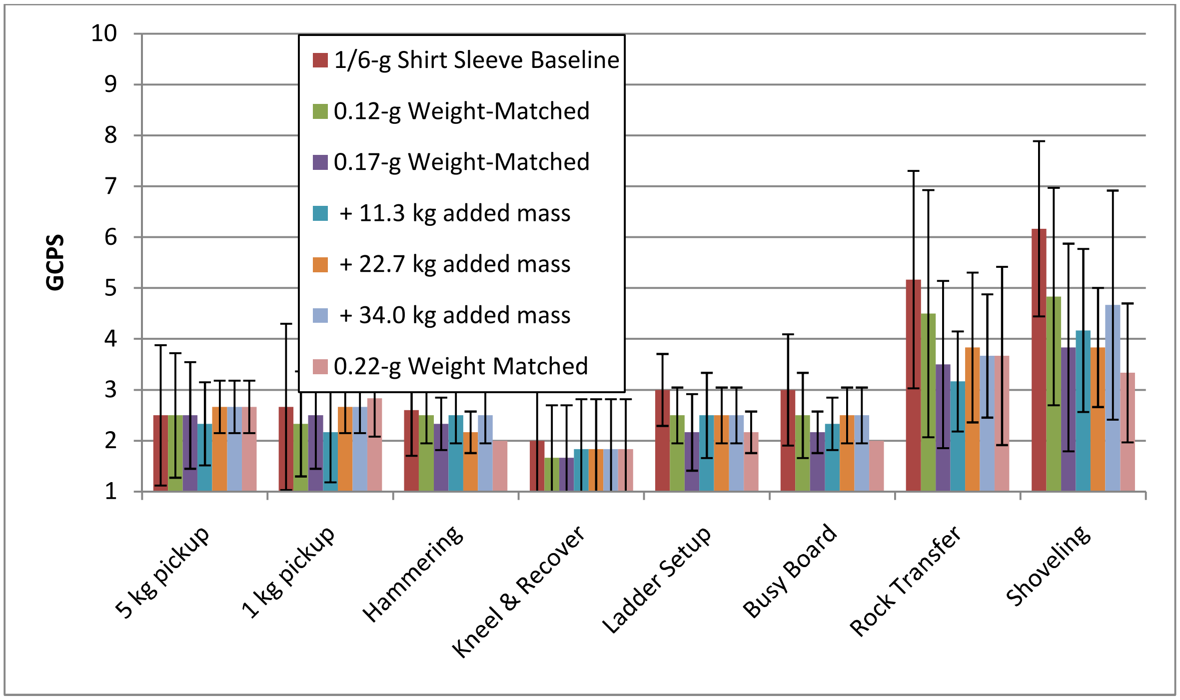


Figure 50. Gravity compensation and performance scale for all exploration tasks at all shirtsleeve conditions.

Biomechanics Findings

Treadmill results

Kinetics

Figure 51 shows the peak normalized GRF at different suit weights. With the heaviest suit weight, the body is loaded as much as 1.7 times BW. As with previous IST results, a trend of increasing peak GRF is observed with increases in suit weight. Additionally, general trends seen in these data demonstrate that subjects experienced peak GRF loads between 0.5 and 1.4 times BW, regardless of walking surface incline.

Hence, by looking at the normalized GRF with respect to 1-g Earth mass, one can easily observe that by modulating suit weights (even minimally), the human musculoskeletal system will be exposed to impacts as much as 1.7 times the BW of the crew member with each step taken. Examining the GRF data with this normalization scheme can provide a useful tool for researchers and suit designers. The GRF analysis with this normalization scheme can be used to help quantify the amount of loading applied to the musculoskeletal system during EVA locomotion. This information can be further used to develop an exercise protocol to complement the loading as a result of an EVA.

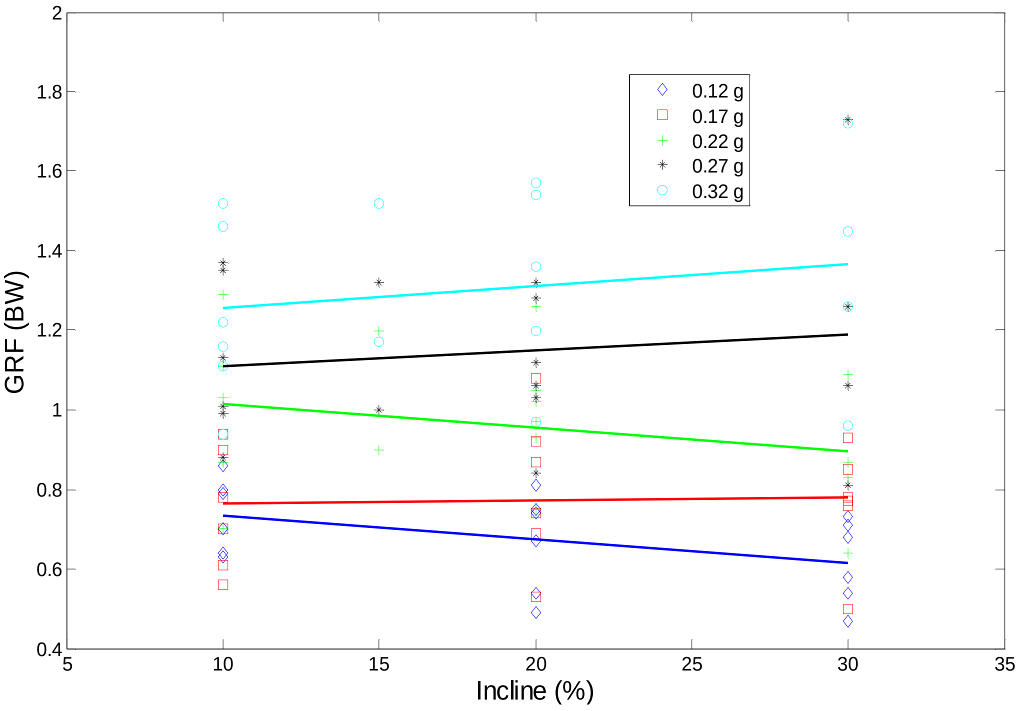


Figure 51. Peak vertical ground reaction force normalized to body weight for all subjects at varying suit weights during suited inclined treadmill walking.

Temporo-spatial characteristics

As incline increased, there was a general trend of increasing cadence (Figure 52). As weight was increased, there was no consistent trend seen with cadence. As stated previously, this may be entirely associated with the fact the subjects are still compensating for the inertia and mass of a 121-kg suit; to date, no studies have characterized the effects of suited ambulation on cadence while walking up an incline.

Joint Kinematics

Results from the inclined treadmill ambulation phase showed a general increase in the hip angle as incline increased for varying suit weight (Figure 53) conditions. Likewise, the hip angle at IC contact and TO increase with increasing offload. The mean knee-joint kinematics, which were time-normalized over the gait cycle for all subjects at varying suit weights, are displayed in Figure 54. Due to the variability among subjects, the only discernable trend was that with increasing inclines, there was an increase in the knee joint angle at IC. As weight increased, the effects of walking on an incline become more pronounced. The loading of the body is seen through the first peak and the swing phase is seen through the second peak. Unlike the rest of the gravity levels, the lowest gravity level has the peak knee flexion occurring near toe off.

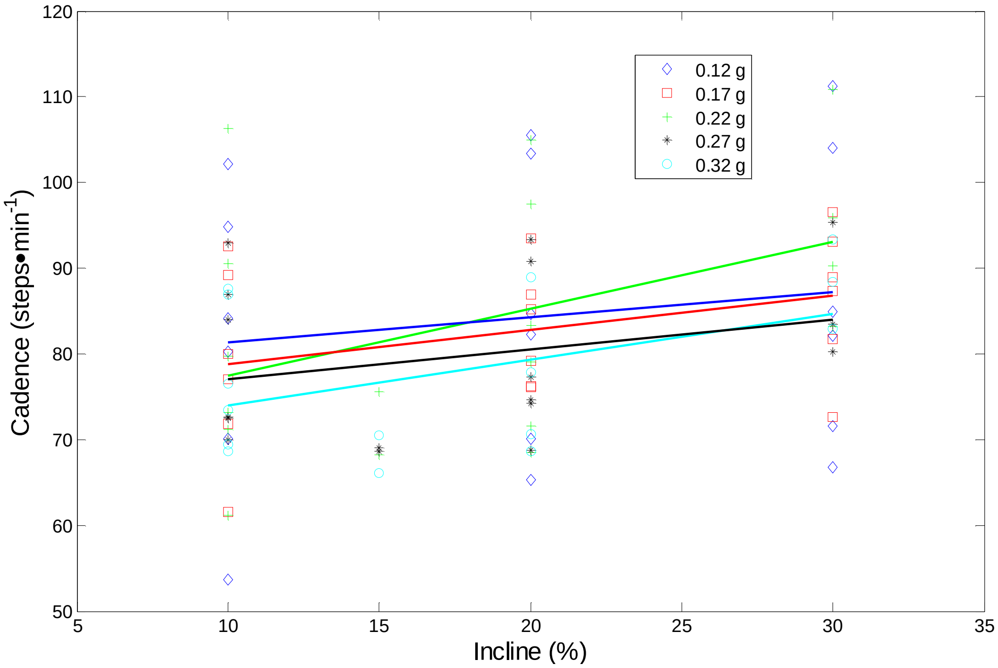


Figure 52. Average cadence for all subjects at different suit weights during suited inclined treadmill walking.

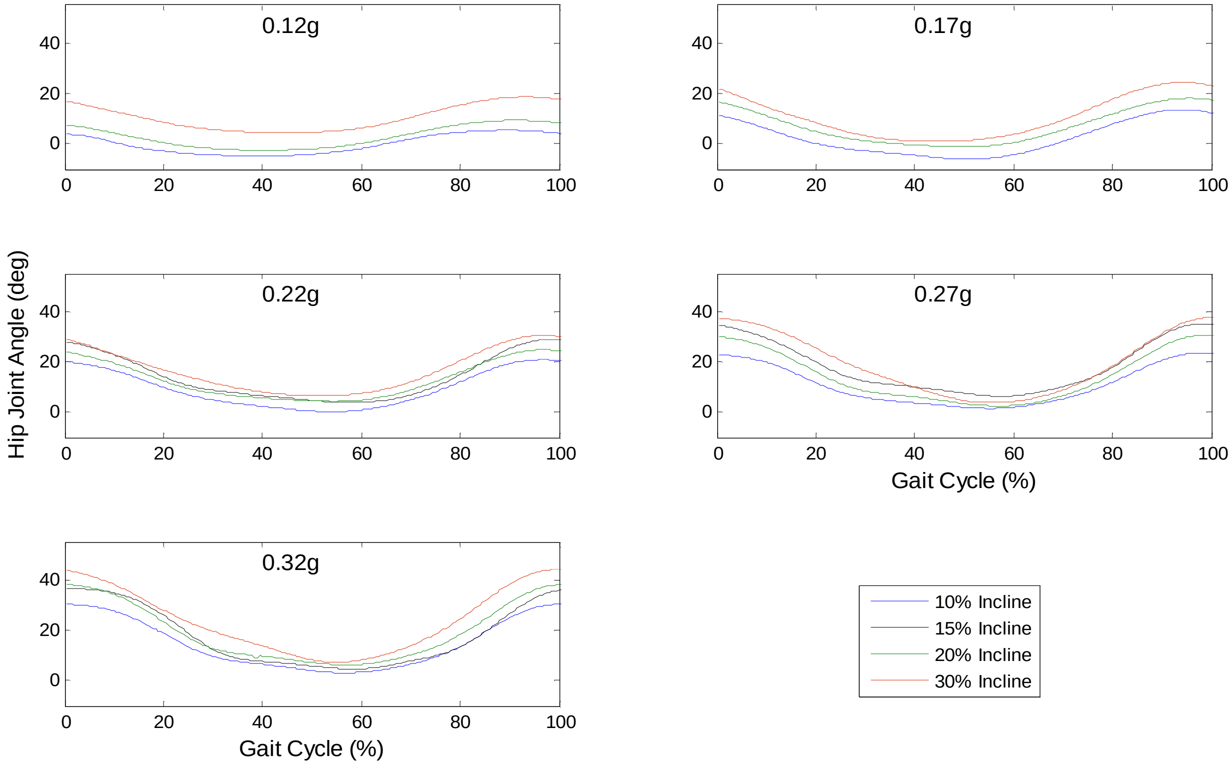


Figure 53. Mean hip angle vs. time normalized to the gait cycle for all subjects at different suit weights during suited inclined treadmill walking.

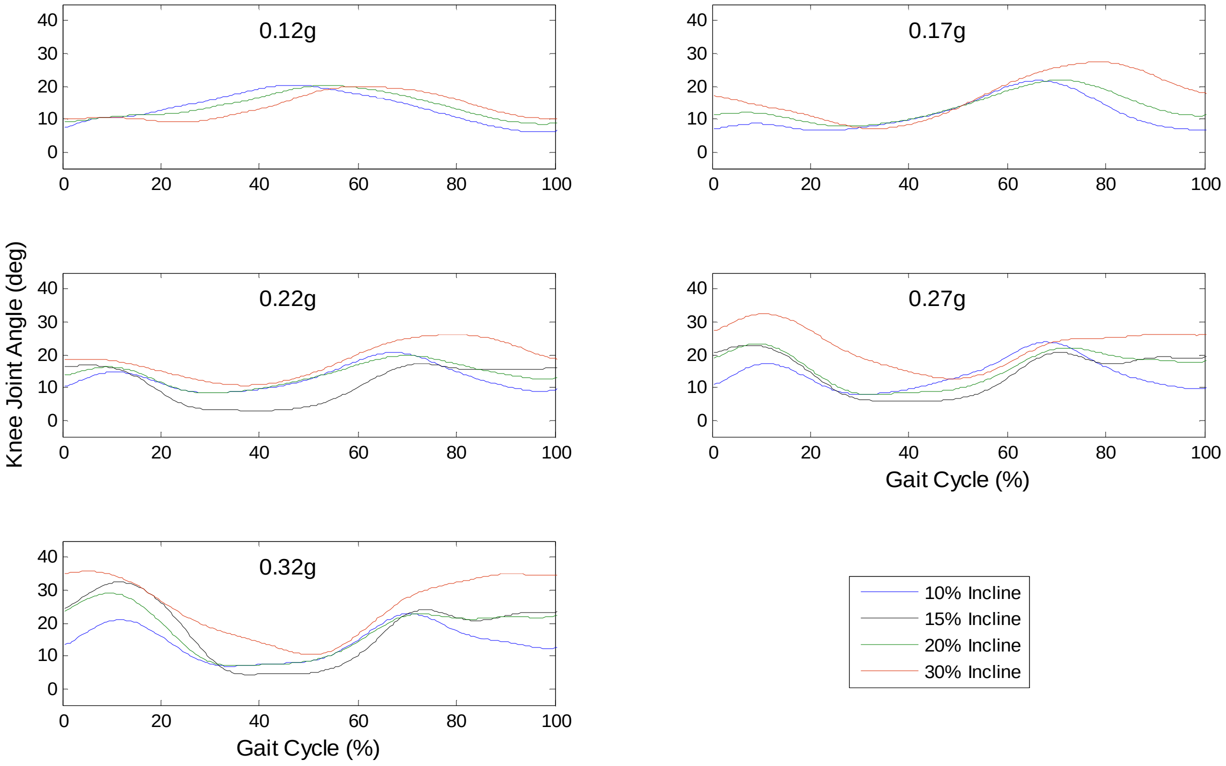


Figure 54. Knee-joint kinematics for varying suit weight conditions during suited inclined treadmill walking.

It was postulated that with increasing inclines of treadmill walking, there would be a change in the position of the knee angle at IC and TO. Plotting the joint position data against incline on the independent axis revealed no observable trends from changing suit weight (Figure 55).

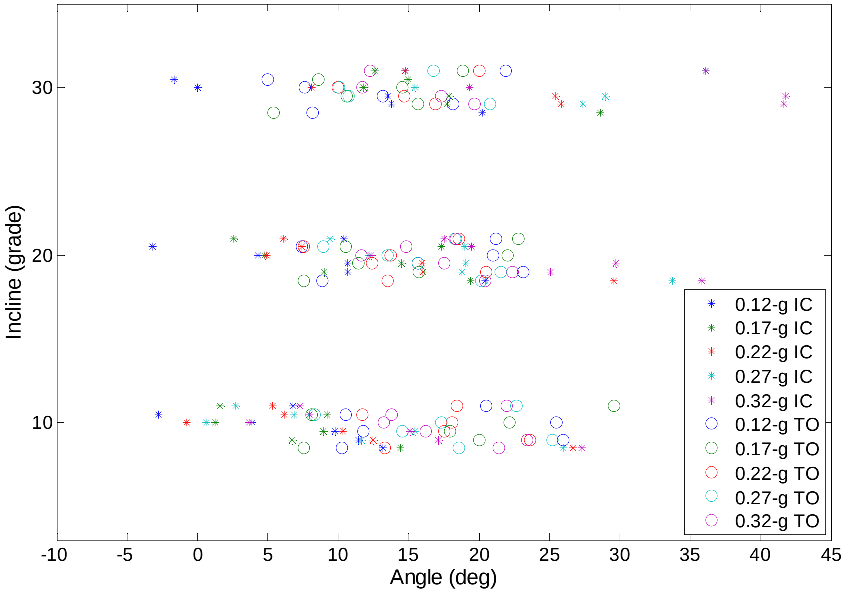


Figure 55. Knee initial contact and toe-off for all subjects at varying weights while walking at 10%, 20%, and 30% grades.

Figure 56 shows that as weight increases, the average initial contact angle of the knee increases. As only two subjects completed the 15% incline conditions, their data were not considered for the analysis. The increase could be that as weight and incline increased; the heavier weight must be compensated for to lessen the impact to the musculoskeletal system. Unlike the IC angles, the TO angles remained relatively unchanged as the weight increased. Therefore, one could assume that weight affected the IC knee angle but did not affect the TO knee angle.

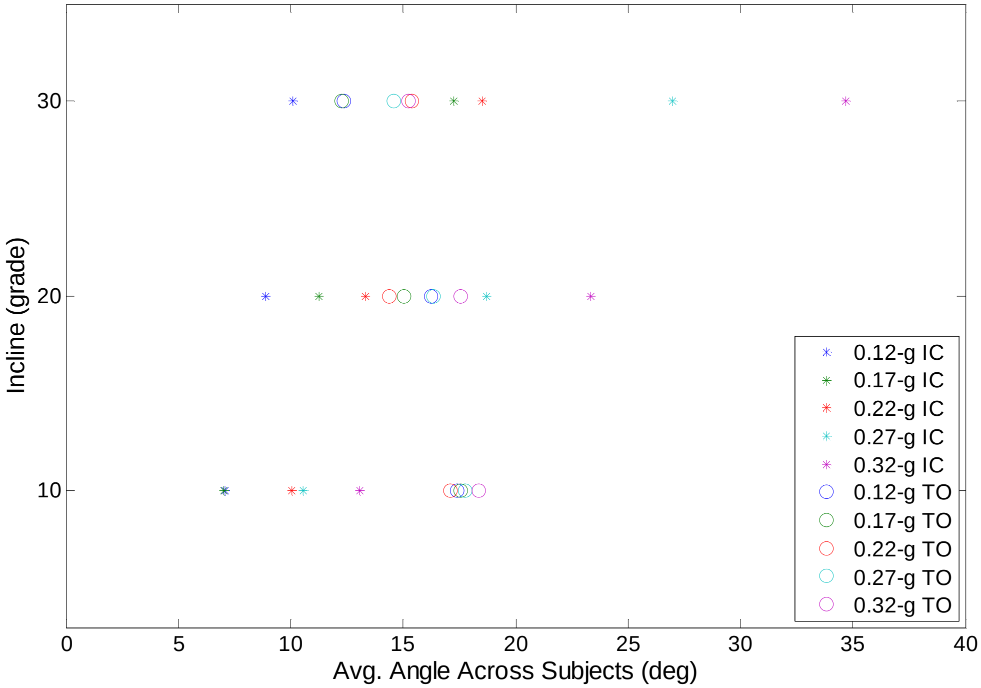


Figure 56. Knee initial contact and toe-off averaged over all subjects at varying weights while walking at 10%, 20%, and 30% grades.

As the angle of incline increased, the ankle angle at IC increased for varying weight conditions (Figure 57). As mentioned previously, this was most likely resulted from the fact that subjects tended to hop or lope during this condition rather than walk. This type of gait would naturally require increased plantar flexion in the ankle joint to propel subjects upward and forward.

Figure 58 shows the mean three lower-extremity joint ROM vs. weight and incline. With the data represented three-dimensionally, the effects of weight and incline on the joint ROM can be more readily seen. The greatest hip ROM was observed at the highest incline with a heavier suit (Figure 58a). Figure 58b demonstrates that a heavy suit and a high surface incline have the greatest effect on knee joint ROM. The ankle joint ROM showed similar patterns to those of the hip and knee; ie, with a high incline, there was an increase in the joint ROM required to complete the task (Figure 58c).

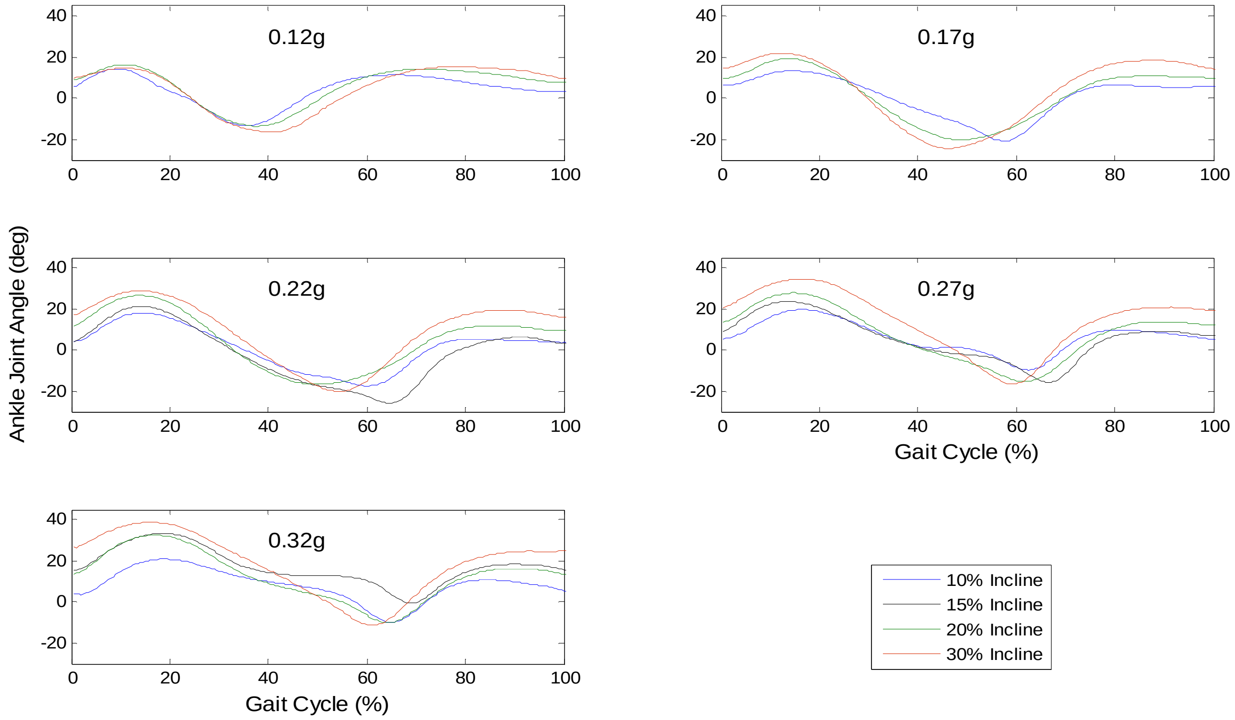
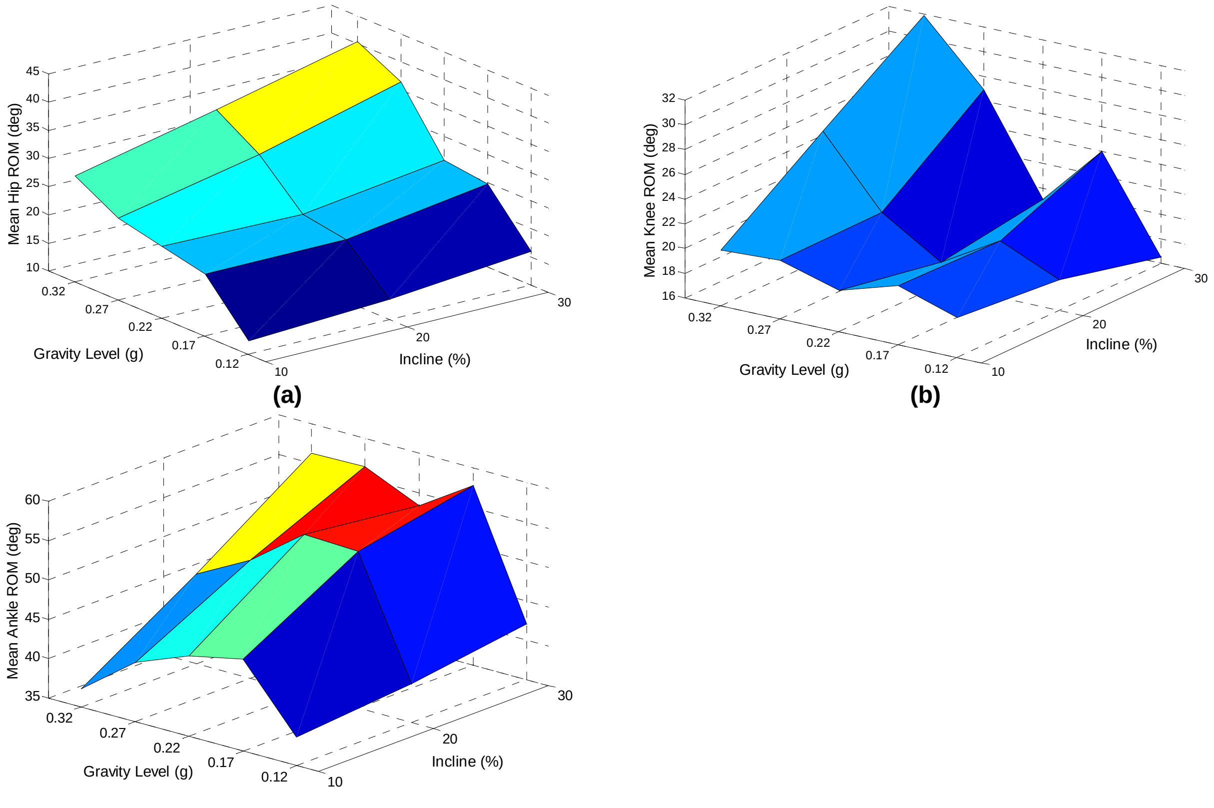


Figure 57. Ankle joint kinematics for varying suit weights while walking at 10%, 15%, 20%, and 30% grades.



(a)

(b)

(c)

Figure 58. Three-dimensional visualization of the mean three lower-extremity joint ranges of motion vs. suit weight and incline.

The joint kinematic results from this study showed that walking on an incline requires greater hip, knee, and ankle ROMs with increasing surface inclines. This test also showed that the suit will require a greater ROM in knee and hip angles as the offload decreases. As the offload increased to the 0.12-g level, the resulting "weight" of the subject was light enough that the subject had reduced dorsiflexion and plantar flexion compared to the other conditions. This was most likely a result of the reduced need for power generation in the ankle. Another finding was that there was the appearance of troughs at the 0.22-g offload for the hip and knee ROM and a ridge for the ankle ROM at the same offload. This suggests that at the 0.22-g offload, there may be some optimum offloading (eg, suit weight) that requires less hip and knee ROM. The results from this study demonstrate that a heavy suit similar in joint design to the MKIII will require increased joint ROM capabilities to perform incline locomotion tasks.

Additional Kinematic Measures

Figure 59 depicts the waist-bearing cycles for all subjects at different suit weights. Much like the GRF data, in which the waist-bearing data were presented in the traditional format of degrees per cycle, these data do not allow for any clear inferences or conclusions to be drawn due to the large variation in their spread.

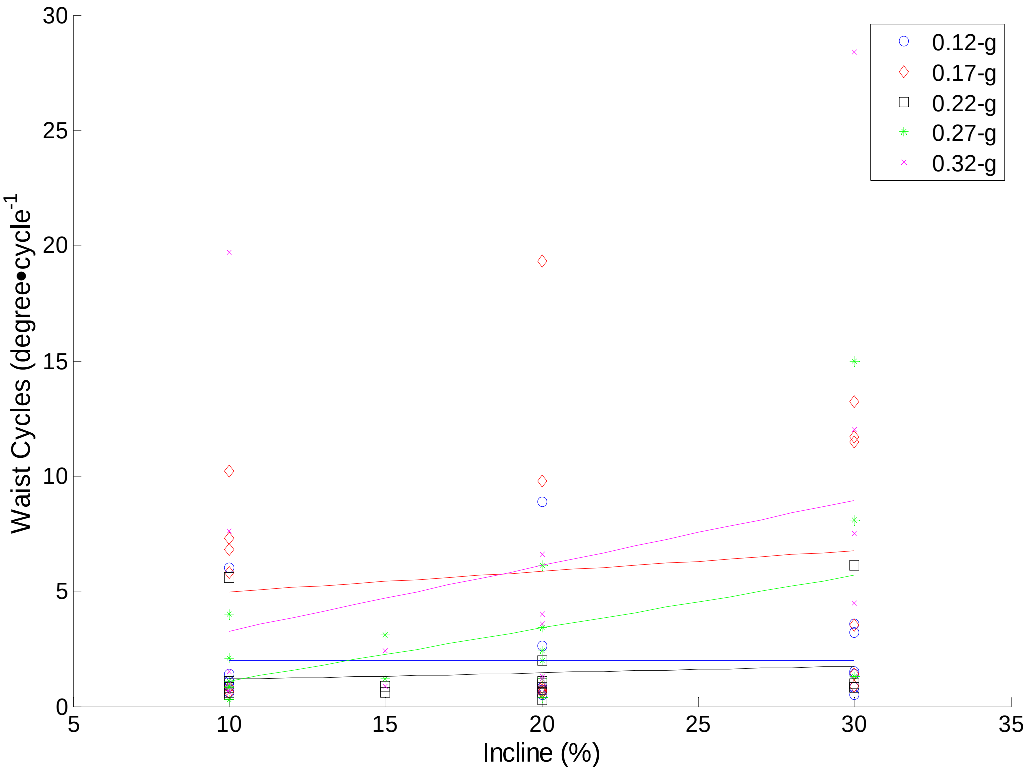


Figure 59. Waist-bearing cycles for all subjects at different gravities during treadmill walking at 10%, 15%, 20%, and 30% grades.

Figure 60 shows the linear travel of the waist bearing per cycle for all subjects who completed the inclines at different suit weights during treadmill walking separated by 10%, 20%, and 30% inclines. This figure reveals that as suit weight and incline increased, there was a general increase in the linear travel of the waist bearing per cycle. This finding can be explained by the fact that a greater demand was placed on the body to lift the foot up an incline to maintain the adopted gait pattern. The joint kinematic data demonstrate an increase in the hip and ankle joint ROM (Figure 58) as suit weight and incline increased. However, with increased weight, an increased rotation of the waist must occur to help the subject achieve the necessary lower-extremity joint ROM to ambulate on the inclined surface. Therefore, it can be concluded that with increasing suit weight, the waist bearing will experience greater wear.

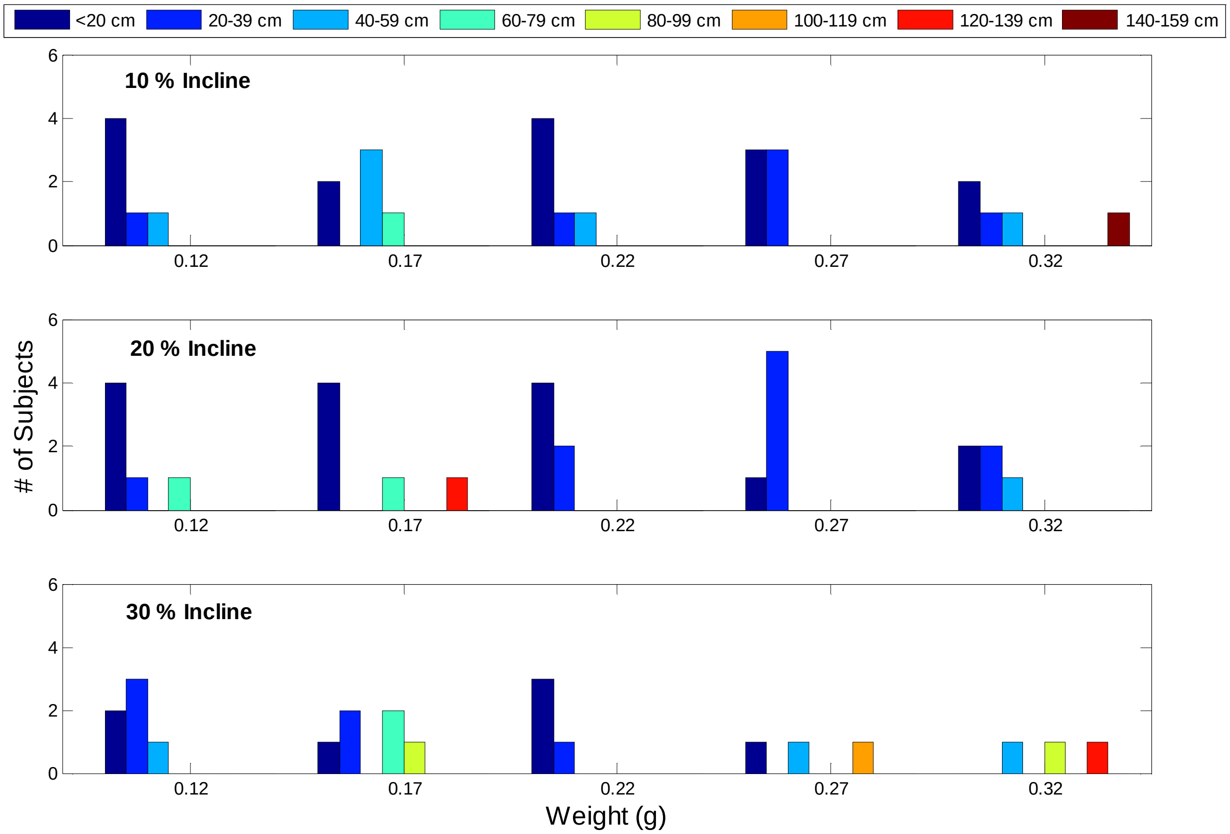
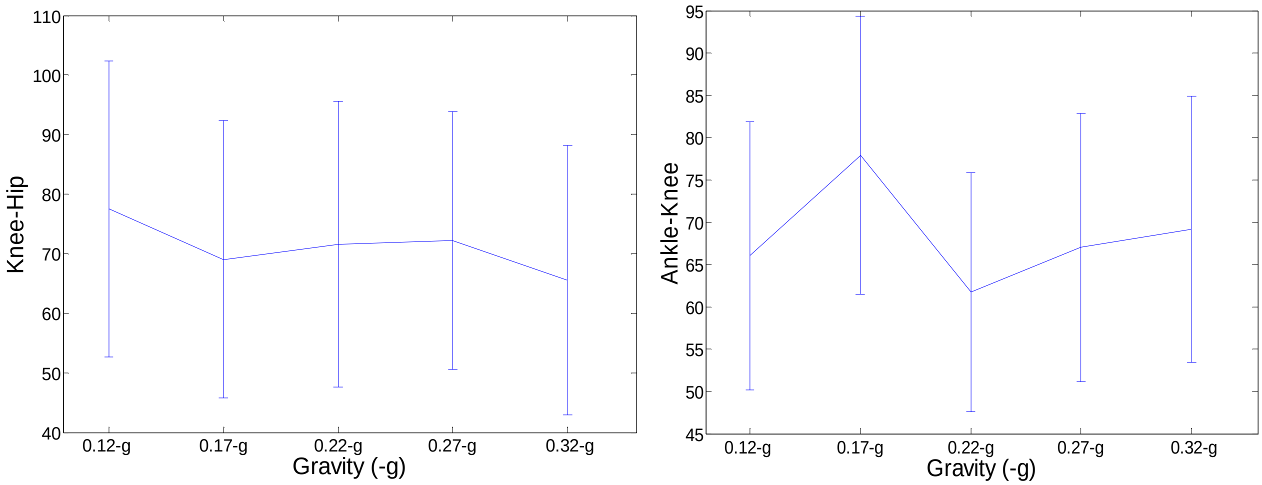


Figure 60. Linear travel of the waist bearing for all subjects at different suit weights during suited inclined treadmill walking.

As previously discussed, a phase portrait is a new technique applied to gait analysis to determine a qualitative picture of the organization of the neuromuscular system. The mean absolute relative phase for the knee-hip and ankle-knee segments is displayed in Figure 61.These data show that the knee and hip joints are more in phase for the heaviest condition at 0.32-g, and the ankle and knee joints are more in phase with heavier suits. However, again the graphs also display the confidence level (via error bars) of the data. The error bars span a large range for all plots, suggesting a large amount of variability among subjects. Future tests with more familiarization time and, possibly, even control over the subjects' gait would reduce the variability observed in this test. Despite the large variability, it is interesting to note that both the knee-hip and ankle-knee interacting segments display more in-phase relationship with a heavier condition. This finding suggests wearing a heavier suit may be more stable and may be closer to walking on Earth.



(a) (b)

Figure 61. Mean absolute relative phase for the interacting segments of the hip and knee and the ankle and knee at different suit weights during inclined treadmill walking.

Exploration results

For the exploration phase of this study, kinematic and kinetic data were collected for the rock pickup and shoveling tasks, and kinematic data only were collected for the kneel-and-recover task. The above information was used to perform specific analysis on each of these tasks, which are addressed in the following paragraphs.

Strategy Analysis
Rock pickup task

When performing the rock pickup task, subjects approached and then stood on dual-force platforms while attempting to maintain contact with the force platforms throughout the duration of the task. Subjects performed three trials using a “large rock” (5.5 kg), and a “small rock” (0.9 kg) for each of the various test conditions.

This examination was performed in an attempt to provide a qualitative estimation of subject stability while performing the rock pickup task. Foot placement was observed for each trial with the goal of determining whether subjects were capable of maintaining consistent contact with the force platforms (ie, stable) throughout the duration of the trial performed (Figure 62). Unstable foot placement occurred when any notable loss of balance or movement control (caused by the POGO, suit, etc.) required a repositioning of the subjects’ feet to complete the trial.

Figure 63 illustrates the concept of increasing stability with increasing weight across all subjects. As no trials at the 0.12-g condition elicited stable foot placement while performing the task, 75% of the rock pickup trials performed at the 0.32-g condition were observed as being performed with stable foot placement on the designated force platform configuration. A more stable foot placement throughout the trial suggests less extraneous effort expended by the subject to maintain balance when performing the task.

Several different movement strategies were adopted by various subjects when performing the rock pickup task. Hand involvement (i.e., the hand used by the subject to pick up/set down the rock) was of particular interest (Figure 63), as this was an integral part of the overall movement strategy employed by the subject, and may have had some influence on how the rest of the body coordinated movement production to perform the task.

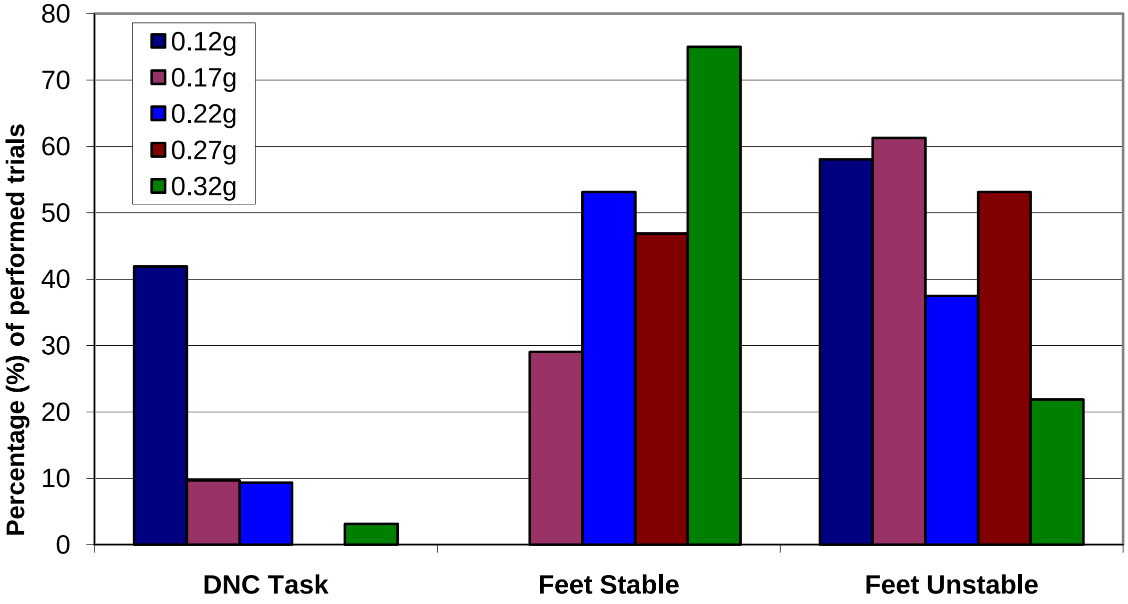


Figure 62. Percentage of trials with observed stable vs. unstable foot placement during rock pickup task. Subjects were rated on consistency of foot contact with force platforms. DNC (did not complete) Task: subject completely lost contact with force platforms, fell over, reported a gravity compensation and performance scale rating of 10, or used assistance (ie, leaned on nearby equipment) during the task.

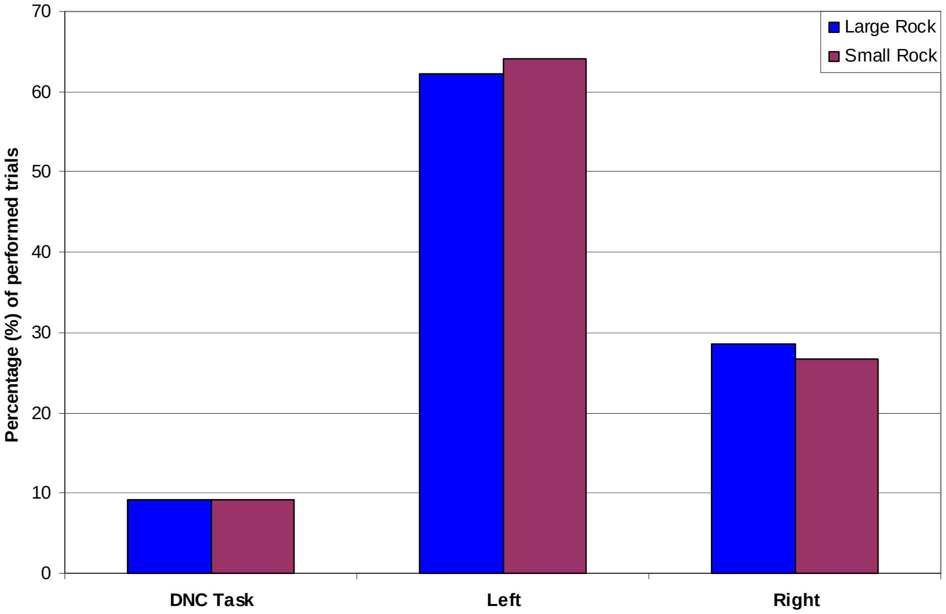


Figure 63. Hand involvement during large and small rock pickup tasks.

As seen in Figure 63, subjects favored employing their left hand when performing both the large and small rock pickup tasks. These results are interesting in that only one of the six test subjects was noted as being left-hand dominant. This suggests that either the novelty of the task as it was performed in the MKIII suit or the overall movement pattern adopted to complete the tasks played a large role in how subjects chose to incorporate their upper extremities.

Given the difference in hand involvement when performing the rock pickup tasks, it is worthwhile to examine the interaction between the upper and lower extremities (ie, how the subjects coupled lower body movement with the reaching movement of the selected arm) during task performance. Analysis of this interaction (Figure 64) provides further insight into the overall movement pattern selected by the subjects when performing the rock pickup tasks.

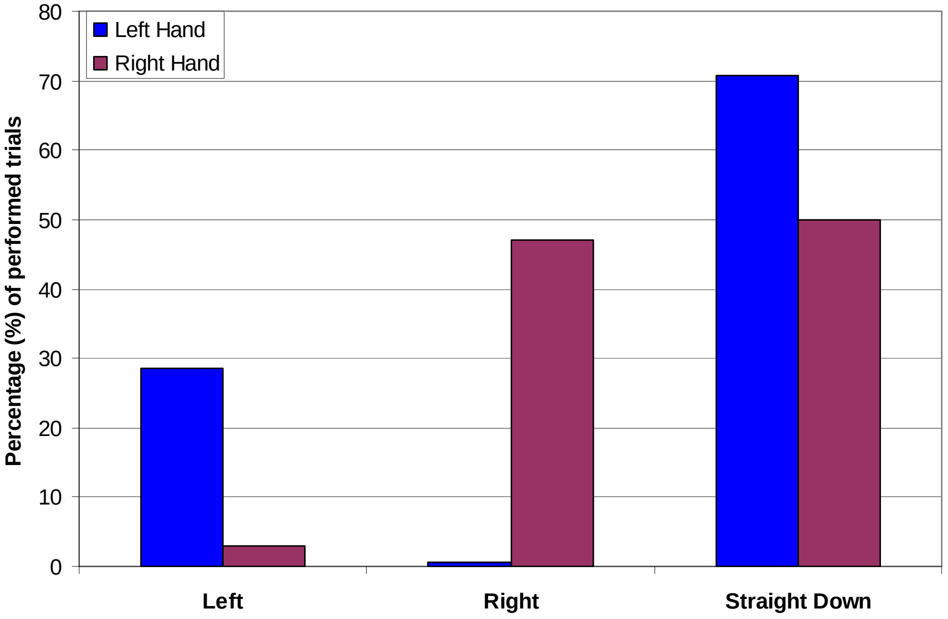


Figure 64. Interaction between upper and lower extremities when performing rock pickup tasks. Subjects either leaned to the left, leaned to the right, or bent straight down (not favoring either left or right side) when picking up the rock.

Figure 64 illustrates the interaction between the selected upper extremity and the movement pattern adopted by the lower extremity when bending to pick up the rock. When the subjects picked up the rock with the left hand, the primary lower-extremity movement pattern adopted was a straight-down, squat-type motion that did not favor one side or the other (ie, leaning to left or right). However, in some instances, subjects picked up the rock with the left hand and also leaned to the left when bending down to complete the task. Picking up the rock with the right hand elicited a similar lower-extremity movement strategy; right hand involvement was coupled with leaning to the right.

These trends in movement strategy provide insight into the subject’s preferred motion pattern(s) when performing a rock pickup task; however, it is unclear whether these preferences arise from movement constraints of the suit or from limitations in study design. The “rocks” were not located on the ground but were atop a large VacuMed (Ventura, Calif.) treadmill, approximately 50 cm above the surface of the force platforms. Additionally, subjects were instructed to stand on and maintain contact with the two force platforms, each with 46 × 51-cm surface dimensions. This likely resulted in movement modification by subjects to remain in contact with the force platforms while still effectively completing the task. Suit constraints may also have affected the subject's ability to perform the task: coordination of movement of varying joint types (eg, scye, convolute) may have been a determining factor in the strategy selected. For instance, movement of the thigh bearings is more conducive to hip external rotation, a movement not readily accomplished when bending straight down. When subjects bent down, rotation of the thigh bearings caused outward rotation of their hips. This can be considered a characteristic of the suit that likely had some influence on the movement strategy selected.

Based on this information, suit designs that included thigh bearings, such as those associated with the MKIII, must also include sufficient knee and ankle ROM. This would accommodate the movement patterns adopted as a result of the inclusion of these thigh bearings. If these suit joints do not allow for adequate ROMs, compensatory actions taken to modify movement strategy may adversely affect the crew member's ability to efficiently complete nominal exploration tasks.

Kneel-and-recovery task

The kneel-and-recovery task was performed over level ground. Subjects were allowed to select their movement pattern when performing the task (ie, which knee contacts the ground). Subjects did not perform the kneel-and-recovery task on force platforms, as the limited surface dimensions of the platforms did not allow subjects to perform a self-selected movement.

Two major techniques were observed (Figure 65) when examining performance of the kneel-and-recovery task: a controlled, deliberate movement when rising from a kneeling position (ie, "stand up"), and a jumping technique in which subjects performed the rise phase via a movement primarily characterized by a disconnect between the feet and the ground on rising (ie, "jump up").

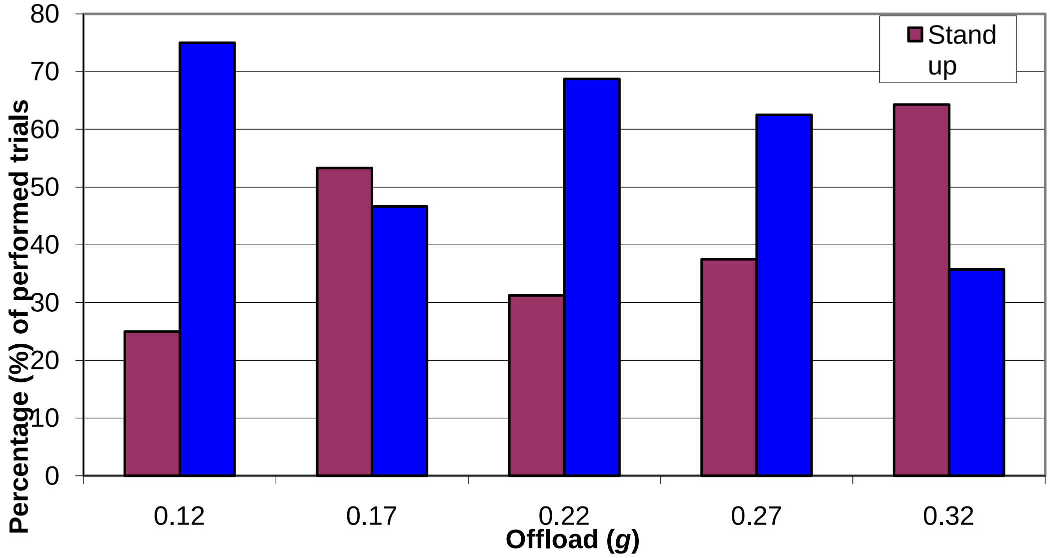


Figure 65. Comparison of two main strategies ("stand up" and "jump up") with varying weighted conditions for the kneel-and-recover task.

As seen in Figure 65, a clear difference exists between observed strategies at the lightest (0.12-g) and heaviest(0.32-g) weight conditions. At the 0.12-g condition, subjects were three times as likely to adopt a “jump-up” movement strategy. This phenomenon may be a product of the amount of weight relief provided by the POGO system – the amount of weight offloaded by the system at this condition provided significantly more assistance to the subject when rising from a kneeling position. However, when offloaded to 0.32-g, subjects did not have as much assistance from the system, thus resulting in a much more deliberate movement pattern (ie, “stand up”).

With the exception of the 0.17-g condition, a general trend is seen in employed movement technique as weight increases. With increasing weight, the percentage of the “jump-up” strategy decreases, while the percentage of “stand-up” trials increases. This suggests, as would be expected, that heavier ground weights translate into a more deliberate movement performed by the subject. It is likely that on the POGO system, a trade-off exists between the offloading amount and the amount of assistance available to the subject during movement production. Specifically, the greatest resistance to downward movement occurred when subjects were at the greatest amount of offloading (ie, the lightest suit weight)**.** Thus, when the subject begins the upward phase of the movement, the POGO pulled upward with greater force, facilitating the use of the “jump-up” strategy. Consider the POGO being loaded like a spring; the more it is pulled on (loaded), the greater the potential energy being stored. Once the spring is released, the potential energy is transferred into kinetic energy and the spring snaps back to its resting state. This is evidenced by the greater frequency of the “jump-up” strategy selected by subjects when offloaded to 0.12-g, and the increasing frequency of the “stand-up” strategy at the 0.22-g, 0.27-g, and 0.32-g offloading conditions.

Examination of selected strategies for the 0.17-g condition reveals an inconsistency with the trend exhibited by the other considered offloading conditions. One possible explanation for this inconsistency may be attributed to the large number of trials performed at this weight condition, albeit at varying pressure conditions. Subjects performed the 0.17-g trials at operating pressures of 6.9 kPa (1.0 psi), 20.7 kPa (3.0 psi), and 29.6 kPa (4.3 psi) in addition to initially performing a familiarization run at 0.17-g with an operating pressure of 29.6 kPa. The higher volume of trials performed at this weight allowed for greater subject acclimation to the weight condition experienced when compared to other weighted conditions.

The inconsistency of trend observed with the 0.17-g results for the kneel-and-recovery task warranted further investigation of this condition, namely at varying operating pressures (Figure 66)

Figure 66 demonstrates that a general trend of increased percentage of the “stand-up” strategy was observed with increased operating pressure. Conversely, a decrease in the percentage of the “jump-up” movement strategy was observed between the 20.7 and 29.6 kPa conditions. No difference in “jump-up” frequency was observed between the 6.9 and 20.7 kPa conditions. Observed trends may be attributed to the increased stiffness of the soft goods components of the suit, which is caused by the increase in operating pressure. This may have worked to hinder the subject’s ability to generate rapid movements, as the subject had to overcome the increased stiffness at various lower-extremity joints, resulting in more deliberate movement patterns not conducive to a forceful, dynamic upward jump from the kneeling position.

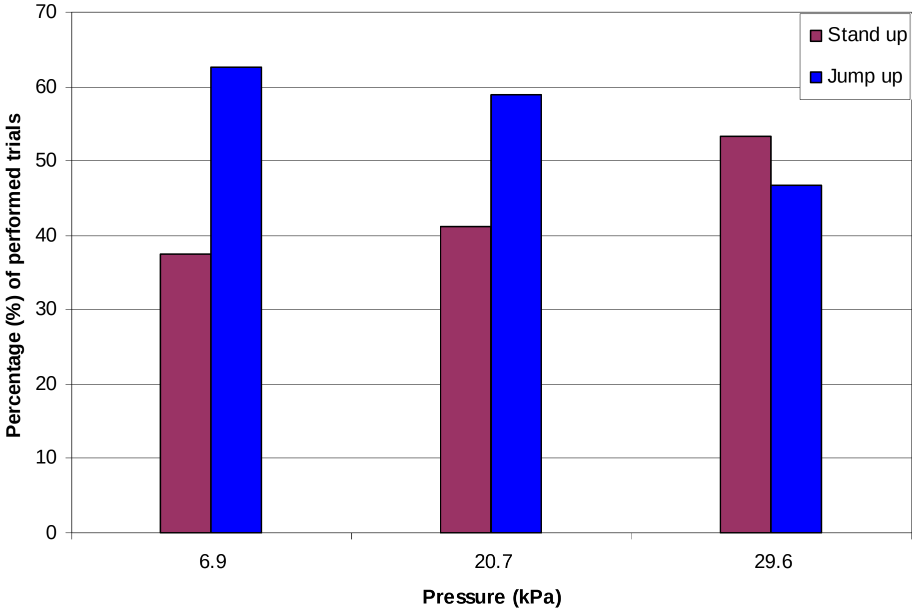


Figure 66. Percentage of "stand-up" and "jump-up" strategies across varying operating pressure conditions at the 121-kg weight condition for the kneel-and-recover task.

Suit operating pressure may have an effect on movement strategy but further testing is warranted. Further analysis is needed due to the small sample size and the small increases observed on the kneel-and-recover strategy for varying pressure conditions. If this relationship is accurate there are implications for suit design, in that the more deliberate movement associated with higher operating pressures may have been the result of increased suit joint stiffness. This joint stiffness likely translated to subject difficulty in bending the convolutes associated with the knee joint. To address this, suit design strategies must account for the variance in joint mobility at different operating pressures and the impact this could have on movement selection patterns.

Shoveling task

Subjects performed the shoveling task while standing atop the aforementioned dual-force platform configuration. During this task, the subjects moved one shovelful of rocks from one bin to another while attempting to maintain consistent contact with the force platforms. Several movement strategies were employed by test subjects when performing this task; this may be attributable to the complex interaction between upper- and lower-extremity segments.

As a result of this complex motion, whole-body coordination was required to perform the task effectively and efficiently. Coupling movement complexity with other test factors, such as varying weight (offloading) conditions and limited force platform dimensions on which to stand, may help provide insight into trends observed in movement strategies adopted by subjects during the shoveling task.

In an effort to provide a qualitative estimation of the effects these factors have on task performance, consistency/stability of foot placement on the force platforms was observed throughout the trial duration (Figure 67).

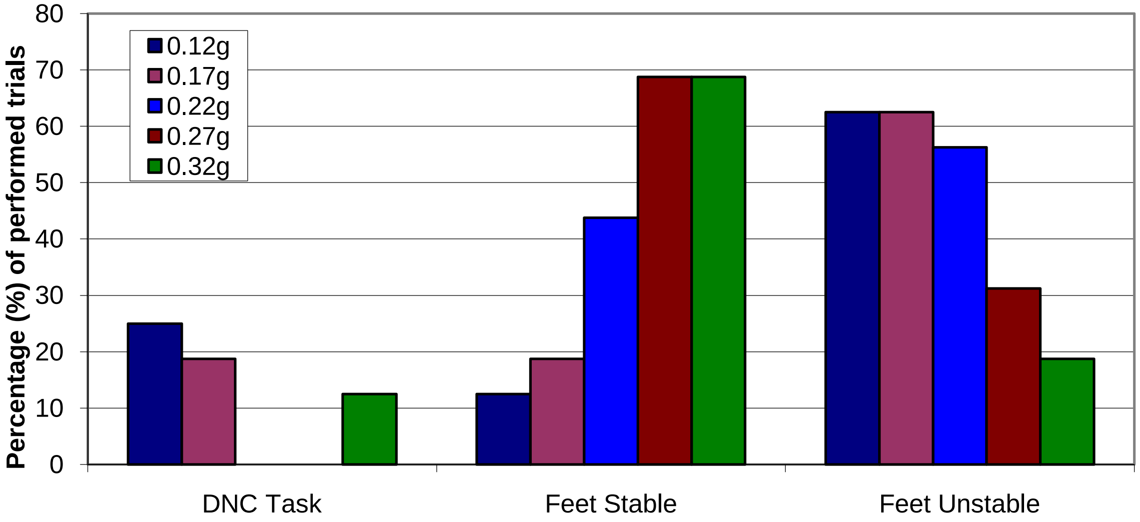


Figure 67. Percentage of observed stable vs. unstable foot placement during shoveling task. Subjects were rated on consistency of foot contact with force platforms. DNC (did not complete) Task: subject completely lost contact with force platforms, fell over, reported a gravity compensation and performance scale rating of 10, or used assistance (ie, leaned on nearby equipment) during the task.

Figure 67 illustrates an increase in stability of foot placement with increasing weight across all subjects. This demonstrates that the amount of weight relief provided by the POGO system profoundly affects the subject's ability to perform the complex shoveling task in an effective manner. This was further evidenced by the frequency of "DNC task" observations. Subjects had a more difficult time maintaining consistent contact with the force platforms while shoveling, often resulting in loss of balance, readjustment of foot placement, or general inability to complete the task. No discernable trends in foot placement stability were observed across varying operating pressures.

In the case of the rock pickup task, subjects simply bent to pick up and replace a rock on a platform. However, during the shoveling task, subjects were asked to perform a movement pattern that required a more involved coupling of upper- and lower-body segments while using a tool that necessitated coordination of both upper extremities. Hence, the shoveling task tended to require greater limb coordination and overall stability when compared to the rock pickup task. Performance of the shoveling task also induced a reaction force on the subject not experienced during the rock pickup task. The act of moving the shovel into the rock pile produced a reactive force on the shovel that translated back to the body, thus creating a condition of increased instability while the subject was attempting to maintain contact with the force platforms. This was exacerbated by lighter weight conditions (eg, 0.12-g and 0.17-g), as the POGO system provided a greater amount of offloading that acted to hinder the balance capabilities of the subjects during tasks. As seen in the kneel-and-recover task, lighter weights appeared to provide greater assistance to the movement produced. However, during a task that required greater stability during movement production, the assistance provided by this increased vertical offloading did not provide the subject with the ability to maintain balance when experiencing the reactive force of the shoveling movement.

Three exploration tasks were qualitatively analyzed to provide an initial, novel interpretation of movement strategies adopted by suited test subjects. When performing the rock pickup and shoveling tasks, foot placement was observed as more stable at higher weight conditions, suggesting a positive relationship between suited weight and stability during task performance. During the kneel-and-recovery task, increases in operating pressure resulted in a change in selected strategy from a more rapid movement to a more controlled and deliberate movement.

Analysis of movement strategies has provided direction for further analysis, including examination of the effects of movement strategy variance or modification on timed task performance, comparison of selected movement patterns and subjective ratings (ie, GCPS), and quantification of joint/bearing rotation and excursion during varying movement strategies and different weight and operating pressure conditions. These analyses of movement strategies during various EVA exploration tasks will provide further input into the characterization of lunar and martian planetary exploration spacesuits.

Center of Pressure

Examination of the percentage of the COP outside of the BOS for the small rock pick up revealed a large amount of variability among subjects. Specifically, some subjects' COP remained within the BOS for an entire trial while others' COP fell outside their BOS for up to 68% of the trial (Figure 68). Despite the variability among subjects, an important trend is readily obtained from this figure. At the heaviest suit weight condition, the percentage of COP outside the BOS was reduced appreciably. This finding suggests that a heavier suit was more ideal for picking up a small rock and reducing stability issues.

However, numerous factors affect the position of the COP. The most notable is the person's BOS. The smaller the BOS, the more likely the COP will fall outside the BOS when performing specific tasks (i.e., rock pickups), which will ultimately result in either the necessity to adjust the BOS or falling down. Other factors include, but are not limited to: suit weight, suited CG, experience in the MKIII, muscle strength and endurance, and inertial effects of the POGO. A combination of any or all of these factors will influence the results.

Both the large rock pickup task (Figure 69) and the shoveling task (Figure 70) exhibited trends similar to those seen with the small rock pickup task, with the exception of one outlier subject for the shoveling task. It is interesting to note that there is a convergence towards a smaller percentage of the COP outside the BOS with a heavier suit. Once again, these findings support the notion that a heavier suit may be more optimal for performing selected EVA tasks.

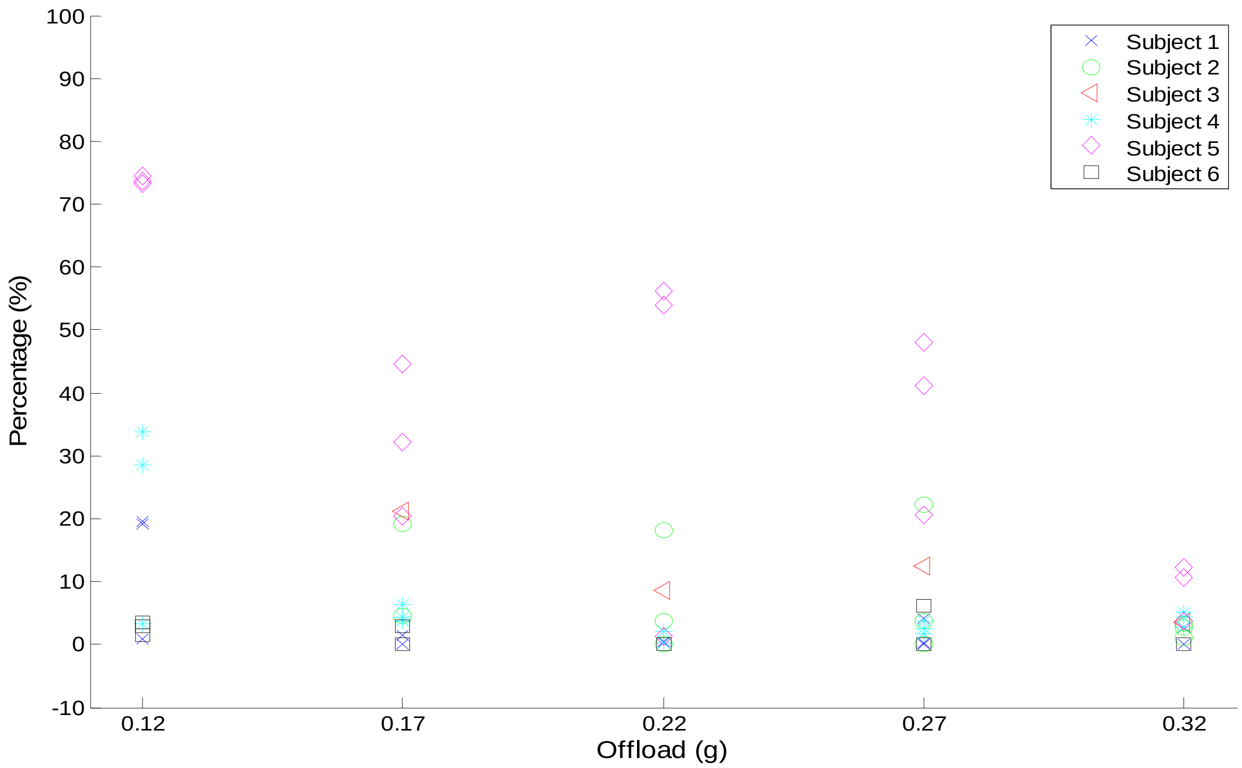


Figure 68. Percentage of center of pressure outside the base of support for the small rock pickup task for all trials for all subjects.

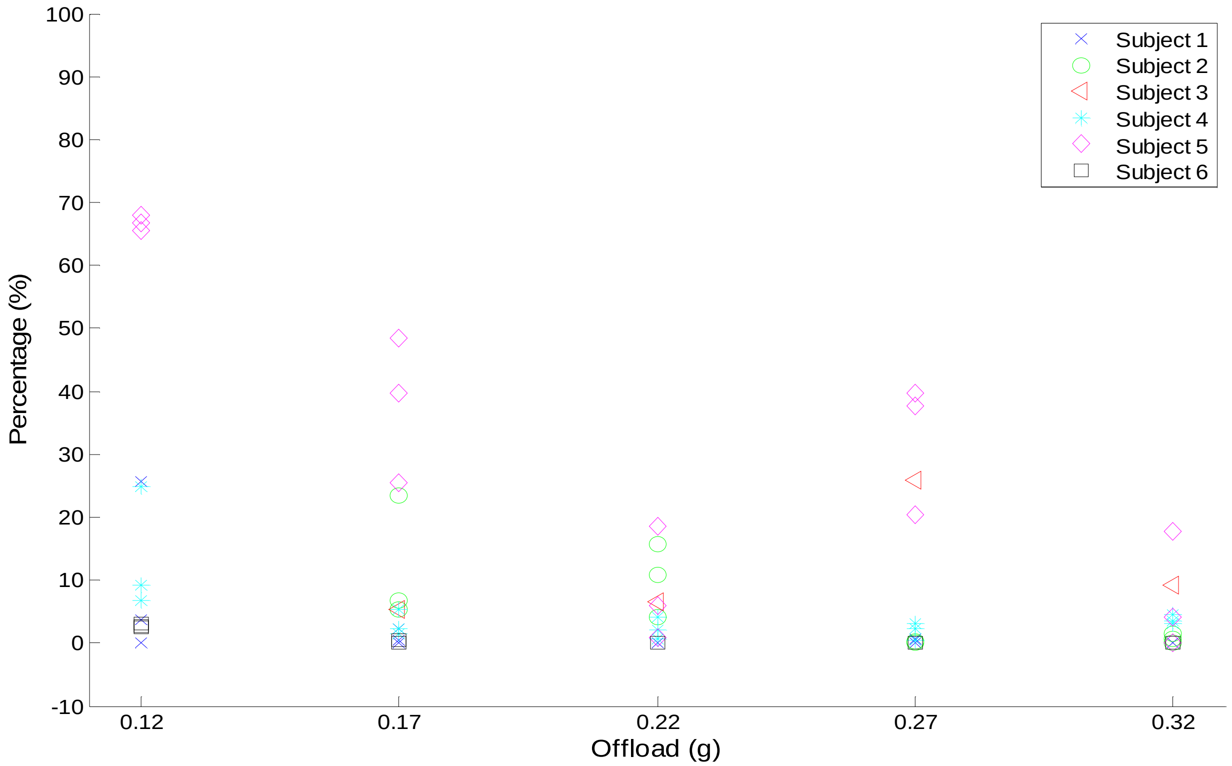


Figure 69. Percentage of center of pressure outside the base of support for the large rock pickup task for all trials for all subjects.

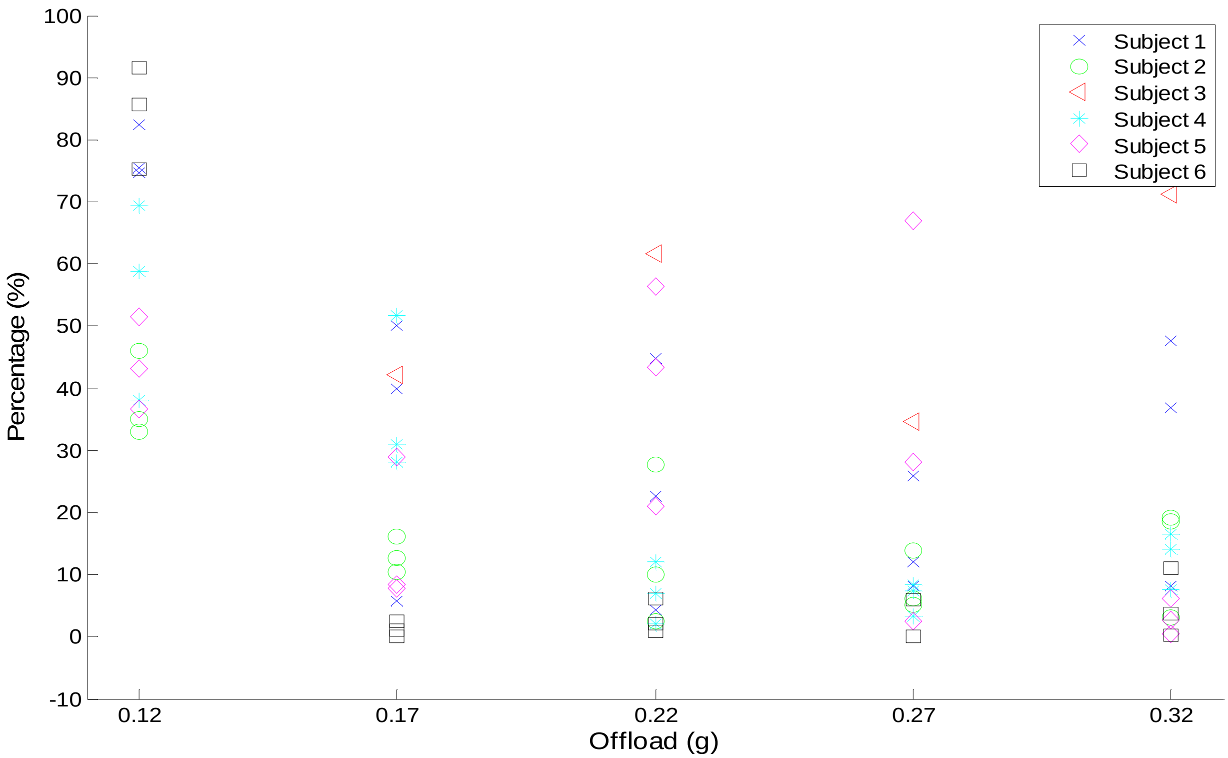


Figure 70. Percentage of center of pressure outside the base of support for the shoveling task for all trials for all subjects.

The COP analysis revealed that a heavier suit may be optimal for performing exploration-type activities. However, as mentioned above, many factors influence the position of the COP. Despite these limitations it is still exciting to realize there was a general trend that suggests a heavier suit may provide more stability.

NASA Task Load Index

For the treadmill activities, all suited subjects reported effort and physical demand as the two primary contributors to workload. For the unsuited treadmill activities, five subjects reported physical demand as a primary contributor to workload, four subjects effort, and two subjects performance as one of the contributors to workload.

For the suited exploration activities, four of the subjects reported physical demand as a primary contributor to workload, three performance, one mental demand, four effort, and one frustration. For the unsuited exploration activities, four reported performance as the primary contributor to workload, two frustration, one temporal demand, one mental demand, and three effort.

The workload scores, which were averaged for each condition, are presented in Table 3 and Table 4.

Table 3. Average Workload Scores for Suited Conditions

Suited Condition		Task Type	
Gravity	**Pressure (kPa)**	**Exploration Tasks**	**Incline Walking**
0.12-g	29.6	50.2	30.5
0.17-g	6.9	42.2	32.4
	20.5	42.2	37.7
	29.6	45.5	48.9
	34.5	Did Not Test	35.1
	44.8	Did Not Test	38.2
0.22-g	29.6	40.2	45.7
0.27-g		39.7	52.1
0.32-g		41.9	61.9
Suited Average		**43.1**	**42.5**

Table 4. Average Workload for Unsuited Conditions

Unsuited Condition		Task Type	
Name	**Average TGAW (lb)**	**Exploration Tasks**	**Incline Walking**
1-g baseline	180	20.8	36.5
0.17-g shirtsleeve baseline	30	32.1	28.1
0.12-g weight-matched	53	31.3	28.9
0.17-g weight-matched	76	21.3	30.4
+ 11.3 kg added mass	76	22.7	30.0
+ 22.7 kg added mass	76	22.3	32.3
+ 34.1 kg added mass	76	25.5	39.0
0.22-g weight-matched	98	18.0	27.8
Unsuited Average		**24.2**	**31.6**

IST-2 was a physically demanding series of test conditions and activities with no time limit, so the investigators expected participants to rate the physical demand of the tasks and the effort involved to complete them higher than the other factors that contribute to overall workload. The average workload scores were lower for unsuited activities (24.2 exploration, 31.6 treadmill) than for suited activities (43.1 exploration, 42.5 treadmill). The perceived workload was within the low to moderate range (0 to 30 low workload, 30 to 60 moderate workload, 60 to 100 high workload) with only one condition (4.3 psi, 0.32-g) for treadmill tasks having a high perceived workload (61.9).

3.3 Test Objective 3: Compare MKIII at POGO Configuration to the MKIII at POGO Configuration with the Waist Bearing Locked

To evaluate the effect of the waist bearing on performing the specified tasks, it was locked out (preventing the subjects from being able to rotate left and right at the waist location specifically).

This was done only at the POGO configuration of 121 kg, 29.6 kPa (4.3 psi), and 1/6-g. The data in Table 5 indicate that locking the waist bearing did not increase the metabolic cost or subjective ratings during exploration tasks. Rather, the trend was quite the opposite, as the waist-locked condition often had a lower metabolic cost and lower subjective ratings.

Table 5. Nominal vs. Waist-locked Configuration at 121-kg Suit Mass and 29.6 kPa

Exploration Task	**Metabolic Cost**		**RPE**		**GCPS**	
	Nominal	Waist-locked	Nominal	Waist-locked	Nominal	Waist-locked
Rock Transfer	4.0 ± 0.1 L/task	3.9 ± 0.6 L/task	11.8 ± 1.2	11.7 ± 0.8	4.5 ± 1.1	4.5 ± 1.2
Busy Board	2.4 ± 0.6 L/task	2.1 ± 0.4 L/task	10.8 ± 1.9	10.5 ± 1.4	4.0 ± 0.9	3.7 ± 1.0
Shoveling	57.5 ± 9.3 mL/kg rock	49.6 ± 12.0 mL/kg rock	13.5 ± 1.5	13.3 ± 1.2	5.2 ± 1.4	4.5 ± 1.0

One possible explanation for the slightly better results seen with the waist-locked condition could be due to the sequencing of trials. All subjects completed a full familiarization run through the whole exploration task course at the nominal configuration. They then repeated all exploration tasks in the nominal configuration in a later trial. Because the waist-locked configuration was not a primary objective, it was always completed last as the ninth trial of the session. By that time, all subjects had significant practice and familiarization with all of the tasks. Therefore, although the data indicated that the waist-locked condition might have been better, the order of trials completed was likely a significant reason for that finding. If the waist-locked condition was part of the balanced trial order, we may have seen different results. To demonstrate this learning effect, the metabolic rates for the familiarization trial at nominal configuration (performed first), the actual nominal configuration trial (performed second through fourth), and the waist-locked configuration trial (performed ninth) are shown in Table 6.

Table 6. Learning Effect for Exploration Task Metabolic Rate

Exploration Task	**Familiarization Trial**	**Actual Trial**	**Waist-locked Trial**
Busy Board (L/task)	3.5 ± 1.0	2.4 ± 0.6	2.1 ± 0.4
Rock Transfer (L/task)	4.7 ± 1.1	4.0 ± 0.1	3.9 ± 0.6
Shoveling (mL/kg rock)	83.3 ± 42.0	57.5 ± 9.3	49.6 ± 12.0

A big performance improvement was noted between the familiarization and actual trials at the nominal configuration. Subjects reported they needed a complete run through of the exploration task course before they understood how to complete the tasks in the suit. Subjects also thought their performance improved with experience. While the vast majority of improvement occurred between the familiarization trial and the first actual testing run, some improvement was witnessed as subjects completed each configuration trial. Balancing the varied pressure and varied weight trials reduced this effect in those data sets, but the waist-lock trial always occurred last, so subjects were completely familiarized with the tasks, likely improving performance.

Neither the strategy analysis data nor the COP analysis supported the metabolic findings that the waist locked condition improved performance. Comparison of the strategy analysis data waist unlocked to waist locked conditions showed that locking the waist affected the foot stability while picking up both the large and small rocks (Figure 71). As seen in Figure 72, subjects still favored using the left hand when performing both the large and small rock pickup tasks even with the waist bearing locked.

Figure 73 and Figure 74 demonstrate that for almost all subjects and instances for both the small and large rock pickup tasks, locking the waist bearing decreased the stability of the subjects. The percentage outside the BOS for almost all subjects increased as a result of locking the waist bearing. This most likely suggests that locking the waist bearing decreases the stability of subjects while performing both a small and a large rock pickup. One explanation of this finding could be that the subjects were instinctively using the suit in a new way to achieve the ROM required to complete the task. In this case, specifically it was possible that the subjects achieved the required ROM by increasing their use of the three-bearing hip/brief to make up for the absense of rotation at the waist.

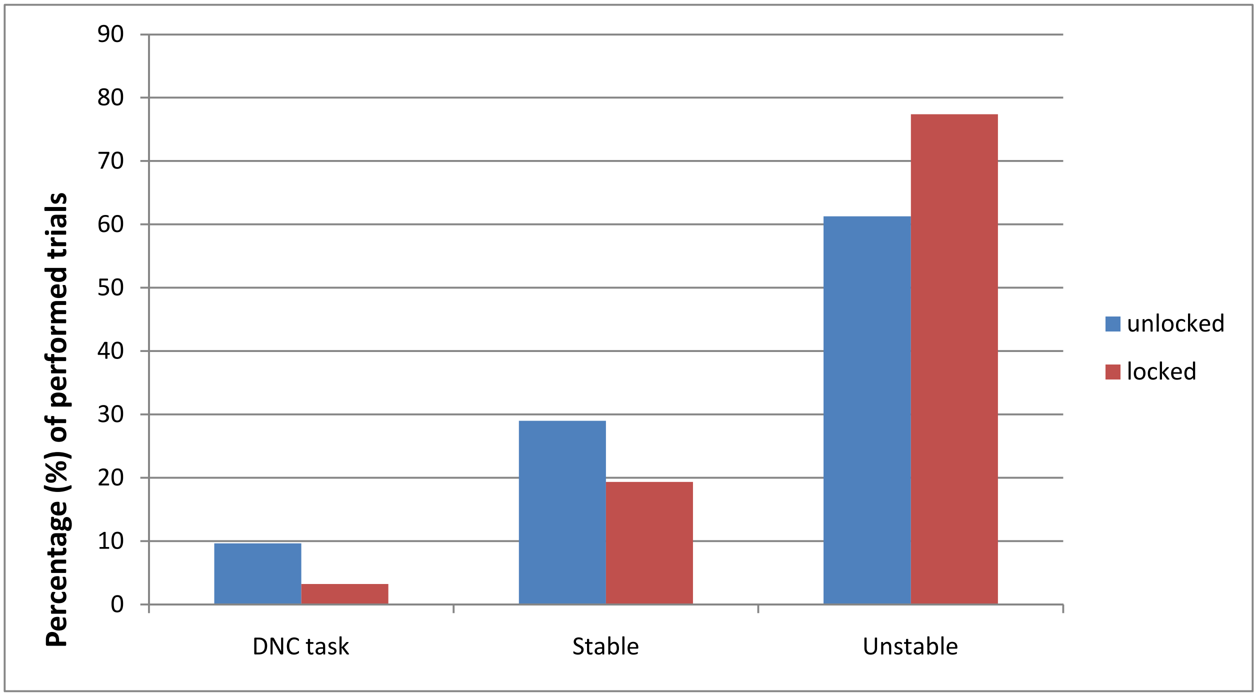


Figure 71. Percentage of performed trials for the rock pickup task, including both small and large for all subjects.

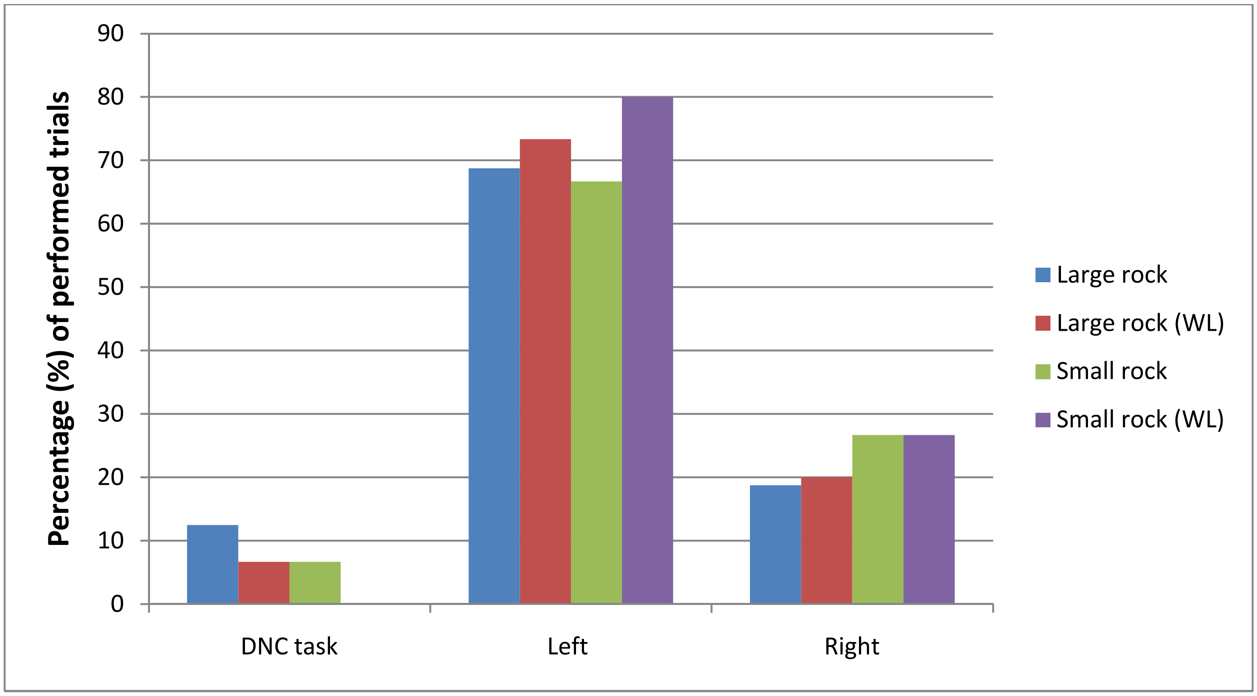


Figure 72. Hand involvement for the rock pickup task comparing waist locked to waist unlocked for all subjects.

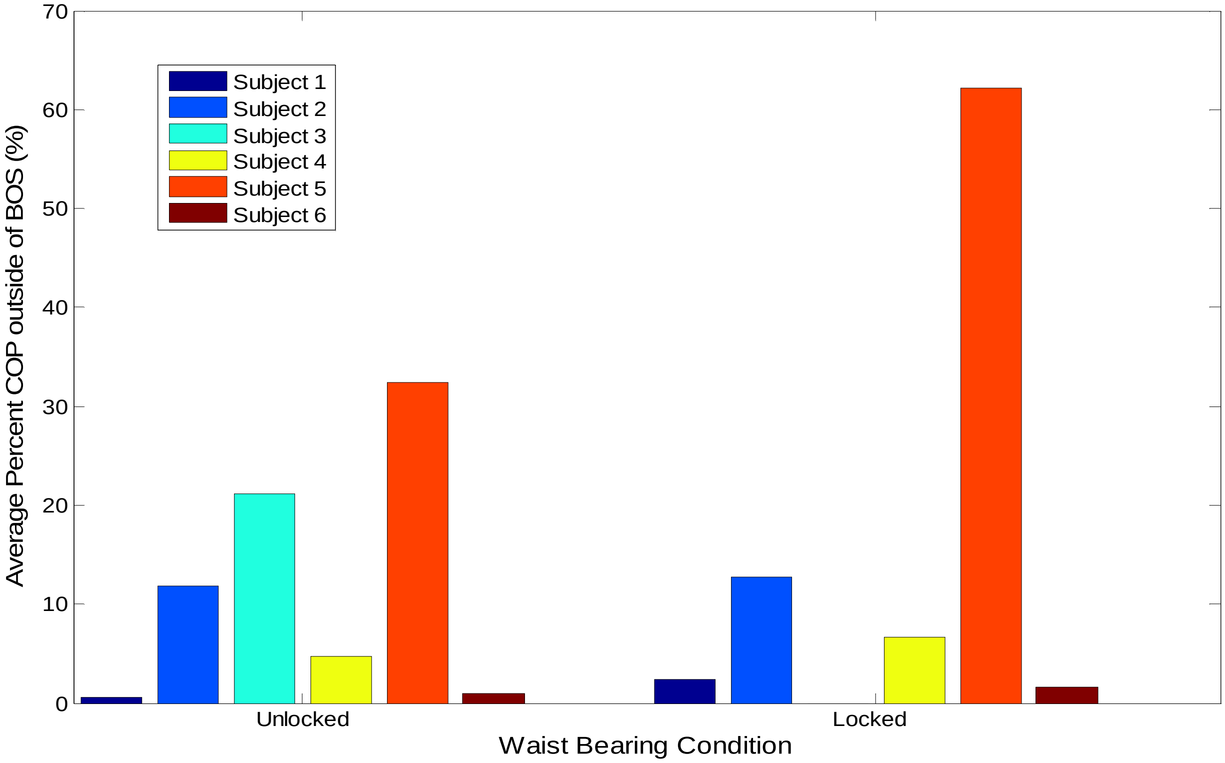


Figure 73. Average percent center of pressure outside the base of support comparing waist locked to waist unlocked for all subjects for the small rock pickup task.

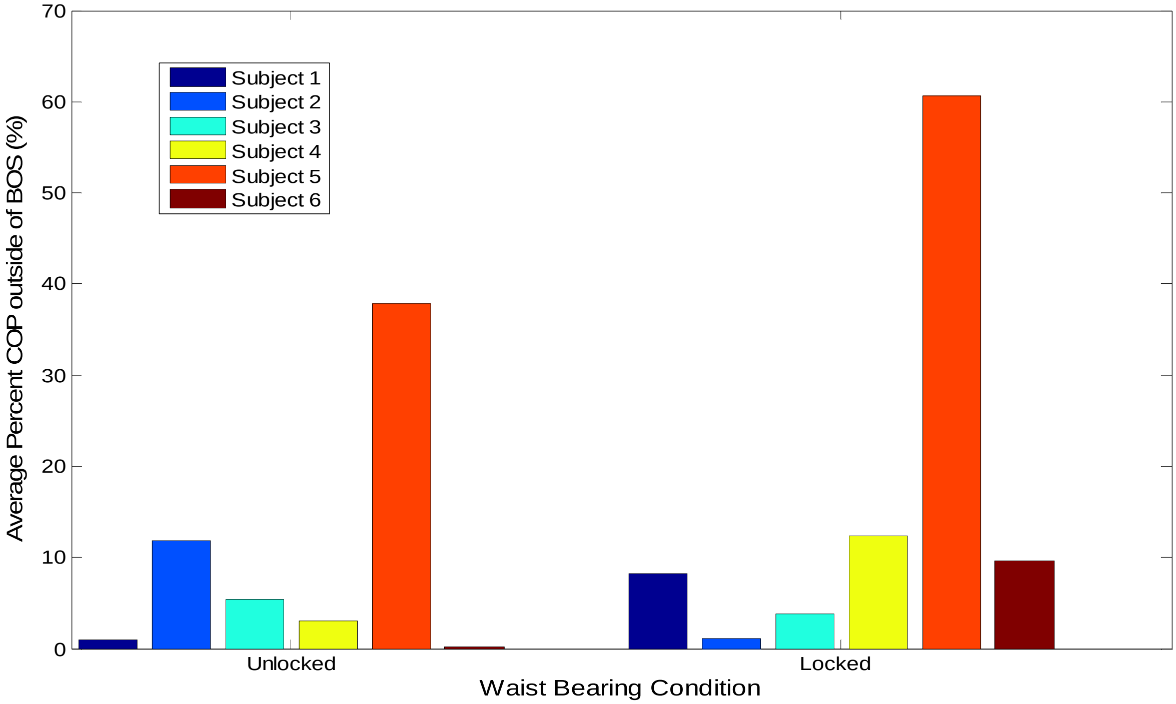


Figure 74. Average percent center of pressure outside the base of support comparing waist locked to waist unlocked for all subjects for the large rock pickup task.

3.4 Test Objective 4: Predictive Models of Metabolic Rates, Subjective Assessments, and Suit Kinematics

Test Objective 3 was "to develop predictive models of metabolic rates, subjective assessments, and suit kinematics based on measurable suit, task, and subject parameters."

3.4.1 Predictive models for metabolic rate

Descriptive statistics were used to characterize the metabolic and human performance variables at all conditions.

A preliminary multiple linear regression model was developed to predict the metabolic rate of incline locomotion in the MKIII suit as a function of the properties of the suit, the anthropometry of the subject, and task properties such as the speed and grade of locomotion. Models were attempted for the exploration tasks, but the lack of steady-state metabolic rates and a significant number of observations prevented development of effective regression models. Inferential statistics were not calculated due to the small sample size (*n* = 6). Additionally, these statistical results should be considered exploratory, ie, only demonstrating the types of tools that could be developed to optimize spacesuit design or consumable usage. Additional data and analyses will be required to improve the predictive accuracy and overall scope of these model equations.

The method of maximum likelihood was used to estimate the parameters ($b_0 - b_5$) from the experiment data. Predictor variables used in the model were chosen: (a) to produce as good a fit as possible using, at most, five terms including interaction terms; and (b) to contain reasonable physiological explanatory information. Future tests would use these input variables to predict outcomes and then complete the tasks to see how closely predictions compared to actual values. This also will help narrow the range of useful predictive input variables. Input variables and equations used to predict metabolic rate for incline walking are summarized below.

Input variables to predict the metabolic rate for incline walking included speed, grade, suit pressure, suit weight, and subject shank length and shoulder width. The inclusion of each variable was due to the statistical improvement in the model; therefore certain parameters, such as shank length or shoulder width, do not have a well-understood scientific rationale for inclusion. The preliminary model, shown in equation (1), uses the following combination of variables to predict absolute metabolic rates during incline locomotion in the MKIII suit:

$$MR = b_0 + b_1 \cdot (V_{locomotion} \times G_{locomotion}) + b_2 \cdot L_{shank} + b_3 \cdot (L_{shoulder}) + b_4 \cdot P_{suit} + b_5 \cdot M_{suit} \qquad (1)$$

where MR = metabolic rate expressed as absolute VO_2 ($l \cdot min^{-1}$)
$V_{locomotion}$ = locomotion speed ($m \bullet s^{-1}$)
$G_{locomotion}$ = locomotion grade (%)
L_{shank} = shank length of unsuited astronaut (cm)
$L_{shoulder}$ = shoulder width of unsuited astronaut (cm)
P_{suit} = suit pressure (kPa)
M_{suit} = suit mass (kg)

The proportion of variance explained by the preliminary model (pseudo R^2) was 0.668. Pseudo R^2 is the best estimate of variance because mixed modeling statistical models cannot calculate a traditional R^2. Figure 75 plots the model-predicted metabolic rate against the actual measured metabolic rates. The yellow trend line is shown as a reference point for a perfect fit with an $R^2 = 1$. In most cases, the residuals were ± 0.30 $L \bullet min^{-1}$, indicating that most of the predictions fell below the level of practical significant difference and were within an acceptable range.

These models should not be generalized beyond the conditions under which the data were collected. Descriptive statistics for the six astronaut subjects are shown in Table 1. The range of experimental suit conditions is shown in Table 7. Speeds used for this testing ranged from 0.56 to 0.97 $m \bullet s^{-1}$, and inclines ranged from 0% to 30%. Further data collection, planned in forthcoming suit test protocols, combined with detailed analysis of biomechanical data will enable development of the model such that it may be generalized to a larger range of suit configurations and astronaut anthropometries.

The application of these models is currently task specific and limited to the subjects and conditions described in Table 1 and Table 7. Currently, this model is a statistically descriptive fit for the IST-2 data, but plans to develop a mechanistic model biomechanics model, whose parameters can be optimized from a range of suit test data, that will result in a generalized predictive model are in work. Further expansion of this model will include incline walking and various exploration tasks as these activities have different subject-suit interactions.

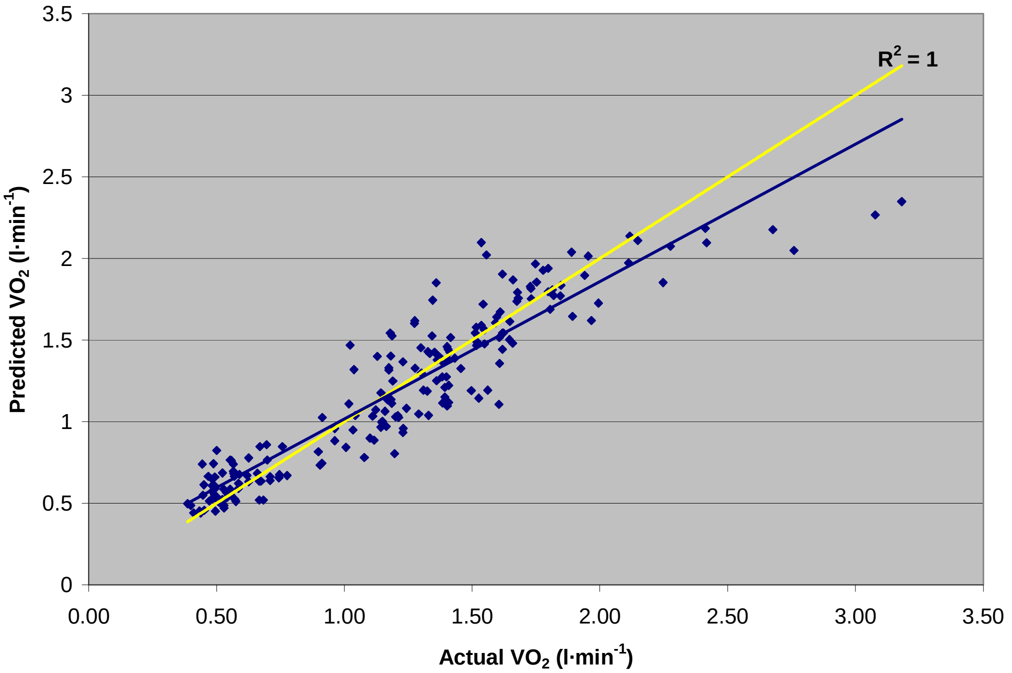


Figure 75. Model-predicted metabolic rate for suited incline ambulation vs. actual data.

Table 7. Range of Experimental Conditions on which the Preliminary Model Is Based

		P_{suit}				
Gravity Level	**Total Gravity Adjusted Weight**	**6.9 kPa (1.0 psi)**	**20.7 kPa (3.0 psi)**	**29.6 kPa (4.3 psi)**	**34.5 kPa (5.0 psi)**	**44.8 kPa (6.5 psi)**
0.12-*g*	**222-245 N 50-55 lb**			X		
0.17-*g*	**307-343 N 69-77 lb**	X	X	X	X	X
0.22-*g*	**405-449 N 91-101 lb**			X		
0.27-*g*	**498-552 N 112-124 lb**			X		
0.32-*g*	**592-654 N 133-147 lb**			X		

Given the limitations of this model, it is still important to recognize the utility of a predictive model of metabolic rate as this model may one day provide the ability to evaluate how EVA system configuration changes affect human performance and consumables without the need for additional testing. With increased data, the quality of these models should only improve.

3.4.2 Predictive model for metabolic rate based on subjective ratings

Previous models focused on crew anthropometrics, suit factors, environmental conditions, and type of task. For these models, we focused on predicting VO_2 from a subject's GCPS and RPE, and on whether or not the subject was suited for the task (Suit). Mixed-effect regression analysis was used to model VO_2 from RPE, Suit, and GCPS scores, including a subject-level grouping to accommodate for the dependence in the data (ie, repeated observations within subjects), and a random intercept term to allow subjects to vary arbitrarily on the *y*-intercept of the model. Model residuals appeared normally distributed with constant variance over the range of the outcomes, suggesting that the data are appropriately analyzed with these techniques.

Ambulation

The model revealed that only RPE made significant variance contributions to VO_2 in this multivariate context ($P < .05$). In this data set, both Suit and GCPS were not statistically significant components of the model, but were included because they increased the overall predictive accuracy of the model and had been significant components in similar models constructed. All factors were positively correlated with VO_2. Model-predicted and -observed VO_2 values are shown in Figure 76. Variation in VO_2 seen per unit of RPE was not fully characterized by the model, but, rather, model-predicted values clustered around the mean.

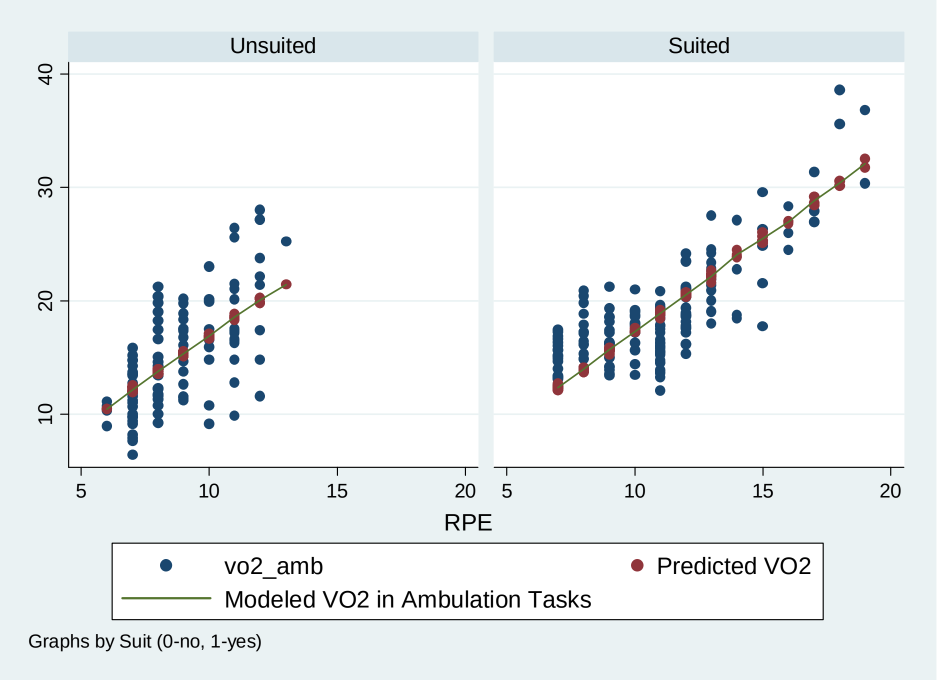


Figure 76. Inclined ambulation model-predicted VO_2 (red) and observed VO_2 (blue) with respect to rating of perceived exertion.

Exploration Tasks

The model revealed that two of three predictors made significant variance contributions to VO_2 in this multivariate context ($P < .05$), with the highest relative contribution observed for the RPE predictor. In this data set, although GCPS was not a statistically significant component of the model, it was included because it increased the overall predictive accuracy of the model and had been a significant component in similar models. All factors were positively correlated with VO_2. Model-predicted and -observed VO_2 values are shown in Figure 77. Variation in VO_2 seen per unit of RPE is partially characterized by the model, but model-predicted values still cluster primarily around the mean.

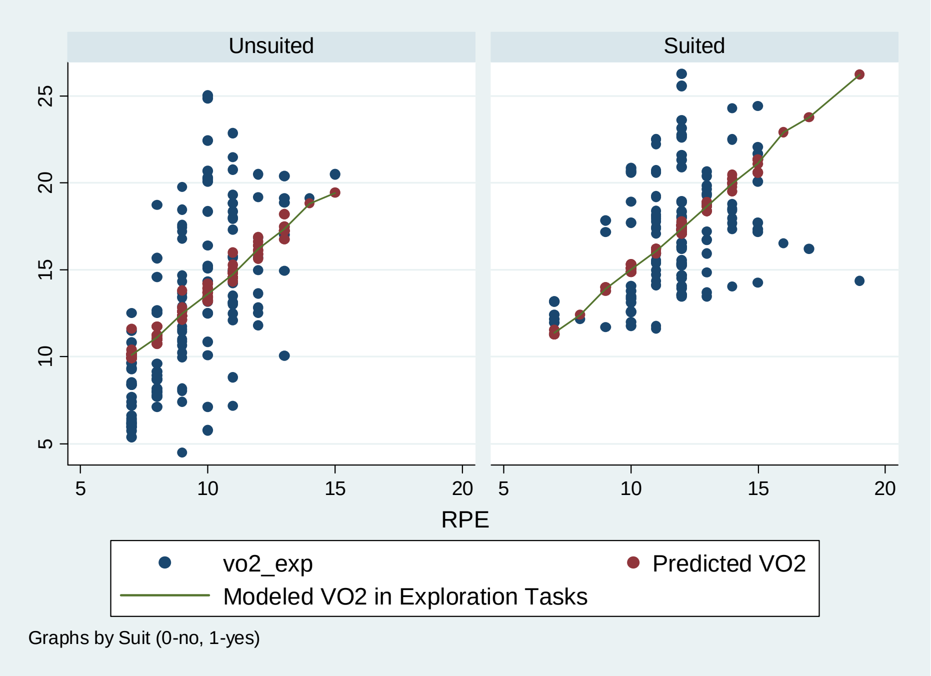


Figure 77. Exploration task model-predicted VO_2 (red) and observed VO_2 (blue) with respect to rating of perceived exertion.

While these effects are statistically significant to traditionally held scientific standards, the reader is reminded they are based on a very small sample of *n* = 6 astronauts. We remain cautious about making inferences to the larger astronaut population or outside of the task tested until these results can be replicated in future work.

3.4.3 Predictive model for suit kinematics

Predictive models also may be developed to predict the number of joint cycles and/or joint displacements across the ankle, knee, hip, and waist in the MKIII suit as a function of the properties of the suit, anthropometry of the subject, and type of task. These models will be developed as an example of the type of predictive model that can be developed and refined in greater detail as additional data are collected and analyzed to determine the number of cycles on any joint of the suit. These analysis tools will be effective for developing suit cycle requirements, and will provide significant cost savings during suit certification compared to the conventional methods of manual video tape review.

3.5 Secondary Test Objectives

3.5.1 Define standard measures and protocols for evaluating exploration suits and requirements verification

The protocols, instrumentation, and analysis techniques developed and applied for this test will be available for future testing of prototype exploration suits. The body of knowledge concerning how to conduct both suited and unsuited testing on the POGO has been greatly expanded. Techniques never before used in biomechanical analysis are being applied to suited models. By refining data-collection techniques and developing an understanding of the factors that affect human performance in the suit and reduced gravity, we will be able to combine these objective measurements with crew subjective comments to assess the performance of future exploration suits.

3.5.2 Understand the specific human performance limitations of a suit compared to matched shirtsleeve controls

Some of the limitations of comparing human performance data in the suit to matched shirtsleeve controls were discussed in Section 3.1. To recap, many differences exist between the suited and the shirtsleeve test conditions present in this study. Some of these differences (eg, weight, mass, pressure, suit fit, and kinematic constraints) will always be present and are specific to the suit tested. While these are the primary factors of interest in understanding suited human performance, there were other factors that contributed to the differences between suited and shirtsleeve performance that need to be discussed.

Factors such as task familiarization, suit familiarization, and fatigue were also present and can be better controlled through balancing the test order and allowing increased familiarization time. Other factors were specific to the use of the POGO, including human/system interactions and differences in the suspension methods for suited and unsuited subjects. To have improved confidence in this type of data comparison in future, an improved gimbal support system that suspends suited and unsuited subjects in the same way is required. Finally, there were differences in the metabolic data collection systems used in suited and unsuited conditions. We recommend that the suited metabolic data collection system measure O_2 consumption directly rather than infer VO_2 from CO_2 production. Limitations of the overall study will be discussed in Section 3.6.

Metrics for comparing suited reduced-gravity performance to Earth shirtsleeve performance include the ESSPI and GCPS. The assumption behind both of these metrics is that Earth shirtsleeve performance or better is the target for ideal suited human performance in reduced gravity. This may or may not actually be achievable, but it provides a novel method of characterizing suited human performance data based on a relative comparison. GCPS was previously described in the subjective findings relevant to Sections 3.2 through 3.4.

Figure 78 and Figure 79 demonstrate the ESSPI, defined in Section 2.6.3, as it relates to suited exploration tasks and incline locomotion at lunar gravity with the MKIII POGO configuration of 121 kg and 29.6 kPa (4.3 psi). Explorations tasks required a metabolic rate approximately three times greater than the 1-g shirtsleeve baseline, clearly indicating that being in the MKIII on the POGO at 1/6-g significantly alters exploration task metabolic rate. For inclined locomotion, we see the opposite; the ESSPI was 1.0 ± 0.2, 0.8 ± 0.2, and 0.6 ± 0.1 for 10%, 20%, and 30% grade, respectively, indicating that suited performance improves as percentage grade increased. However, these data might be misleading because we know the POGO system exerts a large degree of influence on suited performance for certain conditions, especially for inclined ambulation. Further study with an improved offload system is needed for both ambulation and exploration task performance before specific recommendations to improve human performance can be made.

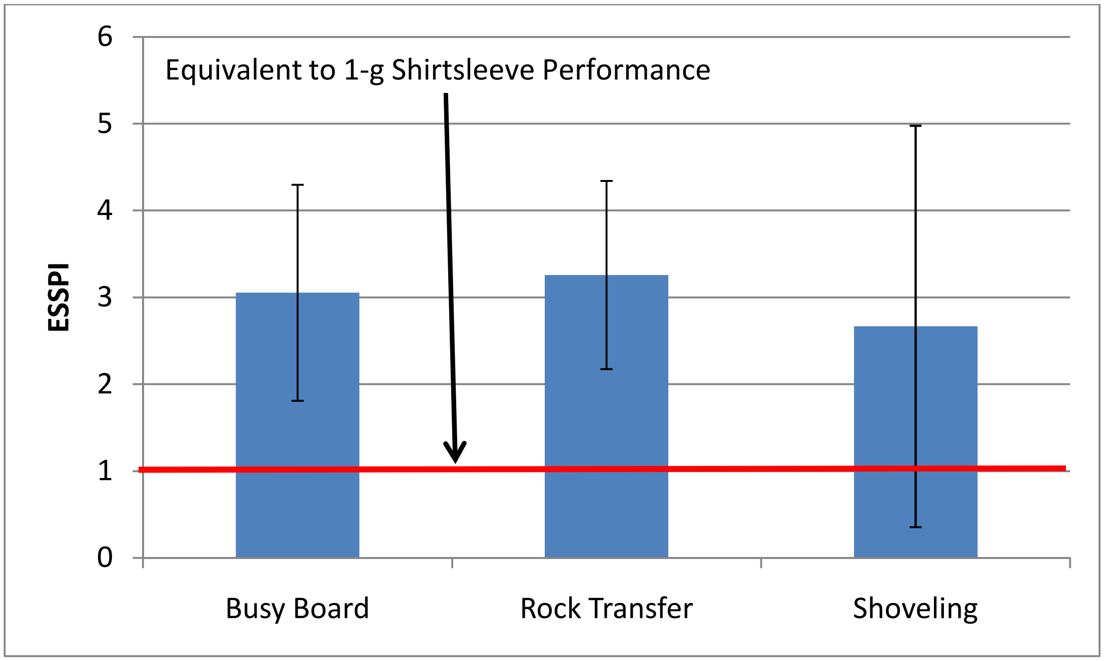


Figure 78. Earth Shirtsleeve Performance Index for suited exploration tasks at lunar gravity with MKIII at POGO configuration (121-kg suit mass at 29.6 kPa).

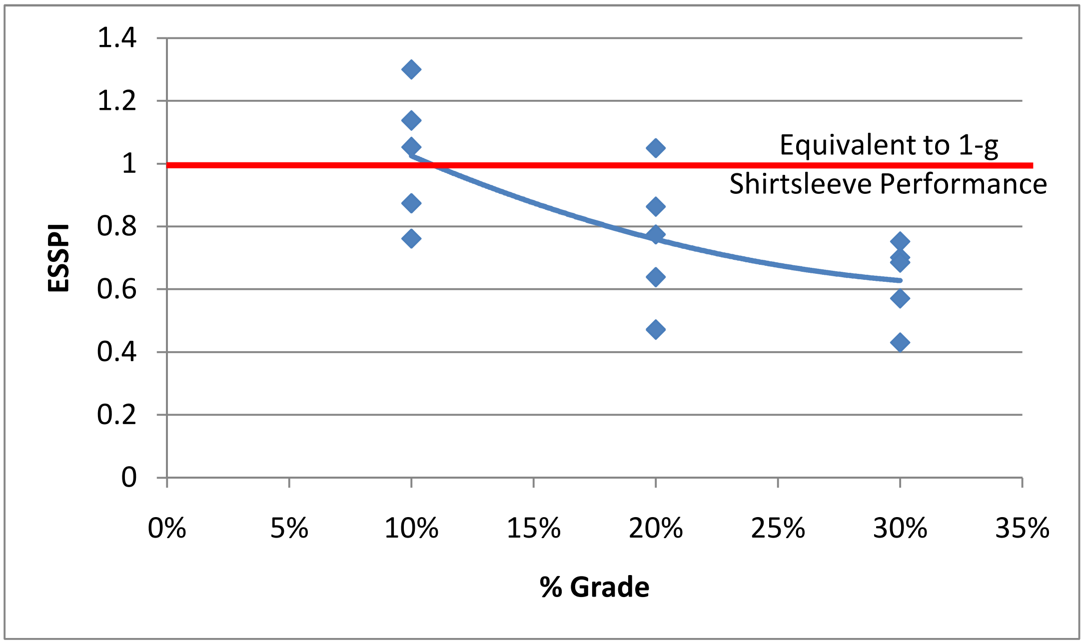


Figure 79. Earth Shirtsleeve Performance Index for suited inclined walking at lunar gravity with MKIII at POGO configuration (121-kg suit mass at 29.6 kPa).

The load carry task was an additional task that was only completed in two different configurations: [1] suited at lunar gravity with the POGO configuration (29.6 kPa, 121-kg suit mass) and [2] shirtsleeve at lunar gravity. Figure 80 shows performance differences between suited and unsuited performance of the task in lunar gravity, with suited metabolic rates always higher than the shirtsleeve metabolic rates; but, as described in previous sections, the applicability of the suited-to-shirtsleeve data comparison is limited for this test. As load increased, metabolic rate also increased in both conditions. The average difference between suited and unsuited metabolic rate was 7.2, 7.1, and 10.0 mL•kg^{-1}•min^{-1} for the 10-, 20-, and 30-lb. load-carry tasks, respectively. This difference in suited to unsuited metabolic rate was consistent with previous data for ambulation in the POGO configuration, indicating that carrying a load does not increase the metabolic differences much more than ambulation alone.

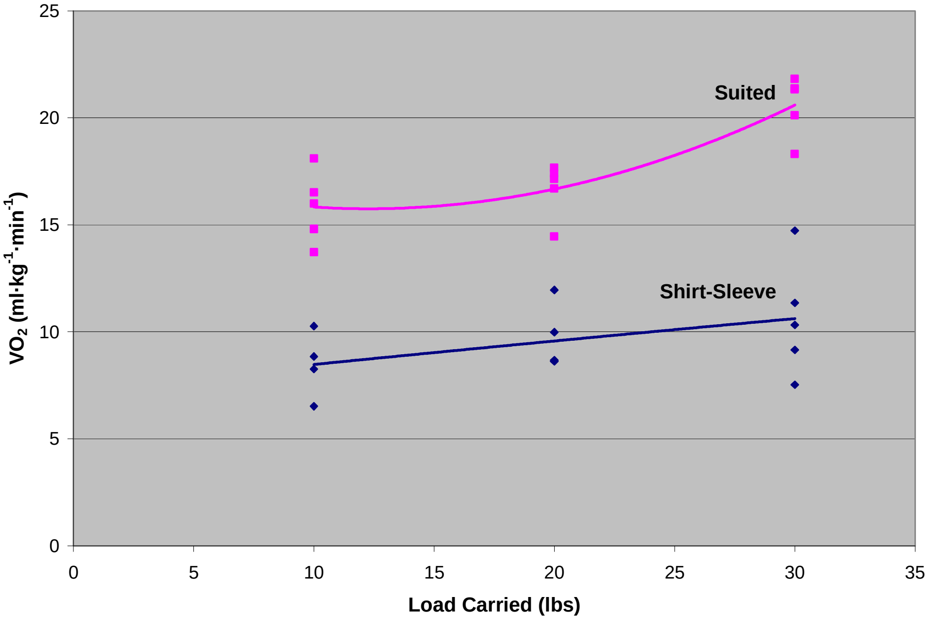


Figure 80. Metabolic rate vs. load carried both suited (POGO configuration) and shirtsleeve at lunar gravity (*n* = 5).

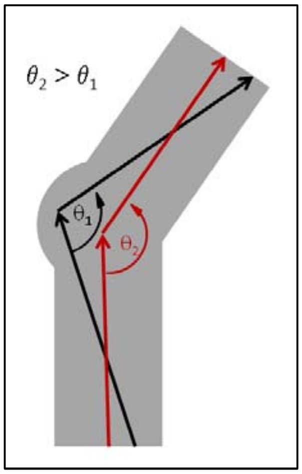


Figure 81. Example of the current difficulties with studying how the suit affects human movement (a possible suit knee angle is shown in red and a possible human knee angle is shown in black).

Finally, an understanding of how a subject moves differently inside and outside of a suit is an important and yet quite difficult question to answer. Understanding these differences is one of the keys to understanding how a suit affects human performance. A difficulty with this type of analysis is that there is no objective measure of suit fit, so while one subject might have a fair amount of travel within the suit before the suit actually moves, another subject might travel very little within the suit. Some of the difficulties with quantifying the kinematic constraints the suit imposes on human movement include differences between the human kinematics and the suit kinematics due to free space within the suit (Figure 81), differences between the constant-volume suit joints/break points and the human joint locations, and the fact that suit joint programming does not necessarily mimic human joint movement. A clear understanding of suit fit is necessary to accurately characterize human performance differences between suited and unsuited subjects in future studies.

3.5.3 Collect metabolic and ground reaction force data to develop an extravehicular activity simulator for use on future prebreathe protocol verification tests

Data from this study and other studies of EVA and human performance in reduced gravity will be used within the Space and Life Sciences directorate at JSC for to develop an EVA simulator for use in verifying prebreathe protocols. Four factors primarily affect the risk of decompression sickness: environmental pressure, time at reduced pressure, prebreathe time, and level of activity (14). Preliminary evidence suggests that a defined level of activity using VO_2 may be more significant than previously thought (15); thus, having an accurate and realistic simulation of EVA activities will help verify current and new prebreathe protocols. In addition to metabolic rate, GRF is also considered to be an important factor that an EVA simulator should control (16). Results of this study expand the dataset beyond level ambulation and encompass a more representative battery of EVA-type tasks.

3.5.4 Provide data to estimate consumables usage for input to suit and Portable Life Support System design

EPSP provided data from this test (accompanied by the critical assumptions and limitations outlined throughout this report) to the suit and PLSS design teams. In addition to the efforts of the hardware design teams, EPSP intends to condense these data into one or more user-friendly tools through the development of a comprehensive model that would allow the user to alter crew, suit, and EVA activity “input” parameters and predict the effect each variable change would have on consumables usage, joint displacement, and/or the crew member subjective ratings. Eventual development and refinement of these models and the resulting tool(s) depends on repeating key test parameters and increasing the amount of data by conducting more tests with more EVA-related tasks, more subjects, and different suit designs and in different lunar analog environments.

3.5.5 Assess the cardiovascular and resistance exercise associated with partial-gravity extravehicular activity for planning appropriate exploration exercise countermeasures

To what extent lunar gravity and lunar EVA will provide a countermeasure to the deconditioning of a crew member’s muscular, cardiovascular, and bone systems is poorly understood. Much has been learned through previous microgravity research on the development of effective exercise and non-exercise countermeasures, but to what extent these lessons learned will be applicable in the lunar architecture is unknown. EPSP intends to use data from this and future studies in this test series as the basis for the development of an EVA simulator that will not only allow for the verification of prebreathe trials, but will also allow for lunar bedrest studies and longitudinal human system modeling.

3.6 Study Limitations

Any study using a reduced-gravity analog will have limitations. An ultimate goal of these studies is to perform the same activities across different reduced-gravity analogs to determine their strengths and weaknesses.

Currently, the usability of POGO as a partial-gravity analog environment for the purpose of conducting human research studies that require control over each specific test variable (as opposed to simply having the subjective feel of being in a reduced-gravity environment, as might be required for crew training purposes) is limited. Presently, these limitations have caused unresolvable issues in the resulting data set that, to fully understand, will require further testing with improved hardware and study designs. A primary limitation of the current data set is the inability to compare the shirtsleeve results to suited results for the purpose of objectively quantifying the effects of wearing a suit, as was originally intended. For example, the estimates of the metabolic cost of the suit in Section 3.1 were based on the assumption that metabolic data across suited and unsuited conditions could be directly compared. Although subjects could conduct identical tasks with identical magnitudes of offloading while on the POGO, suspension methods between the suited and unsuited test conditions were very different, both in design and in their effects on the natural movement of the test subject. As a result, the effect of wearing the suit could not be properly isolated from the effects of all the other test system variables, thereby severely limiting the applicability of a shirtsleeve-to-suited comparison with the current data set. In addition, the equipment used to collect the metabolic data differed between suited and unsuited test conditions. Therefore, the test team has recognized that to improve our confidence in this type of comparison in future studies, an improved gimbal support system that will suspend suited and unsuited subjects in a similar manner and improvements to the suited metabolic data collection system (to measure O_2 consumption directly rather than inferring VO_2 from CO_2 production) are required.

To date, only one suit concept, the MKIII, has been tested during the IST series using the POGO. Therefore, generalization beyond the MKIII cannot safely be done. Testing of another suit design concept is required to determine which results are suit-specific and which are more generic to being in a suit.

During varied-weight testing, the weight (offload) was varied but not the mass. All suited varied weights occurred at a suit mass of 121 kg. It is unknown whether simulating a change in mass by simply changing the TGAW is an accurate simulation when needing to collect research-quality metabolic, subjective, and biomechanical data. Without concurrently adding the mass needed to achieve the same TGAW at 1/6-g or separately characterizing the effects of varied mass, the results of the varied-weight section cannot be assumed to fully reflect the effects of varied mass on suited human performance.

The 30% incline was not attempted by all subjects. As discussed earlier, we expected the 30% incline to be too difficult for the heavier-suited conditions and initially proposed completing the task at 10%, 15%, and 20% instead of 10%, 20%, and 30%. After testing two subjects, it was clear that these subjects could have completed the 30% trials, and the test points were adjusted for the final four subjects. This change to the test plan prevented full characterization of the 30% grade at heavier weights since only four of six subjects completed this condition.

The addition of different tasks beyond ambulation demonstrated previously unknown limitations of the POGO gimbal system. Tasks such as rock pickup, shoveling, and kneel and recover produced comments indicating that subjects were compensating not just for the suit but for POGO gimbal interactions that compromised performance. Part of these interactions is due to the complex interaction between the system CG (subject + suit + gimbal) and two competing sources of support: [1] the subject's standard base of support (ie, feet) and [2] the POGO's overhead suspension lift vector. To understand how these interactions affect performance, these tasks will be cross-tested using parabolic flight to eliminate any POGO gimbal interactions and to determine how significant these interactions were.

Because of the interactions among the MKIII, gimbal, and POGO system, many of the tasks were altered from the expected task-completion methods. Specifically, the surface height for the rock pickup, rock transfer, shoveling and hammering tasks was elevated. In some cases, this change was made because the stroke of the POGO lift cylinder did not go down far enough to let the subjects reach the ground. In other cases, this change was made because awkward gimbal interactions affected the ROM needed to complete the task. These issues and changes to how the subjects completed the tasks did not allow the subjects to use the full ROM of the MKIII suit (as compared to what has been observed in previous suit tests in1-g and during parabolic flight). Therefore, application of the resulting data is somewhat limited. While there will be occasions that do not require an astronaut to go all the way down to the ground to complete a task, normal procedures will likely require astronauts on a planetary surface to pick up samples off the ground, dig into the ground, or retrieve dropped tools from the ground (as occurred several times during the Apollo missions).

All predictive statistical models (discussed in Section 3.4) need to be viewed as preliminary because they are currently in development and the data set is not yet fully crossed; as such, the possible interrelationships that may exist between pressure, weight, mass, and subject characteristics are not yet understood. This is why equation coefficients were not reported at this time per the current data set. Therefore, a future validation effort (to include more suited human performance testing with consistent data collection) will be required for the model(s) to be used for the purposes stated in Section 3.4. Models converting subjective data to metabolic rate are also less prone to these interrelationships, but will need more subjects and trials before they are considered valid to use.

Due to limited time and resources, the subject pool was limited to six male astronauts with limited anthropometric, strength and fitness variability. Ideally, future tests will include females and a broader range of male subjects with different anthropometry, strength, and fitness as these relate to suit fit and the crew member’s ability to effectively function in a suit.

For this study, a specific gait was not prescribed, but subjects were directed to maintain a consistent gait throughout the biomechanics data collection period of each trial. While this eliminated most of the problems of gait change affecting biomechanical data collection, it did complicate data analysis because gait style had a significant impact on many biomechanical metrics. In future tests, subjects may possibly be instructed to employ a symmetric Earth-like gait throughout the study even if an asymmetric gait is favored. Future studies also could examine how changing gait affects results.

The unsuited harness was improved from a comfort standpoint, although leg ROM may have still been affected, which could lead to an altered gait.

Another consideration is that during the reduced-gravity trials, the subjects’ arms and legs still operated in a 1-g field. To what extent this factor affects human performance is unknown and speaks to the importance of using multiple different reduced-gravity analogs for this type of testing.

3.7 Lessons Learned

As discussed in the IST-1 lessons learned section (2), extended familiarization was allowed for all subjects for the exploration task trials. Because this test followed immediately after IST-1 and the six test subjects were the same, full familiarization trials were not included with the ambulation trials, but each subject was allowed some familiarization time at the beginning of each test session. Significant improvements were noted between the familiarization trial and test trial for suited exploration task, indicating that for any novel tasks, familiarization trials should be incorporated or learning affects may interfere with data analysis.

Changing exploration task performance methods (e.g., raising height for rock pickup) may be required to allow all subjects to complete the task within experiment design constraints (eg, POGO limits some ROMs), but making such changes does affect one's ability to infer effects on realistic task performance. Future tests should strive to perform tasks as realistically as possible. The validity of proposed tasks and the methods by which to complete them should be verified in pilot testing prior to actual data collection runs. If, during pilot testing, the test team notes an idiosyncrasy of the experiment design that affects task performance, it should be documented and the implications discussed prior to proceeding with the testing as planned. For cases in which the test system or environment cannot be modified to alleviate system-driven impacts to task performance, the test team must be diligent in recording the variance between actual and expected task performance along with the corresponding implications to results and conclusions. Test teams should not justify test setups using the "that's the way it was done last time" logic without understanding the implications to the data they intend to collect.

Before this test, only treadmill ambulation was tested. Treadmill speed and/or grades could be set, and a fixed workload was applied consistently to the subject, which elicited a steady-state metabolic response. With the inclusion of exploration tasks, there was no controlled, consistent workload; therefore, there was no steady-state metabolic rate. In lieu of metabolic rate, metabolic cost was used, which was the total O_2 consumed to complete the task. Therefore, both time to completion and metabolic rate were required for this calculation, and both parameters had the ability to significantly affect metabolic cost.

The non-steady-state environment of the exploration tasks also precluded the team from taking RPE measurements on tasks other than longer tasks. Because other lunar simulation environments (underwater buoyancy and parabolic flight) do not lend themselves well to metabolic measurements, one way to get a reasonable approximation of effort is to use subjective measures such as RPE even on short tests. All future tests should record RPE for short and long tasks and also include RPE measurements at the 30-second mark of shorter tests as that is a comparable comparison time to what could be recorded during one parabola on a parabolic flight. Other solutions include creating and validating a measure for quantifying metabolic rate over a short duration or the development of metabolic rate measurement capability in all reduced-gravity environments.

For collecting GRF during inclined treadmill trials, it is desirable to have an origin reset of the motion capture system in relation to the force plates to minimize post-processing time and increase accuracy. This was realized immediately prior to the data collection portion of the study. Because of the importance to reset the origin, changing incline cannot be performed in a continuous manner if biomechanics data are to be captured. Rather, short breaks requiring the subject to move off or to the very front of the treadmill were required. Future test procedures need to account for these short breaks required to adjust grade.

GRF data also reported only normal forces and no shear forces. Because shear forces increase and normal forces decrease as grade increases, measurement of only one aspect of GRF is incomplete. Shear forces are also necessary to determine how much relative stability the POGO overhead lift column provides. Future tests using the POGO should strive to measure both normal and shear GRF.

The VacuMed treadmill belt locks for 30 seconds after the belt is stopped. This allows subjects to exit off the treadmill safely. After 30 seconds, the treadmill belt enters a passive mode that does not actively maintain the position of the belt; thus, if mounted at an incline with sufficient force, the belt can slip. This belt slip made stepping onto the treadmill at inclines ≥ 20% a potential hazard if TGAW was ≥ 50 kg. The slip was mediated by either having test personnel "lock" the belt in place by holding it down with one foot, or quickly toggling the treadmill start/stop to engage the active belt locking feature. In most cases, the belt was locked by applying pressure with the foot. Future test teams should take belt slip into account when writing hazard analyses and test procedures.

The VacuMed treadmill is also equipped with an emergency stop button normally installed in the middle of the front handrail of the treadmill. When this button is pressed, all power to the treadmill is cut, and the treadmill belt returns to passive mode. During one suited trial at 30% incline and the heaviest weight condition, the subject was walking close to the front of the treadmill and inadvertently hit the emergency stop, cutting power to the treadmill. Because the subject was in motion, he continued walking when the belt went passive. As power had been killed to treadmill, the only way to return power was to manually reset the emergency stop, which was out of reach for all test operators due to the high incline. Therefore, the subject had no way of safely stopping other than trying to slide off the back of the treadmill or running up to the front and grabbing the front handrail. In this instance, the subject was able to reach the front handrail, although it was quite difficult. As he pushed towards the front of the treadmill with increased effort, the increased forces made the passive belt move even faster. Although the emergency stop button is intended to increase subject safety, by allowing the subject to stop the test at any time, it actually increases the risk of an adverse event when walking on inclines. To remedy the situation, the emergency stop was moved to the far left end of the treadmill. It was still reachable, but would not be hit inadvertently. All subjects were also briefed on this potential risk and were told that communication with the treadmill operator was the safest way to stop the test at higher inclines.

Reduced-gravity weigh-out procedures were improved using the suit/subject/system's static weight on the ground as the target. Force plates in the treadmill were summed to provide this weight, but this process did take longer than subjects would prefer. We recommend that a digital scale providing continuous feedback be used for all future studies to ensure proper and quicker weigh-out procedures.

Near the end of suited data collection trials, a thermal data collection system was integrated into the suit system cooling loop. Data capability included LCG flow rate, inlet/outlet temperatures, and outlet relative humidity. This system will eventually provide data to understand other ways of calculating metabolic rate to provide redundant and/or alternate methods for calculating this critical parameter. This system also provides inputs and feedback to the development of bioadvisory algorithms, which may play an important role in providing feedback for exploration crew members. Initial pilot evaluation of the calculated metabolic rate from the thermal data collection system correlated well with the measured metabolic rate. Subjects also had better heat balance when cooling was adjusted for them based on results from the thermal data collection system compared to when subjects were in complete control of cooling themselves.

As described previously, subject speeds during inclined ambulation were selected on the basis of each individual's PTS, using that subject's lowest ambulation speed. In retrospect, the ambulation speeds should have been consistent for all subjects, and speed selection should be centered on nominal expected translation speeds to aid in the ability to understand suited human performance characteristics at given speeds rather than around a particular speed. For more information regarding the use of PTS vs. fixed speeds in partial gravity, see EWT and IST-1 test reports (1) (2).

As is commonly seen in human research studies that require any kind of offloading, there seems to be no comfortable way to lift a human body vertically and still allow the body to move freely. The kite surfing harness used in this study provided greater surface area in contact with the portion of the subject's body being lifted. The use of neoprene shorts provided another layer of padding and should be included in all future studies if similar offloading hardware is used in the shirtsleeve condition.

A full 1-g baseline (not attached to the POGO) was included for all tasks, except the weight carry. This was always done as the first condition for shirtsleeve trials. A short 1-g familiarization session was also included before suited trials. Having an accurate unsuited 1-g baseline was critical to ESSPI and GCPS. It is recommended that all future human performance studies looking at planetary tasks in reduced gravity should include an unsuited 1-g condition for every subject.

4 Conclusions

4.1 Contributions of Weight, Mass, Pressure, and Suit Kinematics to Metabolic Cost of MKIII in POGO Configuration

By varying suit pressure and weight, the portion of metabolic cost specifically related to those components can be calculated. That leaves the baseline shirtsleeve metabolic costs necessary for the subject to perform the task unsuited as well as the residual cost associated with all other factors, including, but not limited to, suit kinematic constraints, stability, mass, system-level differences between unsuited and suited subjects, POGO/gimbal/suit interactions, suit fit, fatigue, and/or familiarization with the tasks. This detailed evaluation pertains to the MKIII suit in the POGO configuration (121 kg [265 lb], including PLSS, 29.6 kPa [4.3 psi]) during exploration tasks and inclined locomotion in lunar gravity.

For inclined walking, baseline, shirtsleeve costs and the cost of additional weight account for most of the metabolic cost, and the percentage contribution from both of these factors increased as grade increased. For exploration tasks, baseline shirtsleeve costs were also present, but weight actually had the opposite effect and acted to decrease metabolic rate. The component contributing most to the suited metabolic cost of exploration tasks combined other factors, including suit kinematic constraints, stability, mass and suited/unsuited harnessing, and suspension differences. Suit pressure, a minor component of inclined walking metabolic cost, was an insignificant contributor to the exploration tasks evaluated. Graphical results can be seen in Figure 11, Figure 12, Figure 13, and Figure 14. For inclined walking, the baseline shirtsleeve metabolic cost accounted for approximately 50% independent of grade. This indicated that altering suit factors could possibly only change the other 50%. On the other hand, the exploration tasks had only 25% of the metabolic cost accounted for due to the baseline shirtsleeve costs; therefore, suit factors could be altered to significantly improve the other 75%.

Future tests will drive out the individual contributions of these remaining components as well as examine various interrelationships and coupling factors present in untested combinations of these variables. By understanding these individual factors, we will be able to provide specific recommendations for suit design requirements, EVA mission planning, and overall consumables packaging.

4.2 Effects of Varied Weight, Mass, and Pressure on Suited Human Performance

Results suggest that suited TGAW exerts a varied effect from positive to negative on metabolic rate depending on the task. Previous results for level ambulation combined with current results for inclined ambulation indicate that as weight increased, the metabolic cost of ambulation also increased. In this study, metabolic rate differences became most significant at steeper grades (≥ 20%). At lower grades, additional suit weight did not significantly increase metabolic rate, even at the heaviest weights tested. Inclusion of exploration tasks demonstrates that increased weight up to a certain point had a positive effect by lowering metabolic cost. Therefore, increasing suit weight can have a negative, neutral, or positive effect on metabolic rate. Given these results, it is critical to understand what the operational concepts will be for exploring the moon. In the case in which the majority of gross translation will be performed by a rover and the astronaut will primarily be doing exploration tasks and slow walking, a heavy suit might improve human performance. On the other hand, if the astronaut is expected to do most of the translation suited and perform very few exploration tasks, a lighter suit would improve human performance.

Suit pressure does increase metabolic cost on a limited basis. Therefore, for the tasks tested, scant evidence exists that a significant change in suit pressure with an MKIII-type EVA suit would affect metabolic rate for the types of tasks tested. Again, these results should only be applied to the tasks tested. Other types of EVA would likely be affected with a change in suit pressure, such as a typical 0-g EVA, which does not require ambulation or complex whole-body movements, but rather requires foot restraint and extensive use of power and hand tools. Because pressure has little effect on metabolic rate for whole-body tasks, this allows freedom to optimize pressure for decompression sickness and/or extensive hand/glove use of tools depending on what EVA operational concepts drive out.

Adding mass in the increments tested during this study (0 to 34 kg) did not significantly alter metabolic rate. Without the ability to mass-match the varied weight-testing configurations in a way such that the TGAW would be correct in 0.17-g, it is critical that mass eventually be tested in increments similar to the varied weight tests to determine whether varying suit weight alone is an adequate way to evaluate how different suit masses would alter human performance.

Perceived exertion followed a similar trend to metabolic rate as would be expected. GCPS ratings were unchanged by suit pressure, but trended higher with increased weight during inclined ambulation. GCPS during exploration tasks was almost always highest at the lowest suit weight and was best at the weights tested at 0.22-g and 0.27-g.

Joint kinematic results from this study showed that walking on an incline required greater hip, knee, and ankle ROMs with increasing surface inclines. Further, results from this study demonstrated that hip, knee, and ankle ROM decreased with increased pressure. Increasing suit weight led to an increase in hip, knee, and ankle ROM as well as an increase in waist-bearing travel. Therefore, a low-pressure or heavier suit will require increased joint ROM capabilities to perform incline locomotion tasks.

Changes in pressure made little difference in exploration task performance. Increasing weight improved stability and improved overall exploration task performance through the weights achieved at 0.27-g, but results began to trend worse at the 0.32-g condition. Results of this study indicate that more weight, up to a certain point, improves exploration task performance.

4.3 Comparison of the MKIII at POGO configuration to MKIII with the Waist Bearing Locked

Metabolic and subjective data were very similar between conditions demonstrating that locking the waist bearing to prevent rotation around that joint did not negatively affect human performance. However, the strategy analysis and COP analysis data contradict the metabolic findings, demonstrating from a stability standpoint that locking the waist bearing is detrimental to performance. Kinematic analysis also shows that although the subjects were able to adequately perform with the waist locked, all subjects made substantial use of the waist joint when unlocked.

4.4 Development of Predictive Models for Metabolic Rate and Suit Kinematics

Preliminary multiple linear regression models were developed to predict the metabolic cost of different tasks in the MKIII suit as a function of the properties of the suit, anthropometry of the subject, and specific tasks. While preliminary and descriptive in nature, these models highlight the possible applications for a complete model, including: refining operational concepts, defining suit requirements, and predicting consumable usage. Models to determine joint cycles and other life cycle aspects of the suit are in progress. Eventually, with the inclusion of additional data and improved understanding of various interrelationships, these models will be combined into an all-inclusive predictive algorithm that would provide one comprehensive, user-friendly tool that would incorporate the results of applicable human performance testing in reduced gravity.

4.5 Secondary Objectives

This test series provides an ideal opportunity to use the data collected for much more than to address specific primary objectives. Lessons learned from this test can be used to improve test methods, test equipment, and lunar analog environments as well as to prepare for future testing and requirements verification of EVA suit candidates. Data will be used to develop an EVA simulator for use with prebreathe protocol verification and exercise countermeasure studies. Metrics to compare suited to unsuited performance in both reduced and Earth gravity help provide a reference point to determine what normal 1-g human performance entails and how performance changes as gravity changes and as an EVA suit is donned. Currently, a limited number of factors can compare unsuited to suited human performance, and we hope to expand this in the future.

4.6 Summary

One of the key hopes and applications of this study was to further the knowledge of suited human performance and to determine what gaps in knowledge, facilities, or test methodology exist that need to be filled to fully understand this field. IST-2 addressed the primary objectives of the study and has begun to provide some of the data to answer secondary objectives. As more studies are completed, these predictive models, suit parameter interrelationships, standard measures, and new metrics such as ESSPI will become complete products allowing for evidence-based recommendations to optimize suit design and plan EVA operational constraints and consumable targets.

5 Works Cited

1. Norcross JR, Lee LR, Clowers KG, Morency RM, Desantis L, De Witt JK, et al. Feasibility of Performing a Suited 10-km Ambulation - Final Report of the EVA Walkback Test (EWT). NASA/TP–2009–214796. Washington D.C.:; 2009.
2. Norcross JR, Clowers KG, Clark T, Harvill L, Morency RM, Stroud LC, et al. Metabolic Costs and Biomechanics of Level Ambulation in a Planetary Suit. NASA/TP-2010-216115. Washington D.C.:; 2010.
3. Carr CE, Newman DJ. Space suit bioenergetics: cost of transport during walking and running. Aviation, Space, and Environmental Medicine. 2007; 78(12): p. 1093-1102.
4. Carr CE, Newman DJ. Space suit bioenergetics: framework and analysis of unsuited and suited activity. Aviation, Space, and Environmental Medicine. 2007; 78(11): p. 1013-1022.
5. Borg GA. Psychophysical bases of perceived exertion. Medicine and Science in Sports and Exercise. 1982; 14(5): p. 377-381.
6. Corlett EN, Bishop RPA. A technique for assessing postural discomfort. Ergonomics. 1976; 19(2): p. 47-51.
7. Bedford T. The warmth factor in comfort at work. MRC Industrial Health Board Report No. 76. MRC Industrial Health Board Report. London:; 1936.
8. Hart SG, Staveland LE. Development of a multi-dimensional workload rating scale: Results of empirical and theoretical research. In Hancock PA, Meshkati N, editors. Human Mental Workload.; 1988. p. 139-83.
9. Munro CF, Miller DI, Fuglevand AJ. Ground reaction forces in running: a reexamination. Journal of Biomechanics. 1987; 20(2): p. 147-55.
10. McIntosh AS, Beatty KT, Dwan LN, Vickers DR. Gait dynamics on an inclined walkway. Journal of Biomechanics. 2006; 39: p. 2491-2502.
11. Winter DA. The Biomechanics and Motor Control of Human Gait: Normal, Elderly and Pathological. 2nd ed. Waterloo; 1991.
12. Leroux A, Fung J, Barbeau H. Postural adaptation to walking on inclined surfaces. Gait and Posture. 2002; 15(1): p. 64-74.
13. Redfern MS, DiPasquale J. Biomechanics of descending ramps. Gait and Posture. 1997;: p.

119-125.

14. Pilmanis AA, Petropoulos LJ, Kannan N, Webb JT. Decompression Sickness Risk Model: Development and Validation by 150 Prospective Hypobaric Exposures. Aviation, Space, and Environmental Medicine. 2004 September; 75(9): p. 749-759.
15. Webb JT, Gernhardt ML. Metabolic Cost of Experimental Exercises. Aviation, Space, and Environmental Medicine. 2009 March; 80(3): p. Abstract 327.
16. Conkin J, Powell MR. Lower Body Adynamia as a Factor to Reduce the Risk of Hypobaric Decompression Sickness. Aviation, Space, and Environmental Medicine. 2001 March; 72(3): p. 202-214.

Appendix A: Submaximal Test Termination Criteria

Test Termination Criteria for All Submaximal Testing

1. Subject's request to stop at any time
2. Subject's heart rate or measured VO_2 at level > 85% VO_2pk for 2 minutes or longer
3. Failure of POGO hardware and/or treadmill system

Additional Test Termination Criteria for Suited Submaximal Testing

1. Expired CO_2 levels greater than 5%
2. If subject reports discomfort rating $\geq$ 7 (on 10-point scale) for two consecutive recording periods, the subject will be asked to terminate the test. If the subject asks to continue, he/she will be allowed to continue until Condition 3 is met
3. Discomfort rating $\geq$ 7 for three recording periods (may be nonconsecutive) 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_AHI_0009) and addressed in the test readiness review (TRR))

Appendix B: Ratings Scales for Subjective Measures

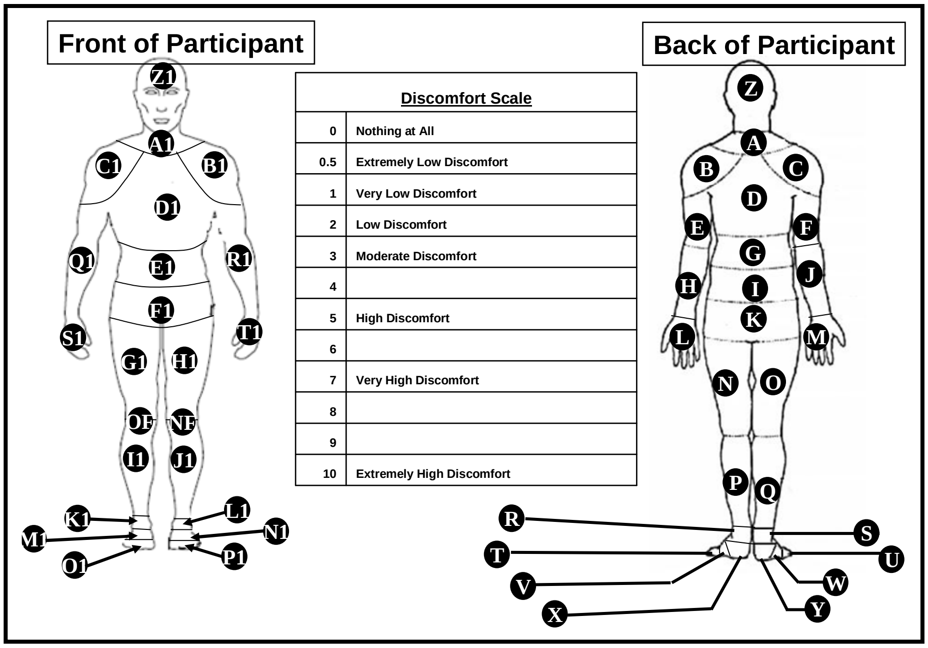
Gravity Compensation and Performance Scale

1	**Excellent** – easier than 1-g
2	**Good** – equivalent to 1-g
3	**Fair** – minimal compensation for desired performance
4	**Minor** – moderate compensation for desired performance
5	**Moderately objectionable** – considerable compensation for adequate performance
6	**Very objectionable** – extensive compensation for adequate performance
7	**Major deficiencies** – considerable compensation for control, performance compromised
8	**Major deficiencies** – intense compensation, performance compromised
9	**Major deficiencies** – adequate performance not attainable with maximum tolerable compensation
10	**Major deficiencies** – unable to perform task

Borg Rating of Perceived Exertion Scale

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



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

Bedford Thermal Scale

-3	Much too cool
-2	Too cool
-1	Comfortably cool
0	Comfortable
1	Comfortably warm
2	Too warm
3	Much too warm

Thermal Preference

-2	Much warmer
-1	A bit warmer
0	No change
1	A bit cooler
2	Much cooler

Acknowledgements

The successful completion of this test would not have been possible without the dedicated support of the following personnel from across JSC who planned and conducted the test:

Constellation EVA Systems Project Office
Jeff Patrick
Jessica Vos

Constellation Advanced Projects Office
Dean Eppler

Astronaut Office (CB)
Chris Cassidy
Jim Dutton
Drew Feustel
Mike Gernhardt
Erlinda Stevenson
Piers Sellers
Joe Tanner
Arthur Van Horne
Dave Wolf

Space Vehicle Mockup Facility (DX14)
Arne Aamodt
John Harvey
Bill Lee
David Pogue
Bobby Vincent

EVA & Spacesuit Systems Branch (EC5)
Lindsay Aitchison
Craig Bernard
Raul Blanco
Craig Dinsmore
Mark Dub
Kevin Groneman
John Harris
Barbara Janoiko
Joe Kosmo
Amy Ross
Kevin Rullman
Nathan Smith
Ben Steinsholt
Greg Tonnies
Steve Wells
Dick Watson
Heather Paul

Safety & Test Operations Division (NS)
Jay Brannum

EPSP Project Team (SK2)
Andrew Abercromby
Jennifer Jadwick
Larry Kuznetz
Jason Norcross
Nick Skytland
Jennifer Tuxhorn

Anthropometry & Biomechanics Facility (SF3)
Sudhakar Rajulu
Tim Clark
Kurt Clowers
Lauren Harvill
Richard Morency
Dan Nguyen
Robert Sweet

Environmental Physiology Laboratory (SK3)
Jill Klein
Jim Wessel
Ramachandra Srinivasan

Exercise Physiology Laboratory (SK3)
Don Hagan
John De Witt
Meghan Everett
Leah Stroud

Usability, Test & Analysis Facility (SF3)
Ron Archer
Lena Desantis
Carlton Donahoo

Space Medicine & Healthcare Systems (SD) & SK Medical Monitors
Jeff Jones
Pete Bauer
Keith Brandt
Rick Scheuring
Todd Schlegel
Linda Shackelford

Bioastronautics Safety
John Byard

Biostatistics (SK)
Al Feiveson
Rob Ploutz-Snyder

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave Blank)*

2. REPORT DATE
June 2010

3. REPORT TYPE AND DATES COVERED
Technical Paper

4. TITLE AND SUBTITLE
Metabolic Costs and Biomechanics of Inclined Ambulation and Exploration Tasks in a Planetary Suit

5. FUNDING NUMBERS

6. AUTHOR(S)
Jason R. Norcross*, Kurt G. Clowers†, Tim Clark†, Lauren Harvill**, Richard M. Morency††, Leah C. Stroud***, Lena Desantis**, Jessica R. Vos††, Michael L. Gernhardt††

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Lyndon B. Johnson Space Center
Houston, Texas 77058

8. PERFORMING ORGANIZATION REPORT NUMBERS
S-1070

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
Washington, DC 20546-0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
TP-2010-216125

11. SUPPLEMENTARY NOTES
*Wyle Integrated Science & Engineering Group, Houston; †MEI Technologies, Inc., Houston; **Lockheed Martin, Houston; ††NASA Johnson Space Center, Houston; ***Rice University, Houston

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Unclassified/Unlimited
Available from the NASA Center for AeroSpace Information (CASI)
7115 Standard
Hanover, MD 21076-1320 Category: 54

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

Observations from Apollo lunar surface extravehicular activities (EVAs) and a few studies conducted in partial-gravity simulation environments have helped us understand suited human performance in reduced-gravity environments. The Constellation Program EVA Systems Project Office initiated a series of tests aimed at increasing our understanding of human performance and suit kinematics under various simulated lunar EVA conditions, including matched unsuited controls, to identify the specific metabolic costs and biomechanics of the prototype Mark III Advanced Spacesuit Technology Demonstrator. A primary goal of the series is to provide evidence-based recommendations for suit mass, center of gravity, pressure, and suit kinematic constraints that optimize human performance in partial-gravity environments. Results will be combined with studies in other lunar analogs to evaluate the effectiveness and limitations of these environments. As our understanding of suited human performance matures, different combinations of variables can be evaluated to determine whether significant interactions exist between parameters. This report provides an overview of key findings of Integrated Suit Test (IST)-2. As future tests are completed, focusing on other suit factors, analog environments, or different suits, study results will be combined and reevaluated. The series of tests comprising IST-2 was conducted from June 13, 2007 through October 24, 2007.

14. SUBJECT TERMS

aerospace environments; extravehicular activity; weightlessness; aerospace environments; Mars environment; lunar environment; space suits

15. NUMBER OF PAGES
108

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT
Unclassified

18. SECURITY CLASSIFICATION OF THIS PAGE
Unclassified

19. SECURITY CLASSIFICATION OF ABSTRACT
Unclassified

20. LIMITATION OF ABSTRACT
Unlimited