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Final Report of the Integrated Parabolic Flight Test: Effects of Varying Gravity, Center of Gravity, and Mass on the Movement Biomechanics and Operator Compensation of Ambulation and Exploration Tasks

Steven P. Chappell[1], Jason R. Norcross[1], Kurt G. Clowers[2], Tim Clark[2], Matthew S. Cowley[3], Lauren Harvill[3], Lena Desantis[3], Richard M. Morency[4], Jessica R. Vos[4], Michael L. Gernhardt[4]

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1.0 Introduction

This test was a continuation of the testing series, sponsored by the Constellation Program (CxP) EVA Systems Project Office (ESPO), that is being conducted to enable development of optimized design requirements for the next-generation lunar extravehicular activity (EVA) suit. The test series is a collaborative effort of the Crew and Thermal Systems Division (CTSD), the EVA Physiology, Systems, and Performance Project (EPSP), the Anthropometry and Biomechanics Facility (ABF), and the Usability Testing and Analysis Facility (UTAF). The investigators aim to understand human performance and suit kinematics under a variety of simulated lunar EVA conditions produced by a parabolic flight aircraft. The ways in which suit kinematics, weight, mass, center of gravity (CG), and pressure affect human performance during EVA-relevant tasks are being systematically evaluated. Investigators are developing a parametric understanding of the interrelationships between suit weight, mass, pressure, CG, and crew anthropometrics and performance, while defining the limitations and correction factors associated with each environment.

This test was designed to provide data to compare with earlier human performance testing on the Space Vehicle Mockup Center's Partial Gravity Simulator (POGO) and to provide guidance for the design of other reduced-gravity simulator projects such as ARGOS (Active Response Gravity Offload System). The test was also designed to conduct new research into the effects of varied CG and varied mass on suited human performance. The results will provide insights that may drive CxP requirement definitions and suit designs that are optimized for the anthropometric range of crewmembers and for the targeted operational environment.

The test was conducted between December 2008 and March 2009 in two separate phases, phase I and phase II. Phases I and II combined tested the effects of varied suit mass, varied gravity level, and varied CG. When the effects of any one of these was studied, the other two were held constant. Unsuited, shirtsleeve baseline testing was also performed.

It should be noted that conducting research in the parabolic flight aircraft is a challenging task, and we remind the reader to interpret the results with care. The lessons learned in how best to conduct tests in partial-gravity conditions provide significant value for conducting future parabolic flight tests. Also, it should be noted that because the number of subjects who were able to take part in the test was small ($n = 6$), intersubject variations often prevented the analysis from revealing differences between the suited conditions tested. We caution anyone from making recommendations for suit or crewmember requirements based solely on the data in this test report. Rather, it is our goal to share every aspect of what we have learned, so that the greater scientific and engineering community can build on both the data and the lessons learned to derive the requirements for the next generation of facilities needed to support space exploration systems research, development, and testing.

1.1 Test Objectives

The purpose of the test was to evaluate mass and CG configurations using the Mark III Advanced Space Suit Technology Demonstrator (MKIII) in simulated reduced gravity. To understand the effects of mass and CG on human performance during ambulation and exploration tasks, data pertaining to the following biomechanical variables and subjective performance ratings were collected:

- Ground reaction forces
- Gait characteristics
- Kinematics
- Ratings of perceived exertion
- Ratings of operator compensation and controllability
- Subject discomfort ratings

The primary objectives of the test were as follows:

1. Compare the test results with a subset of results from previous tests that used the POGO.
2. Assess how varying the simulated gravity level, while keeping CG and mass constant, affects biomechanics and operator compensation.
3. Assess how varying the suit mass, while keeping CG and simulated reduced gravity constant, affects biomechanics and operator compensation.
4. Assess how varying the suit CG, while keeping mass and simulated gravity level constant, affects biomechanics and operator compensation.

Secondary objectives of the test were as follows:

1. Compare the biomechanics and operator compensation of two MKIII suit configurations: nominal and with the waist bearing locked.
2. Establish a biomechanics and operator compensation baseline for the lunar-gravity shirtsleeve condition for the tasks.

2.0 Methods

2.1 Subjects

Subjects were recruited from a pool of personnel who typically perform EVA suited studies for the Engineering Directorate and from the group of astronauts selected to support exploration EVA studies. Checks of suit fit in the MKIII suit had previously been performed on a range of subjects, and only those who had a good suit fit were considered for inclusion in this test because of potential medical and safety issues. From this list, 7 male astronaut subjects (Table) participated in the data collection phases of the test (5 common to both phases). At the time of the test, no available female astronauts properly fit in the MKIII suit. Some subjects had also participated in Integrated Suit Test (IST)-1 and IST-2 and/or had previous experience with the MKIII.

Table 1 - Subject characteristics

n = 7	**Height (cm)**	**Body Mass (kg)**	**Age (years)**
Average	181.3	78.9	47
St. Dev.	6.2	10.1	4
Max	189.2	97.5	53
Min	175.3	67.1	41

All subjects successfully passed a modified Air Force Class III Physical or equivalent examination. Each subject was provided verbal and written explanations of the testing protocols and the potential risks and hazards involved in the testing, and signed NASA Johnson Space Center (JSC) Human Research documentation indicating their understanding and consent. All testing protocols were reviewed and approved by the NASA JSC Committee for the Protection of Human Subjects, and appropriate test readiness reviews were conducted before testing began.

2.2 Equipment

2.2.1 Parabolic Flight Aircraft

The aircraft of the Reduced Gravity Office (RGO), operated by NASA JSC, provides engineers, scientists, and astronauts a unique opportunity to perform testing and training in a reduced-gravity environment without having to leave the confines of the Earth's atmosphere. The environment provides a partial-gravity or microgravity environment for testing and evaluating prototype space hardware and experimental procedures as well as doing research to understand human performance in reduced gravity. A specially modified C-9 turbojet, flying parabolic arcs, produces periodic episodes of reduced gravity lasting about 25 seconds, with parabola durations depending on the gravity level being simulated (Figure 1).

Figure 1 - Reduced Gravity Office C-9 parabolic flight aircraft.

Excluding the C-9 flight crew and the RGO test directors, the NASA C-9 aircraft accommodates seating for a maximum of 20 passengers. The C-9 cargo bay provides a test area that is 13.7 m long, 2.64 m wide and 2.03 m high. The aircraft is equipped with electrical power for test equipment and lighting .[1]

2.2.2 Mark III Advanced Space Suit Technology Demonstrator (MKIII)

For suited testing, the MKIII suit (Figure 2) was used, as it represents a suit concept that provides 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.[2] The MKIII was also used during IST-1 and IST-2 on the ground-based Partial Gravity Offload (POGO) system.

Figure 2 - Mark III Advanced Space Suit Technology Demonstrator (MKIII).

The MKIII is a hybrid spacesuit configuration composed of hard elements, such as a hard upper torso and brief section, and soft components, such as fabric elbows and knees that are designed to handle operating pressures of up to 55.0 kPa (8.0 psi). Another feature of the suit is the use of convolutes and bearings that allow joint systems with multi-axial mobility to be used. The shoulder is a rolling convolute with scye and upper-arm bearings. At the waist, both a bearing and a rolling convolute are used to allow flexion, extension, and rotation. Multiple bearings and a convolute at the hip and thigh allow abduction, adduction, flexion, and extension. The suit is entered through a hatch on the back side of the hard upper torso (rear-entry suit) that also accommodates integration of a backpack portable life support system (PLSS). 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 also is used to improve fit and to avoid pressure or rubbing spots.

2.2.3 Donning Stand and Suit Support Hardware

The donning stand supports and secures the MKIII suit in an upright attitude during suit don and doff activities. The subject may also rest in the stand during nominal aircraft flight periods or during test equipment configuration changes. The stand is a tube structure and was bolted to the floor of the plane. Other hardware required to support the subjects wearing pressurized suits included:

- Suit test equipment tool box
- Suit intercom systems

- K-Bottles of breathing air; manifold support for 6 bottles total
- Breathing air pressurization system
- Breathing air and cooling water umbilical
- Liquid Cooling Garment water cooling system
- Test team communication system

Figure 3 shows the donning stand and equipment installed in the front of the aircraft during testing.

Figure 3 - MKIII donning stand and suit support equipment.

2.2.4 Force Plates

2.2.4.1 Exploration Area Force Plates

Two force plates (Advanced Medical Technology, Inc., Watertown, MA) were attached to the floor of the aircraft to collect data on ground reaction forces (GRF). The force plates were located in front of the station used for rock pickup and shoveling, side by side so that the test subject could place one foot on each force plate (Figure 4). The force plates are capable of measuring x-, y-, and z-axis forces and moments.

Figure 4 - Force plates in front of the shoveling platform.

2.2.4.2 Ambulation Area Force Plates

Force plates were used to record GRF under the subject's feet during ambulation (see Figure 8). The GRF recorded were normal (perpendicular) to the surface of the C-9 floor. The force plates were custom-made by the ABF because of height constraints and safety concerns on the C-9 with the regularly used force plates (see Figure 5). The plates consisted of a top and bottom plate (A36 steel plate) that sandwiched 10 load cells. The load cells were low-profile, through-hole-type load cells (Transducer Techniques, Temecula, CA). The method of attaching the top to the bottom plate was changed from preloaded bolts in phase I to locked, but free-floating, pins in phase II to increase the accuracy. These force plates were only capable of measuring forces normal to the plane floor. The dimensions of the plate assembly were 0.9 m (36 in) wide, 0.9 m (36 in) high, and 0.03 m (1 in) deep.

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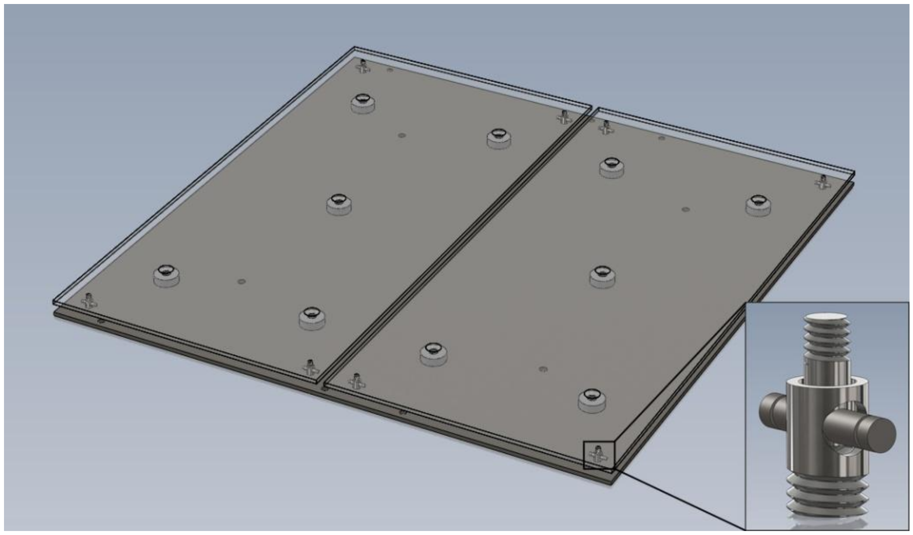

Figure 5 - Illustration of the custom-made force plates that allowed recording of GRF data for ambulation despite the inherent restrictions of testing on the aircraft (phase II version).

2.2.5 Motion-Capture Camera System

For ambulation data, a state-of-the-art Vicon MX motion-capture system (Vicon, Oxford, England) was used to capture the kinematic data. Custom-made camera mounting frames were made by the ABF to ensure the stability of the cameras during flight, which is critical to collecting accurate data. The camera rack was also modified from a square rack type of mount in phase I, with the cameras spread across the crosspieces, to separated posts that were spread farther apart in phase II (Figure 7). This was done to increase the viewing, or capture volume and increase the number of markers visible at any one time.

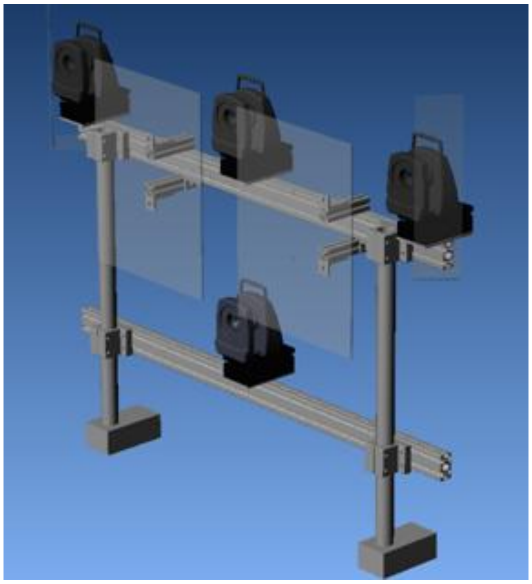

Figure 6 - View of a custom-made camera mounting rack (phase I version) designed to stabilize and protect the cameras during flight.

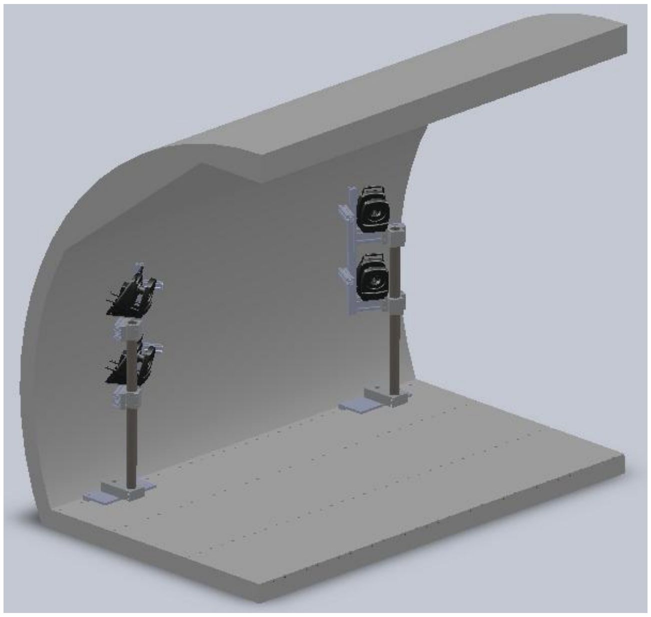

Figure 7 - View of the custom-made camera mounting racks (phase II version) designed to increase the capture volume over that achieved in phase I; shown in a cutaway of the C-9 fuselage.

In the exploration area, six cameras were mounted on RGO-approved poles. Three cameras were on each side of the exploration area. The cameras were positioned to focus only on the feet needed for center-of-pressure analysis.

Figure 8 - Test subject in ambulation motion-capture area showing two of the support poles with cameras mounted.

2.2.6 Equipment for Collecting Motion-Capture and Force-Plate Data

Motion-capture and force-plate data were collected and stored using computer components installed in equipment racks in the front port side of the aircraft (Figure 9). The equipment included:

- Motion-capture data station
- Laptop computer
- Data-collection desktop computer
- Camera cables
- Force-plate data amplifiers

Figure 9 – Data-collection system installed in the front of the aircraft.

2.2.7 Mass-Support Rig

A mass-support rig was designed and attached to the MKIII suit PLSS mockup during portions of the test. The structure was reconfigurable: weights could be moved to different locations to achieve a desired suit mass and/or CG. Figure 10 shows the mass-support rig attached to the MKIII suit during a kneel-and-recover task. The mass of the mass-support rig was about 29.5 kg (65 lb) and each weight set (one on each arm of the support structure) was 30.6 kg (67.5 lb).

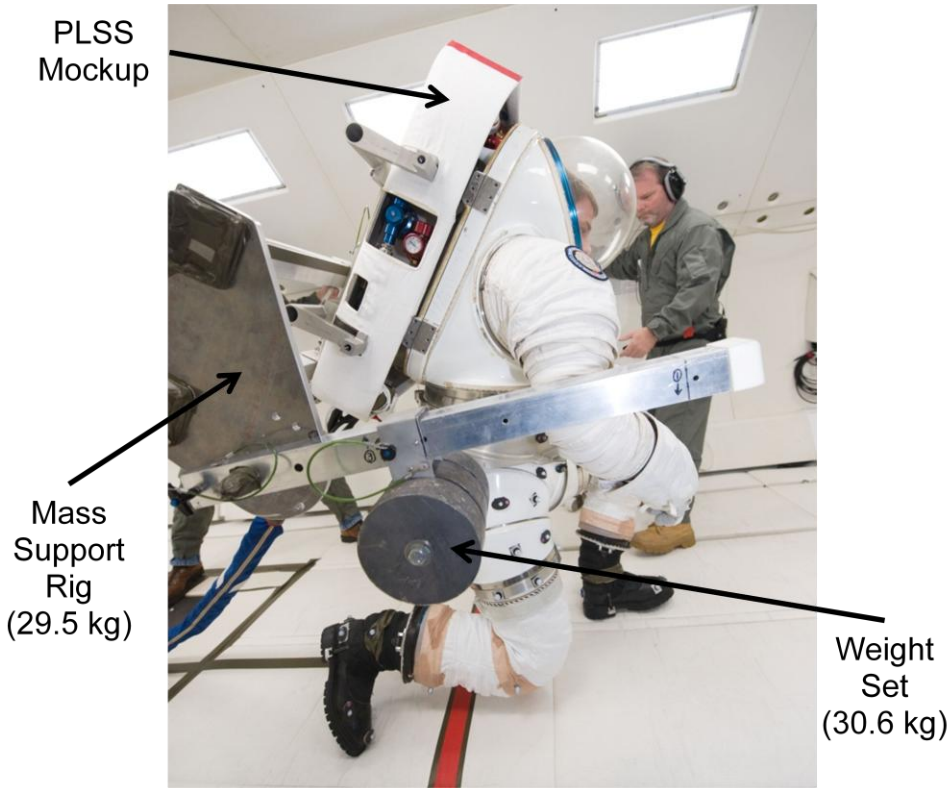

Figure 10 – Mass-support rig attached to the MKIII suit.

2.2.8 Shovel Platform and "Rock Box"

A wooden platform (shown in Figure 4), supporting bags that a subject would either shovel or pick up, was secured to the floor of the aircraft in the exploration area by cargo straps. Once the plane was airborne, the platform was placed on top of camera storage boxes to create an elevated task area 40 cm above the force plates. This elevated height was chosen to keep performance of this task as similar as possible to that of IST-2.[3]

2.2.9 Shovel

An Apollo program replica shovel (Figure 11) was used to move bags of lead shot from one portion of the shovel platform to another. The shovel had an aluminum blade and handle, and the blade edges were taped for safety.

Figure 11 - Apollo program replica shovel.

2.2.10 Lead Shot Bags

Lead shot bags (2.7 kg) were used as simulated rocks in the “rock” box, to be moved by the shovel from one portion of the box to another or to be picked up and set down. The shot bags were used instead of real rocks to enhance safety and to protect the cleanliness of the aircraft. The shot bag outer coverings were doubled and made of rip- and tear-resistant material. The bags can be seen in Figures 4 and 11.

2.3 Equipment Layout in Aircraft

Figure shows the equipment layout for flight during phase I, and Figure shows the layout for phase II. Sections 0 and 0 of the appendix show the equipment layout in the C-9 aircraft for takeoff and landing for both phases of the test. The numbers shown along the fuselage in the figures are station markings in inches.

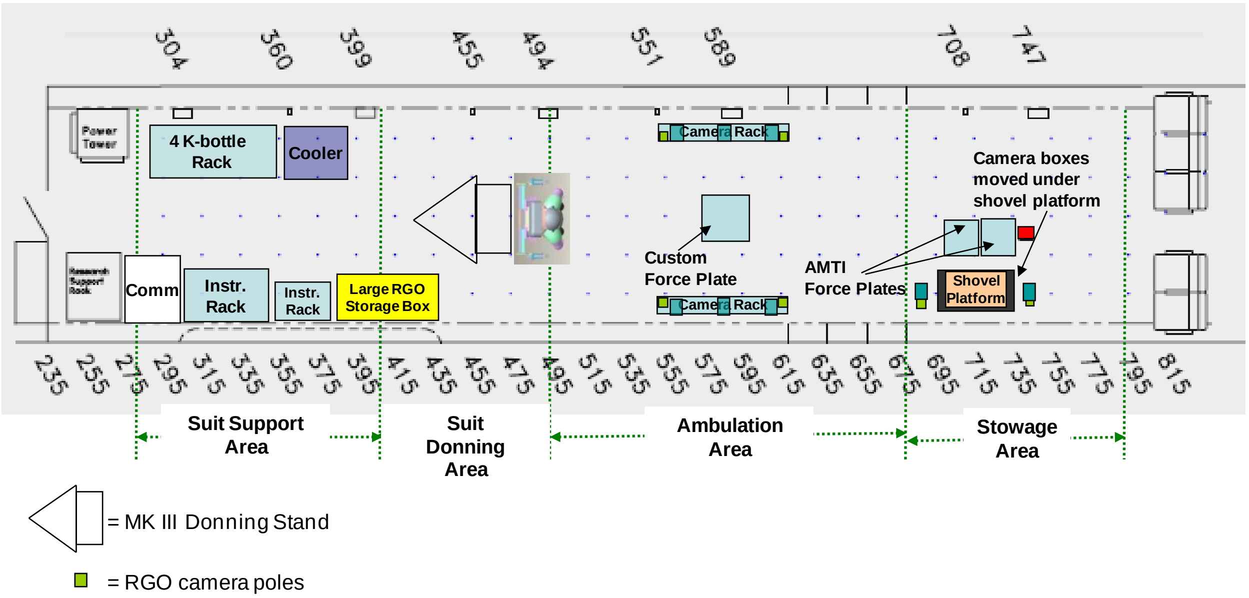

Figure 12 - Phase I equipment layout in flight.

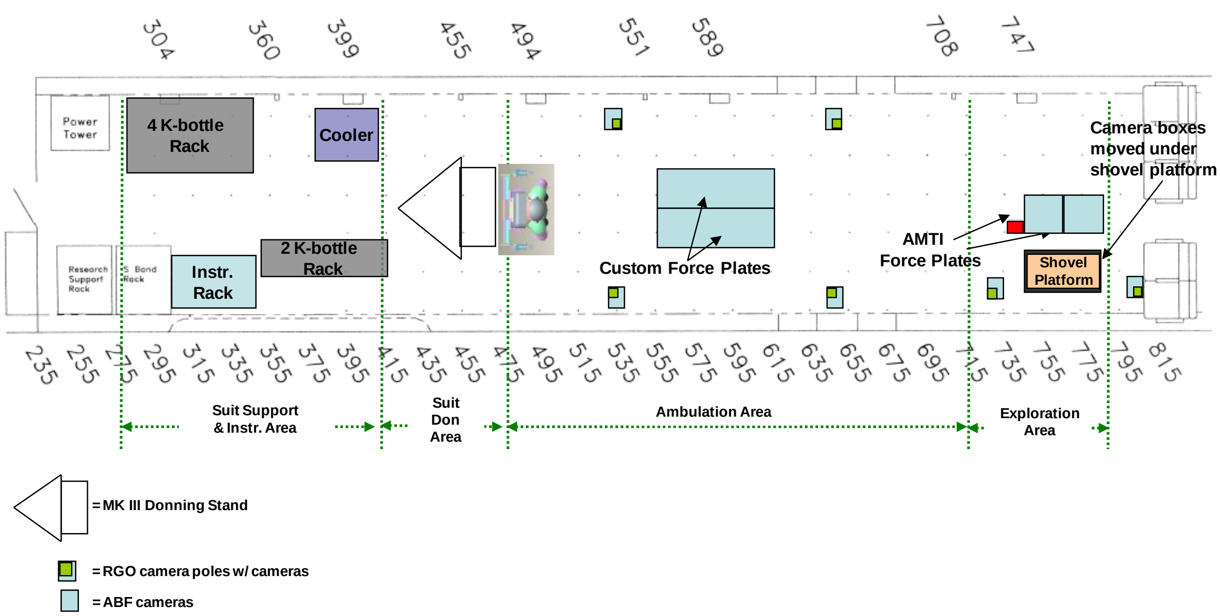

Figure 13 - Phase II equipment layout in flight.

The differences to note between the phase I and phase II layouts are the different configurations of the suit support area in the front of the aircraft and the exploration area in the rear of the aircraft. The suit support area was reconfigured for phase II to allow the use of up to 6 k-bottles of breathing air for potentially longer periods of continuous pressurized suit testing. The exploration area was shifted rearward for phase II to allow more space for ambulation in the center of the aircraft. It should also be noted that the placement of motion-capture cameras was modified for phase II to optimize data capture.

2.4 Test Protocols

2.4.1 Protocol Design

To address the test objectives of comparison with previous IST results, the test conditions were selected so that crossover of mass, weight, and CG conditions were as similar as possible to the previous conditions. **Error! Reference source not found.** shows the varied-weight and varied-mass protocol designs. For protocol-design purposes, an 80-kg subject was assumed. The simulated gravity levels flown (0.1g, 0.17g, 0.3g) were chosen to match as closely as possible the spectrum of gravity levels tested (0.12g, 0.17g, 0.22g, 0.27g, 0.32g) during previous ISTs using POGO. The suit + rig masses chosen, 89, 120, and 181 kg, correspond to the masses of the MKIII suit in the configuration described in section 2.2.2, the MKIII suit with the mass-support rig only, and the MKIII suit with the mass-support rig and weights, respectively. The mass-support rig was designed to have a mass that when added to the baseline MKIII suit would equal the mass of the MKIII suit plus the gimbal support structure that was used to connect the MKIII to the POGO. This is the mass that would be used to compare results of this test to those of the previous POGO tests. The smaller mass was for the MKIII without the mass-support rig and was the lowest mass that could be tested given the requirement that parabolas later in the same flight would require the MKIII with the mass-support rig. The larger mass was chosen to provide a sufficient difference in mass to see the trends associated with mass changes, as well as to have enough added mass so that CG could be altered to three different locations at a constant mass. To compare results from the varied-weight and varied-mass series, total gravity-adjusted weight (TGAW) was used as the common denominator. TGAW is defined as the weight on the ground and is the product of the total mass of the system (suit, subject, mass-support rig) and the gravity level.

Table 2 – Varied-weight and varied-mass testing conditions

	Mass of Subject (kg)	Mass of Suit + Mass-Support Rig (kg)	Gravity Level	Total Gravity-Adjusted Weight (TGAW) (defined in section 0)
∆ Weight (Simulated Mass) Series	80	120	**0.1**	196 N (44 lb)
	80	120	**0.17**	333 N (75 lb)
	80	120	**0.3**	588 N (132 lb)
∆ Mass Series	80	**89**	0.17	282 N (63 lb)
	80	**120**	0.17	333 N (75 lb)
	80	**181**	0.17	435 N (98 lb)

In other tests, investigators have looked at how changing CG affects human performance, but none were completed in an EVA suit. IST-3 was conducted on POGO and used the spider gimbal interfaced to a harness and mass-support rig to perform shirtsleeve testing of CG. Also, CG testing has been performed at JSC's Neutral Buoyancy Lab (NBL) and in NASA Extreme Environment Mission Operations (NEEMO) tests 9 through 13.[4] An attempt was made to use the MKIII suit on POGO to perform CG testing, but POGO could not lift the added mass necessary to create significant changes in CG. Therefore, the C-9 test environment provided the only analog that enabled effective suited CG testing. To be able to directly or indirectly compare CG results and trends between test environments, four centers of gravity were chosen to test in parabolic flight as shown in Table 3. The backpack, CTSD, and POGO CG locations were tested unsuited during IST-3, and all but the backpack and CTSD CG location were tested unsuited in underwater tests. The only direct crossover point between suited tests, however, is the POGO CG, used during IST-1, IST-2, and this test.

Table 3 - CG locations, test environments, and associated mass

CG Description	Location-Aft (cm)	Location-High (cm)	Test Environment	Suited or Unsuited	Mass of Suit + Mass-Support Rig (kg)
Backpack	4.8	1.0	C-9	suited	181
			POGO	unsuited	111
			NBL/NEEMO	unsuited	88
CTSD	7.6	14.4	C-9	suited	181
			POGO	unsuited	111
			NBL/NEEMO	unsuited	88
MKIII w/ mass support rig, stowed arms, no	9.0	14.8	C-9	suited	120

CG Description	Location-Aft (cm)	Location-High (cm)	Test Environment	Suited or Unsuited	Mass of Suit + Mass-Support Rig (kg)
weights					
POGO	11.2	20.1	C-9	suited	181
			POGO	suited	121
				unsuited	111

The chosen CGs - that is, 2005 Crew and Thermal Systems Division (CTSD) baseline (aka CTSD), flexpack Backpack [aka Backpack], and POGO system (aka POGO) - provide a spread of centers of gravity (see Figure 14) in the high and aft quadrant, which is expected to be the likely zone for the suit CG given the need to support a suitport entry into the Space Exploration Vehicle (SEV) Rover with a rear-entry suit. The highest and most aft CG chosen for this test coincided with that of the suit/subject/gimbal CG from suited IST testing on POGO. Additionally, the CG of the MKIII with the mass-support rig with no weights was between the CTSD CG and that achieved during POGO testing, and also provided about the same mass of the system during POGO testing. This configuration provided the best achievable comparison of this test to other ISTs.

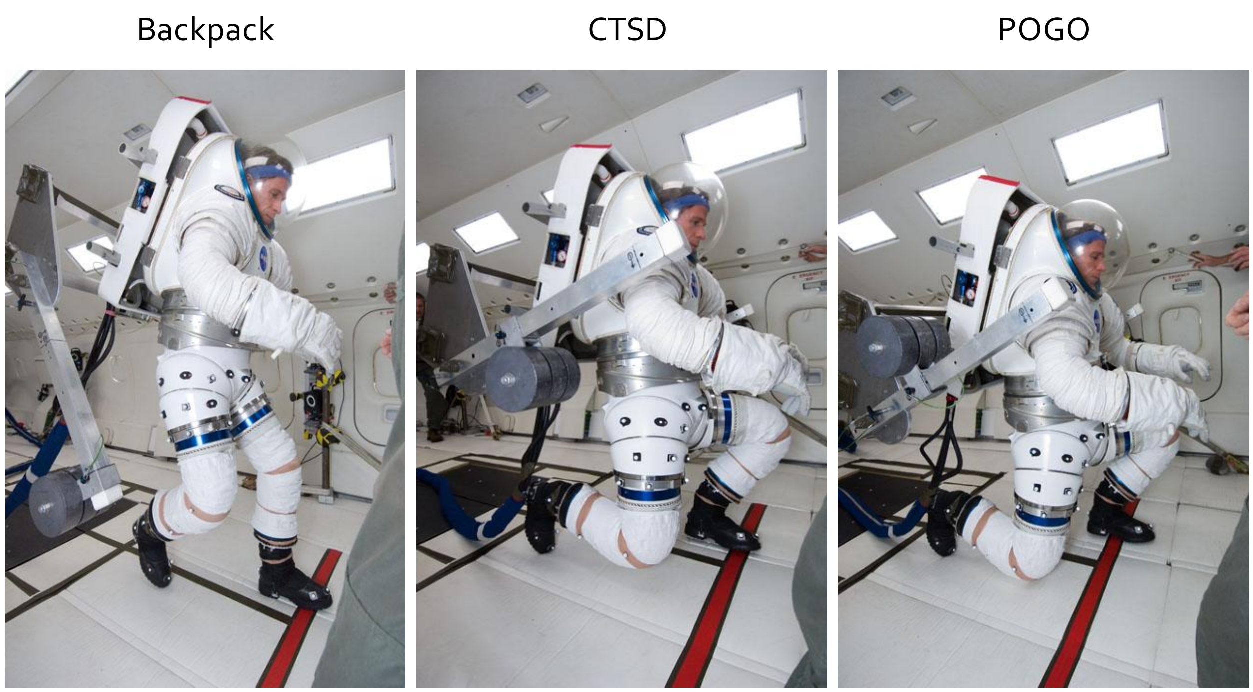

Figure 14 – MKIII suit with the mass-support rig attached, in the Backpack, CTSD, and POGO CG configurations.

The tasks chosen for inclusion in this test were walking, kneel and recover, rock pickup, and shoveling. These tasks were chosen to match the tasks performed on previous ISTs on POGO.[5,3] Because of certain limitations, exact replication of some tasks was not possible. For instance, IST-1 and IST-2 used a treadmill to study ambulation. A treadmill in a ground-based test environment allows exact speed control during walking. However, the C-9 environment has height limitations that make treadmill testing in a suit impossible because the top of the suit could impact the ceiling of the aircraft. Thus, walking was performed on the floor of the aircraft. The kneel-and-recover task was performed the same way as in previous ISTs. The rock pickup and shoveling tasks were modified so that the subject picked up and shoveled bags of lead shot instead of rocks to protect the cleanliness of the aircraft. Also, to replicate limitations of the POGO environment during IST-2, the platform from which rocks were picked up and shoveling was performed was elevated. Although this provided a less realistic task, the intent was to allow more direct comparison with other IST results. The tasks performed are described in more detail in sections 2.4.2 and 2.4.3.

As in all parabolic flight test protocols, the duration of tasks was constrained by the duration of a parabola and the need for test subjects to be able to sit during pull-outs, during which about 1.8g may be felt. The number of repetitions and the length of time needed to perform each task were thus designed to fit within parabolas. Additionally, where more repetitions of tasks were desired, more than one parabola was dedicated to a particular test condition. The order of tasks was coordinated to provide an effective flow between locations on the aircraft and to allow transition into the suit-donning stand when necessary to alter test configurations. Detailed examples of the parabola breakdowns can be found in sections 6.3 and 6.4.

Before the start of suited testing and after aircraft takeoff, the data-collection equipment setup was finalized and the equipment was calibrated. The suit was placed in the donning stand and the suited subject was assisted into the suit. Once the subject was sealed into the suit, the suit pressure was raised to the chosen level of 4.8 psi. During suit donning and pressurization, retroreflective markers were placed on the suit for capture of biomechanics measures by the motion-capture system. Once all equipment and the suited subject were ready, the suited portion of the parabola breakdown was begun. Unsuited tasks were always performed after all suited tasks were completed, sometimes with the same subject after he doffed the suit and other times with a different subject. Unsuited subjects also wore retroreflective markers for collection of data via the motion-capture system.

2.4.2 Ambulation Tasks

Each ambulation trial consisted of walking on the deck of the aircraft to a clearly marked line, turning around, walking back to the starting point in Figure 15, and turning around. As was the case for all tasks, at the start of the parabola the suited subject would be helped into the standing position and before the end of the parabola he would be helped into a seated position. During phase I, the ambulation walkway was about 4 m (13 feet). Because the layout of the data-collection equipment was rearranged for both ambulation and exploration in phase II, the walkway was extended to 5.5 m (18 feet). However, because of volume constraints on turning around, the amount of walkway used was about 3 m during phase I and 4 m during phase II. Four trials of ambulation were performed in each test condition.

Figure 15 - Suited subject performing walking task.

2.4.3 Exploration Tasks

The exploration tasks performed during the protocol were the kneel and recover, rock pickup, and shoveling. At the start of each parabola, the suited subject would be helped into the standing position and execute the task, and then before the end of the parabola he would be helped into a seated position.

2.4.3.1 Kneel and Recover

Each kneel and recover trial consisted of the subject starting in a standing position on both feet, kneeling to touch one knee on the ground (Figure 16), and standing back up on both feet. This was repeated at least twice during each trial. One trial of kneel and recover was performed in each test condition.

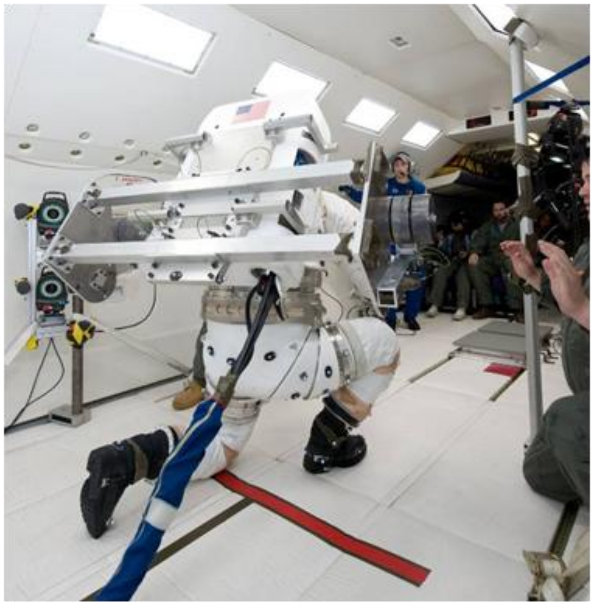

Figure 16 - Suited subject performing kneel-and-recover task.

2.4.3.2 Rock Pickup

Each rock pickup trial consisted of the subject starting in a standing position on both feet with each foot on one of the two force plates in the exploration area. The subject would bend to pick up one of the lead-shot bags on the shovel platform, return to a standing position, and then bend to set the rock back down (Figure 17). Whenever possible, this was repeated at least twice during each trial. Two trials of rock pickup were performed in each test condition.

Figure 17 - Suited subject performing rock pickup task.

2.4.3.3 Shoveling

Each shoveling trial consisted of the subject starting in a standing position on both feet with each foot on one of the two force plates in the exploration area. Test support personnel would hand the shovel to the test subject. The subject would scoop a lead-shot bag from the right side of the shovel platform into the shovel (Figure 18) and dump it into the left side of the shovel platform. Whenever possible, this was repeated at least twice during each trial. Two trials of shoveling were performed in each test condition.

Figure 18 - Suited subject performing shoveling task.

2.5 Test Conditions

2.5.1 Varied Gravity Level

During phase I of the parabolic flight test, three different gravity levels were tested at a single suit mass (120 kg) and a single CG (9.0 cm aft/14.8 cm high for the reference subject of 81.6 kg and 1.83 m; the reference subject was the basis of equipment design for the placement of CG). The gravity levels simulated were 0.1g, 0.17g, and 0.3g with corresponding mean TGAWs of 196, 333, and 588 N, respectively, based on the mean subject mass of 78.9 kg. The 0.17-G gravity level was chosen because it equates with lunar gravity and previous ISTs have included testing at this gravity level. The 0.1-G and 0.3-G gravity levels were chosen to match as closely as possible the gravity levels from previous ISTs while accommodating the limits of aircraft capability.

This portion of the testing was conducted with both suited and unsuited subjects performing all the tasks described in sections 2.4.2 and 2.4.3. Some portions of the varied-gravity-level testing were redone in phase II because of problems with data capture during phase I. Where trials were repeated, both the objective and subjective data from the later trial were used.

2.5.2 Varied CG

Varied-CG testing was performed during phase II of the flights at a single suit mass (181 kg) and single gravity level (0.17g). The CGs simulated were named Backpack, CTSD, and POGO (Backpack = 4.8/1.0, CTSD = 7.6/14.4, and POGO = 11.2/20.1 cm, aft/above the reference subject's CG). All system CG coordinates are in reference to how the system CG varied from the subject's CG. The Backpack and CTSD CGs were chosen because they represent the CG positions of current conceptual designs for space suits, where "space suit" is defined as the combined pressure garment and PLSS. The POGO position was chosen because it matches the system CG achieved during IST-1 and IST-2 and thus would provide the opportunity to see if the high/aft CG adversely affected performance. The system CG was defined as the combined CG of the reference subject (81.6 kg, 1.83 m), the space suit, and the equipment required to change the CG.

This portion of the testing was conducted with only suited subjects performing all the tasks described in sections 2.4.2 and 2.4.3.

2.5.3 Varied Mass

Varied-mass testing was performed during both phases of the flight series. Three different suit masses (89, 120, and 181 kg) were tested at a single gravity level (0.17g) and a near-constant CG. At the mean subject mass of 78.9 kg, this led to TGAWs of 282, 333, and 435 N. The 120-kg (TGAW of 333 N) condition was common to both the varied-weight and varied-mass series. Point-by-point comparison of the varied-weight and varied-mass series was not possible because of limited adjustability of suit mass and parabolic profile options.

This portion of the test was conducted with only suited subjects performing all tasks described in sections 2.4.2 and 2.4.3.

2.6 Data Collection and Analysis

2.6.1 Collection and Analysis of Biomechanics Data

Custom-built force plates were used to record ground reaction forces (GRF) under the subject's feet during ambulation. The GRF recorded were normal (perpendicular) to the surface of the aircraft floor. Two additional force plates (AMTI, Watertown, MA) were used during the exploration task trials to record three-axis GRF and center of pressure (COP). During the exploration tasks, the subjects would stand on top of the force plates while performing their tasks.

A state-of-the-art Vicon MX motion-capture system (Vicon, Oxford, England) was used to capture the kinematic data. Custom-made camera mounting frames were made by the ABF to ensure the stability of the cameras during flight. Small retro-reflective markers were placed on key landmarks of the body, on the MKIII suit, and on the mass-support rig (see Figure 19).

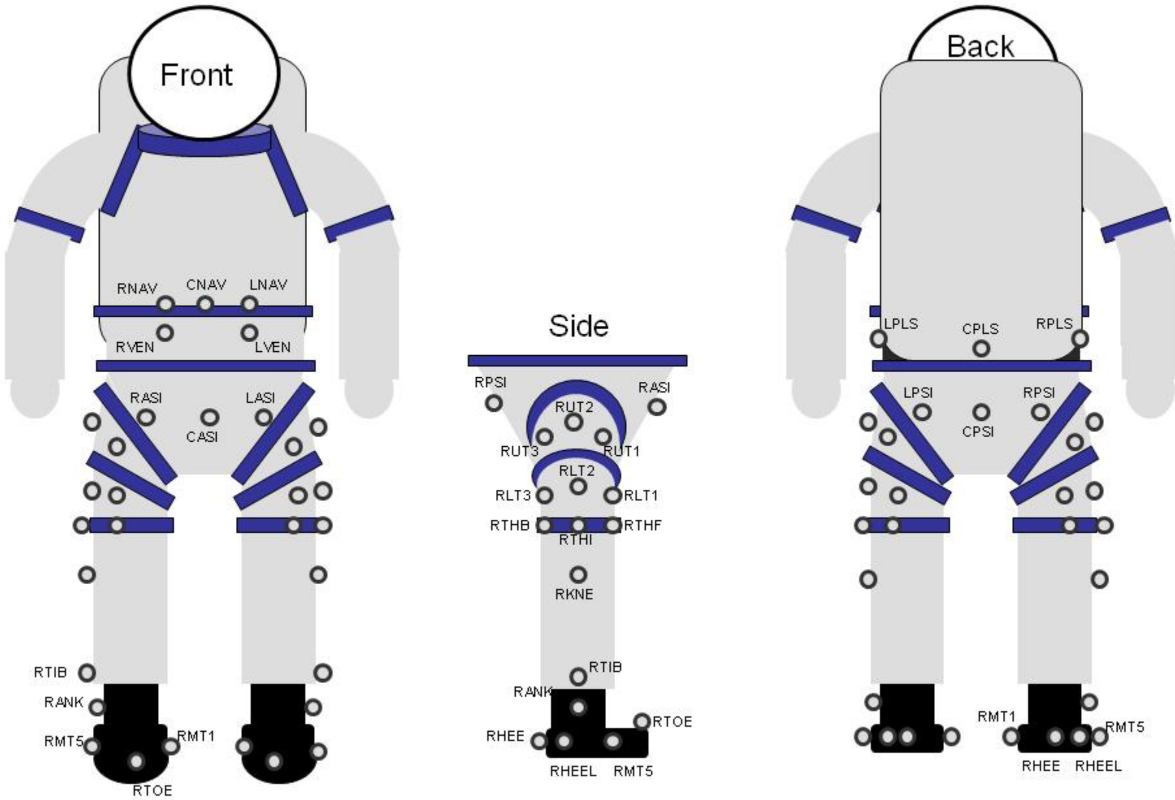

Figure 19 – Illustration of the suited marker set used.

All raw data sets were filtered with appropriate filtering algorithms. Data were processed with a custom-made model for use with the mass-support rig and gimbal. This new model provided additional flexibility and accuracy over previous models. The model uses inverse kinematics and dynamics to calculate the output variables. Data processing with this model outputs kinematic, kinetic, and temporal-spatial information.

This report uses definitions, reference frames, and reference planes commonly used in the field of biomechanics and prescribed by the International Society of Biomechanics.[6] Section 6.5 of the appendix contains reference materials and graphical representation of these items.

The center of pressure (COP) and its relation to the base of support (BOS) was analyzed with the AMTI force plates during the exploration tasks. In the rear of the plane, six Vicon cameras were aimed at the two force plates. Only the trajectories of foot markers were captured and used for the analysis.

2.6.2 Collection and Analysis of Subjective Rating Data

The following subjective ratings were collected during the test:

- Ratings of Perceived Exertion (RPE)[7] were used to gauge how much effort subjects thought they must exert to complete each task in each condition. RPE was collected at the completion of each set of trials of the same task in a given condition.

- The Gravity Compensation and Performance Scale (GCPS)[2] was used to determine the level of compensation a person thought was necessary to maintain performance compared to their performance of the same task unsuited in 1g.

- The Cortlett and Bishop Body Part Discomfort Scale[8] was used to characterize discomfort at different body locations. Discomfort ratings were collected at the completion of all the trials for a given condition.

- Post-test questionnaires were used immediately after each test flight to collect subject rank-ordering of conditions and comments.

The scales were posted in several places on the aircraft that were visible to the test subject during the times they were asked to provide ratings. Discomfort was the primary test-termination criterion and was used to provide feedback to the test team about test hardware and conditions. Discomfort data will not be discussed in this report. Additional information about each of the scales is in section 6.7 of the appendix.

2.6.3 Significant Differences

In comparing the objective data and subjective ratings of different conditions, it is important to define some level of change that is deemed practically significant. Because of the limited sample size (n = 7), inferential statistics were not used; therefore, statistical significance was not calculated. For these analyses, a change in RPE of 2 should be considered of practical significance. RPE changes of one unit are approximately at the level of practical significance for VO_2,[5] but, because RPE is a whole number scale, it would take a change >1 to see practically significant differences in metabolic rate (if it were possible to collect during this test).

GCPS is not a continuously linear scale as is RPE. Therefore, it is more complicated to assign a simple level of practical significance to changes in GCPS. It is reasonable to define a range of GCPS, where changes within the range are of interest, but would not be considered to be practically significant. Using this breakdown, we selected a GCPS category of 1 to 3 as “ideal,” 4 as “acceptable,” 5 to 6 as “modifications warranted,” 7 to 9 as “modifications required,” and 10 as “unable to complete the task.” A level of practical significance for GCPS should be considered as one in which the value changes to a different category.

2.6.4 Images and Video

During all flights in the test series, a NASA still photographer was present and captured images of the test subjects performing tasks in all test conditions. Additionally, digital video cameras were used to capture selected trials as well as specific foot placement on the exploration force plates during task performance.

3.0 Results and Discussion

3.1 Subject Characterization

All of the subjects tested were male crewmembers (see Table 1). Section 6.6 of the appendix shows the distribution of the subjects' height and mass compared to the population in the Human System Integration Requirements (HSIR)[9] database. As shown, the distribution of the subjects' stature was central to that of the database for males, but was skewed high for the distribution of the database for combined males and females. The distribution of the subjects' mass was also relatively centered in the male distribution, but not in the combined distribution.

3.2 Center of Gravity Variation by Subject

The system CGs used during the testing were defined as the combined CG of the reference subject (81.6 kg, 1.83 m), the space suit, and the equipment required to change the CG. As all subjects were not identical to the reference subject, the system CG that was achieved varied by subject. Figure 20 shows the groupings of achieved system CGs based on subject differences.

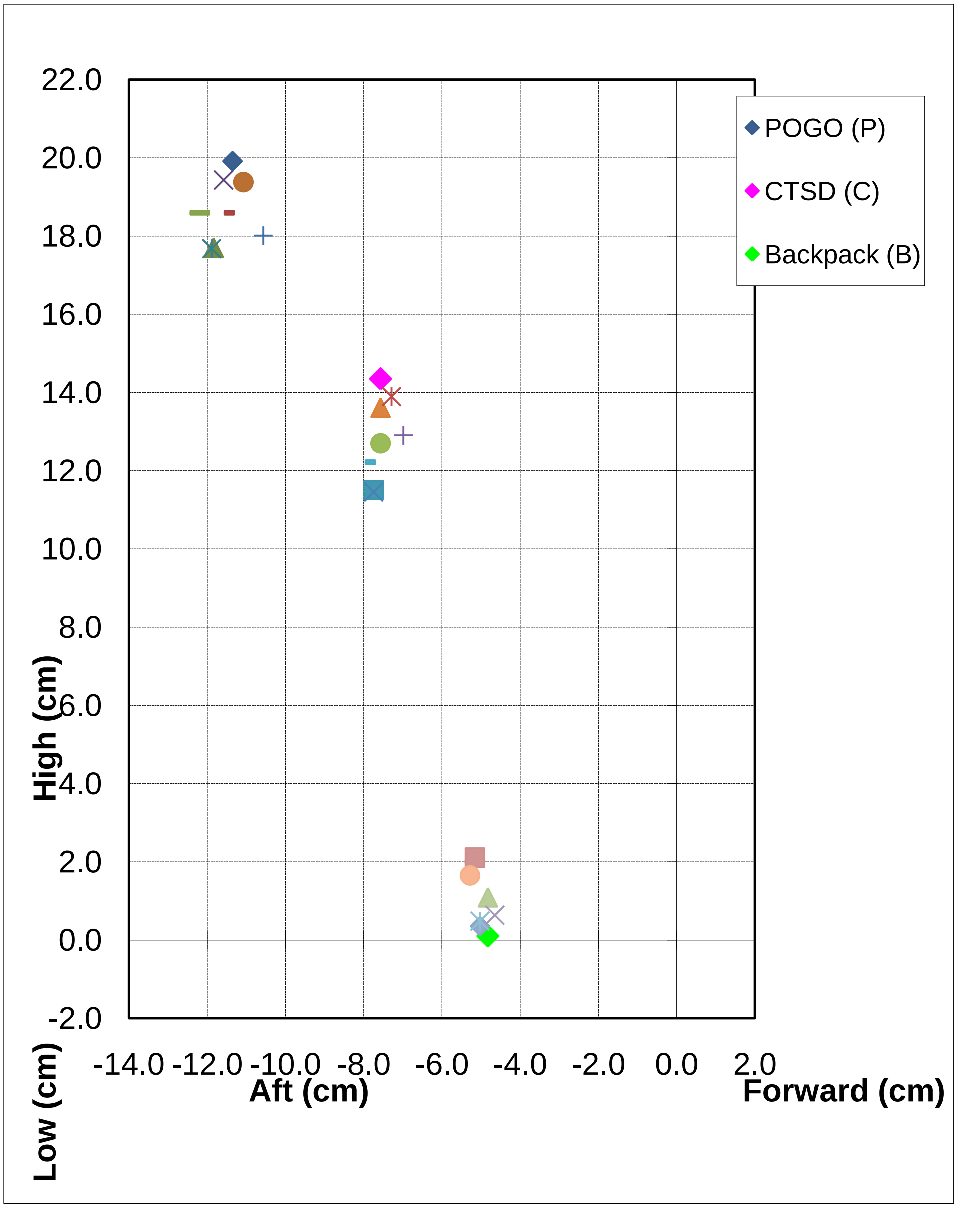

Figure 20 - System CG variation by subject; the symbols for the P, C, and B points shown in the legend are the reference locations based on the reference subject used to design test equipment; all other points are the locations of the CGs for the test subjects.

3.3 Reduced-Gravity Environment

To better understand the actual testing environment, the ABF analyzed the reduced gravity levels for a large number of the parabolas flown during testing. Figure 21A shows the actual vertical acceleration trace for a sample parabola (black line), the parabola mean acceleration (dashed line), and 1/6 Earth gravity (gray line). As shown, the gravity level varied considerably. The rest of the accompanying graphs show the velocity (B), jerk (C), and work (D) as calculated from the original acceleration data. For reference, running on a level plane costs roughly 3.4 $J \cdot kg^{-1} \cdot m^{-1}$, independent of running speed.[10]

Since no displacement data for the plane itself were available and doubly integrating the aircraft acceleration profile created excessive noise, the following equation (Eq. 1) was used to calculate the work through the change in kinetic energy of the system, where *v* is the velocity of the aircraft (Figure 21B).

$$W \approx \Delta KE = \frac{1}{2} m v_{final}^2 - \frac{1}{2} m v_{initial}^2 \quad (1)$$

Figure 22 shows the resulting change in gravity as an induced force for an average male. Variations like this can have considerable effects on the performance of the subjects. The mass used for the work and force calculations was 80 kg. For reference, the weight of an 80-kg subject at 1/6 Earth gravity is roughly 130 N, so the minimum shown in Figure 22 would produce a reduction in the subject's weight of more than 30%.

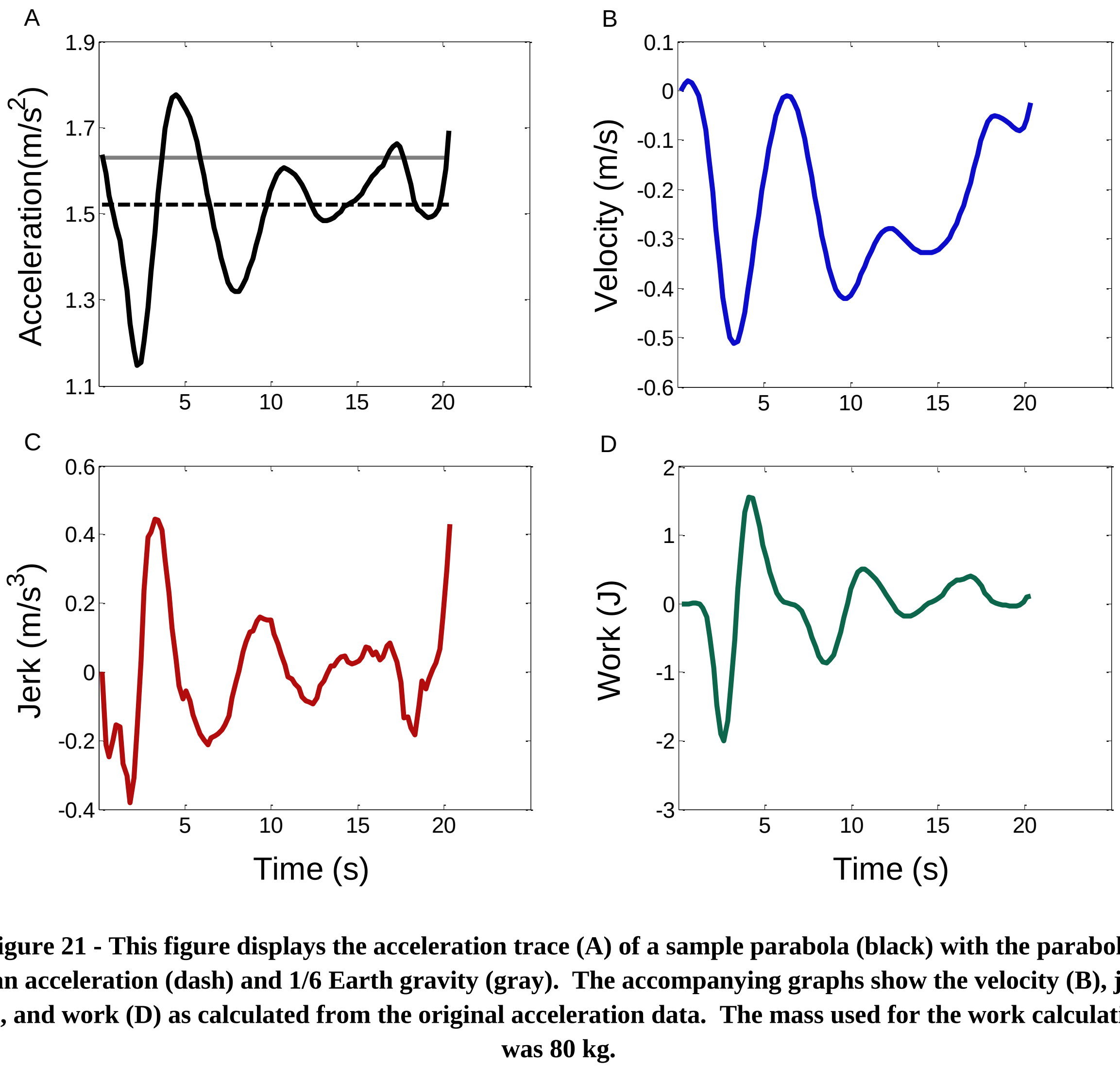

Figure 21 - This figure displays the acceleration trace (A) of a sample parabola (black) with the parabola mean acceleration (dash) and 1/6 Earth gravity (gray). The accompanying graphs show the velocity (B), jerk (C), and work (D) as calculated from the original acceleration data. The mass used for the work calculation was 80 kg.

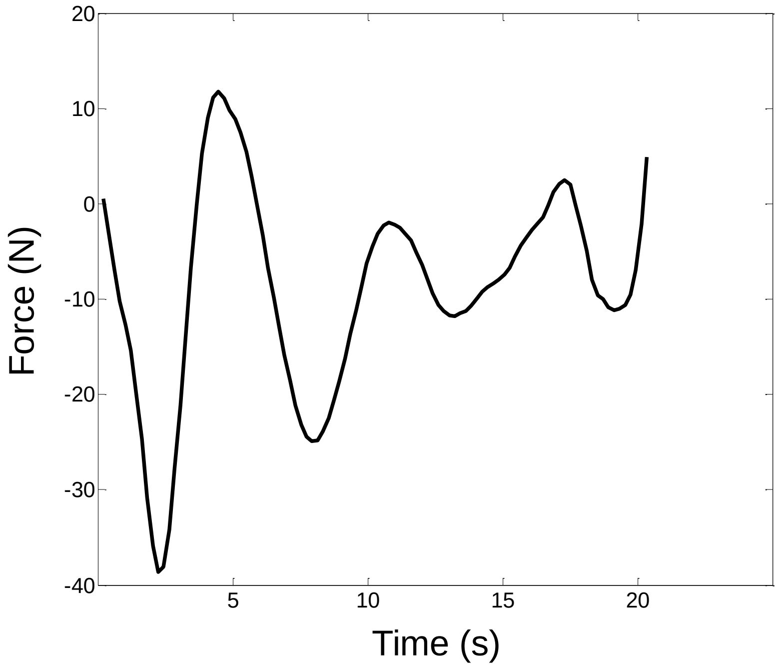

Figure 22 - From the same example as Figure 21 (above), this figure displays the resultant change in force from the desired lunar gravity. The mass used for the calculation was 80 kg.

If the rest of the parabola data are examined we can extract the mean of the mean acceleration during the parabolas and the standard deviation of the parabola mean acceleration. Table 4 is a summary of the collected parabola data shown. The "x Acceleration" line was calculated from each individual parabola's overall mean value, while the "Δ Acceleration" line was calculated from the maximum and minimum changes in acceleration in each parabola from that parabola's mean. The mean values seemed to be fairly consistent, but some sizable changes in acceleration occurred during the parabolas, as seen in the example in Figure 21A. Changes in acceleration were also calculated into velocity changes and jerk by means of integration or derivation, respectively. Acceleration data were processed for 219 parabolas. Each parabola was considered to have begun when the acceleration dipped below 2 m/s^2 and the data were then filtered with a moving-average filter with a 1-second window to eliminate electrical noise and smooth the data.

Table 4 - The mean, standard deviation, minimum, and maximum for most of the parabolas flown.

	Mean	***St Dev***	***Max***	***Min***
Velocity (m/s)	0.34	0.56	10.44	-6.78
x Acceleration (m/s^2)	1.60	0.14	1.85	1.45
Δ **Acceleration** (m/s^2)	-	-	0.7	-0.54
Jerk (m/s^3)	-0.02	0.11	0.44	-0.80

3.4 Biomechanics Results & Discussion

3.4.1 Ambulation: Kinetics

Kinetic analysis describes the methods the body uses to store, absorb, transfer, and expend energy. By studying kinetics, one can determine the nature of the interactions between the human body and its environment. Normally, the body is a self-sustaining, dynamic entity that receives no energy inputs from the surrounding environment. The C-9 reduced-gravity environment is not a purely static environment and may impart energy from acceleration variations into the human body while the body is performing tasks.

For the six crewmembers in phase I, the ABF measured kinetics through the ground reaction forces (GRF) in all conditions, using custom-fabricated force plates mounted to the floor of the aircraft. Unlike the protocol of previous tests performed on a treadmill, subjects ambulated at self-selected speeds (Figure 23) over ground through the capture volume on the aircraft. Ambulation speeds for each condition have a fairly large range. Factors contributing to this could include the dynamic variability of the test environment, the range of subjects' experience in this test environment, the range of their experience in the MKIII suit, and the ensuing stability issues. Differences between suited conditions were negligible. Unsuited ambulation was generally faster than suited ambulation.

For phase II, ambulation speeds for these conditions were fairly close in range (Figure 24). Factors contributing to this could include the subjects' increased experience in the test environment, increased experience in the MKIII suit, and increased caution because of the added mass and bulk of the mass-support rig.

In the following set of plots starting with Figure 23, nomenclature is used to denote different conditions. The "0.17g (no rig)" label denotes the 0.17g suited condition with no mass-support rig attached and also no lead weights. Likewise, the "0.17g (WL)" label denotes the 0.17g suited condition with the mass-support rig attached, with no lead weights, but with the waist bearing on the MKIII locked to prevent rotation. The "0.1g", "0.17g", and "0.3g" conditions are suited with the mass-support rig attached with the lead weights at those gravity levels. The "0.17g (US)" label denotes the unsuited condition at 0.17g.

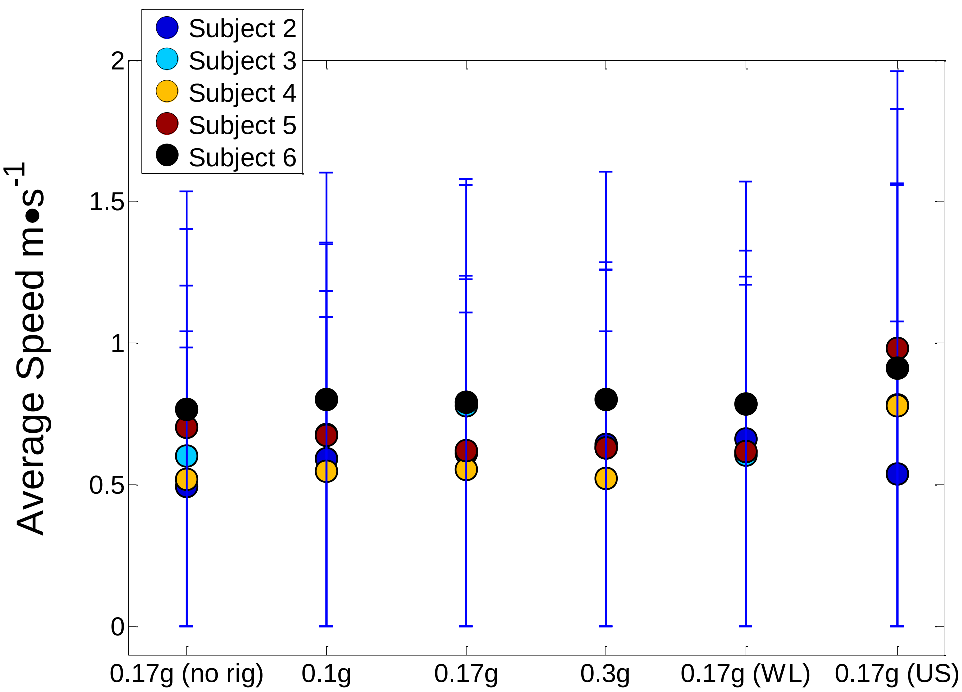

Figure 23 – Ambulation speed for 5 of 6 subjects in varied reduced-gravity conditions (phase I). One subject had insufficient motion-capture data from which to derive ambulation speed data.

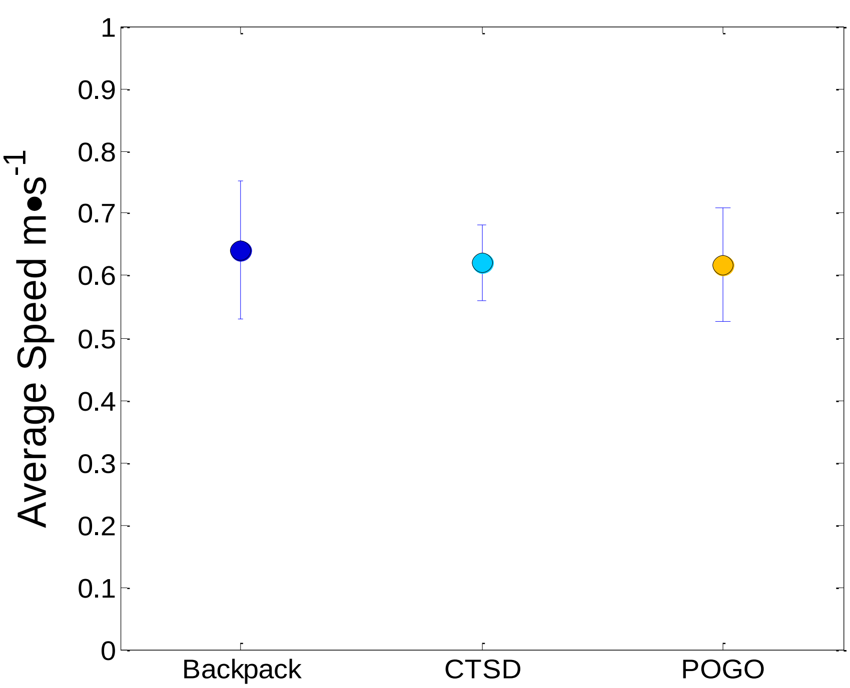

Figure 24 - Average over-ground ambulation speed for subjects in varied CG conditions (phase II).

3.4.1.1 Ground Reaction Forces

Peak vertical ground reaction forces (GRF) were collected; these represent the normal force acting on the subject when the subject is in contact with the walking surface of the airplane. GRF values for all tested conditions were normalized to the subjects' 1g body weight (BW). Normalization of the GRF data to subjects' respective BW allows a direct comparison to be made across these subjects for the tested conditions. Kinetics were measured by measuring the vertical GRF of the six crewmembers for all tested conditions (Figure 25).

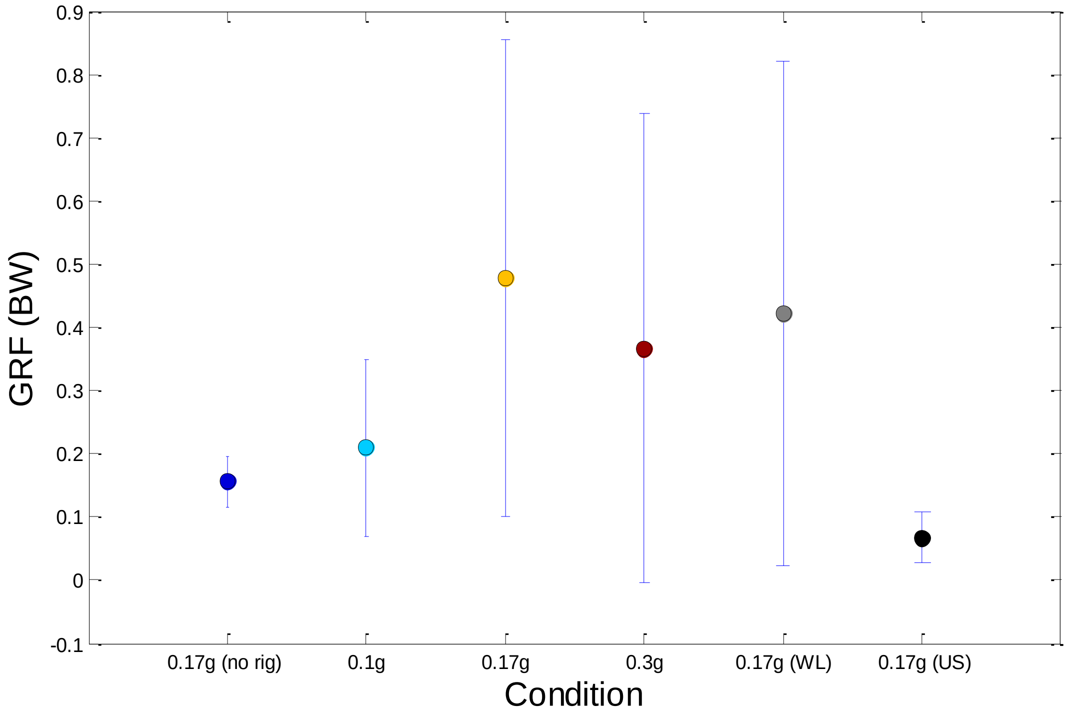

Figure 25 – Mean peak vertical ground reaction force (GRF), normalized to subjects' 1g body weight, for ambulation at varying self-selected speeds on the C-9 aircraft during varied reduced-gravity conditions (phase I).

Data from the varied gravity-level conditions reveal that GRF experienced by suited subjects while wearing the mass-support rig ranged from less than 0.1 BW to about 0.8 BW (Figure 25). Unsuited ambulation in 0.17g yielded the lowest mean peak vertical GRF. This was to be expected, as unsuited subjects were not carrying the added mass of the suit and/or mass-support rig.

For phase I of the flights, the 0.17g condition without the mass-support rig was always performed first in the sequence of conditions. This may have led to the normalized GRF for this condition being notably smaller than the GRF for other conditions, because some learning effect may have occurred. Additionally, not having the mass-support rig attached during this condition decreased the amount of force imparted to the ground during contact and thus the magnitude of the GRF. The variability observed for this condition was considerably less than variability for other suited conditions, which suggests that the mass-support rig increased subject variability during ambulation. Also, the 0.17g waist-locked condition was always the last suited condition performed.

Several other factors also added to the large amount of variability. Notable inconsistency in the subjects' ability to strike the force plates cleanly often led to partial contact or no contact. Subjects would often target the force plates, resulting in short steps or exaggerated steps, either of which could provide erroneous GRF data. Other factors such as restricted walkway space and length, limited ceiling height, wearing of the mass-support rig, and firm time restrictions with each parabola had an effect on the ability of subjects to reach and maintain a steady gait. There is a considerable amount of instability inherent in walking through the C-9 aircraft. It has been estimated that for the phase I test, the error in recorded force data could be up to 30% for the whole ambulation force plate and about 18% for the center of the force plate. Normalization of the GRF data on a parabola-by-parabola basis to remove aircraft acceleration differences was not performed.

In phase II, no considerable differences were observed in GRF between CG conditions Figure 26). The GRF observed in phase II (all performed at 0.17g) compared to GRF on phase I flights at 0.17g with the suit (no rig) showed a large increase in average GRF, which occurred partly because of the mass (that is, 90.7 kg [200 lb] of weight) of the added mass-support rig. However, little increase in GRF came from the phase I suit and rig frame without the weights. The amount was much less than anticipated with the increase in mass of 61 kg (135 lb). This again could be caused in part by the large variability induced by the mass-support rig.

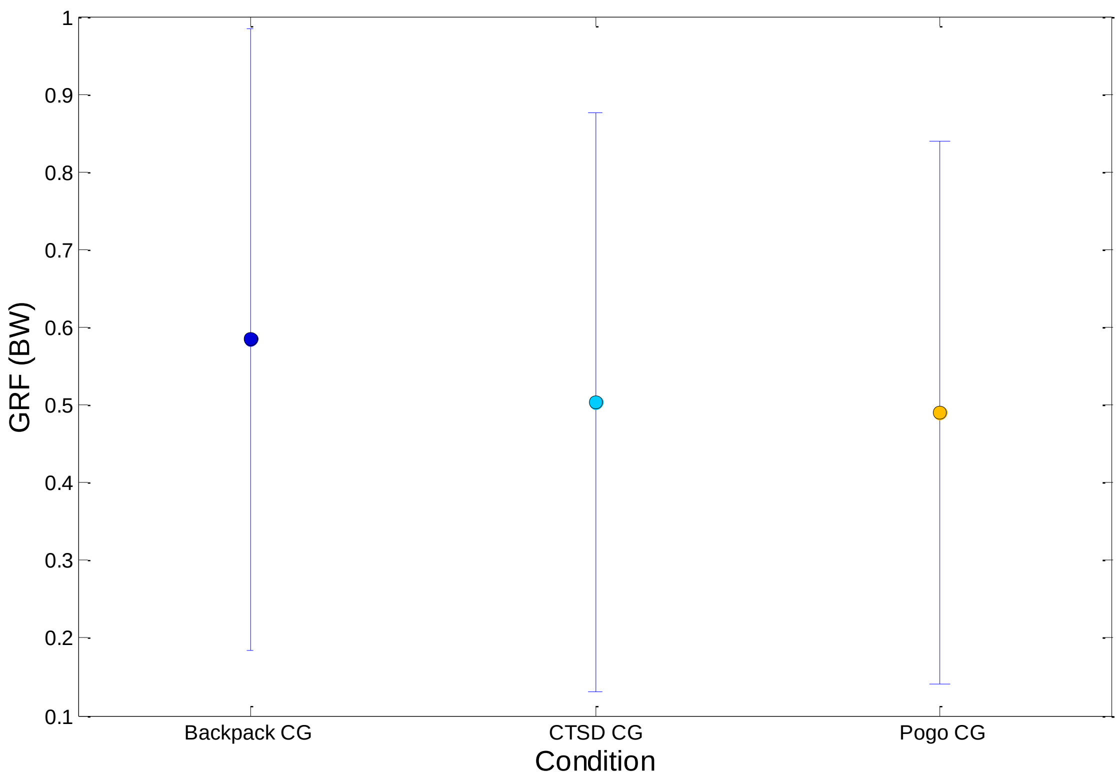

Figure 26 – Mean peak vertical ground reaction force (GRF), normalized to subjects' 1g body weight, for ambulation at varying self-selected speeds on the C-9 aircraft during varied reduced-gravity conditions (phase II).

3.4.2 Ambulation: Temporal-Spatial Characteristics

3.4.2.1 Cadence

Cadence is defined as the number of steps taken per minute. Cadence values collected during this test may indicate the effect of a limited walkway and that subjects were unable to attain a steady gait pattern, thus resulting in lower mean cadence than expected.

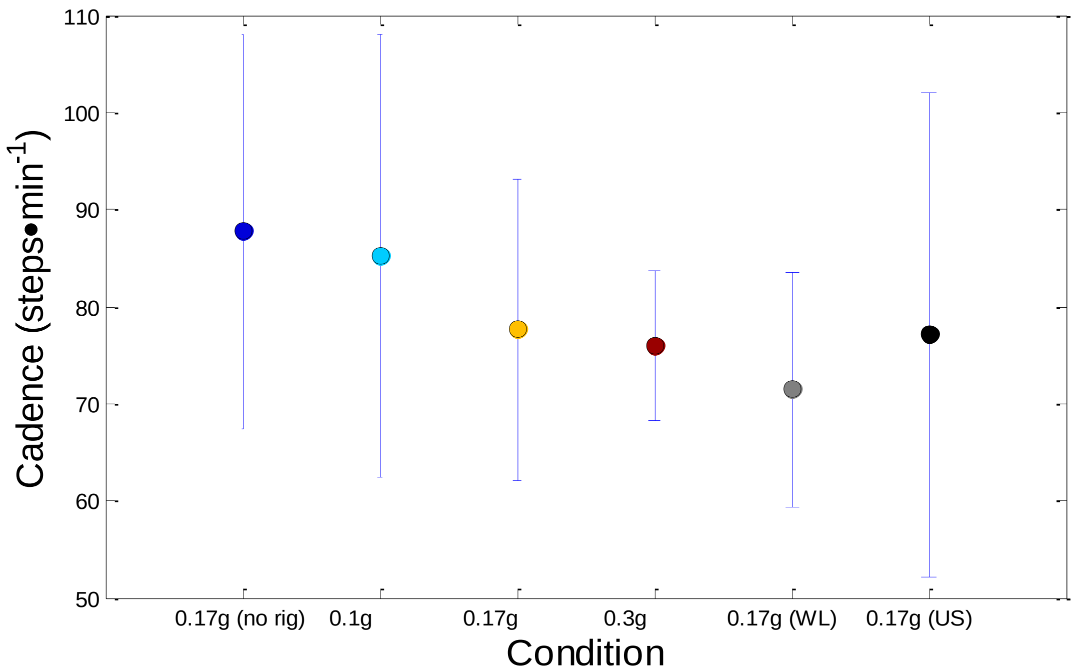

Figure 27 – Mean cadence for ambulation at varying self-selected speeds on the C-9 aircraft during varied reduced-gravity conditions (phase I).

As seen in Figure 27, cadence results had their smallest standard deviation at the heaviest gravity level (0.3g). This indicates that the higher gravity may have allowed more control during walking trials and thus a greater consistency of subjects' gait pattern from step to step as they moved through the capture volume. Conversely, high variability was observed with the 0.1g condition, indicating that the lighter gravity may have decreased the subjects' ability to maintain a consistent gait pattern while moving through the capture volume. The lowest mean cadence was associated with the 0.17g waist-locked condition ("0.17g (WL)"in Figure 27). It should be noted that the waist-locked condition was always the final suited condition performed, so it is possible that a learning effect may have contributed to this result.

In phase II, the CTSD CG condition exhibited the lowest mean cadence and the smallest variability Figure 28). The POGO CG was associated with the largest mean cadence as well as the greatest variability.

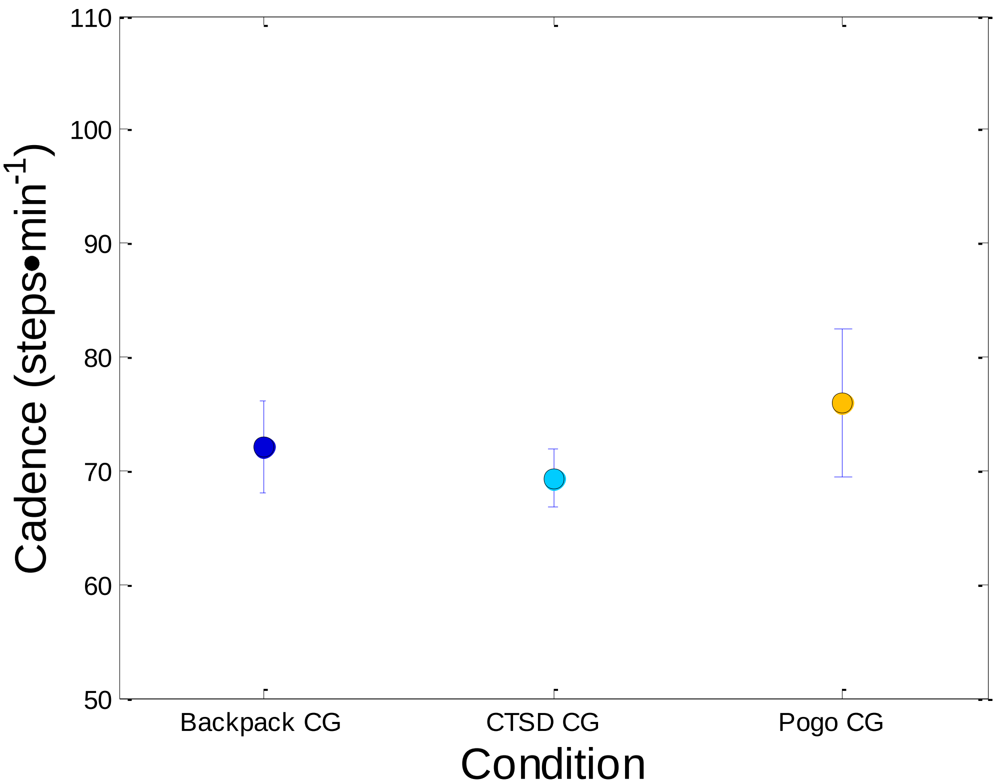

Figure 28 - Mean cadence for ambulation by suited subjects at self-selected speeds in varied CG conditions (phase II) on the C-9 aircraft during lunar-gravity parabolas.

As also seen with mean ambulation speed, all mean cadence values for conditions tested in phase II were notably lower than those observed in phase I, with the exception of the phase I waist-locked condition. This is most likely because of the increase in weight mass/inertia and geometric volume of the system conditions in phase II.

Literature has shown that the mean adult (1g, unsuited) cadence is about 113 steps/min for a freely chosen walking speed.[3] All of the mean cadence values observed in the current test were notably lower. The cadence values seen in the current test indicate that (a) subjects had difficulty attaining a consistent gait pattern because of several factors, including aircraft dynamics and the limited walkway available in the C-9 fuselage, (b) higher gravity levels (0.3g) allowed more control by the subjects and therefore somewhat greater consistency of gait pattern from step to step, and (c) the high variability of unsuited cadence data most likely was caused by subject experimentation and altered gait patterns, as they often rushed through the capture volume in an attempt to complete the second pass within a parabola.

3.4.2.2 Stance Time

If the body's center of mass were treated as a point and its motion were plotted, the trajectory of this point would resemble that of a sinusoidal parabolic projectile. During locomotion (regardless of type: walking, running, loping), when the foot is in contact with the ground the skeletal muscles work to adjust the position of the body's total center of mass to the optimal position to continue moving in that sinusoidal pattern. Stance refers to the portion of the gait cycle in which the foot is in contact with the walking surface. In phase I, Figure 29 shows that the 0.3g condition was associated with a greater mean stance time, which may indicate a greater amount of stability during ambulation. However, the increased weight of the suit and attached objects such as the Backpack and PLSS could have caused the greater stance time, because the body needs more support time so that it can continue to redirect the center of mass. These results coincide with the lower cadence observed during the 0.3g condition (see Figure 27). The greatest stance time was observed with the 0.17g waist-locked condition, which again may be the result of several factors, including an effect of locking the suit waist on gait kinematics and the potential for learning effects, as the waist-locked condition was always the final condition performed by the subjects.

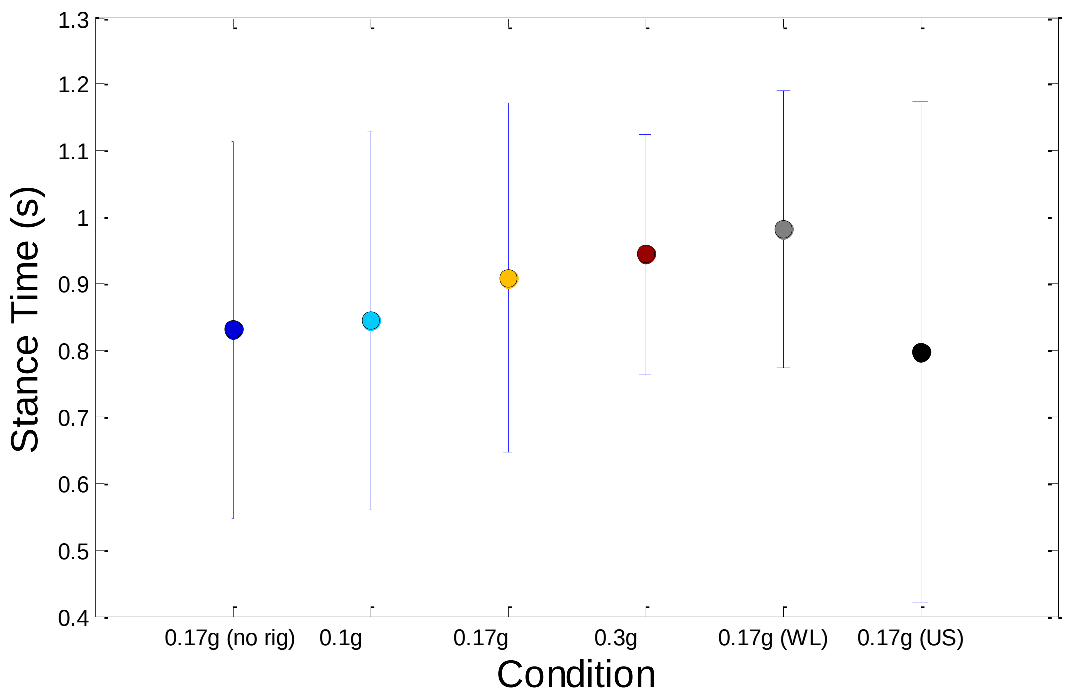

Figure 29 – Mean stance time for ambulation at varying self-selected speeds on the C-9 aircraft in varied reduced-gravity conditions (phase I).

The results from unsuited trials during phase I ("0.17g (US)" in Figure 29) show the lowest mean stance time, but also the greatest amount of variability. This variability can be attributed to several factors, including subject experimentation with gait patterns, a short walkway and small capture volume, and the dynamic nature of the C-9 environment (see section 3.1).

For phase II, mean stance times in seconds for suited subject ambulation at self-selected speeds are presented in Figure 30. The Backpack CG condition had the longest mean stance time. The POGO CG had the shortest mean stance time but the greatest variability. Phase I results show that for 0.17g conditions the mean stance time was about 0.9 seconds (Figure 29). All mean stance times for conditions tested in phase II were greater than those seen in phase I, indicating that the mass added to the mass-support rig to change CG may have affected the subjects' ambulation. The large amount of variability makes any comparisons between conditions inconclusive.

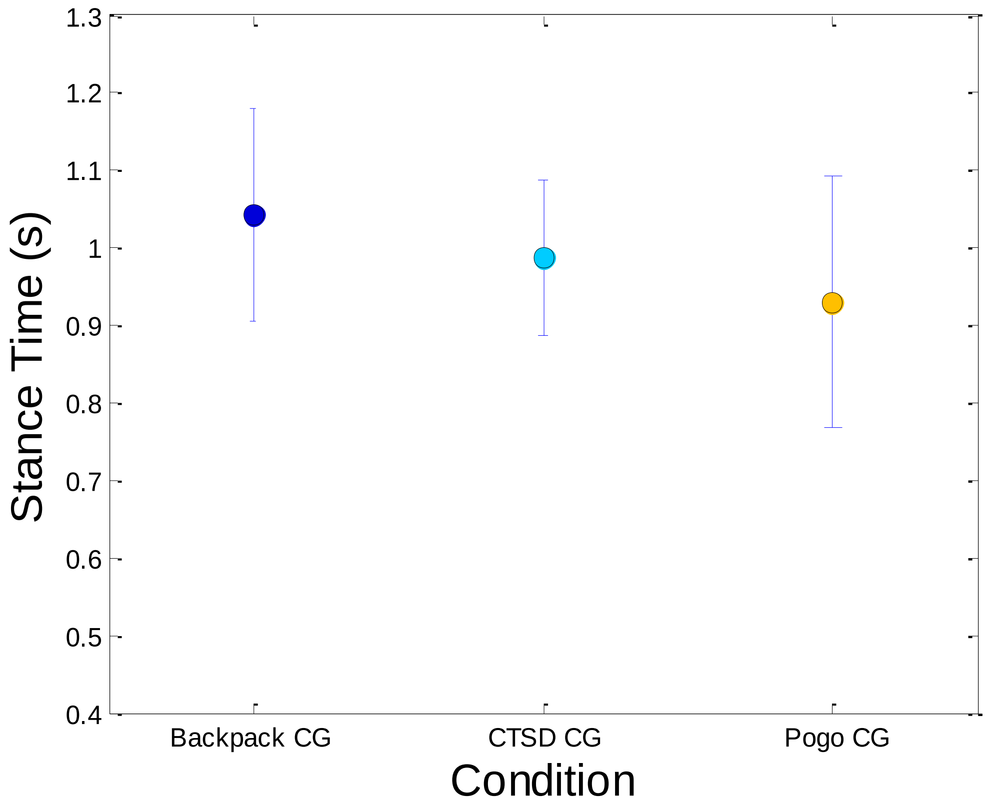

Figure 30 – Mean stance time for ambulation by suited subjects at self-selected speeds in varied CG conditions on the C-9 aircraft during lunar-gravity parabolas (phase II).

3.4.2.3 Step Length

Step length is defined as the anterior-posterior distance between the left and right foot for consecutive gait events, that is, initial contact of one foot to the initial contact of the opposite foot. The term "initial contact" is used to describe this event, as gait on the C-9 was not always performed in a heel-toe manner. For consistency, this distance was calculated using the trajectories of the retro-reflective markers that were placed on the left and right heels.

Figure 31 shows the calculated step lengths for subject ambulation at varying self-selected speeds on the C-9 aircraft during phase I. The shortest step length was observed with the 0.17g (no rig) condition, which had a large standard deviation. The low mean step length indicates attempts by subjects to take short steps during ambulation. The large variability may be due to the fact that this was always the first condition performed, and subjects may have been less familiar with suited ambulation in the C-9 environment during this portion of the testing.

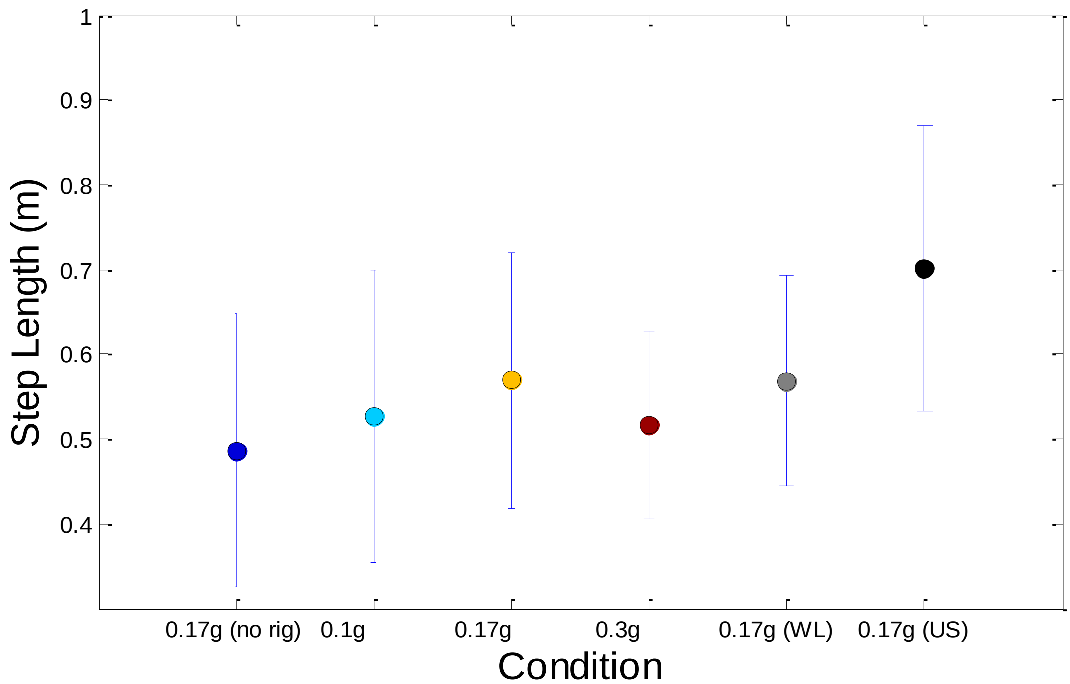

Figure 31 – Mean step length for ambulation at varying self-selected speeds on the C-9 aircraft in varied reduced-gravity conditions (phase I).

The greatest mean step length was observed with the 0.17g unsuited condition ("0.17g (US)" in Figure 31). This condition was highly variable across trials, suggesting subject experimentation or inability to control step length through the capture volume.

Phase II mean step lengths for suited subjects in varied CG conditions are presented in Figure 32. Mean step length calculated for the 0.17g condition during phase I was about 0.58 m (see Figure 31). Figure All conditions tested in phase II had lower mean step-length values (Figure 32). This may indicate that subjects experienced decreased stability during phase II when they were required to ambulate with the mass-support rig in different configurations (increased mass, varied mass-support rig arm placement). The Backpack CG condition had the shortest step length of the conditions tested in phase II. This suggests that subjects may have felt less stable with this condition and may have altered their step length to compensate. These results coincide with increased stance time for this condition (Figure 30), which indicates an attempt by subjects to maintain stability during performance of the ambulation tasks.

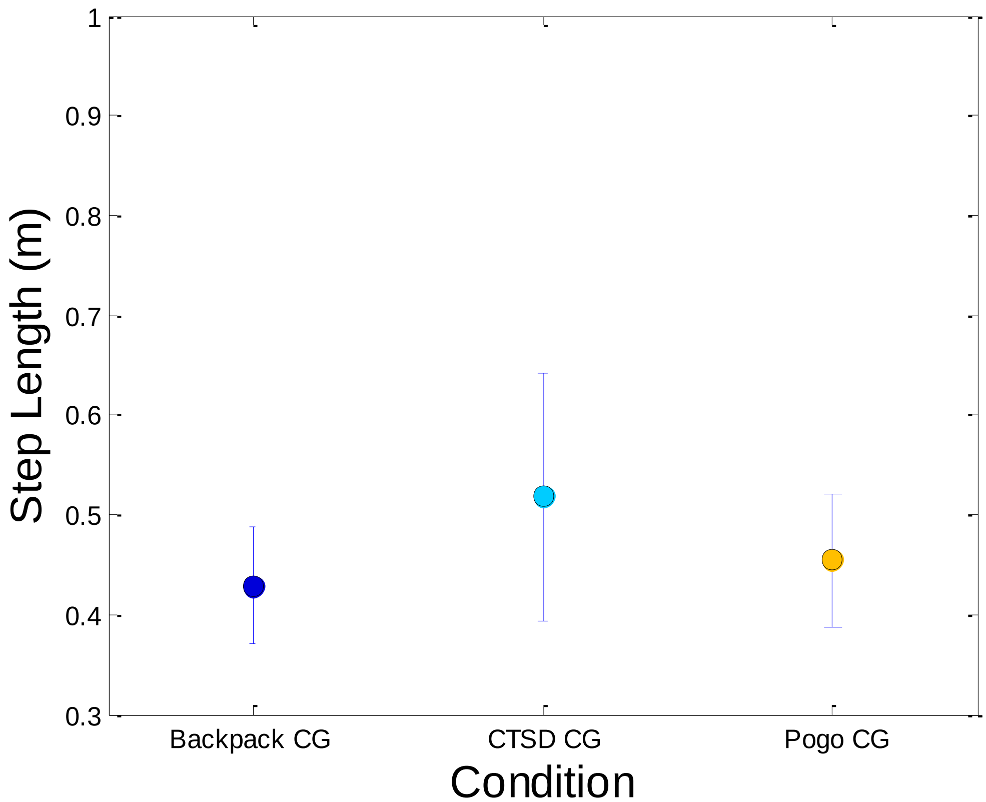

Figure 32 – Mean step length for suited subjects at self-selected ambulation speeds in varied CG conditions on the C-9 aircraft during lunar-gravity parabolas (phase II).

Literature has shown that 1g unsuited mean step length (right to left) is about 0.78 m.[4] In the current test, step lengths were much smaller, likely because of several factors. The effect of an insufficient walkway length was outlined by,[11] who stated that too short a walkway (for example, 3 m) results in a walking velocity that is slower than normal. This decrease in velocity is also associated with a decrease in temporal-spatial variables, including step length. The slow, deliberate (that is, attempting to maintain stability and strike force plates), and unstable gait adopted by subjects in the C-9 aircraft had an impact on the variables collected and calculated.

3.4.2.4 Step Width

Step width is defined as the mediolateral distance between the two feet during foot-to-floor contact (stance phase of gait). For phase I, the largest mean step width was seen with the suited 0.17g condition with the mass-support rig, indicating that subjects may have had to compensate to maintain stability during ambulation in this condition. Conversely, the smallest mean step width was observed with the 0.3g suited condition. This small mean step width is associated with greater stability during gait, which would be expected at higher gravity levels and has been confirmed through examination of other temporal-spatial gait metrics.

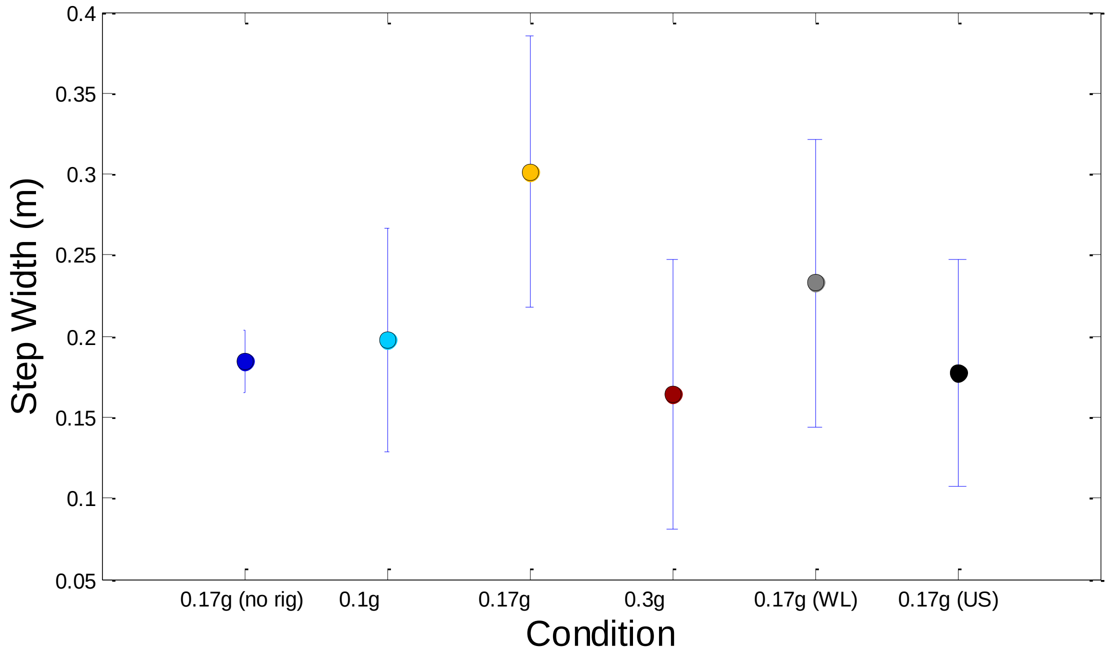

Figure 33 – Mean step width for ambulation at varying self-selected speeds on the C-9 aircraft in varied reduced-gravity conditions (phase I).

For the 0.17g unsuited condition, the mean step width value across subjects was about 0.18 m ("0.17 g (US)" in Figure 33). The variability seen for this and other conditions may be attributable to the slow and varying ambulation speeds on the C-9 aircraft during different parabolas, the dynamic nature of the test analog environment, and the short walkway afforded the subjects.

Phase II mean step widths for suited subjects in varied CG conditions are presented in Figure 34. All conditions had notable variability, which may have been caused by the same factors described for phase I. The largest mean step width in phase I was seen with the 0.17g suited condition(Figure 33). Mean step widths from phase II were only slightly less than those seen for this same gravity level in phase I. However, the large amount of variability makes any comparisons between CG conditions inconclusive.

It has been reported in the literature that a 1-G normal stride width is 0.08 m.[12] Values seen in the current test were notably greater, especially for the 0.17g condition. This was likely caused by inconsistencies in adopted gait patterns. The slow walking speed and unstable walking surface (inside an aircraft in parabolic flight experiencing turbulence) resulted in larger and more varied step widths.

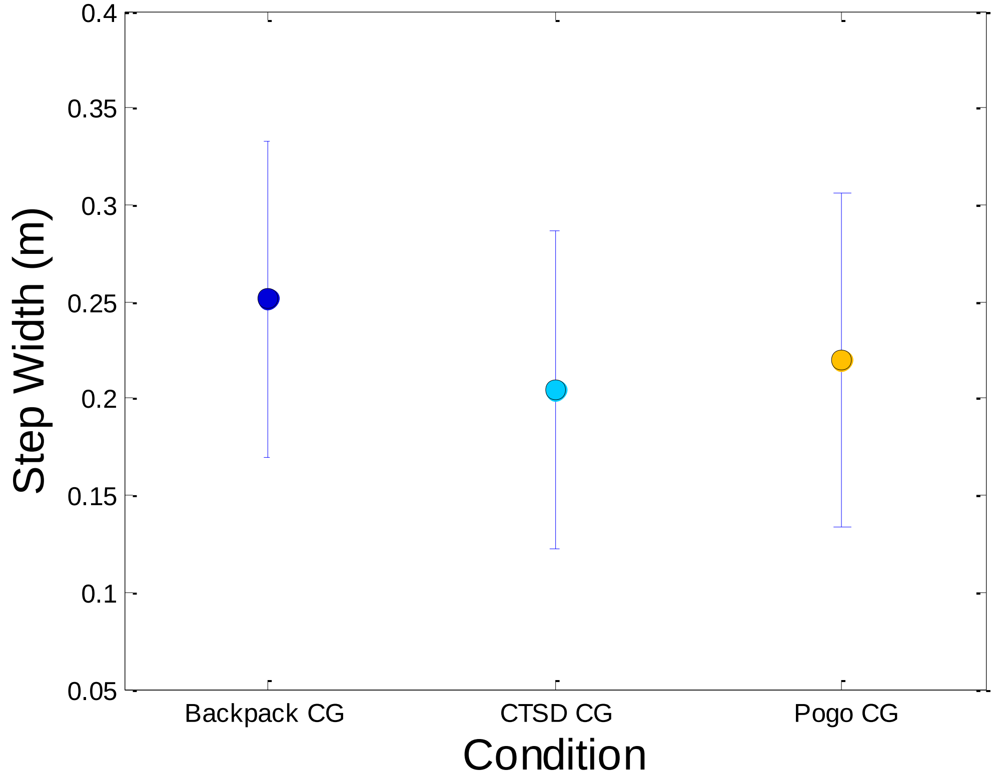

Figure 34 – Mean step width for suited subjects at self-selected ambulation speeds in varied CG conditions on the C-9 aircraft during lunar-gravity (0.17g) parabolas (phase II).

3.4.2.5 Stride Length

Stride length is considered the distance between consecutive gait events for the same foot (that is, the distance between initial contact of the left foot with the walking surface to the subsequent initial contact of the left foot with the surface). Figure 35 shows stride length results for ambulation at varying self-selected speeds on the C-9 aircraft during phase I.

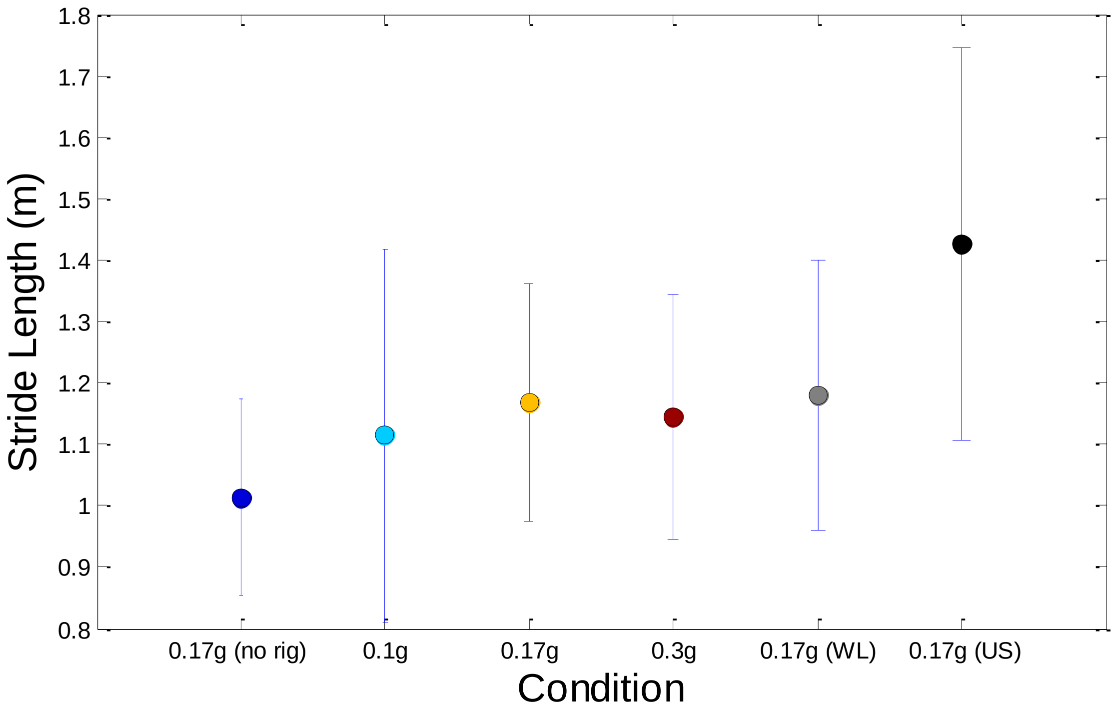

Figure 35 – Mean stride length for ambulation at varying self-selected speeds on the C-9 aircraft in varied reduced-gravity conditions (phase I).

As seen in Figure 35, the 0.17g suited (no added mass-support rig) condition had the shortest mean stride length. This may be due to the fact that this condition was always the first to be performed, and subject familiarity with suited ambulation in the C-9 environment was not yet established. The 0.1g suited condition exhibited the next shortest stride length, possibly because of the lighter gravity level, which would inherently cause decreased subject stability during movement.

Literature indicates that average adult stride length in 1g for freely selected gait speeds is about 1.5 m.[12] The longest mean stride length, about 1.4 m, of all conditions tested in the current test was seen with the unsuited 0.17g condition. Results for this condition were also the most variable. This may have been the result of altered gait patterns adopted by unsuited subjects. Subjects sometimes experimented and ended up bounding through the capture volume (due in part to the low gravity and lack of stability); they would also stutter-step in an attempt to strike the force plates. Moreover, the greater ease of unsuited movement compared to suited movement allowed many subjects more rapid ambulation through the capture volume; more passes were performed per unsuited parabola than per suited parabola.

Phase II mean stride length data for suited subjects in varying CG conditions are presented in Figure 36. The longest stride length from the phase II conditions tested was observed with the CTSD CG condition. This condition also had the greatest variability across performed trials. Greater measured stride length generally indicates a greater amount of subject stability, associated with the ability to take longer steps during ambulation. However, the large amount of variation in the data suggests that this CG condition did not have consistent effects on all subjects. Mean stride lengths for the phase II conditions were shorter than those seen for the 0.17g condition in phase I, likely related to the notably lower ambulation speeds observed in phase II.

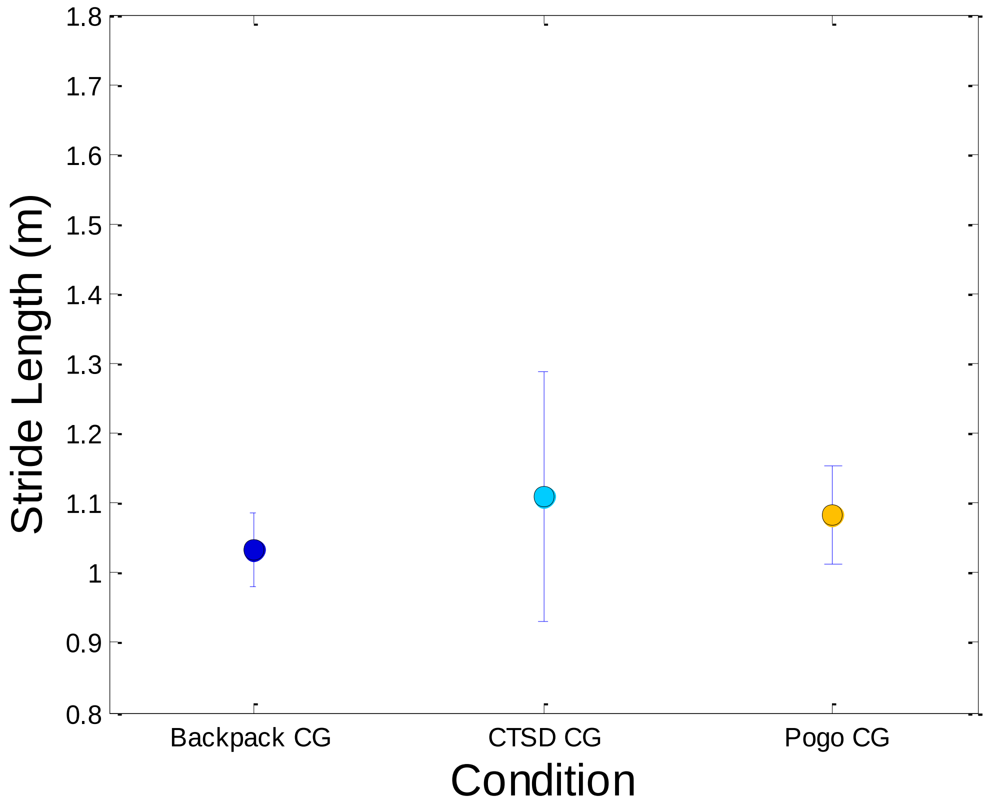

Figure 36 – Mean stride length for suited subjects at self-selected ambulation speeds in varied CG conditions on the C-9 aircraft during lunar-gravity parabolas (phase II).

3.4.3 Ambulation: Kinematics

It is important to define some of the terminology used to describe the 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 (see section 6.5). Flexion will always be referred to as a positive angle, extension as a negative angle. 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: the thigh segment moves from a neutral position of 0° and achieves some value, then returns to the neutral position of 0°. However, during ambulation the subject may never achieve a neutral position, given the dynamic nature of the movement. More specifically, walking is not a series of isolated movements; numerous concurrent actions are taking place during walking.

In the gait cycle the onset of the stance phase will be referred to by the generic term *initial contact*. Conversely, at the end of the floor contact the generic term *end contact* will be used to describe the instant when the foot leaves the floor.

The next few graphs show the average angles for specific joints over the gait cycle, separated by condition during phase I. Noticeable in all the figures are distinct differences in pattern between normal unsuited ambulation in Earth gravity and ambulation in the C-9 reduced-gravity environment during phases I and II.[13] These patterns differ in shape, magnitude, and timing of the maximum flexion and extension peaks. Some differences do seem to exist between the different gravity conditions. There are also noticeable differences between the unsuited condition and the suited conditions during phase I.

For the phase II plots, little variation is seen across conditions. It should be noted that some of the differences between phase I and phase II may stem in part from improvements made in data collection hardware, protocols, and an improved number of viable trials collected. The raw phase I data for the knee, hip, and pelvis joints were difficult to reconstruct because of the environmental conditions and layout of the hardware on the airplane. This resulted in missing data during phase I, with only a single subject's data for some conditions, and large standard deviations. Some of the plots reflect this limitation of a single subject and do not show any standard deviation data. This was done because there was not enough usable data to calculate a proper standard deviation. Thus, for these cases, only the mean is shown.

For phase I ankle angle (Figure 37), the traces for all conditions were generally similar in shape and timing with a few subtle differences. For the suited 0.17g condition, the foot started off relatively neutral, went into peak dorsiflexion at around 10% to 20%, went into peak plantar flexion at around 45% to 60%, then went into dorsiflexion again during the swing phase. For the suited 0.1g condition, the peak dorsiflexion was somewhat reduced, and the peak plantar flexion occurred near 40% of the gait cycle. For the suited 0.3g condition, the stance phase was comparatively flat but never reached the neutral point, as it did in the other conditions. For all suited conditions, the dorsiflexion peak during the swing phase was higher than the dorsiflexion peak during stance. This was the opposite of what it would be in a 1g environment. The unsuited 0.17g condition showed a peak in dorsiflexion during stance, but the plantar flexion peak and the swing phase dorsiflexion peak were greatly reduced. For all conditions the plantar flexion peak never really passed the neutral point, which was also very different from a 1g environment.

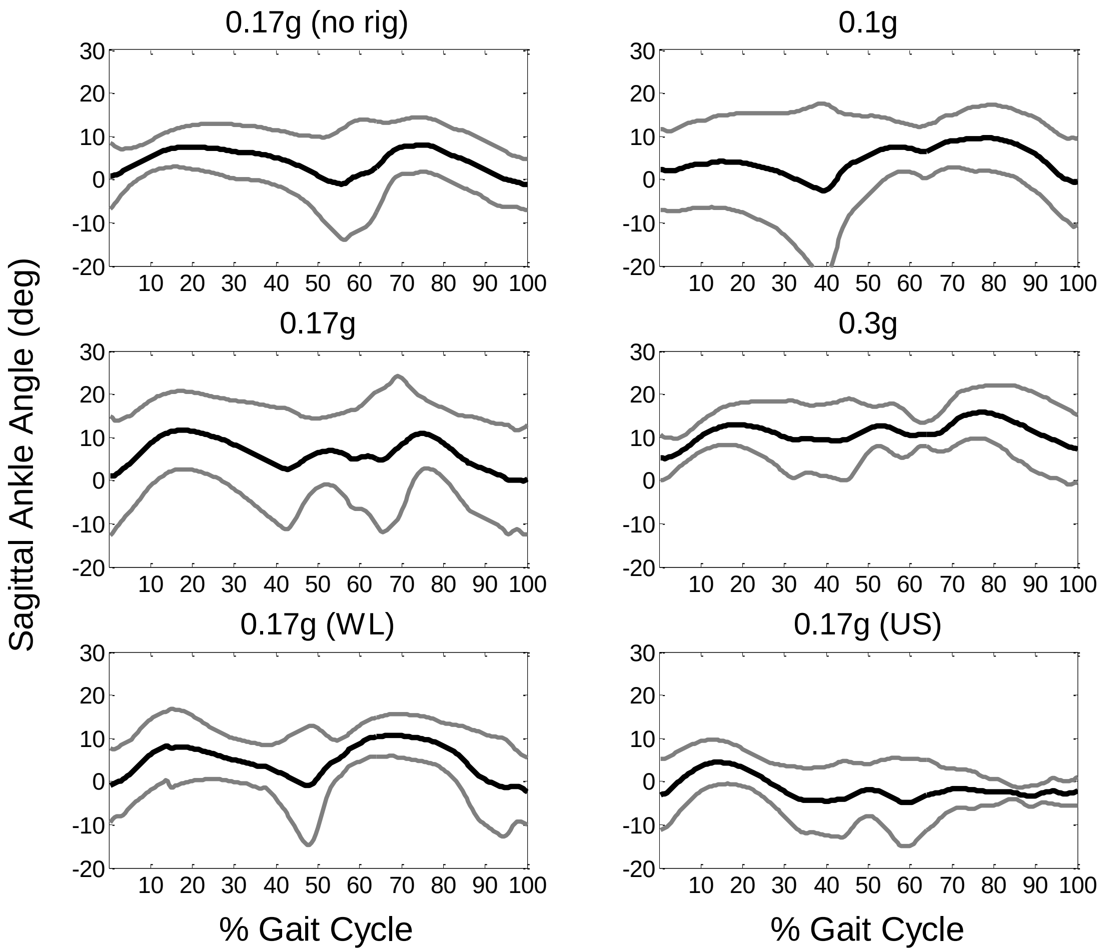

Figure 37 – Mean sagittal ankle angles over one gait cycle for each condition in phase I. The thick black line represents the condition mean; the thin gray lines represent one standard deviation.

In phase II, the traces of ankle angle (Figure 38) for all conditions were generally similar in shape and timing with a few subtle differences. For all conditions the plantar flexion peak never really passed the neutral point, meaning the foot remained in relative dorsiflexion through the entire cycle. The first dorsiflexion peak during the stance phase of the cycle occurred earlier than would be expected and no plantar flexion occurred at initial contact. There was also an increase in the dorsiflexion peak during the swing phase. The only real difference between the conditions was that the CTSD condition had a markedly larger standard deviation for the plantar flexion peak at end contact. Overall, the dorsiflexion peaks were similar to ambulation in the 1g environment, although they occurred much earlier in the cycle, but the plantar flexion peaks were greatly reduced.

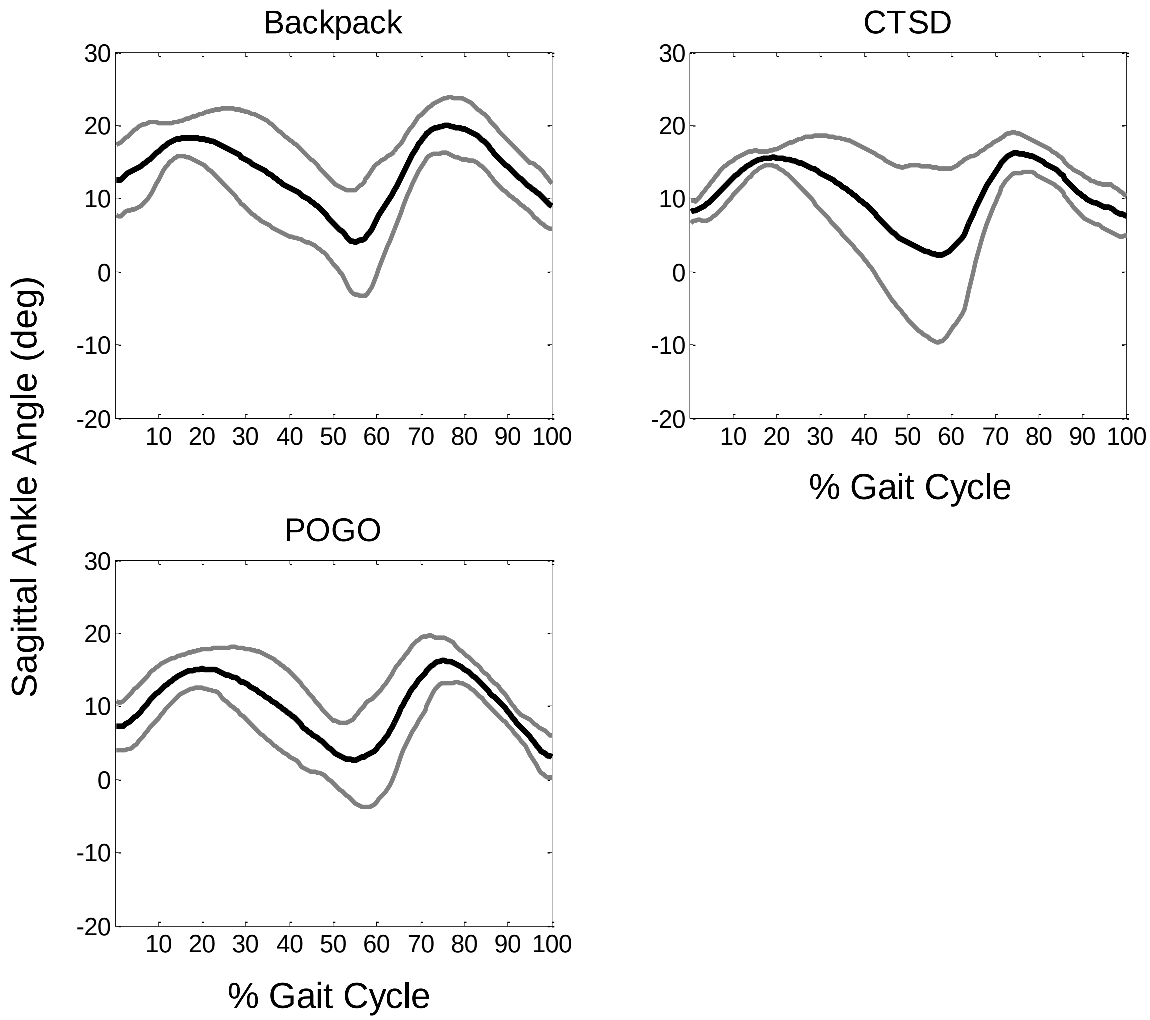

Figure 38 – Mean sagittal ankle angles over one gait cycle for each condition (phase II). The thick black line represents the condition mean; the thin gray lines represent one standard deviation.

The basic shape of the phase I knee angles(Figure 39) was fairly similar, but did show some strong dissimilarity between the different conditions. For the suited conditions, the initial flexion peak during the stance phase was proportionally greater than the flexion peak during the swing phase as gravity was reduced. The initial flexion peak during the stance phase and the flexion peak at end contact occurred later in the cycle as gravity was reduced. Of note, the suited conditions never reached the neutral point, as did the unsuited condition.

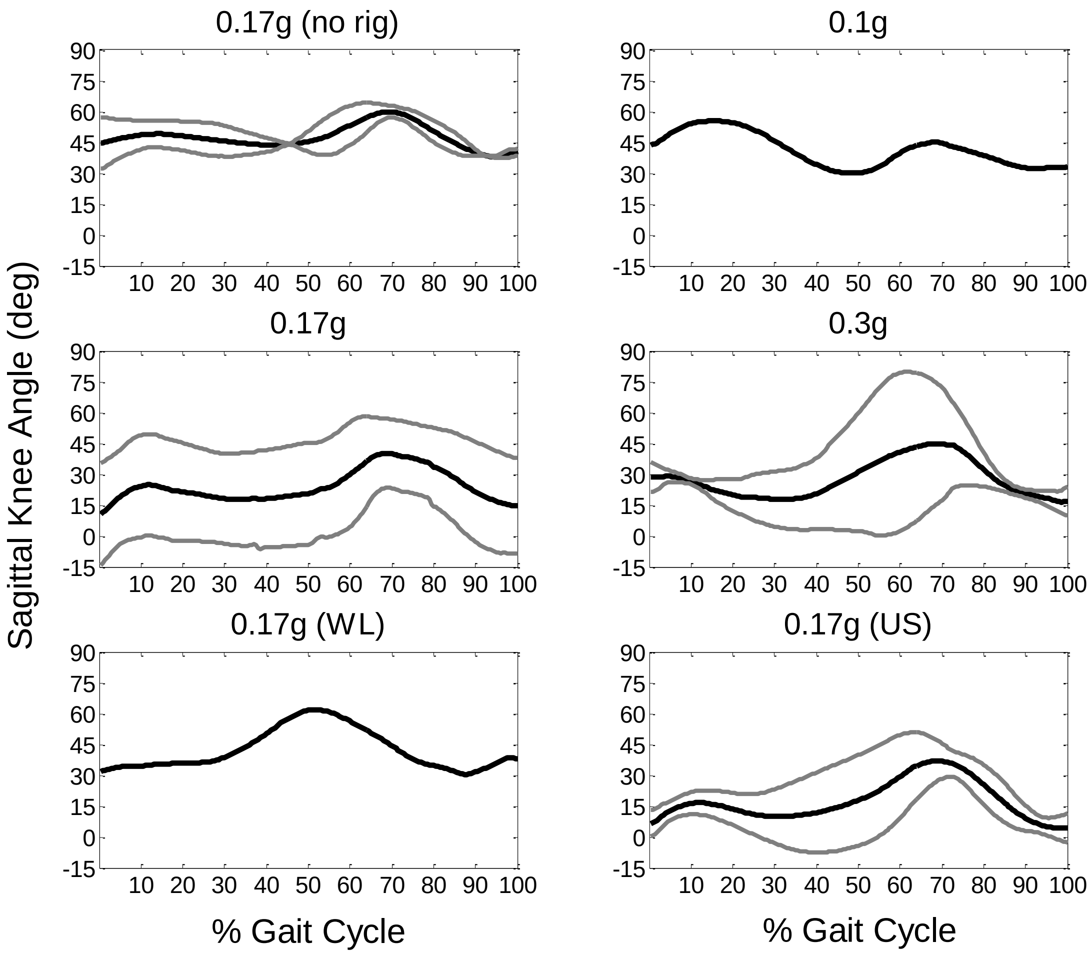

Figure 39 - Mean sagittal knee angles over one gait cycle for each condition (phase I). The thick black line represents the condition mean; the thin gray lines represent one standard deviation.

Phase II knee joint angles had the expected general shape and timing, but the magnitudes were quite different from normal ambulation and somewhat reduced in magnitude (Figure 40). The initial knee flexion peak during the stance phase was much greater and the second flexion peak was smaller than in normal ambulation. The initial flexion peak also showed some tendency to decrease as the CG location was raised (from Backpack to CTSD to POGO), and the secondary peak showed some tendency to increase as the CG was raised.

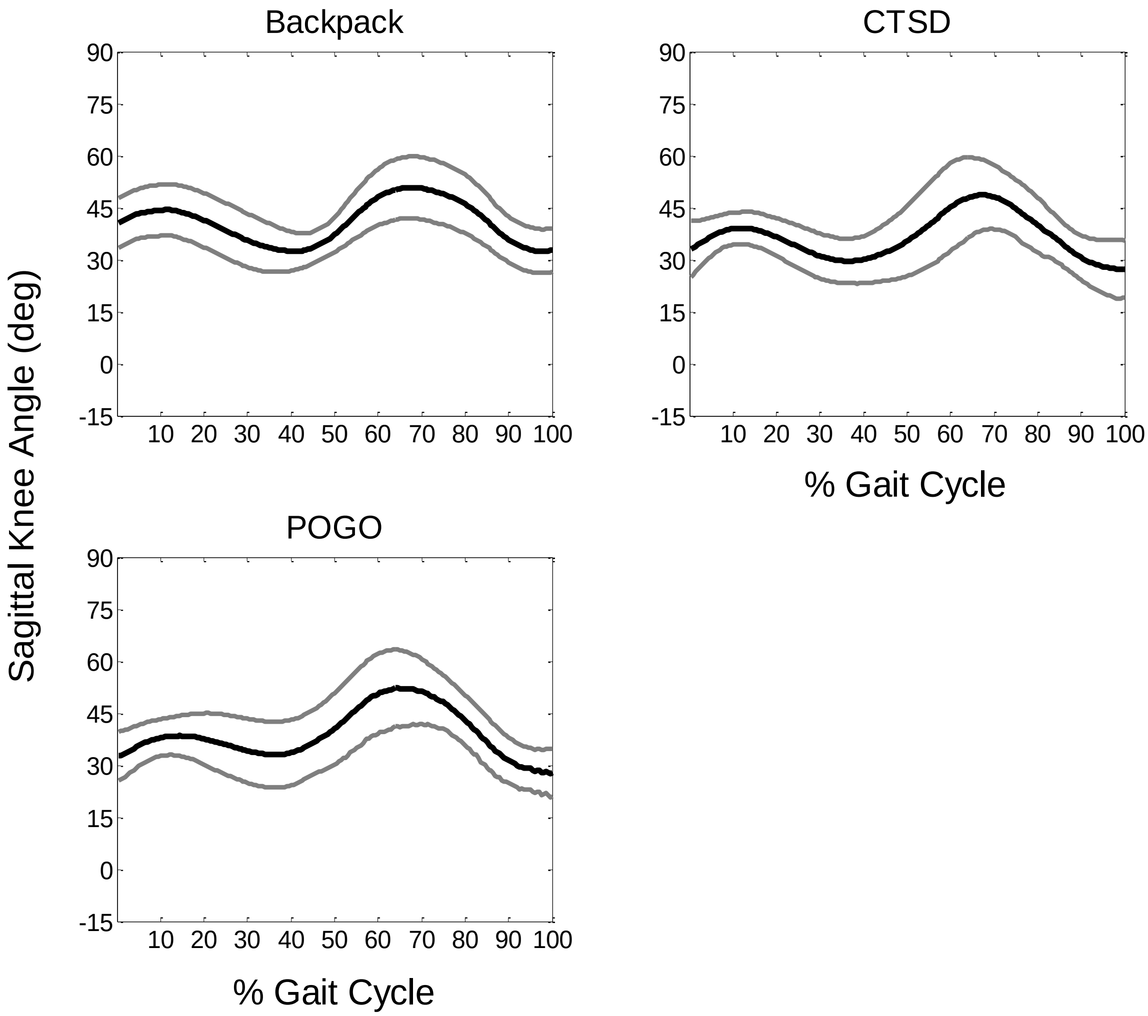

Figure 40 – Mean sagittal knee angles over one gait cycle for each condition (phase II). The thick black line represents the condition mean; the thin gray lines represent one standard deviation.

The suited hip angles (Figure 41) were relatively unchanged between gravity conditions and also remained in a perpetual flexed state. There was a noticeable shift in hip angles between the suited and unsuited conditions because different marker systems were used.

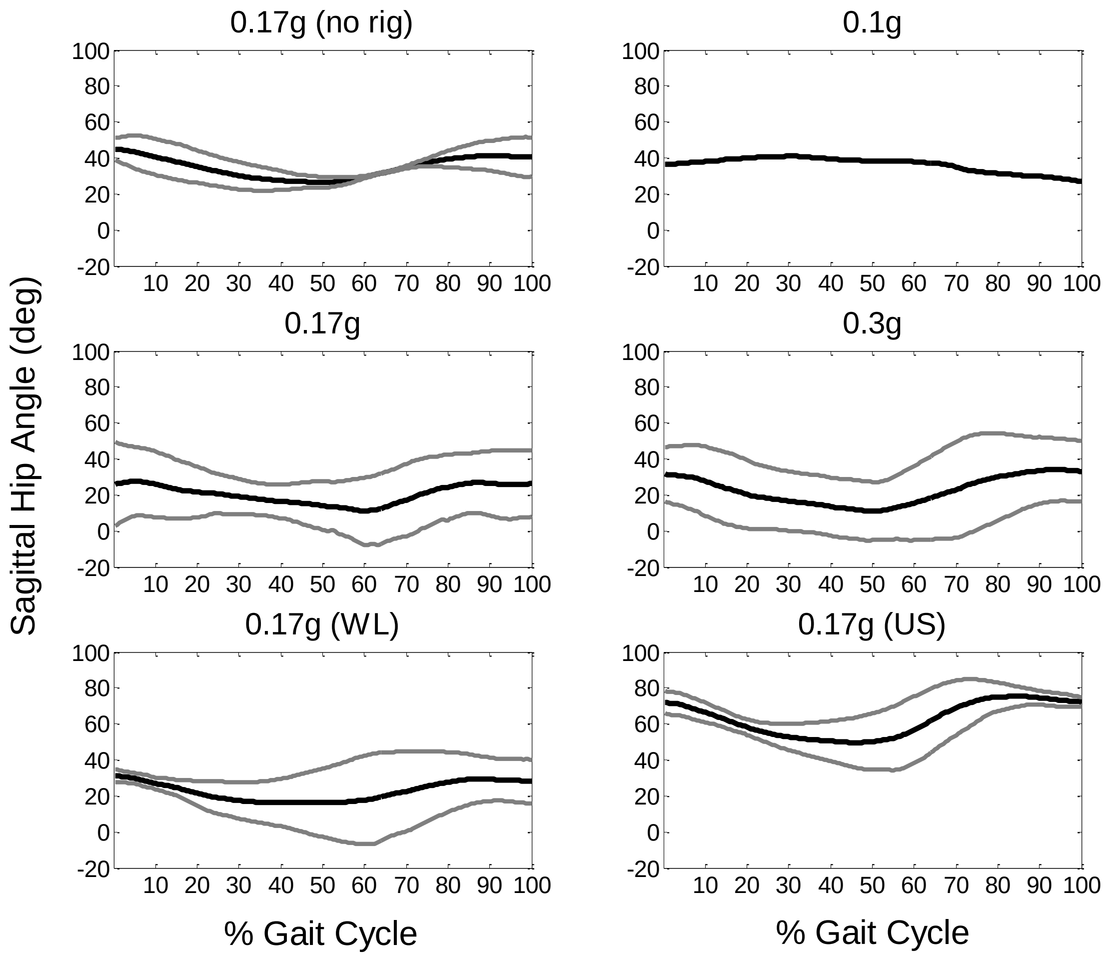

Figure 41 – Mean sagittal hip angles over one gait cycle for each condition (phase I). The thick black line represents the condition mean; the thin gray lines represent one standard deviation.

The phase II suited hip angles (Figure 42) were relatively unchanged between gravity conditions and also remained in a perpetual flexed state. Peak values were noticeably reduced from those of normal gait, but results were otherwise very similar.

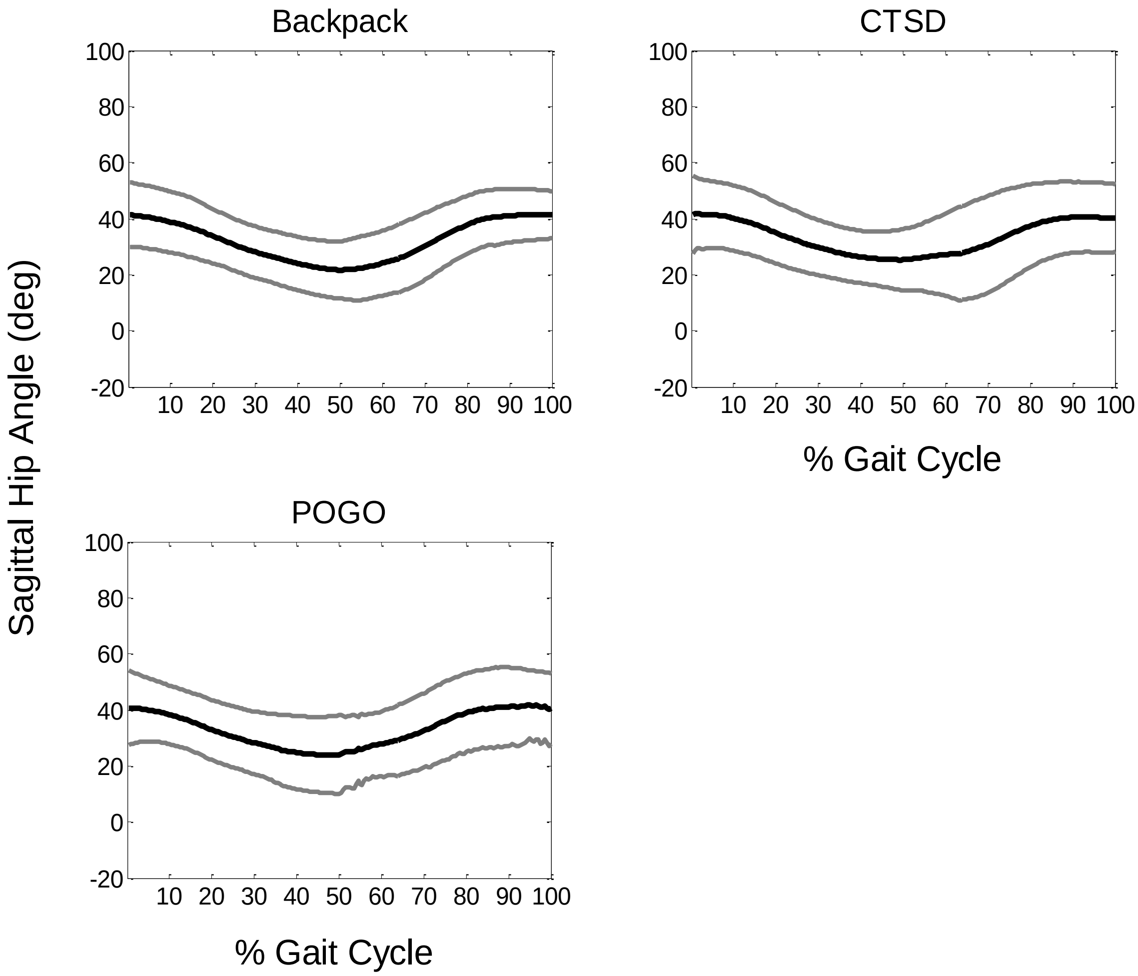

Figure 42 – Mean sagittal hip angles over one gait cycle for each condition (phase II). The thick black line represents the condition mean; the thin gray lines represent one standard deviation.

The phase I sagittal pelvis motion (Figure 43) had several noticeable pattern changes compared to normal ambulation in a 1g environment. First, the timing for flexion and extension was different for all conditions. Second, there is usually a double peak in 1-G ambulation, but only a single peak occurred in the conditions studied.

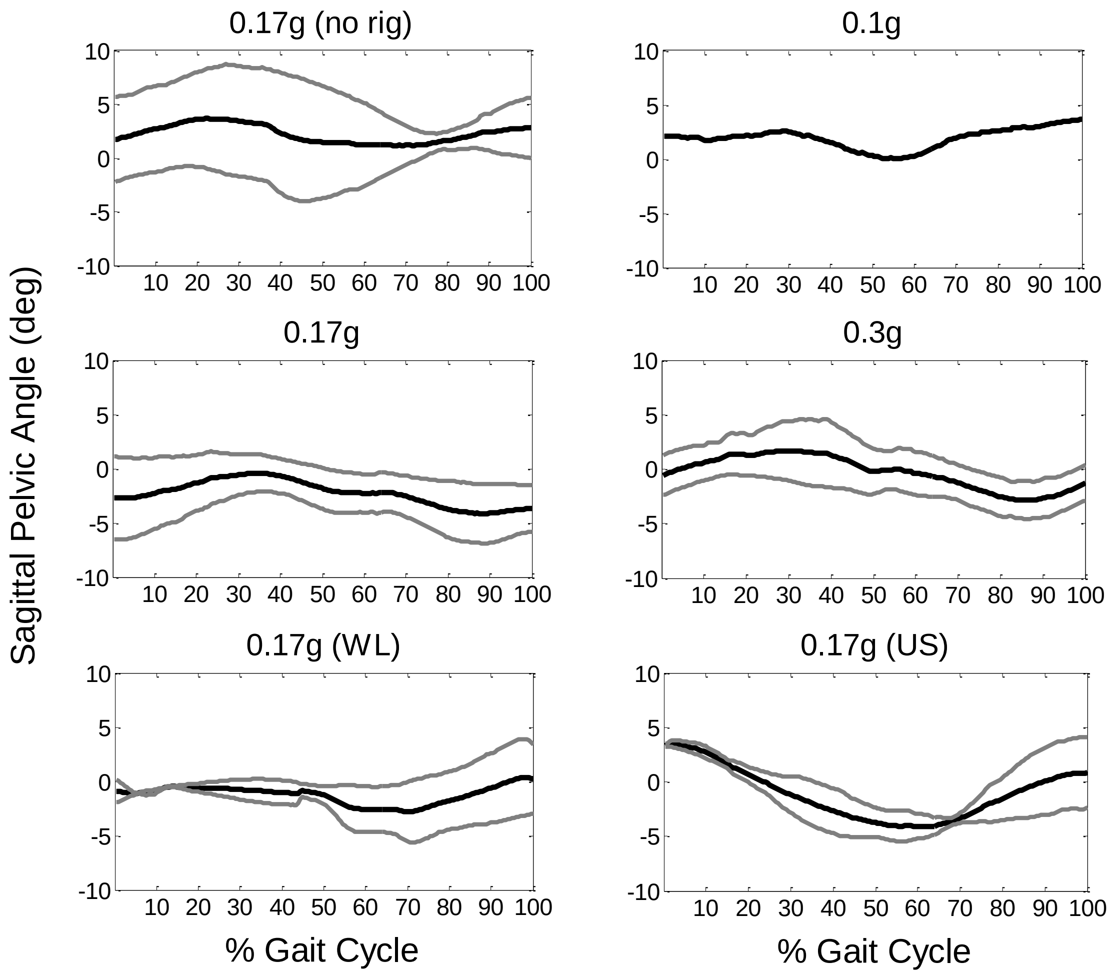

Figure 43 – Mean sagittal pelvic angles over one gait cycle for each condition (phase I). The thick black line represents the condition mean; the thin gray lines represent one standard deviation.

The phase II sagittal pelvic angles (Figure 44) for the different conditions had a similar pattern with only a single peak. The CTSD condition had a sizeable increase in the standard deviation of the extension peak angle.

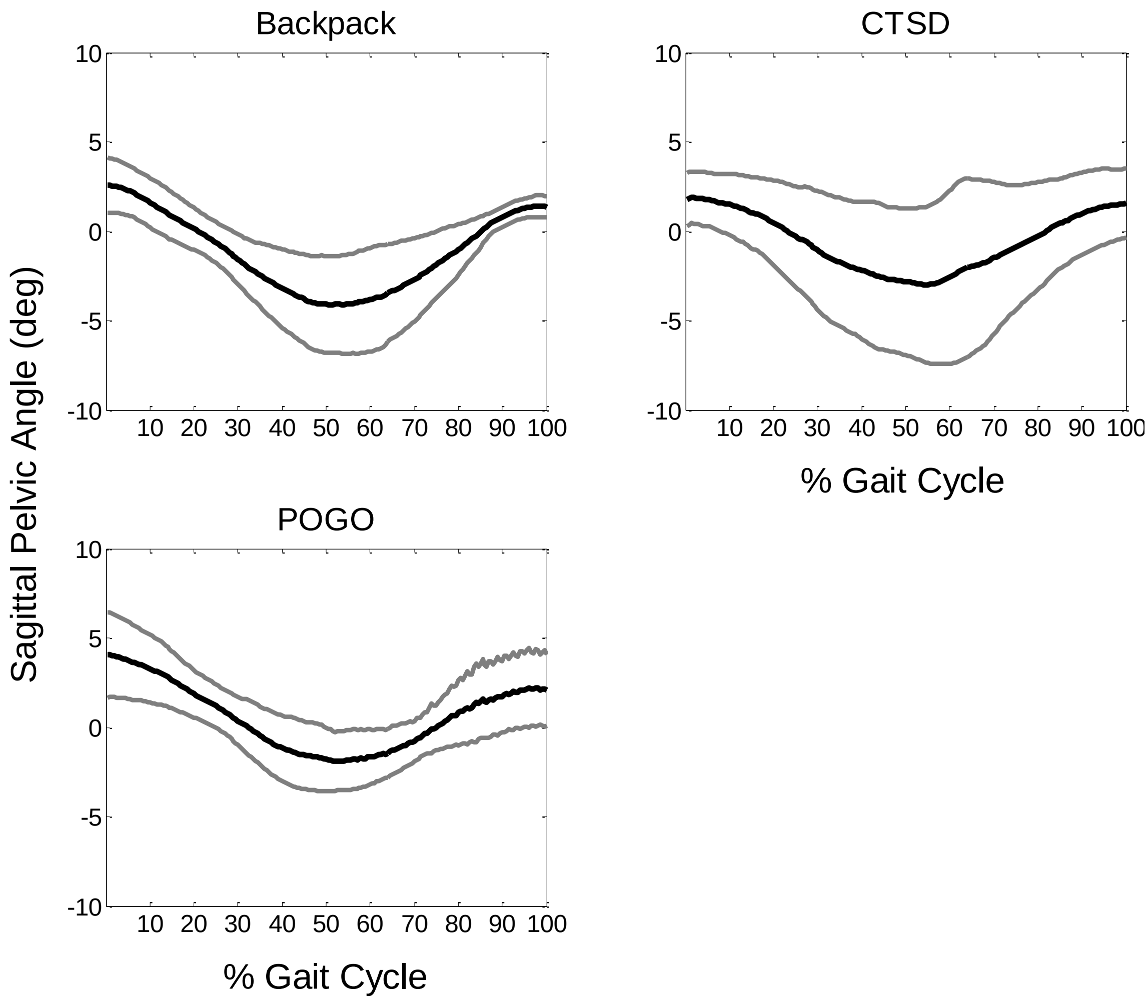

Figure 44 – Mean sagittal pelvic angles over one gait cycle for each condition (phase II). The thick black line represents the condition mean; the thin gray lines represent one standard deviation.

The phase I transverse hip motion (Figure 45) resembled normal 1g gait to a greater degree than did sagittal motion, but was fairly inconsistent with the timing and magnitude of the peaks. Second, the motion was reduced from what would be expected from previous IST tests. Third, the flexion/extension tended to be asymmetric.

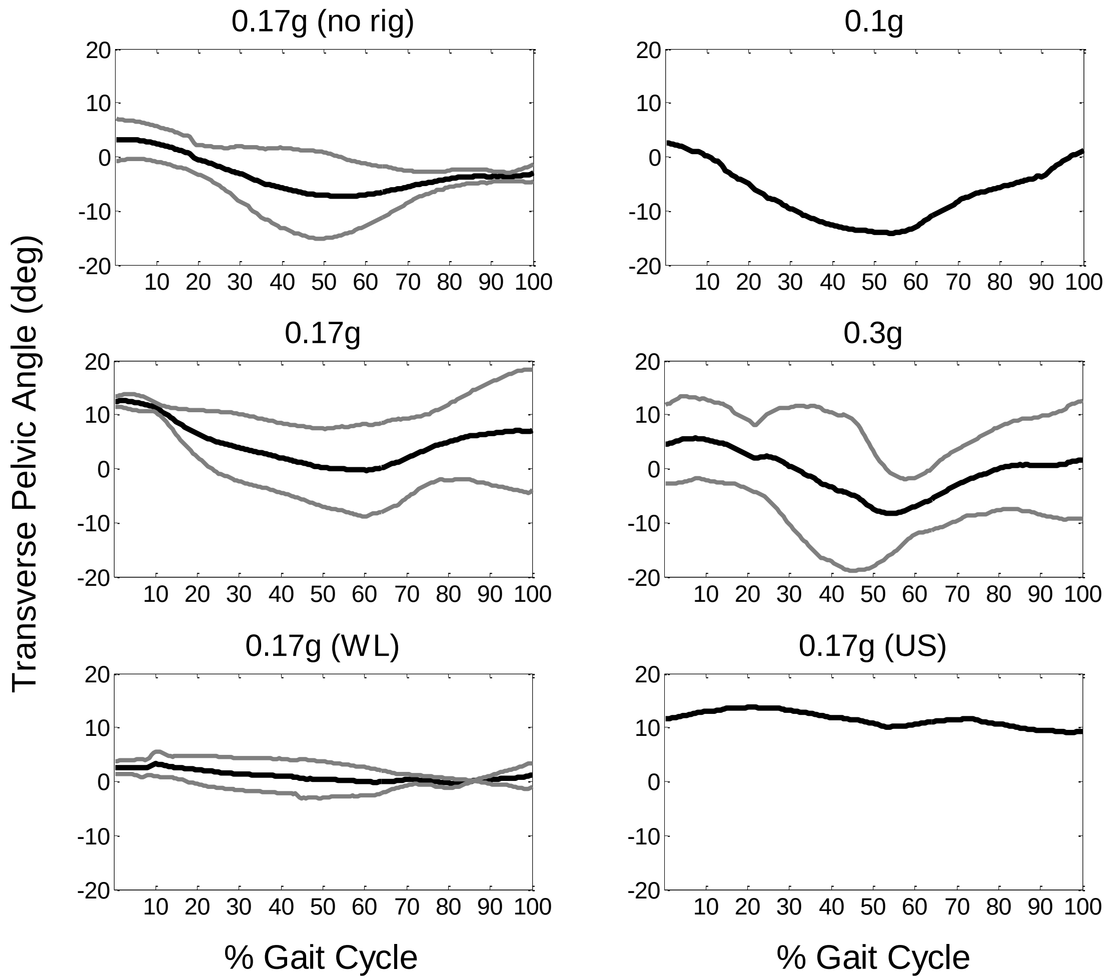

Figure 45 – Mean transverse pelvic angles over one gait cycle for each condition (phase I). The thick black line represents the condition mean; the thin gray lines represent one standard deviation.

The phase II transverse hip motion (Figure 46) resembled normal gait to a greater degree than did the sagittal hip motion. There was, however, an actual increase in overall peak angles compared to normal gait.

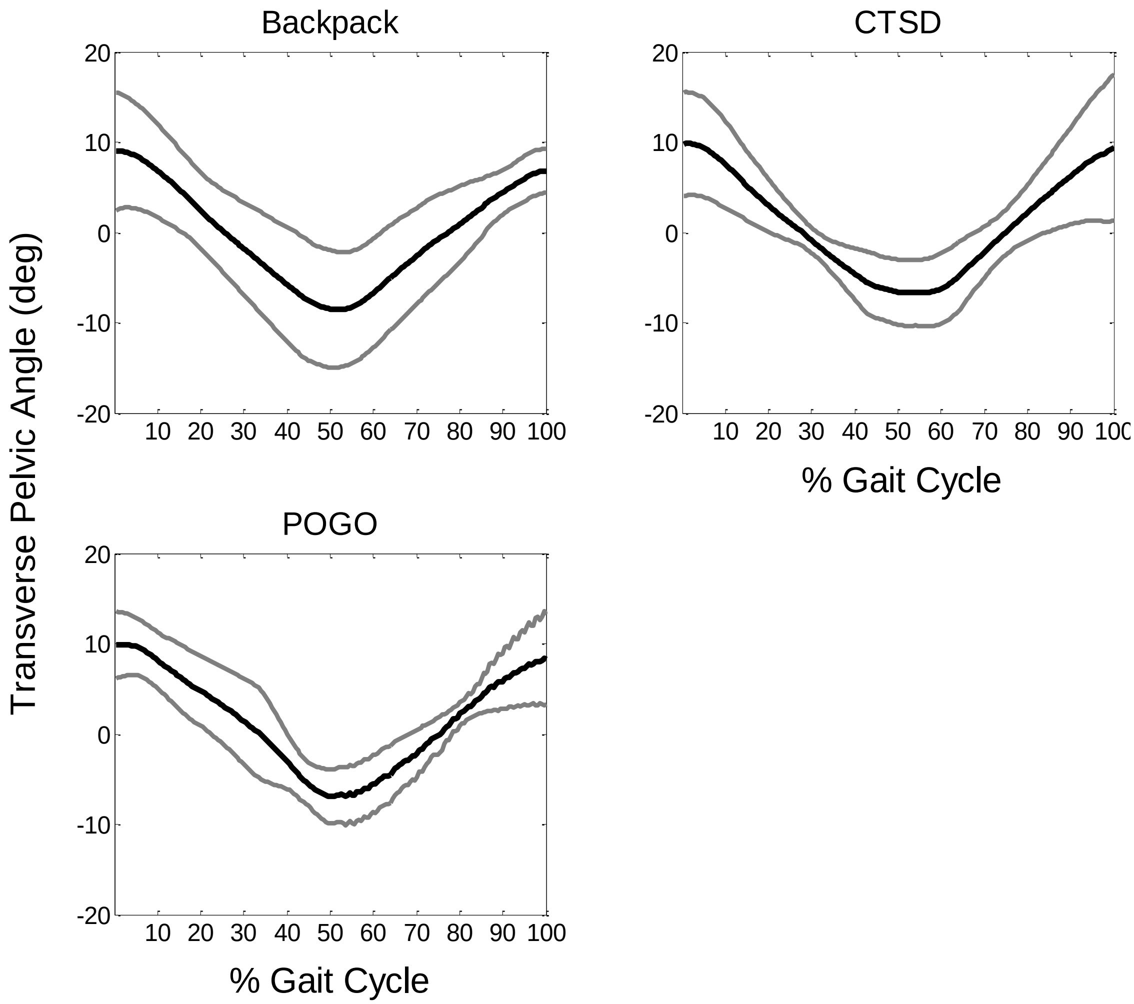

Figure 46 – Mean transverse pelvic angles over one gait cycle for each condition (phase II). The thick black line represents the condition mean; the thin gray lines represent one standard deviation.

The bar graph of range of motion (RoM) for the lower-body joints during phase I (Figure 47) shows only a few consistent trends. Hip motion increased during the 0.3g condition but not in other suited conditions. Suited pelvic transverse rotation decreased in the waist-locked condition but not in the other 0.17g conditions. There was an overall reduction from 1g ambulation of roughly 50% for ankle, knee, and hip.

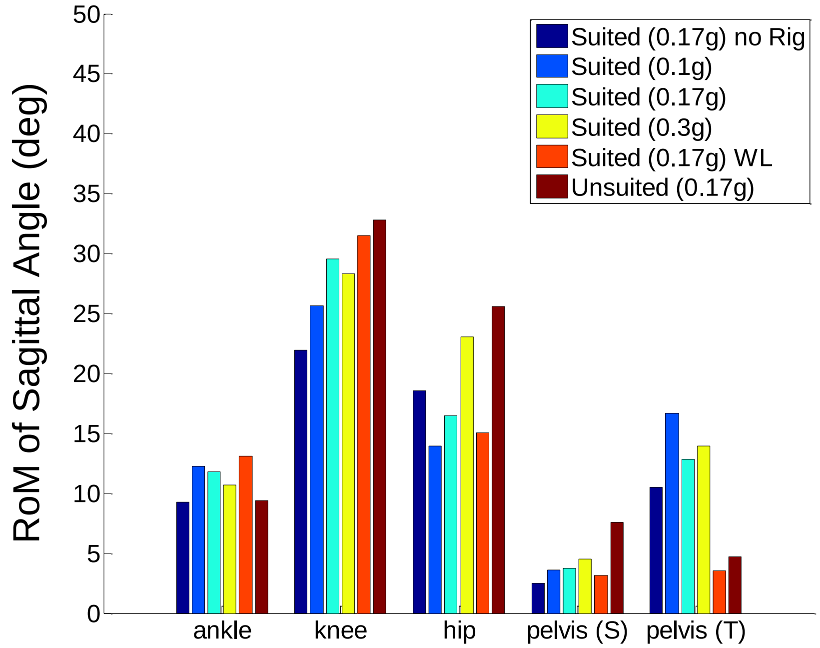

Figure 47 – Mean RoM angles over one gait cycle for each condition (phase I) and joint, including hip, knee, ankle, and sagittal (S) and transverse (T) pelvis.

The bar graph of RoM for the lower-body joints for phase II (Figure 48) shows few differences between conditions. There was an overall reduction from normal ambulation of roughly 50% for ankle, knee, and hip. Some difference in RoM of the knee occurred between the POGO and Backpack conditions.

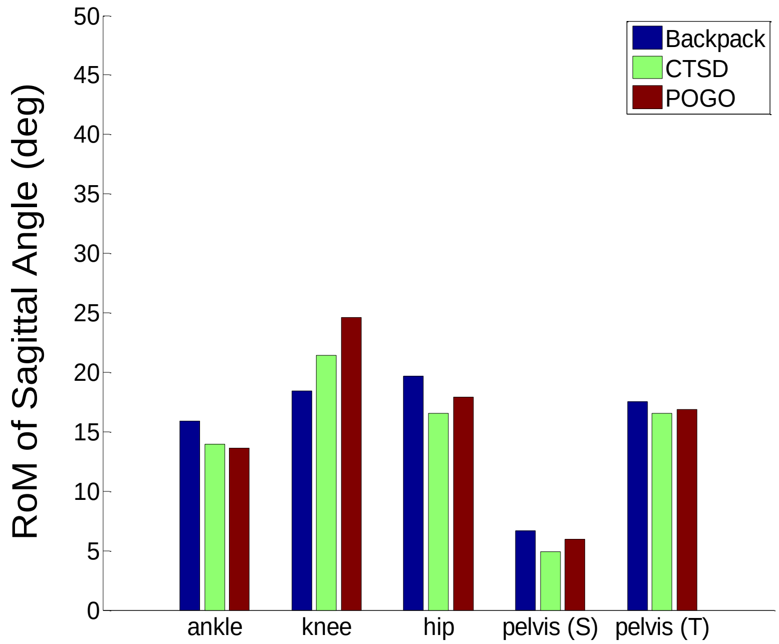

Figure 48 – Mean RoM angles over one gait cycle for each condition (phase II) and joint, including hip, knee, ankle, and sagittal (S) and transverse (T) pelvis.

The limited number of subjects, difficulties with the test environment, and the limited number of trials made data collection and analysis difficult for these measures. In general, there was a large reduction in viable data compared to previous studies, which were done on the POGO. As an example, for one of the joints all data were missing for one condition, and for a few other joints, data were available for only a single subject. The reduction in the amount of data makes the analysis difficult since no general trends were present to overshadow the individual anomalies that are ever present in human biomechanics. Added to this was the uncertainty of random interaction with the unstable gravity environment. For example, a sudden increase in gravity at the time of initial contact may increase the joint flexion angles until the body compensates.

The improvements made in the data-collection hardware and test environment for phase II produced great improvements over the phase I data. However, the small sample size and random interaction with the unstable gravity environment still created a large standard deviation in the data, which hinders the ability to see trends and variations between conditions.

Nevertheless, some gait characteristics were discernible for the suited conditions tested. The ankle remained in a dorsiflexed state throughout the gait cycle and had limited plantar flexion at the end contact period. The increase in knee flexion with increased gravity was most likely caused by the need for more clearance during swing, or the increased amount of flexion from the ambulation style, or both. The knee never reached the neutral point and remained in permanent flexion. The hip showed similar trends of constant flexion. All three joints had a reduced RoM compared to normal ambulation. These facts indicate a crouching gait. This style of gait uses more energy, as the leg muscles are constantly contracted, but it creates a more stable and quickly adaptable base of support.[5]

The lack of the common traits for the hip joints, normally seen in 1g ambulation, is not fully understood at this time, but could be a result of the odd gait style adopted by the suited subjects in response to the airplane dynamics, or (the most likely case) the overshadowing of the starting and stopping mechanics because of the short walkway. The increase in transverse peak pelvic angles could be a result of the subject attempting to narrow the stance width during ambulation. The over-rotation in the pelvis allows a subject to place the feet closer together while minimizing rotations in the frontal plane.

The decrease in the RoM of unsuited subjects compared to RoM in normal 1g ambulation implies that the body is not using the full amount of available power in reduced gravity. The RoM of the knee and hip in the reduced-gravity conditions was about 50% of that used in 1g ambulation, but RoM of the ankle was only 25% of RoM in 1g ambulation. This is not unexpected as the total need for power is greatly reduced in reduced-gravity environments. Compared to the phase I data, in phase II a slight increase occurred in ankle and hip RoM and a decrease in knee RoM. This indicates that the overall amount of crouching was reduced in the phase II CG conditions. Unfortunately, such a comparison might not have been true if all of the data had been available. However, there still remains a question of whether subjects would use the available power during ambulation if the test environment did not restrict their motions.

In the phase II data, the slight shift in angles with CG indicates that the leg was straighter at initial contact as the CG was raised, but it was more flexed during the swing phase. This could be a result of the subjects adopting a more Earth-like gait strategy as the CG was raised, or of a strategy adopted to compensate for the changing location of the mass-support rig arms and weights.

3.4.4 Exploration: Strategy

Three exploration tasks were performed during phase I flights: rock pickup, shoveling, and kneel and recover. The rock pickup and shoveling tasks were performed on strain-gauge force platforms (AMTI, Watertown, MA) in the aft section of the C-9 aircraft. All three exploration tasks were also captured on video for later analysis of subjects' adoption of strategies for task performance. Video data were collected for all three tasks.

3.4.4.1 Rock Pickup Task

Similar to previous tests in the IST series, the rock pickup was performed while subjects stood on two force plates. Qualitative analyses of this task were performed using video data, to provide some general information about the strategies the subjects adopted to complete this task. Figure 49 summarizes the analysis performed on rock pickup strategies in phase I.

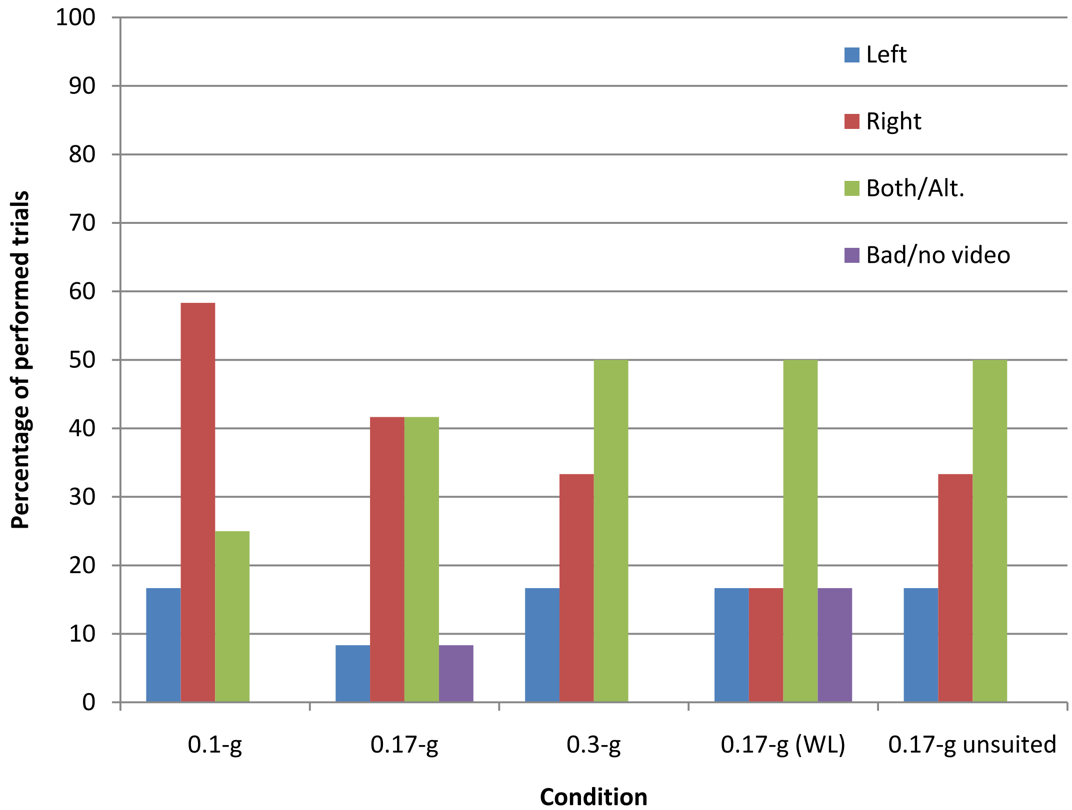

Figure 49 – Phase I strategy analysis – subject hand involvement in the rock pickup task. More specifically, the data shown are the percentage of total rock pickup trials performed in which subjects used left, right, or alternating hands to complete the task.

As can be seen in Figure 49, subjects alternated left and right hands when performing the rock pickup over multiple trials. It was noted that subjects sometimes had difficulty remaining stable on the force plates while performing the rock pickup task. This may have occurred because of the constraints of the testing environment, including space limitations and a limited timeframe in which to complete the task.

In all trials performed in the 0.1g condition in phase I, foot placement by subjects on the force plates was unstable (Figure 50). Conversely, in nearly 95% of the trials performed in the 0.3g condition, foot placement on the force plates was stable. Also in the unsuited condition, foot placement in a high percentage of trials was stable throughout the task. Although stable and unstable trials were fairly even for the lunar (0.17g) condition with the mass-support rig, more unstable trials were seen with the waist-locked condition.

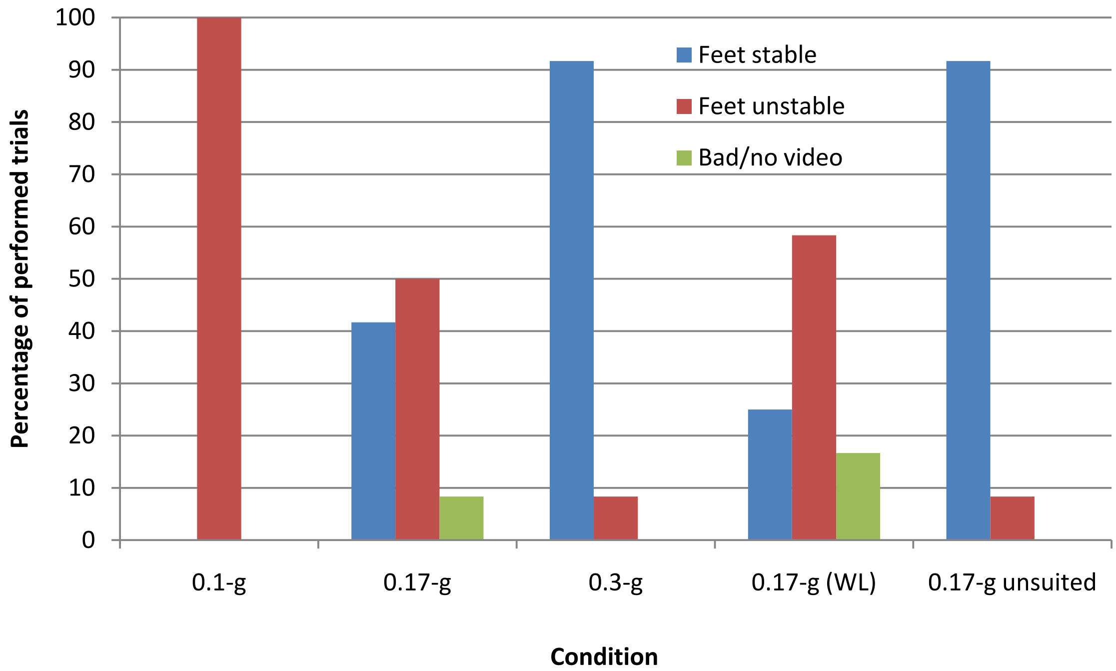

Figure 50 – Percentage of total rock pickup trials performed in phase I in which subjects were able to maintain stable foot placement on the force plates during performance of the task.

During phase II, in the CTSD and POGO CG conditions, alternating left and right hands was the strategy used the greatest number of times when subjects performed the task over multiple trials (Figure 51). In the Backpack CG configuration with the mass-support rig, more trials involved use of only the mass-supported right hand to perform the task. This may be attributed to the movement pattern adopted by subjects, given the considerably different mass-support rig arm position with this condition compared to the other two conditions. Only a total of three trials were omitted due to lack of video data. However, subjects had visible difficulty staying stable on the force plates to perform the task multiple times.

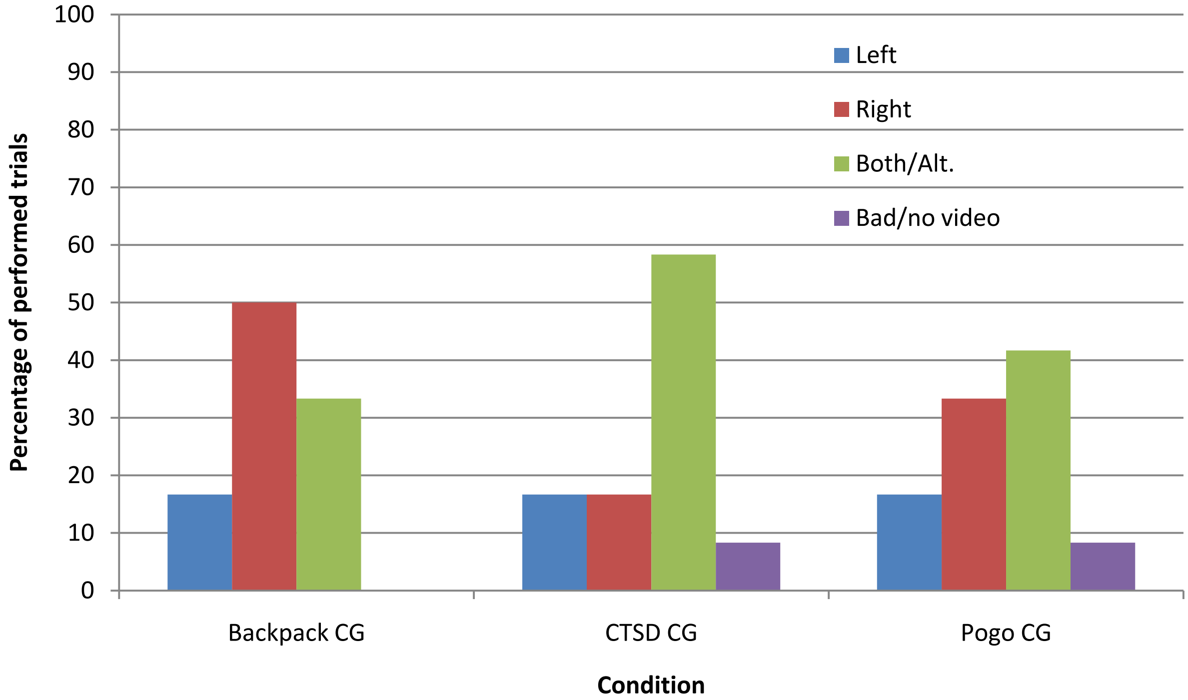

Figure 51 – Hand involvement in rock pickup trials performed in varied CG conditions (phase II).

During phase II, more feet-stable trials were observed during the rock pickup task when it was performed in the CTSD CG condition; both the Backpack and the POGO CG conditions were associated with more instability on the force plates (Figure 52). In fact, nearly 70% of trials performed in each of these two conditions involved subject inability to maintain consistent, stable contact with the force plates. This may have been partially caused by the inertial components of the mass-support rig, or by energy imparted to the suited subject by the moving aircraft (see section 3.1 for energy discussion).

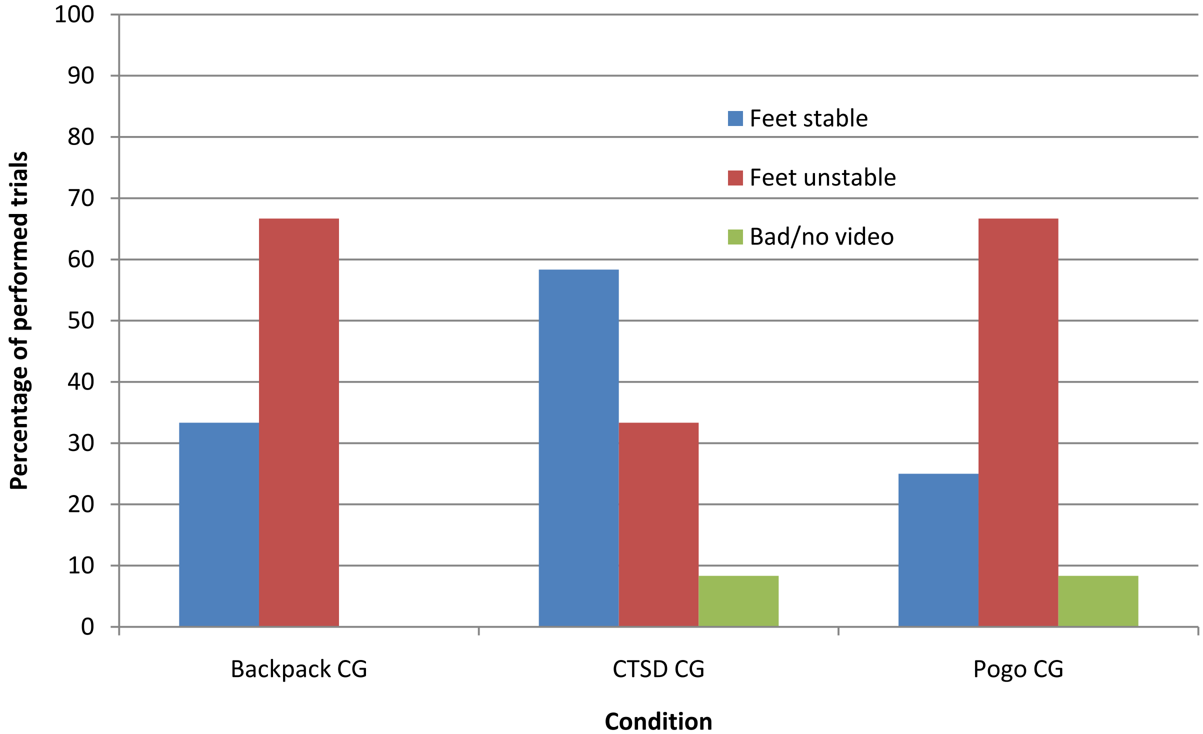

Figure 52 – Percentage of total rock pickup trials, performed in varied CG conditions (phase II), in which subjects were able to maintain stable foot placement on the force plates during performance of the task.

3.4.4.2 Shoveling Task

As with previous IST series tests, the shoveling task was performed while subjects stood on two force plates. A qualitative analysis of this task was performed using video data. The purpose of this analysis was to provide information about the stability of the subjects as they performed the shoveling task.

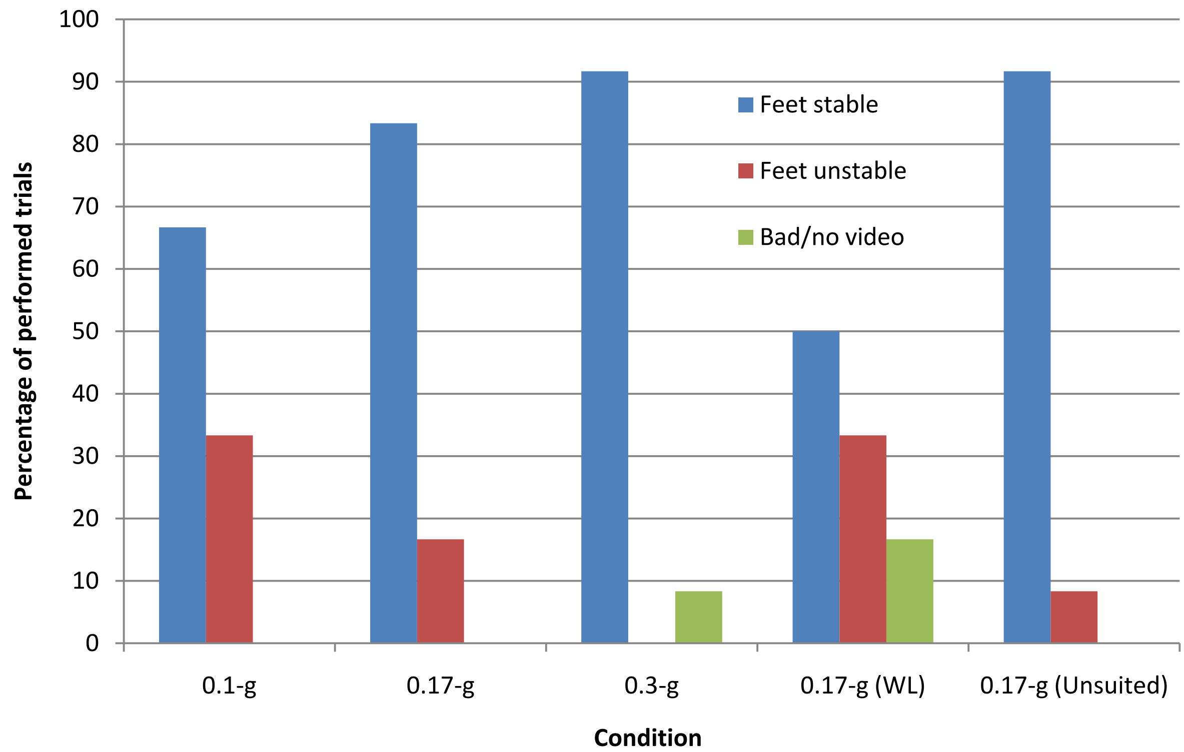

Figure 53 – Percentage of total shoveling trials performed in phase I in which subjects were able to maintain stable foot placement on the force plates during performance of the task.

During phase I, the highest percentage of stable trials was seen with the heaviest condition, 0.3g (Figure 53). In general, subjects were much more stable for the shoveling task than for the rock pickup task. This finding might be explained by subjects being able to use the shovel to brace themselves during performance of the task.

In phase II (Figure 54), the CTSD CG condition had the highest percentage of trials with stable foot placement. These results were similar to those for the 0.17g suited condition on the phase I flights. The POGO CG condition had the highest percentage of trials with unstable foot placement.

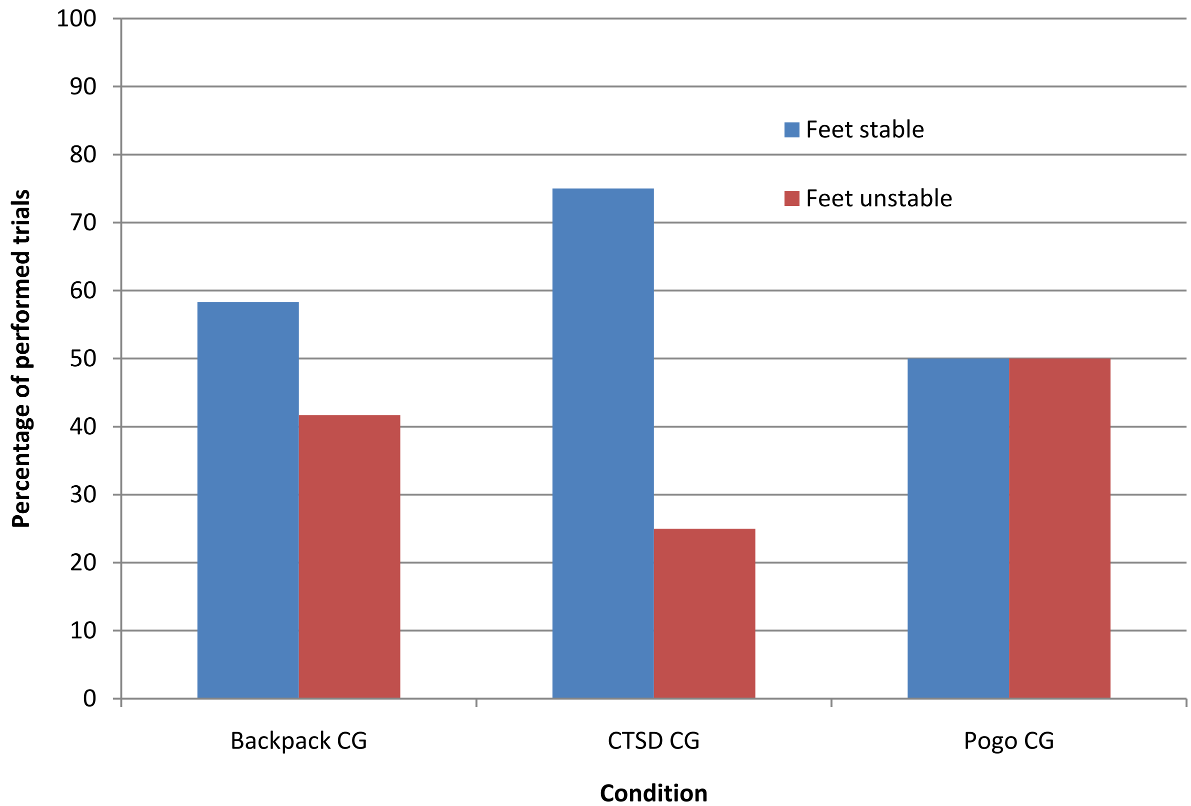

Figure 54 – Percentage of total shoveling trials, performed in varied CG conditions in phase II, in which subjects were able to maintain stable foot placement on the force plates during performance of the task.

3.4.4.3 Kneel-and-Recover Task

No force-plate data were collected for this task, as multiple contact points between the subject and the floor would have made identification and interpretation of any relevant kinetic data extremely difficult. Qualitative analysis was performed using video data to examine the strategy with which the subjects returned from the kneeling position to the standing position.

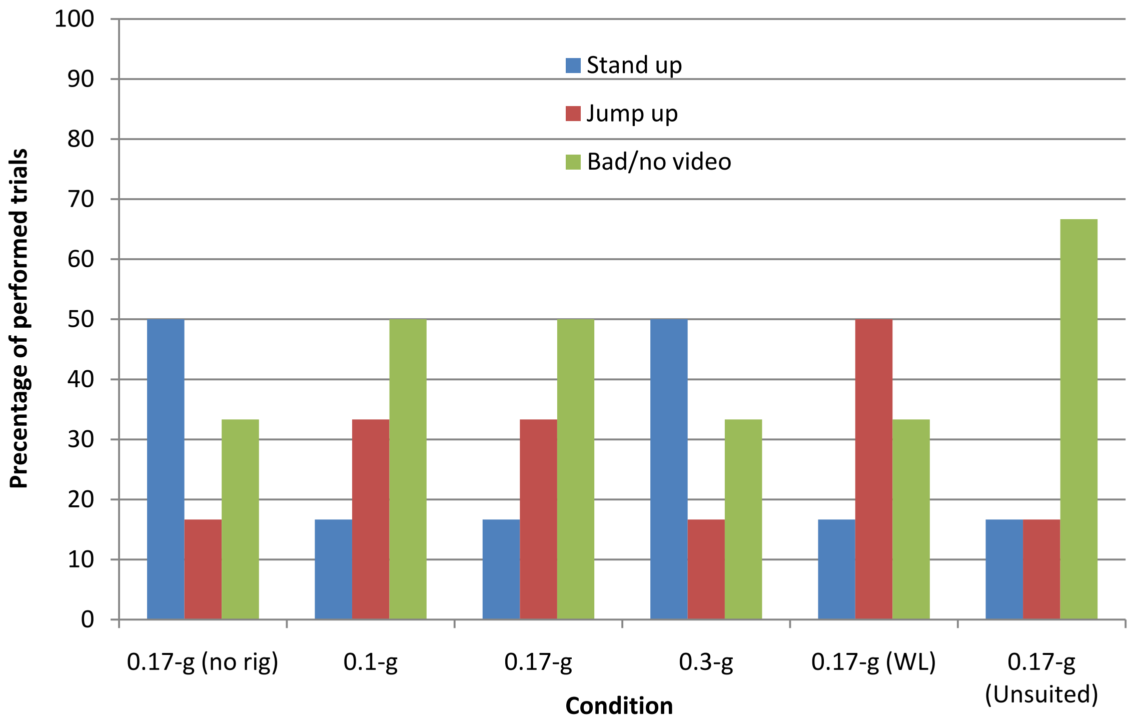

Figure 55 – Percentage of total kneel-and-recover trials performed in phase I in which subjects either stood up in a controlled manner or jumped up from a kneeling position. Many trials were not analyzed due to lack of video or blocking of camera views.

During phase I, more subjects tended to stand up in the 0.17g (no rig) condition, which may have happened because this condition was consistently the first one performed (Figure 55). As would be expected, at the lightest gravity level more subjects jumped up, whereas at the heaviest gravity level a higher percentage of trials performed involved a more controlled stand-up from the kneeling position. Many trials performed during phase I were not analyzed due to lack of usable video data.

During phase II, in the Backpack CG condition, about 65% of the trials performed involved standing up from the kneeling position (Figure 56). In this condition, the lead weights often hit the floor when the subjects were kneeling, thus limiting some subjects to a stand-up strategy. Subject height may have played a role in this result. For the CTSD CG condition, about 65% of trials involved subjects jumping up from the kneeling position. This indicated that it may have been easier for many subjects to perform the task in these conditions, leading to their using a jump-up strategy.

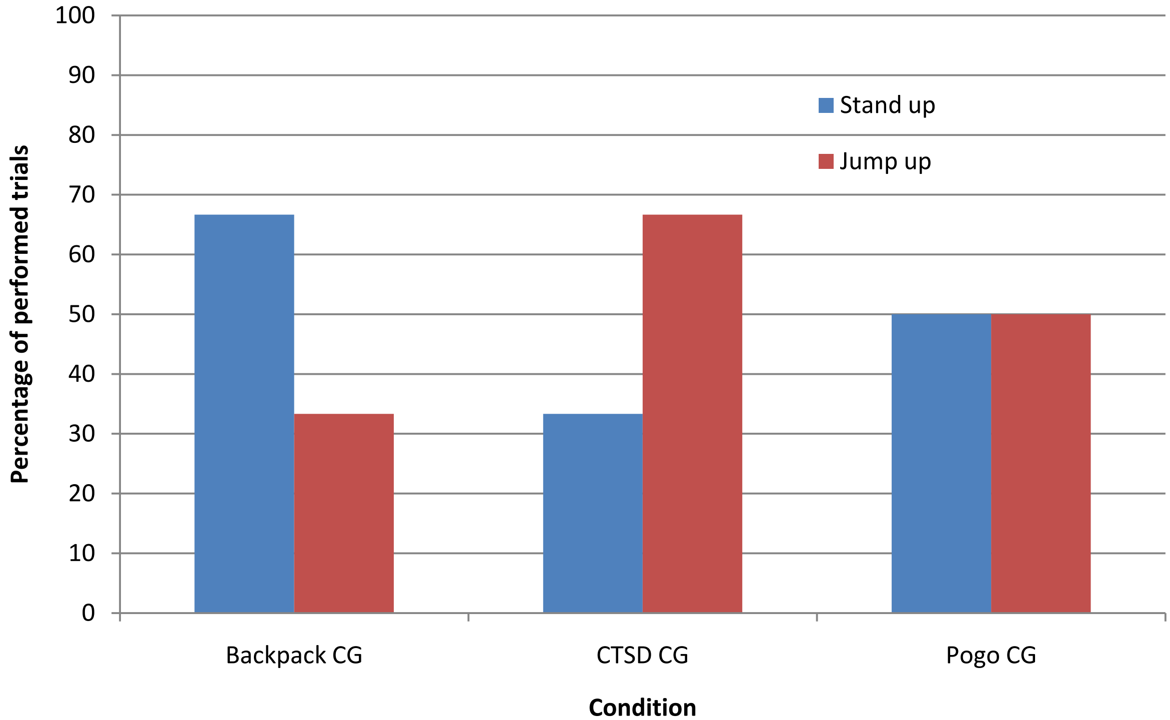

Figure 56 – Percentage of total kneel-and-recover trials, performed in varied CG conditions (phase II) in which subjects either stood up in a controlled manner or jumped up from a kneeling position.

3.4.4.4 Discussion

The instability observed during the exploration tasks was highly influential on the subjects' ability to perform the tasks successfully. As would be expected, in most trials performed at the heaviest gravity level (0.3g), foot placement on the force plates was stable, whereas in most trials performed at the 0.1g gravity level, placement of the feet was unstable.

When performing the kneel-and-recover task, subjects would often kneel on alternating sides (that is, right knee then left knee). Space limitations and safety concerns with the mass-support rig arms did not allow subjects to easily perform the task in the allotted timeframe. Subjects were often assisted by suit technicians during the trials because of these concerns.

The strategies adopted by subjects to perform the exploration tasks may be partially attributed to the different arm positions of the mass-support rig. Subjects made discernible changes in strategy depending on the CG condition. Available space was an issue, as the location of data-collection equipment depended on the placement of existing C-9 hardware (such as seat tracks), and available space limitations were one of the restrictions of this space flight analog. During the rock pickup and shoveling tasks, more feet-stable trials were performed in the CTSD CG condition than in the other two conditions, which may indicate that the mass-support rig inertia, arm positioning, or CG location were advantages for this condition.

3.4.5 Exploration: Stability

An example of the center of pressure (COP) trace for a rock pickup during phase I is shown in Figure 57. The thick black squares represent the force plates. The blue and red represent the left- and right-foot COPs respectively, and the green is the combined COPs of the two feet for the entire trial. The thin black line represents the base of support (BOS) for one frame of data only.

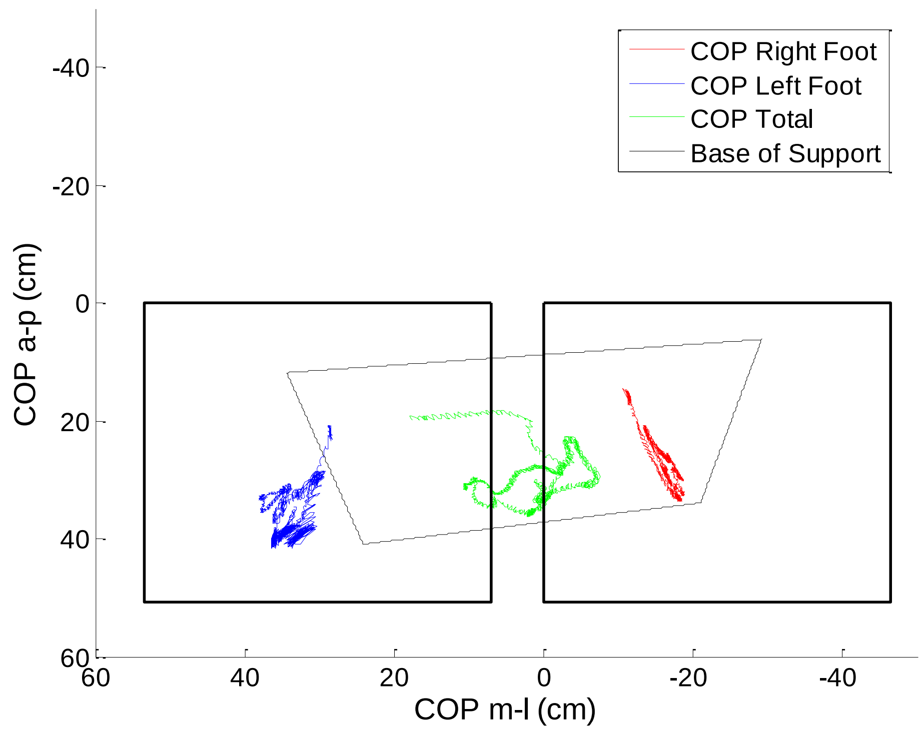

Figure 57 – Sample center-of-pressure (COP) trajectory.

At the beginning of the data-collection trial, each subject was required to step onto the force plates, stabilize himself, perform the task, stabilize again, and step off the plates. The metrics used to determine stability were the percentage of time the COP was outside of the BOS, the number of times the COP fell outside of the BOS, the average area of the BOS, and the total distance traveled by the COP.

There was inconsistency between subjects in methods of performing the tasks. The protocol during the rock pickup was to step up, bend down to pick up the rock, stand up, bend down to set the rock down, and then step off the force plates. Some subjects bent down to pick up the rock and then dropped the rock after they stood up. Because the methods differed between subjects, only the pickup motion was analyzed.

The results from the rock pickup task during phase I are presented in Figure 58. The values for the total travel for 0.17g and 0.3g were 45.7 ± 22.2 m and 9.1 ± 2.6 m, respectively. As gravity increased, the percentage of time the COP spent outside the BOS, the number of times it fell outside the BOS, and the total distance traveled by the COP all decreased. This shows that the subjects had more control over the movement of the COP as gravity increased.

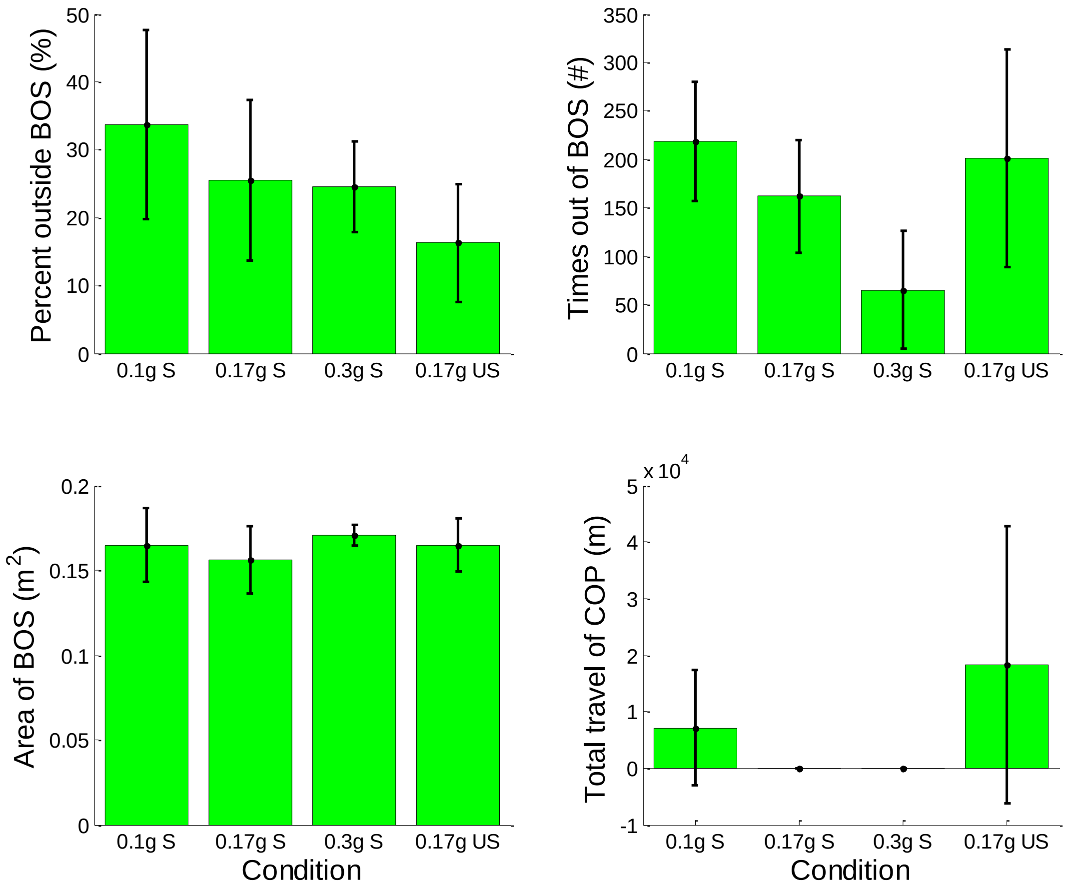

Figure 58 – Rock pickup COP metrics for subjects wearing an MKIII suit (S) with the mass-support rig, no weights in the stalled position, at varied gravity levels, and for the unsuited (US) subjects at 0.17g.

As with the rock pickup, the stability while shoveling increased as the gravity level increased (Figure 59). Subjects were less stable in the unsuited 0.17g condition than when suited at the same gravity level, most likely because the addition of mass improved their performance.

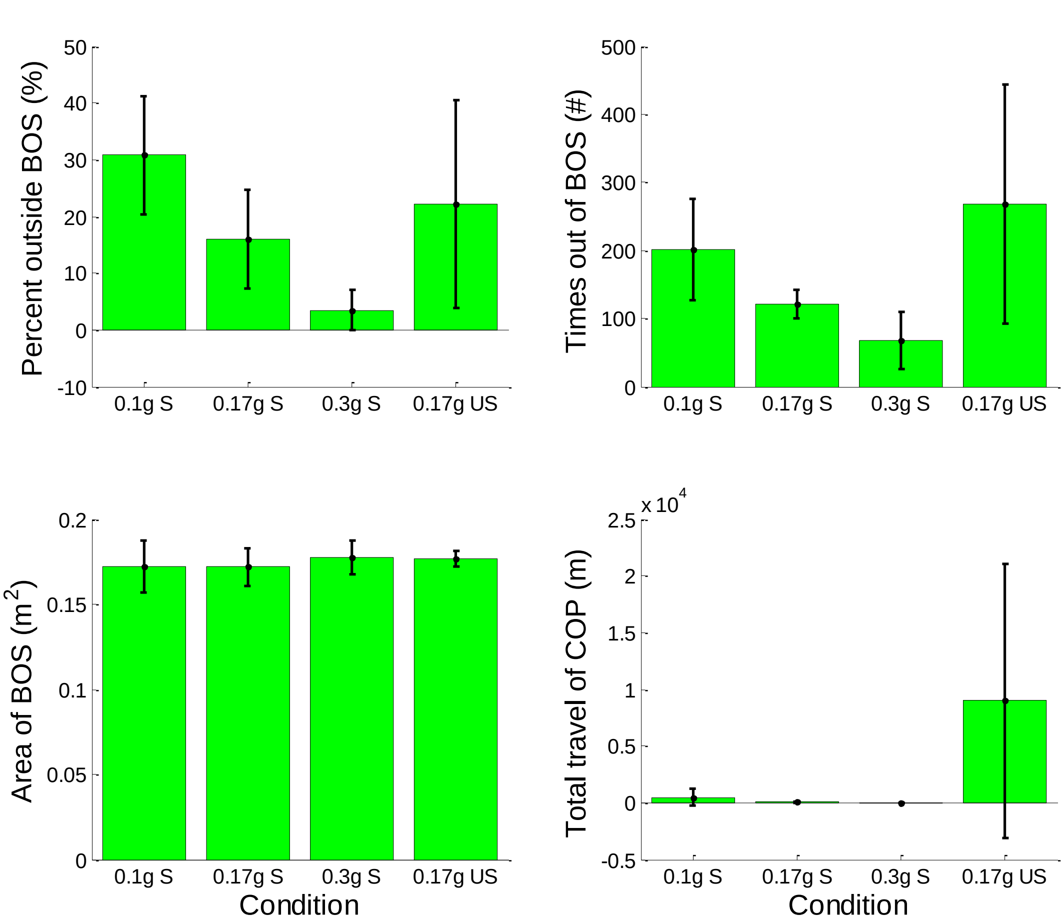

Figure 59 – COP metrics for shoveling in suited (S) conditions with the mass-support rig, no weights in the stalled position, at varied gravity levels, and for the unsuited (US) condition at 0.17g (phase I).

For the phase II rock pickup task, the CTSD CG configuration had the smallest amount of time the COP was outside the BOS, number of times the COP fell outside the BOS, and total distance traveled by the COP (Figure 60). This configuration also had the smallest amount of variation between subjects, whereas the Backpack CG configuration had the greatest amount of variability.

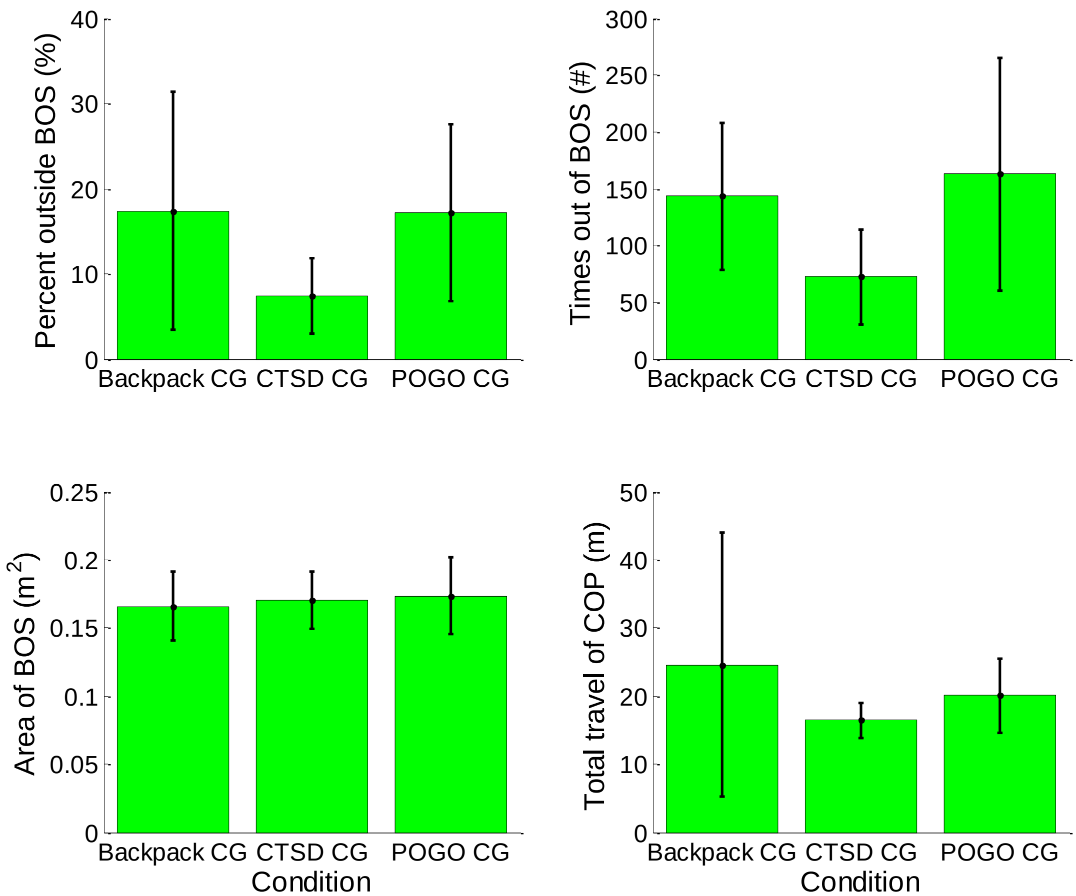

Figure 60 – COP metrics for rock pickup. All CG configurations used the mass-support rig at 0.17g (phase II).

As with the rock pickup, the stability while shoveling increased as the gravity level increased (Figure 61). However, unlike the rock pickup results, on average subjects were less stable in the unsuited 0.17g condition than when they were suited at the same gravity level. The unsuited 0.17g condition also had the largest standard deviation, implying that some subjects had a more difficult time than others.

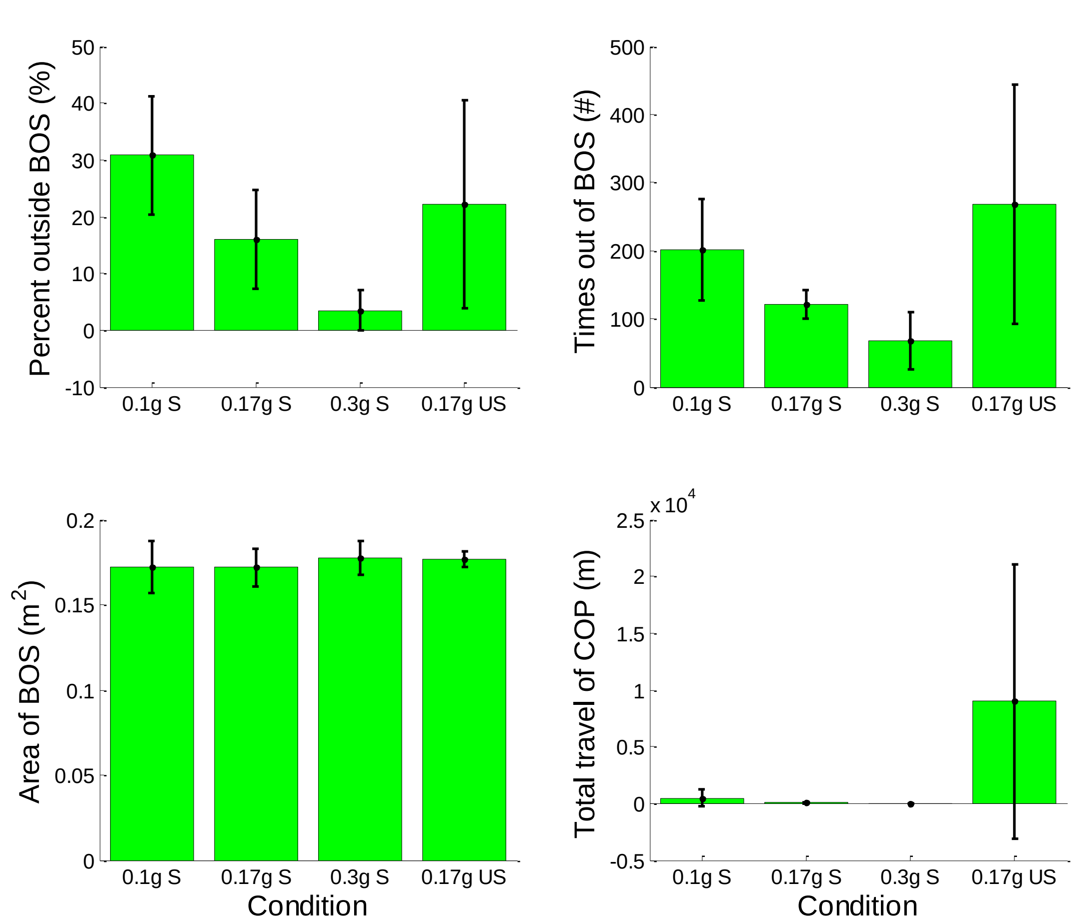

Figure 61 – COP metrics for shoveling in suited conditions (S) with the mass-support rig, no weights in the stalled position, at varied gravity levels, and in the unsuited (US) condition at 0.17g (phase I).

In the CTSD CG configuration, on average, the COP had less time outside the BOS (Figure 62). The total distance traveled by the COP was about equal for the CTSD and Backpack CG configurations, and the number of times the COP fell out of the BOS was about equal for the CTSD and POGO CG configurations.

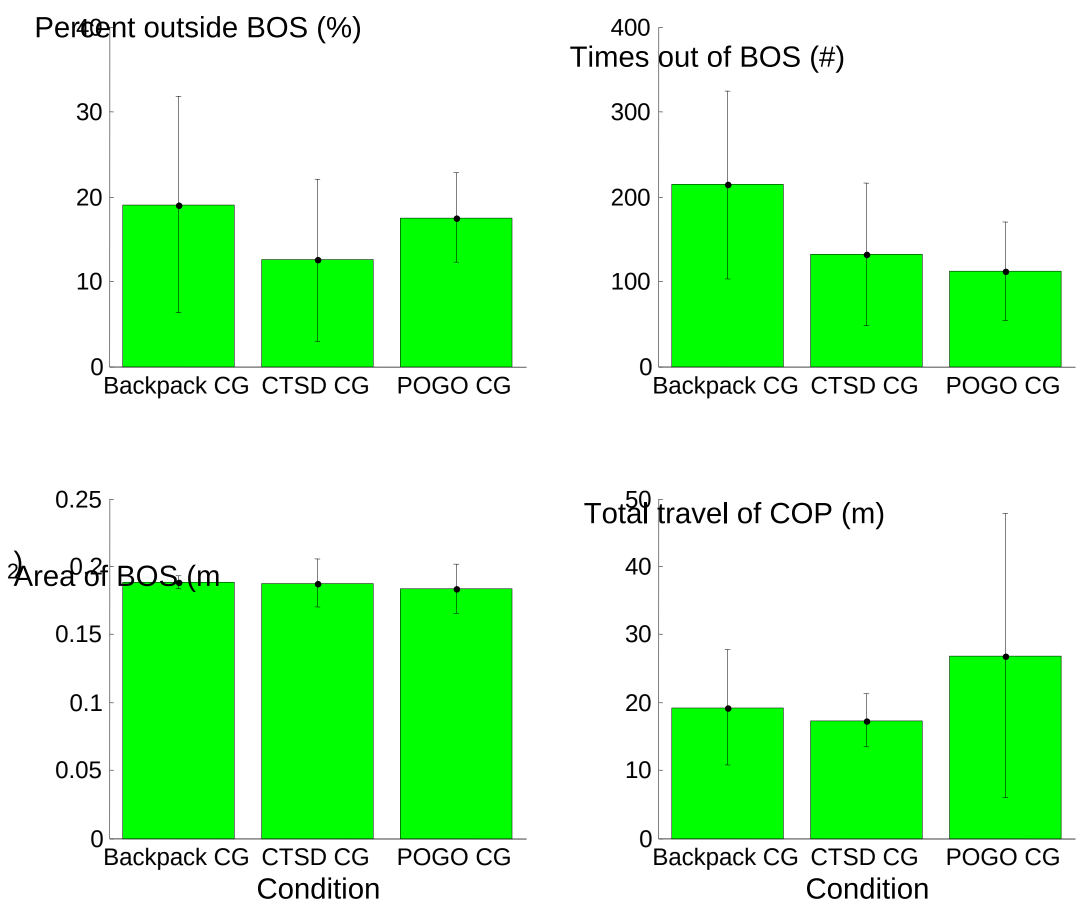

Figure 62 – COP metrics for shoveling. All CG configurations used the mass-support rig at 0.17g (phase II).

3.4.5.1 Waist Bearing Locked or Unlocked

On average, the locked and unlocked waist bearing conditions used in phase I had no differing effects on stability during the rock pickup task. The main difference seen was for the total distance the COP traveled, Figure 63. Locking the waist resulted in about a 15× increase in the COP travel. The large deviation for locked conditions was most likely caused by subjects having a difficult time controlling the movement of the COP.

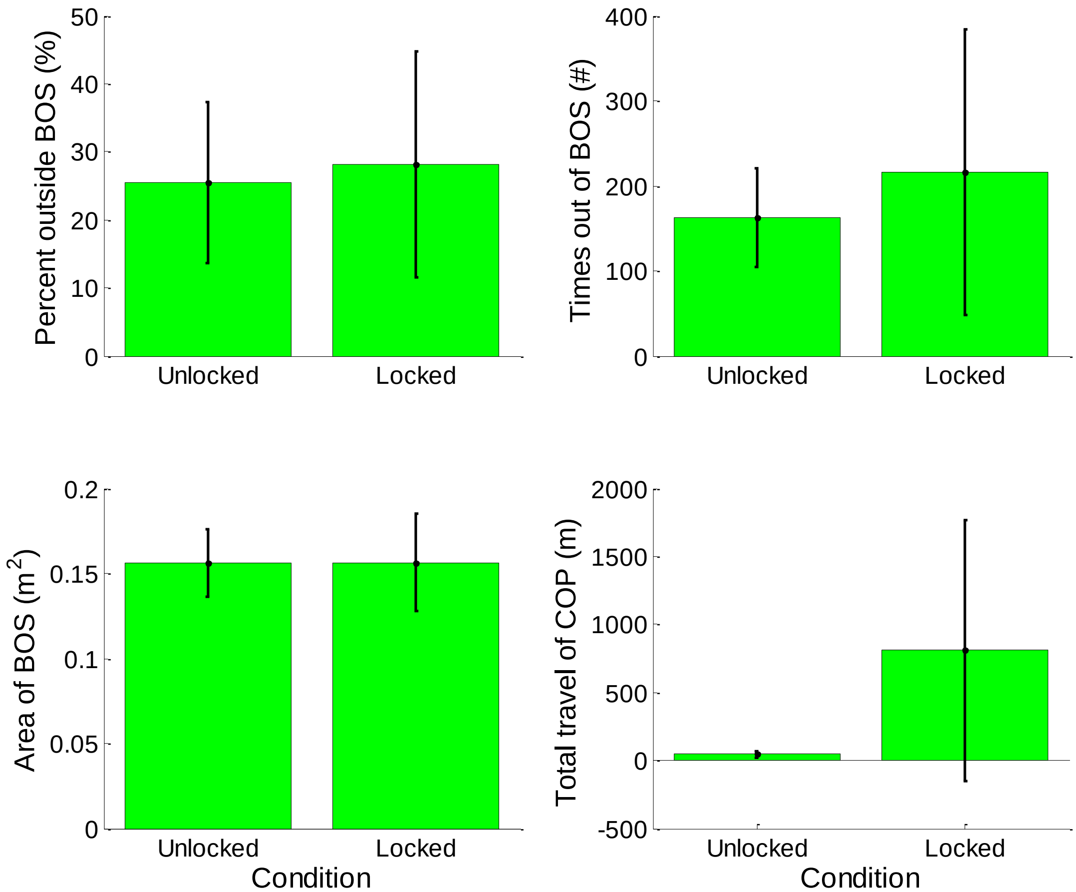

Figure 63 – COP metrics for rock pickup in the suited 0.17g condition with locked or unlocked waist bearings (phase I).

During shoveling, in phase I the amount of time the COP spent outside of the BOS was greater in the waist-locked condition (Figure 64). The total distance traveled by the COP was also greater, but the standard deviation for the locked condition was also greater because one subject had difficulty with this condition.

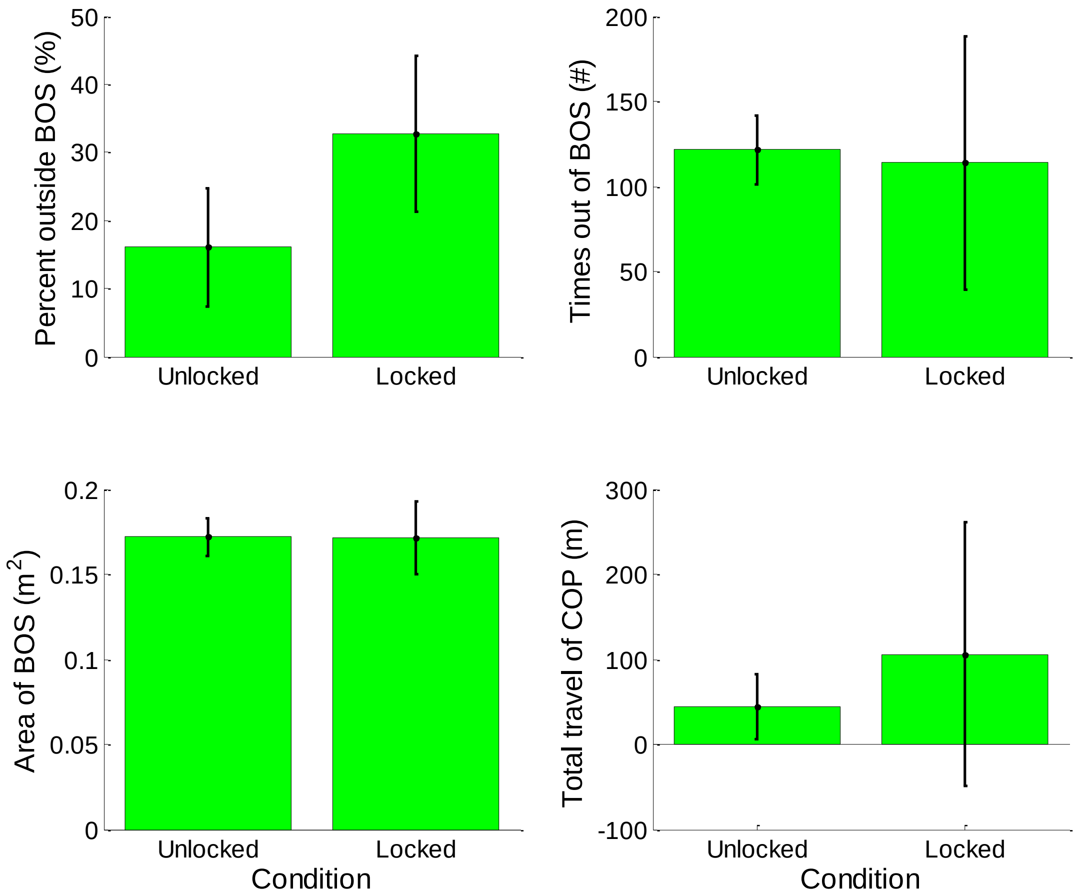

Figure 64 – COP metrics during shoveling in the suited 0.17g condition with locked or unlocked waist bearings (phase I).

At the lower gravity level of 0.1g and in unsuited conditions, the COP calculation was unreliable. The subjects could not get firm foot contact with the force plates, resulting in erratic COP results (Figure 65). Without consistent contact with the force plates, many of the variables became invalid.

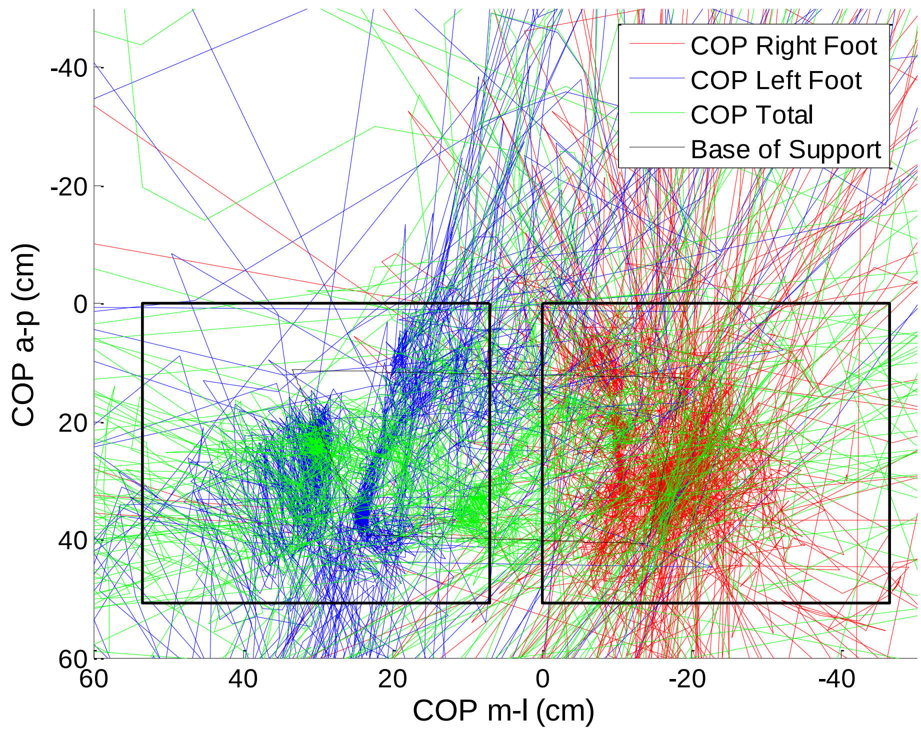

Figure 65 – Sample COP trajectory of insufficient contact with force plates.

With increasing gravity level, the suited exploration tasks showed more stability. Variability between subjects was high for the different CG configurations. Height and weight had no influence on performance. Of the three CG configurations tested, it appeared that the CTSD CG configuration was on average the most stable. Because of the large amount of variation and difficulties related to the testing environment, only limited conclusions can be drawn about the effect of CG on the suited subjects or the effect of locking the waist bearing on stability.

3.5 Subjective Ratings Results and Discussion

Subjective ratings were collected from the subjects in phases I and II as described in section 2.6.2; see appendix section 6.7 for details on the rating scales utilized. The collected ratings were analyzed and plotted for comparison across gravity level, CG, and mass conditions. Figure 66 shows the gravity compensation and performance scale (GCPS) ratings, averaged by task across the different simulated gravity levels achieved during phase I, including the waist-locked and non–waist-locked conditions for 0.17g. Except for the kneel-and-recover task, mean GCPS ratings were higher for the 0.1g condition. This suggests that subjects felt as though they had to compensate more in this condition to achieve desired performance. The mean values for waist-locked and non–waist-locked conditions showed no substantial differences for most tasks.

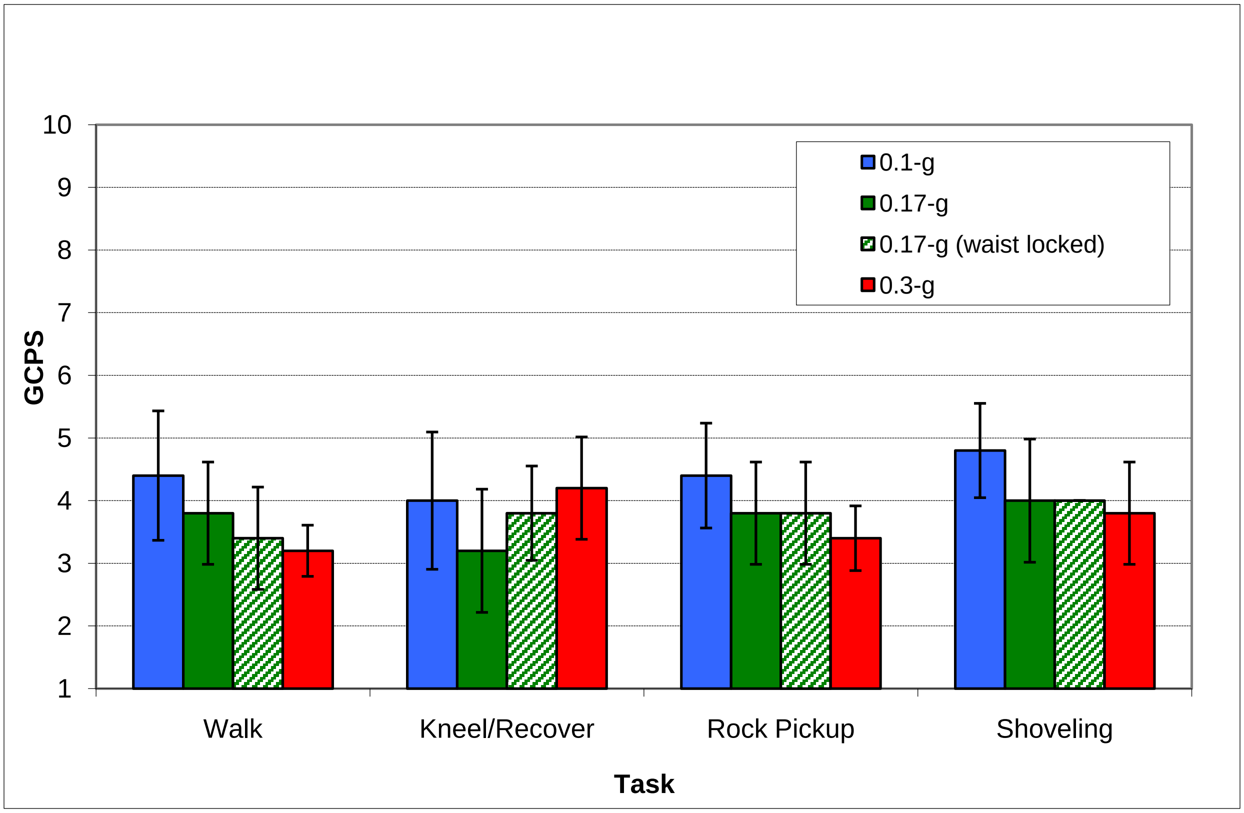

Figure 66 - Phase I GCPS ratings as a function of task.

For Ratings of Perceived Exertion (RPE), the highest means were associated with the 0.3g condition, which was to be expected because subjects were required to support more weight while performing tasks. Although the 0.1g condition showed the highest mean GCPS ratings, it resulted in the lowest mean RPE ratings. Again, no substantial difference was noted between the waist-locked and the non–waist-locked conditions.

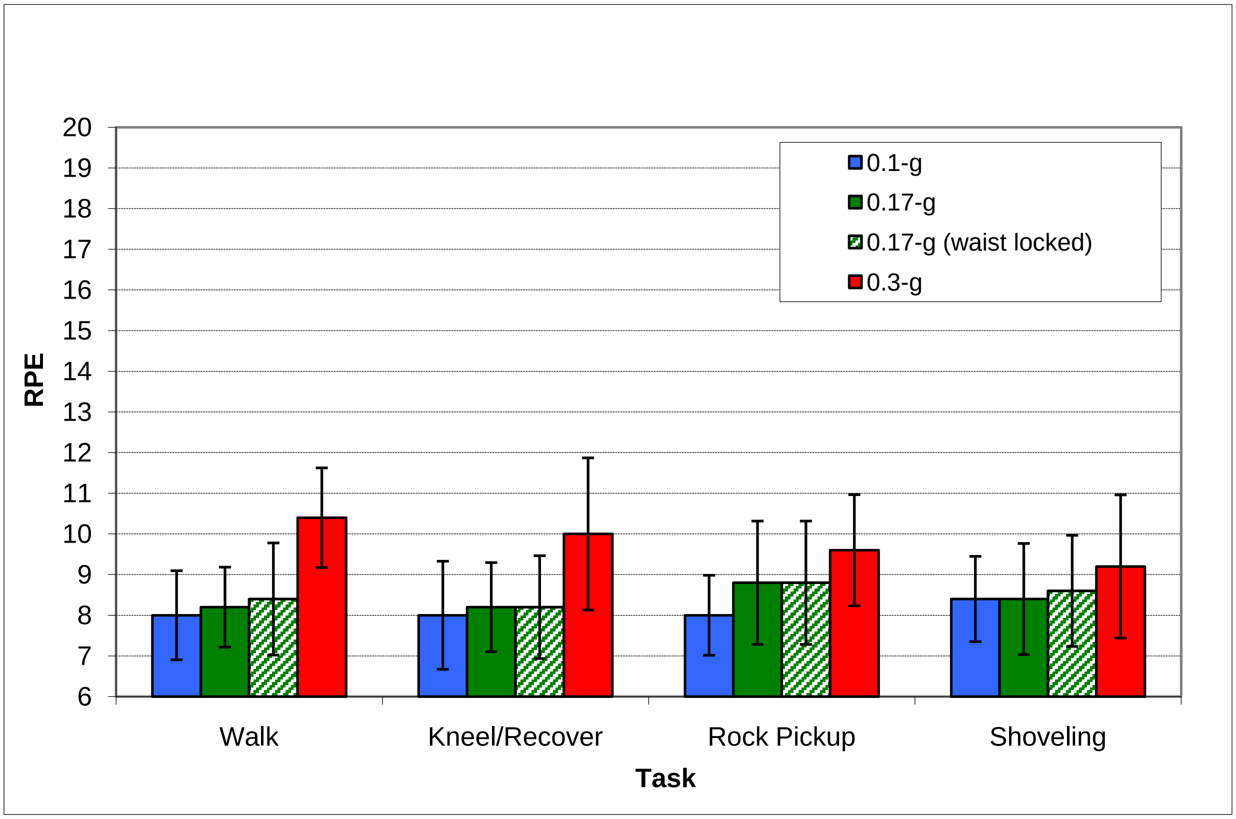

Figure 67 - Phase I RPE ratings as a function of task.

The GCPS ratings for the different CG conditions at 0.17g in phase II are shown in Figure 68. It should be noted that, unlike in phase I, separate GCPS ratings were collected from subjects for the kneel and stand portions of the kneel-and-recover task. The highest mean GCPS rating was for the POGO CG, with the Backpack and CTSD CGs both being less, but not substantially different from one another. Some subjects commented that they felt the most unstable during the POGO condition, and that the POGO condition required more compensation than the other two conditions. Several subjects stated that their center of gravity felt unusually off-center and lower than in the other conditions. It should also be noted that the GCPS ratings for both the Backpack and the POGO CG conditions exhibited a high degree of variability. A number of factors could have contributed to the variability, including the dynamic environment of the C9 aircraft, the small sample size (n = 6), and subject-to-subject anthropometric and strength differences. However, without further testing, it is difficult to determine the specific contributions of each factor to the variability.

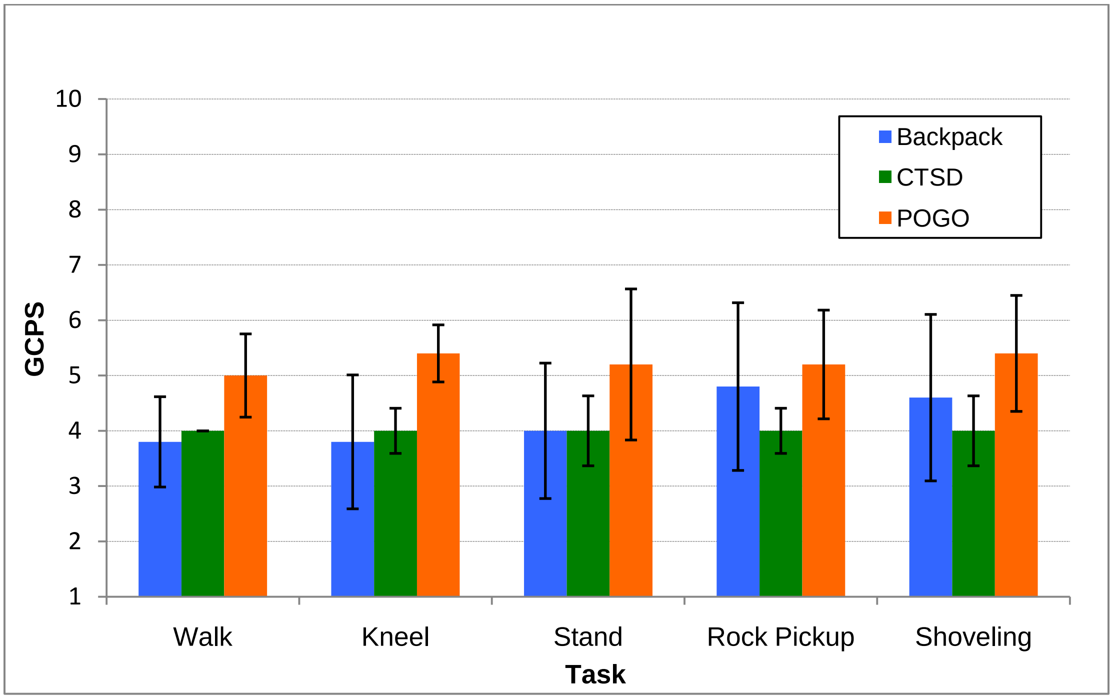

Figure 68 - Phase II GCPS ratings as a function of CG.

Figure 69 compares the RPEs from phase II as a function of CG and task. No substantial differences were noted across CG conditions, with the majority of tasks not showing more than a 1-unit rating difference across conditions. However, the mean RPEs for the POGO condition were slightly higher.

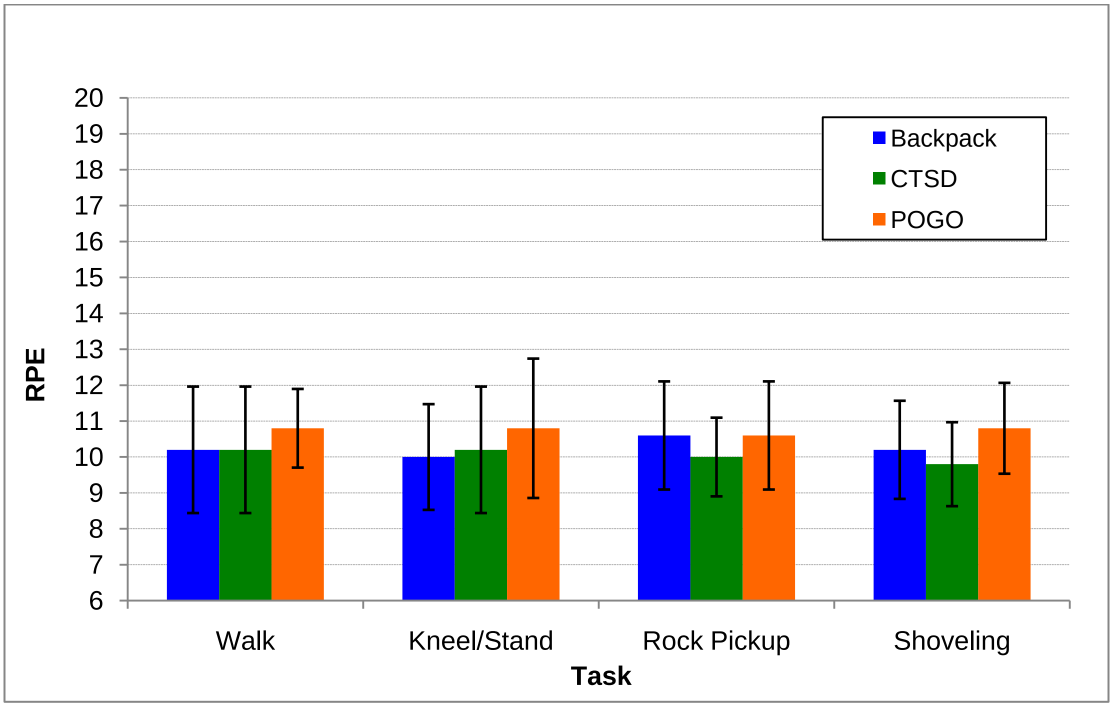

Figure 69 - Phase II RPE ratings as a function of CG.

Comparing GCPS means for phases I and II of the test allows the effects of mass to be examined. It should be noted that the means presented are for all subjects, not just the 5 subjects who were common to both phases. Figure 70 shows that regardless of the magnitude of inertial mass (89, 120, or 181 kg), the mean GCPS ratings indicate that subjects were able to achieve desired performance with moderate to minimal compensation. Figure 71 shows that RPE increased as mass increased, as would be expected, and that mean RPE ratings were within the light exertion levels at the greatest inertial mass.

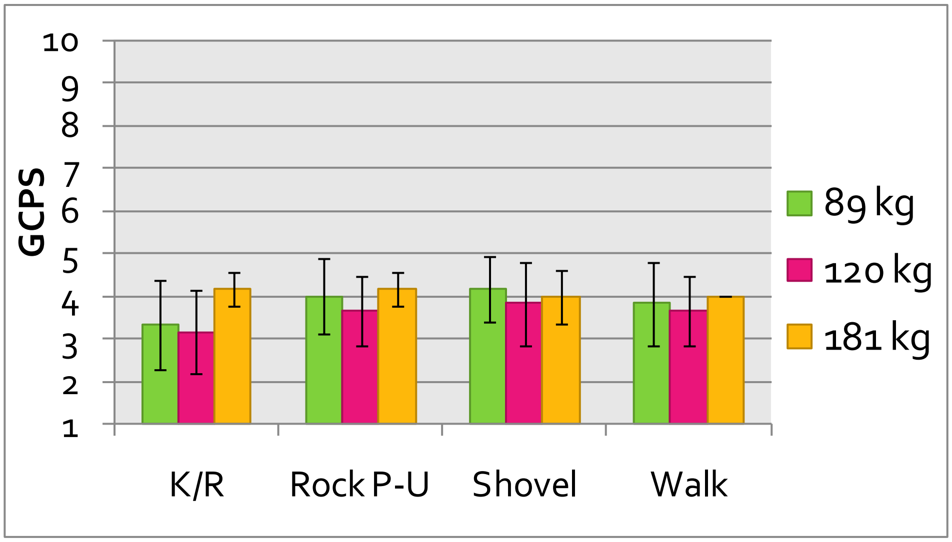

Figure 70 – GCPS as a function of suit mass for each task in 0.17g. K/R, kneel and recover.

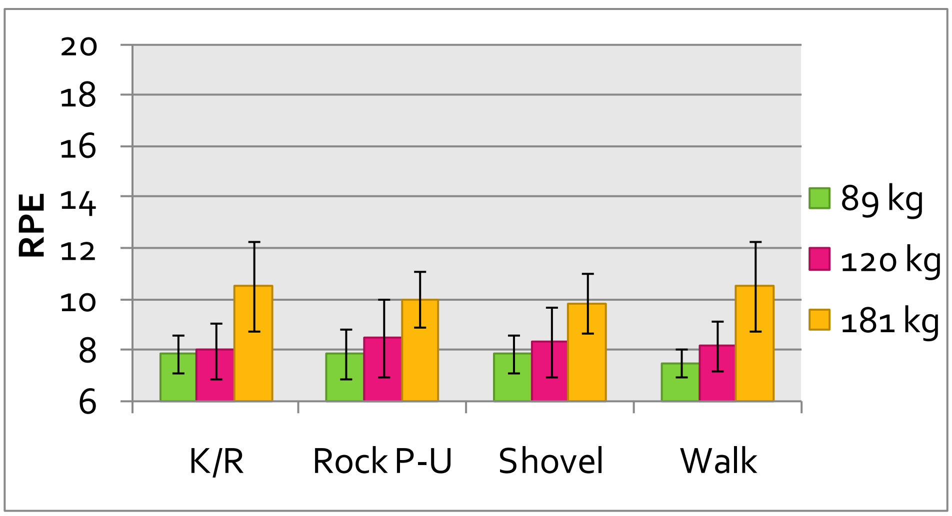

Figure 71 – RPE as a function of suit mass for each task in 0.17g. K/R, kneel and recover.

Continuing the comparison of the effects of mass, the variation in TGAW shown in Figure 72 was produced in phase I by holding mass constant and varying the gravity level. The variation in TGAW produced by varying mass was achieved in both phase I and phase II while holding gravity level constant. The CG was held close to constant across all conditions shown. Figure 72 shows that at low TGAW, GCPS ratings were nearly equivalent regardless of the presence of mass. At higher TGAW, with the presence of mass a possible trend toward higher GCPS ratings was seen. This may indicate that the presence of mass causes subjects to compensate more for a given TGAW than if the mass were not there and, instead, a higher gravity level were used to provide the higher TGAW. However, this interpretation is based on a limited data set that has a high degree of variability and requires extrapolation outside of the tested TGAW range. Because of this, personnel from the Usability, Testing, and Analysis Facility

(UTAF) did not agree with this analysis. Further study would need to be undertaken to assess the validity of this potential interpretation.

Figure 73 shows some sensitivity of RPE to the presence of mass. At lower TGAW, with mass present, less exertion was required and therefore mean RPE ratings were lower. At higher TGAWs, the mean RPE ratings for varied mass increased, with a greater slope than for varied weight.

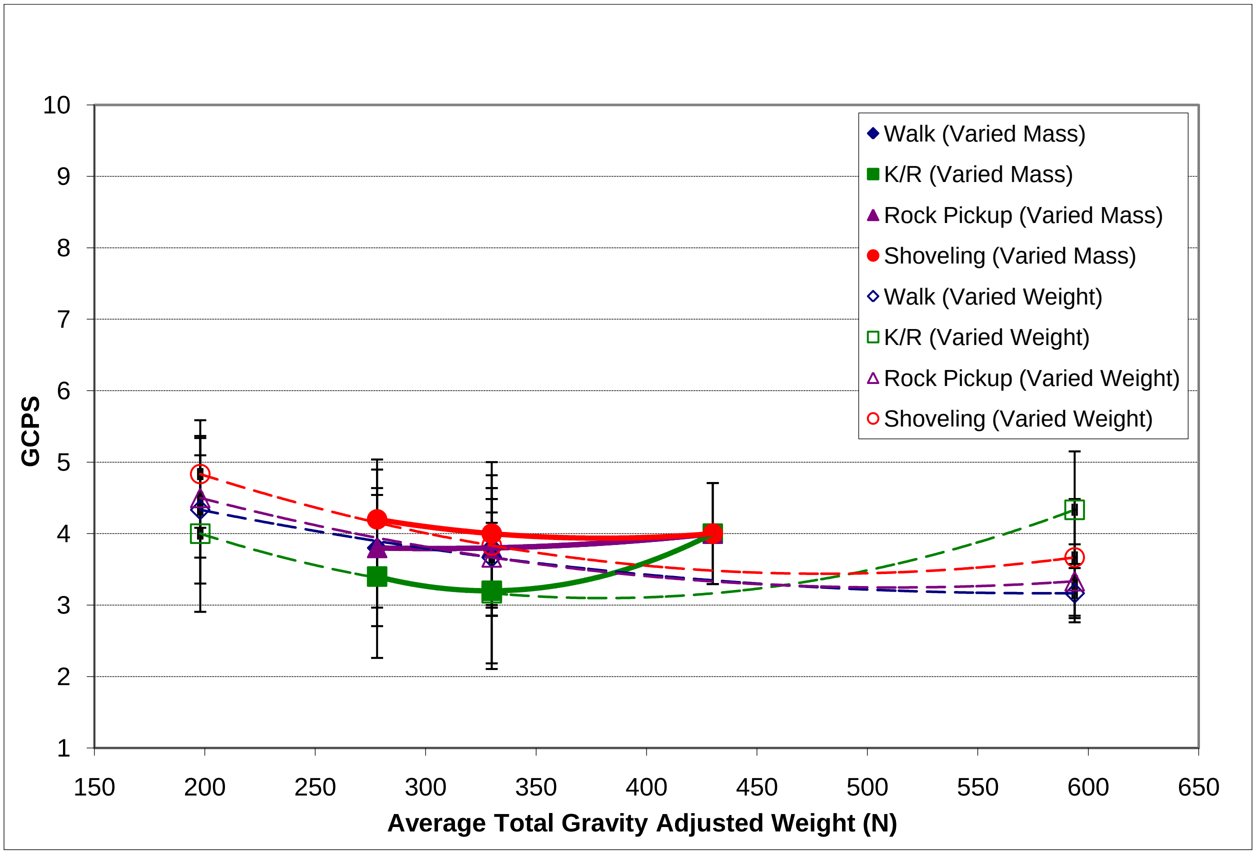

Figure 72 – Phase I and II GCPS as a function of TGAW. K/R, kneel and recover.

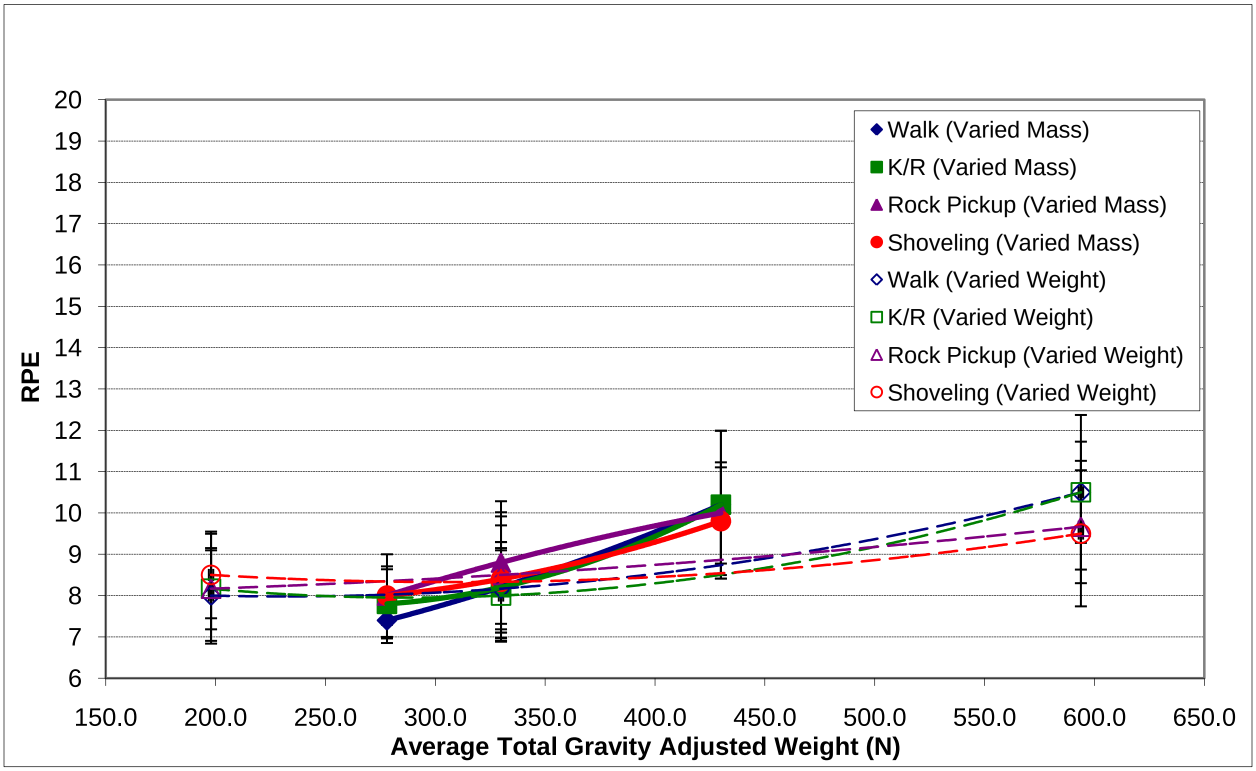

Figure 73 – Phase I and II RPE as a function of TGAW. K/R, kneel and recover.

Turning to a comparison of the nominal versus waist-locked configurations of the MKIII in 0.17g, no substantial differences in GCPS or RPE (Figure 74 and Figure 75, respectively) were noted between the two conditions.

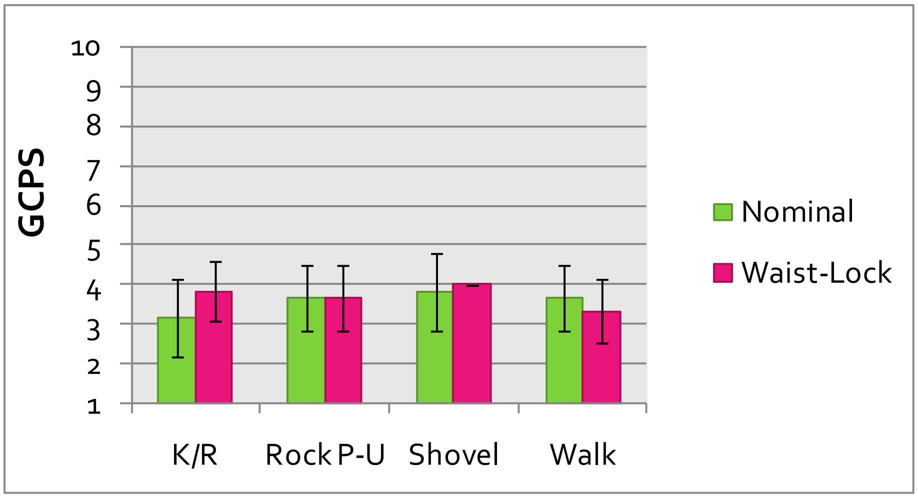

Figure 74 – GCPS ratings in MKIII suited nominal versus waist-locked configurations. K/R, kneel and recover.

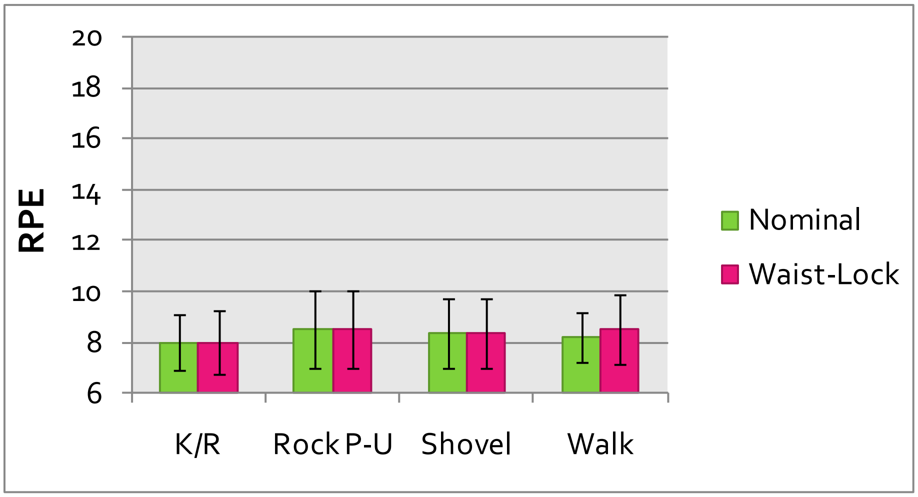

Figure 75 – RPE ratings in MKIII suited nominal versus waist-locked configurations. K/R, kneel and recover.

The post-test questionnaires that were provided to the test subjects immediately after each test flight collected rank-ordering of the test conditions that the test subjects had just experienced. After their phase I flight, subjects were asked to rank-order the gravity conditions (0.1, 0.17, 0.3) from most preferred (1) to least preferred (3). After their phase II flight, subjects were asked to similarly rank-order the different CG conditions from most preferred to least preferred. Table 5 and table 6 show the average of the rank-orders provided by the subjects for gravity level and CG, respectively. The average rank-orders indicate a preference for the 0.17g gravity level and the CTSD CG. Consistent with other subjective ratings collected, the least preferred gravity level was 0.1g and the least preferred CG was POGO.

Table 5 - Average gravity level rank-ordering from postflight questionnaires

	Gravity Level		
	0.1g	0.17g	0.3g
Walking	2.7	1.5	1.8
Kneel/Recover	2.2	1.3	2.5
Rock Pickup	2.7	1.3	2.0
Shoveling	2.5	1.3	2.2
Overall	2.5	1.4	2.1

Table 6 - Average center of gravity rank-ordering from postflight questionnaires

	Center of Gravity		
	Backpack	CTSD	POGO
Walking	1.8	1.7	2.2
Kneel/Recover	1.8	1.3	2.5

	Center of Gravity		
	Backpack	CTSD	POGO
Rock Pickup	1.8	1.3	2.7
Shoveling	1.7	1.3	2.8
Overall	1.8	1.4	2.5

4.0 Conclusions

This section contains a summary of conclusions, limitations, and lessons learned from the test. For additional details about the biomechanical aspects of the test, please see the C-9 phase I and II Quick Look Report completed by the ABF.[14]

4.1 Test Objectives

4.1.1 Comparison with POGO Results

One of the primary objectives of this test was to compare its results with those of the IST-1 and IST-2 tests on the POGO. This comparison seemed to show that both systematic and task-specific differences may exist between the two test environments. This is best evidenced through comparison of GCPS ratings from the present testing with those from POGO testing for similar conditions as TGAW (weight on the ground) was varied. Performing this comparison for walking and rock pickup showed similar results for the same task at some TGAW ranges but diverging results for other TGAW ranges. However, for tasks such as shoveling, the GCPS for the present testing was consistently offset from the POGO results, being about one point higher across the entire TGAW range. Finally, for kneel and recover, a quite similar trend was seen, possibly indicating the lack of an effect of simulation environment on this task. Further analysis of the biomechanics differences and more detailed comparisons of results across tests and analog environments is presented in the analog comparison report.[15]

4.1.2 Effects of Varied Gravity

A primary objective of the test was to assess how varying the gravity level, while keeping CG and mass constant, affected biomechanics and operator compensation. For ambulation, the biomechanics results generally indicated that higher gravity levels may allow more control during walking and that lower gravity levels may decrease the subject’s ability to maintain stability and a consistent gait. Strategy and stability analysis of the exploration tasks also indicated more stability at higher gravity levels. Subjective ratings also showed higher degrees of operator compensation at lower gravity levels. However, perceived exertion was highest at the highest gravity level, indicating that the stability enabled by larger ground reaction forces does not come without cost.

4.1.3 Effects of Varied Mass

Another primary objective of the test was to assess how varying the suit mass, while keeping CG and simulated reduced gravity constant, affects biomechanics and operator compensation. Most measures did not show discernible differences as mass varied, mostly because of the large variability in the data.

However, the means of the results suggest that higher masses may have provided more stability during task performance. Also, perceived exertion did show an increase as mass increased, as would be expected.

It was determined that simulating a change in mass by manipulating simulated gravity level does not lead to the same human performance changes as does changing the mass directly. Simulating mass by altering gravity level tends to underestimate human performance metrics at heavier masses and overestimate them at lighter masses. At heavier masses this is most likely because, with gravity changes alone, subjects' ground reaction forces increased without the additional mass to provide stability and control. Similarly, at lighter masses and with gravity changes alone, subjects' ground reaction forces decreased, but they had the same additional mass and therefore increased controllability. In general, modeling a change in suit mass by altering weight alone may be an adequate simulation through a limited range when looking at gross metrics of subjective performance of suited humans, but whether it would be sufficient for more precise metrics of human performance still needs further study.

4.1.4 Effects of Varied Center of Gravity

Another primary objective of the test was to assess how varying the suited CG, while keeping mass and simulated gravity level constant, affect biomechanics and operator compensation. Overall, kinematics and kinetics showed little difference between CG conditions. However, modifying CG during suited testing seems to affect operator compensation. Intersubject variation in subjective ratings at a given CG indicated that further study is needed to evaluate interactions among lunar-gravity simulation analog, system CG, system mass, and subject characteristics such as anthropometry, strength, and fitness.

4.1.5 Waist Bearing Locked/Non-Locked Comparison

A secondary objective of the test was to compare the nominal configuration of the MKIII suit to its configuration with the waist bearing locked. There were no substantial differences in subjective measures of performance (GCPS and RPE). The biomechanics measures also showed no substantial difference between the two conditions, except for step width. There was some indication from the COP analysis of the two conditions that the waist bearing locked configuration may have been more unstable. It should be noted that because the waist-locked condition was always performed as the last suited set of trials, a learning effect may have contributed to the results.

4.2 Limitations of Test Conclusions

There were limitations in the ability to design the protocol and equipment for this test to meet its objectives. The ability to compare results from parabolic flight with those from ground-based tests was limited. Differences in experiment setup, lack of direct crossover test points, and subject population differences may have contributed to the lack of comparability of the results.

Kinematic and ground-reaction-force data were highly variable because of the limited volume for testing on the C-9 airplane and the variability of the acceleration levels during a parabola. Volume constraints affected the ability of the subjects to attain a stable gait during walking because of the need to stop, turn, and start in the confined area, compared to an uninterrupted treadmill gait on the ground.

The mass-support rig had to be designed with large amounts of weight on lever arms to achieve the specific targeted CGs, and the increased rotational inertia and physical volume of the mass-support rig had some effects on subject performance. These effects included increasing the difficulty for subjects to rotate and perform tasks requiring significant bending forward at the waist. Also, subjects may have modified their strategy or speed for performing some tasks on the basis of a real or perceived reduction in available performance volume, or out of concern that they could strike test equipment with the mass-support rig.

The locked waist condition is not a nominal configuration for the MKIII suit. Mobility of the suit can be achieved, but through movement patterns different from those for the waist-unlocked configuration. Mobility is achieved through changes in the dominant joint for motion, which can affect different-sized subjects in different ways. Overall, the waist-locked / not locked results may not be generalizable to suit design without further testing.

4.3 Lessons Learned for Future Work

Much can be done to improve the utility of data collected during parabolic flight and its applicability across other lunar-gravity analogs. Utilization of aircraft and aircrews that can provide maximum-duration parabolas with the required acceleration accuracy will provide the best environment for research. Maximizing the length of the cabin available for tasks such as ambulation or increasing cabin height to allow use of a treadmill fitted with a force plate will allow suited subjects to attain a stable gait. To maximize the ability to compare data from parabolic flight with data from other simulated reduced-gravity analogs, tests performed in other analogs should be designed with identical constraints regarding conditions, equipment, task duration, methods, and subjects. Additionally, to better understand the source of subject-to-subject variability, anthropometric and strength analyses should be performed on all subjects before they participate in studies. Finally, the costs associated with performing experiments using parabolic flight must be kept within reach of available research budgets that provide sufficient numbers of subjects and task repetitions. These improvements would maximize the ability to achieve meaningful, significant differences and to make the most informed recommendations for future lunar space suit designs to optimize human performance.

5.0 References

1. National Aeronautics and Space Administration. C-9 and Other Microgravity Simulations Summary Report. Houston: National Aeronautics and Space Administration; 2009. Report No.: NASA/TM-2009-214794.

2. Norcross J, Lee L, Clowers K, Morency R, Desantis L, De Witt J, et al. Feasibility of Performing a Suited 10 km Ambulation on the Moon: Final Report of the EVA Walkback Test (EWT). Houston: National Aeronautics and Space Administration; 2009. Report No.: NASA/TP–2009–214796.

3. Norcross J, Clowers K, Clark T, Harvill L, Morency R, Stroud L, et al. Metabolic Costs and Biomechanics of Inclined Ambulation and Exploration Tasks in a Planetary Suit. Houston: National Aeronautics and Space Administration; 2010. Report No.: NASA/TP-2010-216125.

4. Jadwick J, Rullman K, Skytland N, Gernhardt M. Influence of center of gravity on human performance. In Proceedings of the Aerospace Medical Association Annual Conference; 2008; Boston.

5. Norcross J, Clowers K, Clark T, Harvill L, Morency R, Stroud L, et al. Metabolic Costs and Biomechanics of Ambulation in a Planetary Suit. Houston: National Aeronautics and Space Administration; 2010.

6. Wu G, Siegler S, Allard P, Kirtley A, Leardini A, Rosenbaum D, et al. ISB Recommendations on Definitions of Joint Coordinate System of Various Joints for the Reporting of Human Joint Motion--Part I: Ankle, Hip, and Spine. Journal of Biomechanics. 2002; 35: p. 543-548.

7. Borg G. Psychophysical bases of perceived exertion. Medicine and Science in Sports and Exercise. 1982; 14(5): p. 377-381.

8. Cortlett E, Bishop R. A technique for assessing postural discomfort. Ergonomics. 1976; 19(2): p. 47-51.

9. National Aeronautics and Space Administration. Human System Integation Requirements. Houston: National Aeronautics and Space Administration; 2009-In Press. Report No.: CxP 70024.

10. Minetti A, Moia C, Roi G, Susta D, Ferretti G. Energy cost of walking and running at extreme uphill and downhill slopes. Journal of Applied Physiology. 2002; 93: p. 1039-1046.

11. Perry J. Gait Analysis: Normal and Pathological Function New York: McGraw-Hill; 1992.

12. Murray M, Drought A, Kory R. Walking patterns of normal men. The Journal of Bone and Joint Surgery American. 1964; 46: p. 335-360.

13. Norcross J, Clowers K, Clark T, Cowley M, Harvill LCS, Stroud L, et al. Effects of Changing Center of Gravity on Shirtsleeve Human Performance in Reduced Gravity. Houston: National Aeronautics and Space Administration; 2010. Report No.: NASA/TM-2010-216127.

14. Clark T, Clowers K, Cowley M, Harvill L. Integrated Suit Test X (C-9) Phase I & II Quick Look Report. Houston: Anthropometry and Biomechanics Facility, NASA Johnson Space Center; 2009.

15. Norcross J, Chappell S, Clowers K, Clark T, Cowley M, Harvill L, et al. Characterization of Partial Gravity Analog Environments for EVA Suit Testing. Houston: National Aeronautics and Space Administration; 2010-In Publication.

6.0 Appendices

6.1 Phase I Equipment Layout

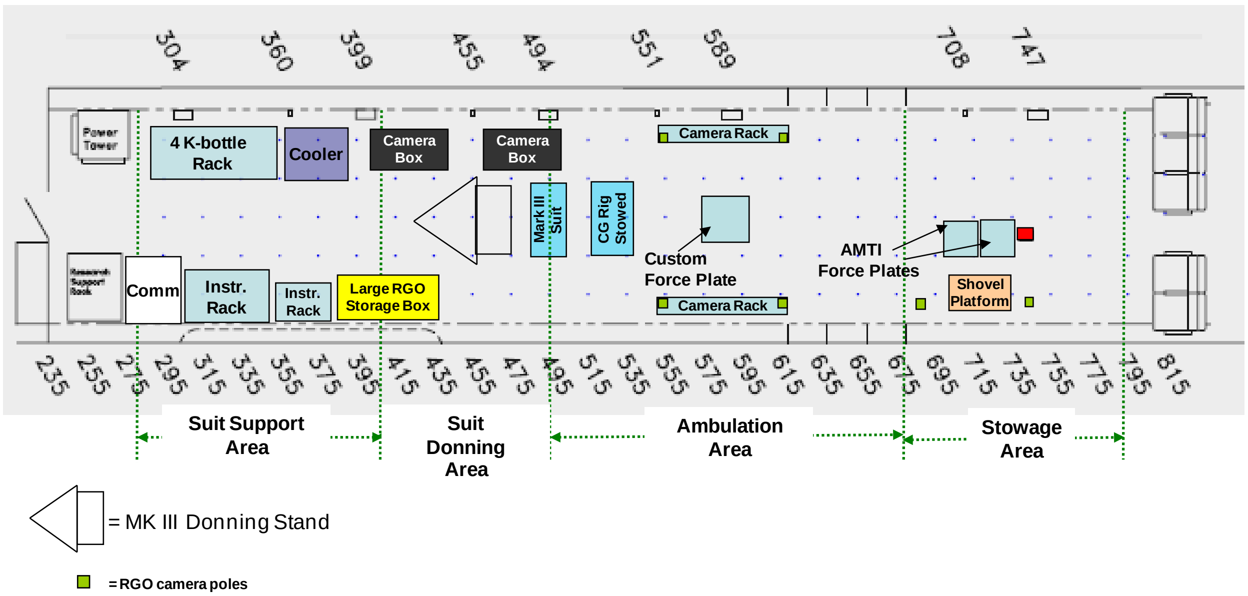

Figure 76 - Phase I equipment layout for takeoff and landing.

6.2 Phase II Equipment Layout

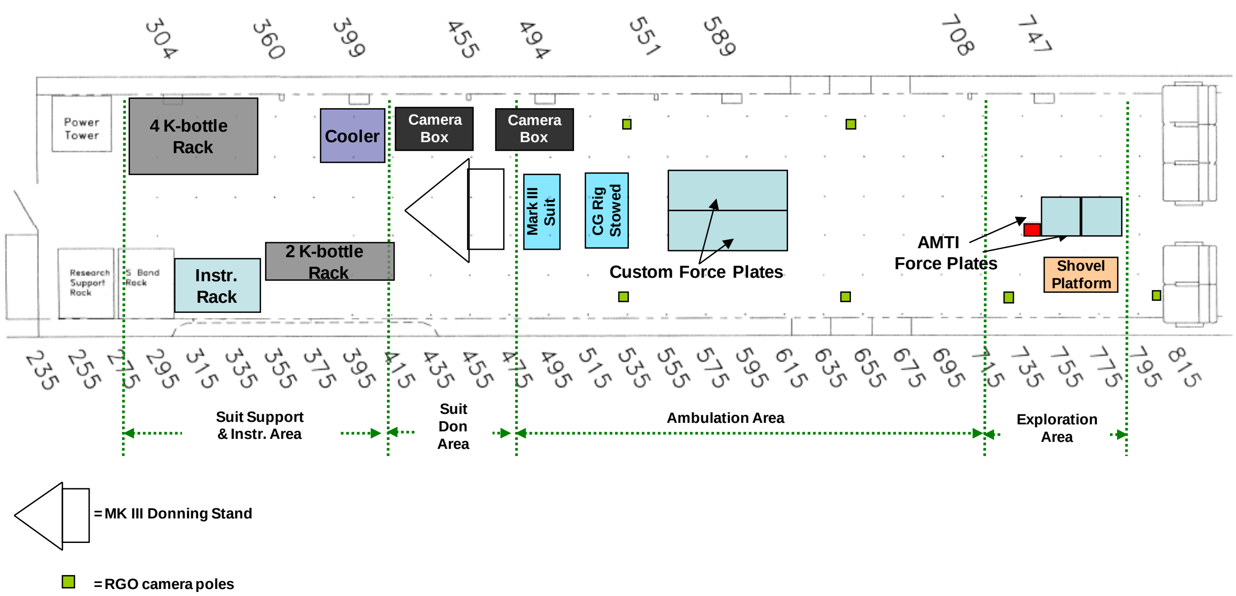

Figure 77 - Phase II equipment layout for takeoff and landing.

6.3 Representative Phase I Parabola Breakdown & Procedures

Planned Parabola #	Actual Parabola #	Gravity	RPE	GCPS	Subject 1 (suited)	Subject 2 (unsuited)	EPSP Tasks	EC Tasks	ABF Tasks	UTAF Tasks
Ascent & Level Flt (~15 min)		Level Flt			- Don LCG - Don MKIII w/ PLSS Mockup & spider plate (pressurized) -Have markers applied to suit	- Have markers applied - Assist w/ remainder of test and crew consensus report	- Setup test config - Unstow shovel & lead shot bags - Check that all equipment is ready for testing - Check that all data takers are ready	- Unstow MKIII, PLSS mockup, laptop and data acquizition - Assist subject in donning suit - Pressurize suit - Make sure waist ring is unlocked	- Configure & calibrate motion capture - Configure & calibrate GRF plates - Apply markers to suited/unsuited subjects	- Prep for data collection - Prepare crew instructions and data sheets
1		1/6-g			**STILL SHOT:** **- Move to center of motion capture area** - Stand as still as possible			- Assist subject from donning stand - Assist sit of subject	- Capture and confirm still shot	
2		1/6-g			**WALK:** - Perform walking task - Return to start point			- Assist stand/sit of subject	- Collect motion capture & GRF	
3		1/6-g			**WALK:** - Perform walking task - Return to start point			- Assist stand/sit of subject	- Collect motion capture & GRF	
4		1/6-g			**WALK:** - Perform walking task - Return to start point			- Assist stand/sit of subject	- Collect motion capture & GRF	
5		1/6-g			**WALK:** **- Perform walking task** **- Return to start point** **- Provide RPE & GCPS**		- Log backup RPE & GCPS	- Assist stand/sit of subject	- Collect motion capture & GRF	- Log RPE & GCPS
6		1/6-g			**KNEEL/RECOVER:** **- Move near rear plates** **- Kneel to one knee** **- Stand back up** **- Do 3-4 times** **- Translate to near donning stand if time allows** **- Provide RPE & GCPS**		- Log backup RPE & GCPS	- Assist stand/sit of subject - Assist subject into donning stand if time allows		- Log GCPS

Planned Parabola #	Actual Parabola #	Gravity	RPE	GCPS	Subject 1 (suited)	Subject 2 (unsuited)	EPSP Tasks	EC Tasks	ABF Tasks	UTAF Tasks
7		1/6-g			**STILL SHOT:** **- Stand on expl. force plates as still as possible**			- Assist stand/sit of subject	- Capture and confirm still shot	
8		1/6-g			**SMALL ROCK PICKUP:** - Pick up small rock, stand up - Set down small rock, stand up - Repeat			- Assist stand/sit of subject	- Collect motion capture & GRF	
9		1/6-g			**SMALL ROCK PICKUP:** **- Move to rear force plates** **- Pick up small rock, stand up** **- Set down small rock, stand up** **- Repeat** **- Provide RPE & GCPS**		- Log backup RPE & GCPS	- Assist stand/sit of subject	- Collect motion capture & GRF	- Log GCPS
10		1/6-g			**SHOVELING:** - Pick up shovel - Scoop rocks into shovel - Dump rocks on side of bin - Repeat - Hand shovel to test team			- Assist stand/sit of subject	- Collect motion capture & GRF	
11		1/6-g			**SHOVELING:** **- Pick up shovel** **- Scoop rocks into shovel** **- Dump rocks on side of bin** **- Repeat** **- Hand shovel to test team** **- Provide RPE & GCPS**		- Log backup RPE & GCPS	- Assist stand/sit of subject	- Collect motion capture & GRF	- Log GCPS - Log discomfort
12		1/6-g			**Suited Subject into Donning Stand**			- Assist subject into donning stand		
Level Flt (5 min)		**Level Flt**			- Position as necessary for attachment of mass rig to suit - Move to walk start		- Unstow mass rig	**- Attach mass rig to MKIII w/ quick disconnect pins**		

Planned Parabola #	Actual Parabola #	Gravity	RPE	GCPS	Subject 1 (suited)	Subject 2 (unsuited)	EPSP Tasks	EC Tasks	ABF Tasks	UTAF Tasks
13		0.1-g			**WALK:** - Perform walking task - Return to start point			- Assist stand/sit of subject	- Collect motion capture & GRF	
14		0.1-g			**WALK:** - Perform walking task - Return to start point			- Assist stand/sit of subject	- Collect motion capture & GRF	
15		0.1-g			**WALK:** - Perform walking task - Return to start point			- Assist stand/sit of subject	- Collect motion capture & GRF	
16		0.1-g			**WALK:** **- Perform walking task** **- Return to start point** **- Provide RPE & GCPS**		- Log backup RPE & GCPS	- Assist stand/sit of subject	- Collect motion capture & GRF	- Log RPE & GCPS
17		0.1-g			**KNEEL/RECOVER:** **- Move near rear plates** **- Kneel to one knee** **- Stand back up** **- Do 3-4 times** **- Provide RPE & GCPS**		- Log backup RPE & GCPS	- Assist stand/sit of subject		- Log GCPS
18		0.1-g			**SMALL ROCK PICKUP:** - Pick up small rock, stand up - Set down small rock, stand up - Repeat			- Assist stand/sit of subject	- Collect motion capture & GRF	
19		0.1-g			**SMALL ROCK PICKUP:** **- Move to rear force plates** **- Pick up small rock, stand up** **- Set down small rock, stand up** **- Repeat** **- Provide RPE & GCPS**		- Log backup RPE & GCPS	- Assist stand/sit of subject	- Collect motion capture & GRF	- Log GCPS

Planned Parabola #	Actual Parabola #	Gravity	RPE	GCPS	Subject 1 (suited)	Subject 2 (unsuited)	EPSP Tasks	EC Tasks	ABF Tasks	UTAF Tasks
20		0.1-g			**SHOVELING:** - Pick up shovel - Scoop rocks into shovel - Dump rocks on side of bin - Repeat - Hand shovel to test team			- Assist stand/sit of subject	- Collect motion capture & GRF	
21		0.1-g			**SHOVELING:** **- Pick up shovel** **- Scoop rocks into shovel** **- Dump rocks on side of bin** **- Repeat** **- Hand shovel to test team** **- Provide RPE & GCPS**		- Log backup RPE & GCPS	- Assist stand/sit of subject	- Collect motion capture & GRF	- Log GCPS - Log discomfort
Switch Gravity Levels					**- Provide discomfort rating**					**- Log discomfort**
22		0.3-g			**SHOVELING:** - Pick up shovel - Scoop rocks into shovel - Dump rocks on side of bin - Repeat - Hand shovel to test team			- Assist stand/sit of subject	- Collect motion capture & GRF	
23		0.3-g			**SHOVELING:** **- Pick up shovel** **- Scoop rocks into shovel** **- Dump rocks on side of bin** **- Repeat** **- Hand shovel to test team** **- Provide RPE & GCPS**		- Log backup RPE & GCPS	- Assist stand/sit of subject	- Collect motion capture & GRF	- Log GCPS - Log discomfort
24		0.3-g			**SMALL ROCK PICKUP:** - Pick up small rock, stand up - Set down small rock, stand up - Repeat			- Assist stand/sit of subject	- Collect motion capture & GRF	

Planned Parabola #	Actual Parabola #	Gravity	RPE	GCPS	Subject 1 (suited)	Subject 2 (unsuited)	EPSP Tasks	EC Tasks	ABF Tasks	UTAF Tasks
25		0.3-g			**SMALL ROCK PICKUP:** **- Move to rear force plates** **- Pick up small rock, stand up** **- Set down small rock, stand up** **- Repeat** **- Provide RPE & GCPS**		- Log backup RPE & GCPS	- Assist stand/sit of subject	- Collect motion capture & GRF	- Log GCPS
26		0.3-g			**KNEEL/RECOVER:** **- Move near donning stand** **- Kneel to one knee** **- Stand back up** **- Do 3-4 times** **- Provide RPE & GCPS**		- Log backup RPE & GCPS	- Assist stand/sit of subject		- Log GCPS
27		0.3-g			**WALK:** - Perform walking task - Return to start point			- Assist stand/sit of subject	- Collect motion capture & GRF	
28		0.3-g			**WALK:** - Perform walking task - Return to start point			- Assist stand/sit of subject	- Collect motion capture & GRF	
29		0.3-g			**WALK:** - Perform walking task - Return to start point			- Assist stand/sit of subject	- Collect motion capture & GRF	
30		0.3-g			**WALK:** **- Perform walking task** **- Return to start point** **- Provide RPE & GCPS**		- Log backup RPE & GCPS	- Assist stand/sit of subject	- Collect motion capture & GRF	- Log RPE & GCPS
Switch Gravity Levels					**- Provide discomfort rating**					**- Log discomfort**

Planned Parabola #	Actual Parabola #	Gravity	RPE	GCPS	Subject 1 (suited)	Subject 2 (unsuited)	EPSP Tasks	EC Tasks	ABF Tasks	UTAF Tasks
31		1/6-g			**WALK:** - Perform walking task - Return to start point			- Assist stand/sit of subject	- Collect motion capture & GRF	
32		1/6-g			**WALK:** - Perform walking task - Return to start point			- Assist stand/sit of subject	- Collect motion capture & GRF	
33		1/6-g			**WALK:** - Perform walking task - Return to start point			- Assist stand/sit of subject	- Collect motion capture & GRF	
34		1/6-g			**WALK:** **- Perform walking task** **- Return to start point** **- Provide RPE & GCPS**		- Log backup RPE & GCPS	- Assist stand/sit of subject	- Collect motion capture & GRF	- Log RPE & GCPS
35		1/6-g			**KNEEL/RECOVER:** **- Move near rear plates** **- Kneel to one knee** **- Stand back up** **- Do 3-4 times** **- Provide RPE & GCPS**		- Log backup RPE & GCPS	- Assist stand/sit of subject		- Log GCPS
36		1/6-g			**SMALL ROCK PICKUP:** - Pick up small rock, stand up - Set down small rock, stand up - Repeat			- Assist stand/sit of subject	- Collect motion capture & GRF	
37		1/6-g			**SMALL ROCK PICKUP:** **- Move to rear force plates** **- Pick up small rock, stand up** **- Set down small rock, stand up** **- Repeat** **- Provide RPE & GCPS**		- Log backup RPE & GCPS	- Assist stand/sit of subject	- Collect motion capture & GRF	- Log GCPS

Planned Parabola #	Actual Parabola #	Gravity	RPE	GCPS	Subject 1 (suited)	Subject 2 (unsuited)	EPSP Tasks	EC Tasks	ABF Tasks	UTAF Tasks
38		1/6-g			**SHOVELING:** - Pick up shovel - Scoop rocks into shovel - Dump rocks on side of bin - Repeat - Hand shovel to test team			- Assist stand/sit of subject	- Collect motion capture & GRF	
39		1/6-g			**SHOVELING:** **- Pick up shovel** **- Scoop rocks into shovel** **- Dump rocks on side of bin** **- Repeat** **- Hand shovel to test team** **- Provide RPE & GCPS**		- Log backup RPE & GCPS	- Assist stand/sit of subject	- Collect motion capture & GRF	- Log GCPS - Log discomfort
Lock Waist & Switch Gravity Levels					**- Provide discomfort rating** - Prepare to perform all the same tasks w/ waist ring locked			**- Lock MKIII waist ring**		**- Log discomfort**
40		1/6-g			**SHOVELING:** - Pick up shovel - Scoop rocks into shovel - Dump rocks on side of bin - Repeat - Hand shovel to test team			- Assist stand/sit of subject	- Collect motion capture & GRF	
41		1/6-g			**SHOVELING:** **- Pick up shovel** **- Scoop rocks into shovel** **- Dump rocks on side of bin** **- Repeat** **- Hand shovel to test team** **- Provide RPE & GCPS**		- Log backup RPE & GCPS	- Assist stand/sit of subject	- Collect motion capture & GRF	- Log GCPS - Log discomfort

Planned Parabola #	Actual Parabola #	Gravity	RPE	GCPS	Subject 1 (suited)	Subject 2 (unsuited)	EPSP Tasks	EC Tasks	ABF Tasks	UTAF Tasks
42		1/6-g			**SMALL ROCK PICKUP:** - Pick up small rock, stand up - Set down small rock, stand up - Repeat			- Assist stand/sit of subject	- Collect motion capture & GRF	
43		1/6-g			**SMALL ROCK PICKUP:** **- Move to rear force plates** **- Pick up small rock, stand up** **- Set down small rock, stand up** **- Repeat** **- Provide GCPS**		- Log backup RPE & GCPS	- Assist stand/sit of subject	- Collect motion capture & GRF	- Log GCPS
44		1/6-g			**KNEEL/RECOVER:** **- Move near donning stand** **- Kneel to one knee** **- Stand back up** **- Do 3-4 times** **- Provide RPE & GCPS**		- Log backup RPE & GCPS	- Assist stand/sit of subject - Assist subject into donning stand if time allows		- Log GCPS
45		1/6-g			**WALK:** - Perform walking task - Return to start point			- Assist stand/sit of subject	- Collect motion capture & GRF	
46		1/6-g			**WALK:** - Perform walking task - Return to start point			- Assist stand/sit of subject	- Collect motion capture & GRF	
47		1/6-g			**WALK:** - Perform walking task - Return to start point			- Assist stand/sit of subject	- Collect motion capture & GRF	

Planned Parabola #	Actual Parabola #	Gravity	RPE	GCPS	Subject 1 (suited)	Subject 2 (unsuited)	EPSP Tasks	EC Tasks	ABF Tasks	UTAF Tasks
48		1/6-g			**WALK:** **- Perform walking task** **- Return to start point** **- Provide RPE & GCPS**		- Log backup RPE & GCPS	- Assist stand/sit of subject	- Collect motion capture & GRF	- Log RPE & GCPS
Start of Unsuit Subject					**- Provide discomfort rating** **- Prepare for test of deployed rig**		**- Remove marker balls from suit**	**- Deploy CG rig arms** **- Remove marker balls from suit**	- Check unsuited subjects readiness **- Remove marker balls from suit**	**- Log suited subject discomfort**
49		1/6-g			- Walk and move around w/ CG rig deployed, assessing differences	**STILL SHOT:** - Move to exploration area - Stand as still as possible			- Capture and confirm still shot	
50		1/6-g			- Walk and move around w/ CG rig deployed, assessing differences	**SHOVELING:** - Pick up shovel - Scoop rocks into shovel - Dump rocks on side of bin - Repeat - Hand shovel to test team			- Collect motion capture & GRF	
51		1/6-g			- Walk and move around w/ CG rig deployed, assessing differences **- Seat near and facing donning stand**	**SHOVELING:** **- Pick up shovel** **- Scoop rocks into shovel** **- Dump rocks on side of bin** **- Repeat** **- Hand shovel to test team** **- Provide RPE & GCPS**	- Log backup RPE & GCPS		- Collect motion capture & GRF	- Log GCPS
52		1/6-g			**Suited Subject into Donning Stand** - Doff suit - Assist w/ remainder of test and crew consensus report	**SMALL ROCK PICKUP:** - Pick up small rock, stand up - Set down small rock, stand up - Repeat	- Remove & stow mass ri	- Assist subject into donning stand - Depressurize and doff suit - Stow MKIII & PLSS mockup	- Collect motion capture & GRF	

Planned Parabola #	Actual Parabola #	Gravity	RPE	GCPS	Subject 1 (suited)	Subject 2 (unsuited)	EPSP Tasks	EC Tasks	ABF Tasks	UTAF Tasks
53		1/6-g				**SMALL ROCK PICKUP:** **- Pick up small rock, stand up** **- Set down small rock, stand up** **- Repeat** **- Provide RPE & GCPS**	- Log backup RPE & GCPS		- Collect motion capture & GRF	- Log GCPS
54		1/6-g				**STILL SHOT:** **- Move to center of motion capture area** - Stand as still as possible			- Capture and confirm still shot	
55		1/6-g				**KNEEL/RECOVER:** **- Move near donning stand** **- Kneel to one knee** **- Stand back up** **- Do 3-4 times** **- Provide RPE & GCPS**	- Log backup RPE & GCPS			- Log GCPS
56		1/6-g				**WALK:** - Perform walking task - Return to start point			- Collect motion capture & GRF	
57		1/6-g				**WALK:** - Perform walking task - Return to start point			- Collect motion capture & GRF	
58		1/6-g				**WALK:** - Perform walking task - Return to start point			- Collect motion capture & GRF	
59		1/6-g				**WALK:** **- Perform walking task** **- Return to start point** **- Provide RPE & GCPS**	- Log backup RPE & GCPS		- Collect motion capture & GRF	- Log RPE & GCPS
Level Flt/ Descent		Level Flt			- Prepare for landing	**- Provide discomfort rating** - Prepare for landing	- Stow shovel & level shot bags - Prepare for landing	- Stow any remaining gear for landing - Prepare for landing	- Remove markers from unsuited subject - Prepare for landing	**- Log discomfort** - Prepare for landing

6.4 Representative Phase II Parabola Breakdown & Procedures

Planned Parabola #	Actual Parabola #	Gravity	RPE	GCPS	CG Cond.	Subject	EPSP Tasks	EC Tasks	ABF Tasks	UTAF Tasks
Ascent & Level Flt (~15 min)		Level Flt			**CG 1 (Back-pack)**	- Don LCG - Don Mk-III w/ PLSS Mockup & spider plate (pressurized) -Have markers applied to suit	- Oversee test config setup - Unstow shovel & lead shot bags - Check that all equipment is ready for testing - Check that all data takers are ready	**- Unstow Mk-III, PLSS mockup, laptop and data acquizition** **- Assist subject in donning suit; pressurize** **- Attach spider** **- Attach mass rig to Mk-III pins** **- Add weights and configure for 1st CG**	- Configure & calibrate motion capture - Configure & calibrate GRF plates - Apply markers to suited/unsuited subjects	- prep for data collection - prepare crew instructions and data sheets
1		1/6-g			CG 1 (Back-pack)	**STILL SHOT:** **- Move to center of motion capture area** - Stand as still as possible		- Assist subject from donning stand - Assist sit of subject	- Capture and confirm still shot	
2		1/6-g			CG 1 (Back-pack)	**WALK:** - Perform walking task - Return to start point		- Assist stand/sit of subject	- Collect motion capture & GRF	
3		1/6-g			CG 1 (Back-pack)	**WALK:** - Perform walking task - Return to start point		- Assist stand/sit of subject	- Collect motion capture & GRF	
4		1/6-g			CG 1 (Back-pack)	**WALK:** - Perform walking task - Return to start point		- Assist stand/sit of subject	- Collect motion capture & GRF	
5		1/6-g			CG 1 (Back-pack)	**WALK:** **- Perform walking task** **- Return to start point** **- Provide RPE & GCPS**	- Log backup RPE & GCPS	- Assist stand/sit of subject	- Collect motion capture & GRF	- Log RPE & GCPS

Planned Parabola #	Actual Parabola #	Gravity	RPE	GCPS	CG Cond.	Subject	EPSP Tasks	EC Tasks	ABF Tasks	UTAF Tasks
6		1/6-g			CG 1 (Back-pack)	**KNEEL/RECOVER:** **- Move near rear plates** **- Kneel to one knee** **- Stand back up** **- Do 2 times** **- Translate to near donning stand if time allows** **- Provide RPE & GCPS (up/dn)**	- Log backup RPE & GCPS	- Assist stand/sit of subject - Assist subject into donning stand if time allows		- Log GCPS
7		1/6-g			CG 1 (Back-pack)	**STILL SHOT:** - **Stand on expl. force plates as still as possible**		- Assist stand/sit of subject	- Capture and confirm still shot	
8		1/6-g			CG 1 (Back-pack)	**SMALL ROCK PICKUP:** - Pick up small rock, stand up - Set down small rock, stand up - Repeat		- Assist stand/sit of subject	- Collect motion capture & GRF	
9		1/6-g			CG 1 (Back-pack)	**SMALL ROCK PICKUP:** **- Move to rear force plates** **- Pick up small rock, stand up** **- Set down small rock, stand up** **- Repeat** **- Provide RPE & GCPS**	- Log backup RPE & GCPS	- Assist stand/sit of subject	- Collect motion capture & GRF	- Log GCPS
10		1/6-g			CG 1 (Back-pack)	**SHOVELING:** - Pick up shovel - Scoop rocks into shovel - Dump rocks on side of bin - Repeat - Hand shovel to test team		- Assist stand/sit of subject	- Collect motion capture & GRF	

Planned Parabola #	Actual Parabola #	Gravity	RPE	GCPS	CG Cond.	Subject	EPSP Tasks	EC Tasks	ABF Tasks	UTAF Tasks
11		1/6-g			CG 1 (Back-pack)	**SHOVELING:** **- Pick up shovel** **- Scoop rocks into shovel** **- Dump rocks on side of bin** **- Repeat** **- Hand shovel to test team** **- Provide RPE & GCPS**	- Log backup RPE & GCPS	- Assist stand/sit of subject	- Collect motion capture & GRF	- Log GCPS - Log discomfort
12		1/6-g			CG 1 (Back-pack)	**Suited Subject into Donning Stand**		- Assist subject into donning stand		
Level Flt (2 min)		**Level Flt**			**CG 3 (POGO)**			**- Attach spider** **- Attach mass rig to Mk-III w/ pins** **- Add weights and**		
13		1/6-g			CG 3 (POGO)	**WALK:** - Perform walking task - Return to start point		- Assist stand/sit of subject	- Collect motion capture & GRF	
14		1/6-g			CG 3 (POGO)	**WALK:** - Perform walking task - Return to start point		- Assist stand/sit of subject	- Collect motion capture & GRF	
15		1/6-g			CG 3 (POGO)	**WALK:** - Perform walking task - Return to start point		- Assist stand/sit of subject	- Collect motion capture & GRF	
16		1/6-g			CG 3 (POGO)	**WALK:** **- Perform walking task** **- Return to start point** **- Provide RPE & GCPS**	- Log backup RPE & GCPS	- Assist stand/sit of subject	- Collect motion capture & GRF	- Log RPE & GCPS
17		1/6-g			CG 3 (POGO)	**KNEEL/RECOVER:** **- Move near rear plates** **- Kneel to one knee** **- Stand back up** **- Do 2 times** **- Provide RPE & GCPS (up/dn)**	- Log backup RPE & GCPS	- Assist stand/sit of subject		- Log GCPS

Planned Parabola #	Actual Parabola #	Gravity	RPE	GCPS	CG Cond.	Subject	EPSP Tasks	EC Tasks	ABF Tasks	UTAF Tasks
18		1/6-g			CG 3 (POGO)	**SMALL ROCK PICKUP:** - Pick up small rock, stand up - Set down small rock, stand up - Repeat		- Assist stand/sit of subject	- Collect motion capture & GRF	
19		1/6-g			CG 3 (POGO)	**SMALL ROCK PICKUP:** **- Move to rear force plates** **- Pick up small rock, stand up** **- Set down small rock, stand up** **- Repeat** **- Provide RPE & GCPS**	- Log backup RPE & GCPS	- Assist stand/sit of subject	- Collect motion capture & GRF	- Log GCPS
20		1/6-g			CG 3 (POGO)	**SHOVELING:** - Pick up shovel - Scoop rocks into shovel - Dump rocks on side of bin - Repeat - Hand shovel to test team		- Assist stand/sit of subject	- Collect motion capture & GRF	
21		1/6-g			CG 3 (POGO)	**SHOVELING:** **- Pick up shovel** **- Scoop rocks into shovel** **- Dump rocks on side of bin** **- Repeat** **- Hand shovel to test team** **- Provide RPE & GCPS**	- Log backup RPE & GCPS	- Assist stand/sit of subject	- Collect motion capture & GRF	- Log GCPS - Log discomfort
22		1/6-g			CG 3 (POGO)	**Suited Subject into Donning Stand**		- Assist subject into donning stand		
Level Flt (2 min)		**Level Flt**			**CG 2 (CTSD)**	**- Provide discomfort rating**		**- Configure for 3rd CG**		**- Log discomfort**
23		1/6-g			CG 2 (CTSD)	**WALK:** - Perform walking task - Return to start point		- Assist stand/sit of subject	- Collect motion capture & GRF	

Planned Parabola #	Actual Parabola #	Gravity	RPE	GCPS	CG Cond.	Subject	EPSP Tasks	EC Tasks	ABF Tasks	UTAF Tasks
24		1/6-g			CG 2 (CTSD)	**WALK:** - Perform walking task - Return to start point		- Assist stand/sit of subject	- Collect motion capture & GRF	
25		1/6-g			CG 2 (CTSD)	**WALK:** - Perform walking task - Return to start point		- Assist stand/sit of subject	- Collect motion capture & GRF	
26		1/6-g			CG 2 (CTSD)	**WALK:** **- Perform walking task** **- Return to start point** **- Provide RPE & GCPS**	- Log backup RPE & GCPS	- Assist stand/sit of subject	- Collect motion capture & GRF	- Log RPE & GCPS
27		1/6-g			CG 2 (CTSD)	**KNEEL/RECOVER:** **- Move near rear plates** **- Kneel to one knee** **- Stand back up** **- Do 2 times** **- Provide RPE & GCPS (up/dn)**	- Log backup RPE & GCPS	- Assist stand/sit of subject		- Log GCPS
28		1/6-g			CG 2 (CTSD)	**SMALL ROCK PICKUP:** - Pick up small rock, stand up - Set down small rock, stand up - Repeat		- Assist stand/sit of subject	- Collect motion capture & GRF	
29		1/6-g			CG 2 (CTSD)	**SMALL ROCK PICKUP:** **- Move to rear force plates** **- Pick up small rock, stand up** **- Set down small rock, stand up** **- Repeat** **- Provide RPE & GCPS**	- Log backup RPE & GCPS	- Assist stand/sit of subject	- Collect motion capture & GRF	- Log GCPS

Planned Parabola #	Actual Parabola #	Gravity	RPE	GCPS	CG Cond.	Subject	EPSP Tasks	EC Tasks	ABF Tasks	UTAF Tasks
30		1/6-g			CG 2 (CTSD)	**SHOVELING:** - Pick up shovel - Scoop rocks into shovel - Dump rocks on side of bin - Repeat - Hand shovel to test team		- Assist stand/sit of subject	- Collect motion capture & GRF	
31		1/6-g			CG 2 (CTSD)	**SHOVELING:** **- Pick up shovel** **- Scoop rocks into shovel** **- Dump rocks on side of bin** **- Repeat** **- Hand shovel to test team** **- Provide RPE & GCPS**	- Log backup RPE & GCPS	- Assist stand/sit of subject	- Collect motion capture & GRF	- Log GCPS - Log discomfort
32		1/6-g			CG 2 (CTSD)	**Suited Subject into Donning Stand**		- Assist subject into donning stand		
Level Flt (2 min)		**Level Flt**			**n/a**	**- Provide discomfort rating** - Prepare to perform make-up tasks w/out the weights		**- Remove weights** **- Arms to stowed pos.**		**- Log discomfort**
33		0.1-g			n/a	**SMALL ROCK PICKUP:** - Pick up small rock, stand up - Set down small rock, stand up - Repeat		- Assist stand/sit of subject	- Collect motion capture & GRF	
34		0.1-g			n/a	**SMALL ROCK PICKUP:** **- Move to rear force plates** **- Pick up small rock, stand up** **- Set down small rock, stand up** **- Repeat** **- Provide GCPS**	- Log backup RPE & GCPS	- Assist stand/sit of subject	- Collect motion capture & GRF	- Log GCPS

Planned Parabola #	Actual Parabola #	Gravity	RPE	GCPS	CG Cond.	Subject	EPSP Tasks	EC Tasks	ABF Tasks	UTAF Tasks
35		0.1-g			n/a	**SHOVELING:** - Pick up shovel - Scoop rocks into shovel - Dump rocks on side of bin - Repeat - Hand shovel to test team		- Assist stand/sit of subject	- Collect motion capture & GRF	
36		0.1-g			n/a	**SHOVELING:** **- Pick up shovel** **- Scoop rocks into shovel** **- Dump rocks on side of bin** **- Repeat** **- Hand shovel to test team** **- Provide RPE & GCPS**	- Log backup RPE & GCPS	- Assist stand/sit of subject	- Collect motion capture & GRF	- Log GCPS - Log discomfort
Switch Gravity Levels					**n/a**	**- Provide discomfort rating**				**- Log discomfort**
37		1/6-g			n/a	**SMALL ROCK PICKUP:** - Pick up small rock, stand up - Set down small rock, stand up - Repeat		- Assist stand/sit of subject	- Collect motion capture & GRF	
38		1/6-g			n/a	**SMALL ROCK PICKUP:** **- Move to rear force plates** **- Pick up small rock, stand up** **- Set down small rock, stand up** **- Repeat** **- Provide GCPS**	- Log backup RPE & GCPS	- Assist stand/sit of subject	- Collect motion capture & GRF	- Log GCPS
39		1/6-g			n/a	**SHOVELING:** - Pick up shovel - Scoop rocks into shovel - Dump rocks on side of bin - Repeat - Hand shovel to test team		- Assist stand/sit of subject	- Collect motion capture & GRF	

Planned Parabola #	Actual Parabola #	Gravity	RPE	GCPS	CG Cond.	Subject	EPSP Tasks	EC Tasks	ABF Tasks	UTAF Tasks
40		1/6-g			n/a	**SHOVELING:** **- Pick up shovel** **- Scoop rocks into shovel** **- Dump rocks on side of bin** **- Repeat** **- Hand shovel to test team** **- Provide RPE & GCPS**	- Log backup RPE & GCPS	- Assist stand/sit of subject	- Collect motion capture & GRF	- Log GCPS - Log discomfort
Switch Gravity Levels					**n/a**	**- Provide discomfort rating**				**- Log discomfort**
41		0.3-g			n/a	**SMALL ROCK PICKUP:** - Pick up small rock, stand up - Set down small rock, stand up - Repeat		- Assist stand/sit of subject	- Collect motion capture & GRF	
42		0.3-g			n/a	**SMALL ROCK PICKUP:** **- Move to rear force plates** **- Pick up small rock, stand up** **- Set down small rock, stand up** **- Repeat** **- Provide GCPS**	- Log backup RPE & GCPS	- Assist stand/sit of subject	- Collect motion capture & GRF	- Log GCPS
43		0.3-g			n/a	**SHOVELING:** - Pick up shovel - Scoop rocks into shovel - Dump rocks on side of bin - Repeat - Hand shovel to test team		- Assist stand/sit of subject	- Collect motion capture & GRF	
44		0.3-g			n/a	**SHOVELING:** **- Pick up shovel** **- Scoop rocks into shovel** **- Dump rocks on side of bin** **- Repeat** **- Hand shovel to test team** **- Provide RPE & GCPS**	- Log backup RPE & GCPS	- Assist stand/sit of subject	- Collect motion capture & GRF	- Log GCPS - Log discomfort

Planned Parabola #	Actual Parabola #	Gravity	RPE	GCPS	CG Cond.	Subject	EPSP Tasks	EC Tasks	ABF Tasks	UTAF Tasks
Lock Waist					**n/a**	**- Provide discomfort rating**		**- Lock waist joint**		**- Log discomfort**
45		1/6-g			n/a	**SMALL ROCK PICKUP:** - Pick up small rock, stand up - Set down small rock, stand up - Repeat		- Assist stand/sit of subject	- Collect motion capture & GRF	
46		1/6-g			n/a	**SMALL ROCK PICKUP:** **- Move to rear force plates** **- Pick up small rock, stand up** **- Set down small rock, stand up** **- Repeat** **- Provide GCPS**	- Log backup RPE & GCPS	- Assist stand/sit of subject	- Collect motion capture & GRF	- Log GCPS
47		1/6-g			n/a	**SHOVELING:** - Pick up shovel - Scoop rocks into shovel - Dump rocks on side of bin - Repeat - Hand shovel to test team		- Assist stand/sit of subject	- Collect motion capture & GRF	
48		1/6-g			n/a	**SHOVELING:** **- Pick up shovel** **- Scoop rocks into shovel** **- Dump rocks on side of bin** **- Repeat** **- Hand shovel to test team** **- Provide RPE & GCPS**	- Log backup RPE & GCPS	- Assist stand/sit of subject	- Collect motion capture & GRF	- Log GCPS - Log discomfort
49		1/6-g			n/a	**Subject into Donning Stand**		- Assist subject into donning stand		
Level Flt (2 min) **Start of Unsuit**		**Level Flt**			**n/a**	**- Provide discomfort rating** - Prepare to perform unsuited tasks		**- Remove rig & stow** **- Depress and doff suit**	**- Assist subject in putting on markered shoes**	**- Log discomfort**

Planned Parabola #	Actual Parabola #	Gravity	RPE	GCPS	CG Cond.	Subject	EPSP Tasks	EC Tasks	ABF Tasks	UTAF Tasks
50		1/6-g			n/a	STILL SHOT: - Move to exploration area - Stand as still as possible		**- Stow Mk-III**	- Capture and confirm still shot	
51		1/6-g			n/a	SMALL ROCK PICKUP: - Pick up small rock, stand up - Set down small rock, stand up - Repeat			- Collect motion capture & GRF	
52		1/6-g			n/a	**SMALL ROCK PICKUP:** **- Pick up small rock, stand up** **- Set down small rock, stand up** **- Repeat** **- Provide RPE & GCPS**	- Log backup RPE & GCPS		- Collect motion capture & GRF	- Log GCPS
53		1/6-g			n/a	SHOVELING: - Pick up shovel - Scoop rocks into shovel - Dump rocks on side of bin - Repeat - Hand shovel to test team			- Collect motion capture & GRF	
54		1/6-g			n/a	**SHOVELING:** **- Pick up shovel** **- Scoop rocks into shovel** **- Dump rocks on side of bin** **- Repeat** **- Hand shovel to test team** **- Provide RPE & GCPS**	- Log backup RPE & GCPS		- Collect motion capture & GRF	- Log GCPS
Level Flt/ Descent		**Level Flt**			**n/a**	**- Provide discomfort rating** - Prepare for landing	- Stow shovel & level shot bags - Prepare for landing	- Stow any remaining gear for landing - Prepare for landing	- Stow any remaining gear for landing - Prepare for landing	**- Log discomfort** - Prepare for landing

6.5 Biomechanics Definitions and Reference Frames

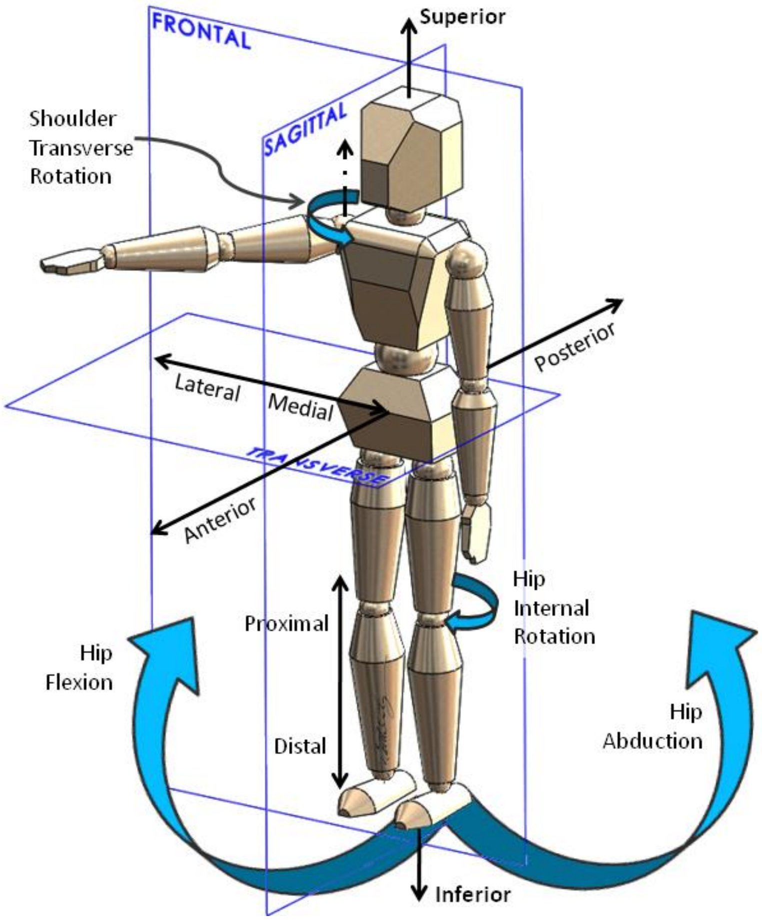

Figure 78 - Commonly used biomechanics nomenclature of the body planes, the types of joint motion, positive rotation directions, and the body-based directions.

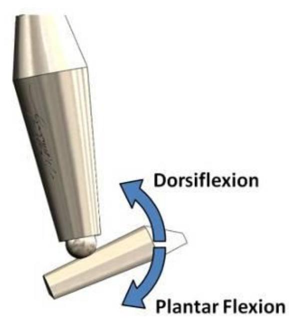

Figure 79 - Designations for the ankle joint directional rotations.

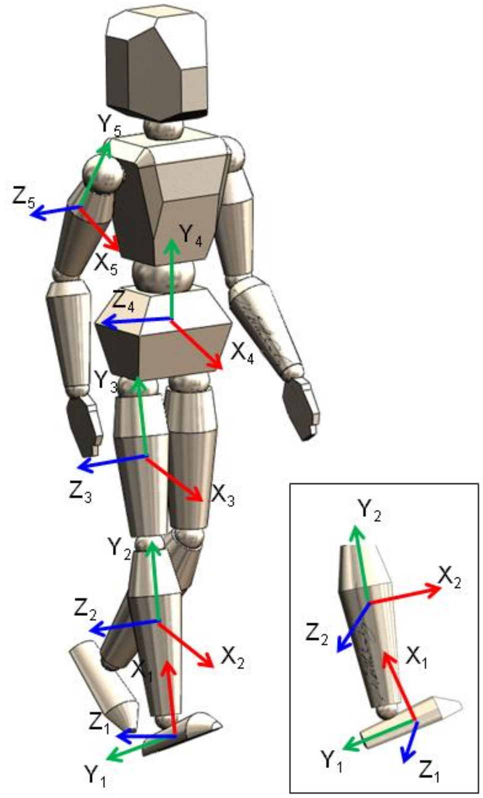

Figure 80 - Convention for local reference frames as prescribed by the International Society of Biomechanics and used by the ABF.

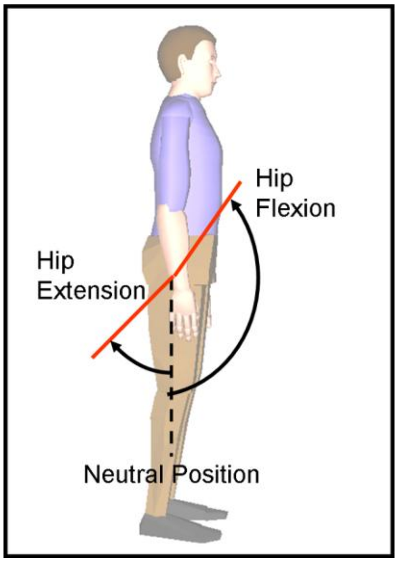

Figure 81 - Flexion is defined as the decrease in the relative angle between two segments. Flexion/dorsiflexion of a joint will always be a positive rotation in this report.

6.6 Phase I & II Subject Population Comparison to HSIR

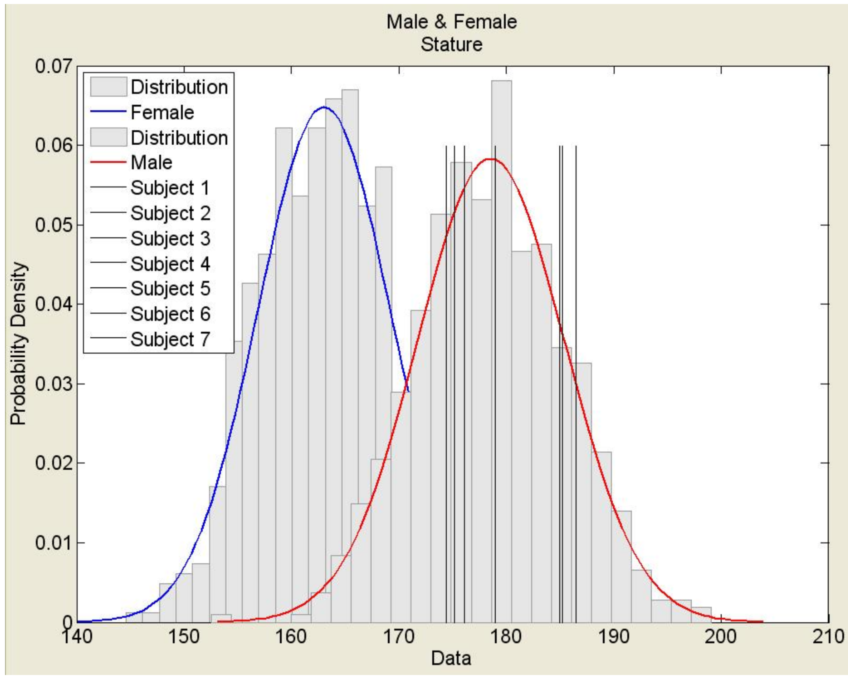

Figure 82 - Distribution of stature (cm) of the phase I & II subject population and the population in the HSIR database. HSIR, Human System Integration Requirements.

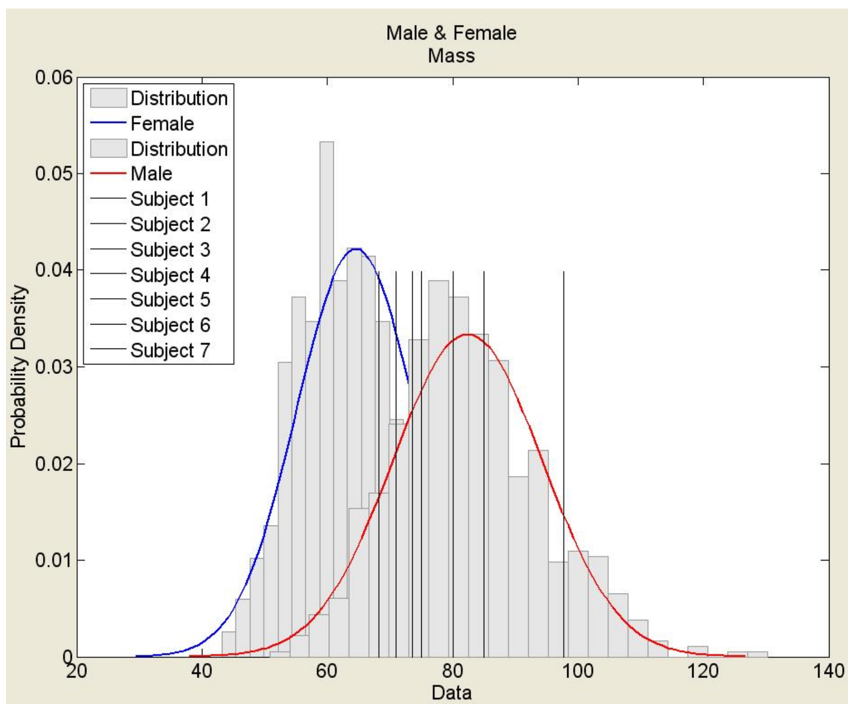

Figure 83 - Distribution of the mass (kg) of the phase I & II subject population and the population in the HSIR database. HSIR, Human System Integration Requirements.

6.7 Rating Scales for Subjective Measures

Table 7 - Gravity Compensation and Performance Scale

1	**Excellent** – easier than 1g
2	**Good** – equivalent to 1g
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

Table 8 - Borg Rating of Perceived Exertion Scale (RPE)

6	No exertion at all
7	Extremely light
8	
9	Very light
10	
11	Light
12	
13	Somewhat hard
14	
15	Hard (heavy)
16	
17	Very hard
18	
19	Extremely hard
20	Maximal exertion

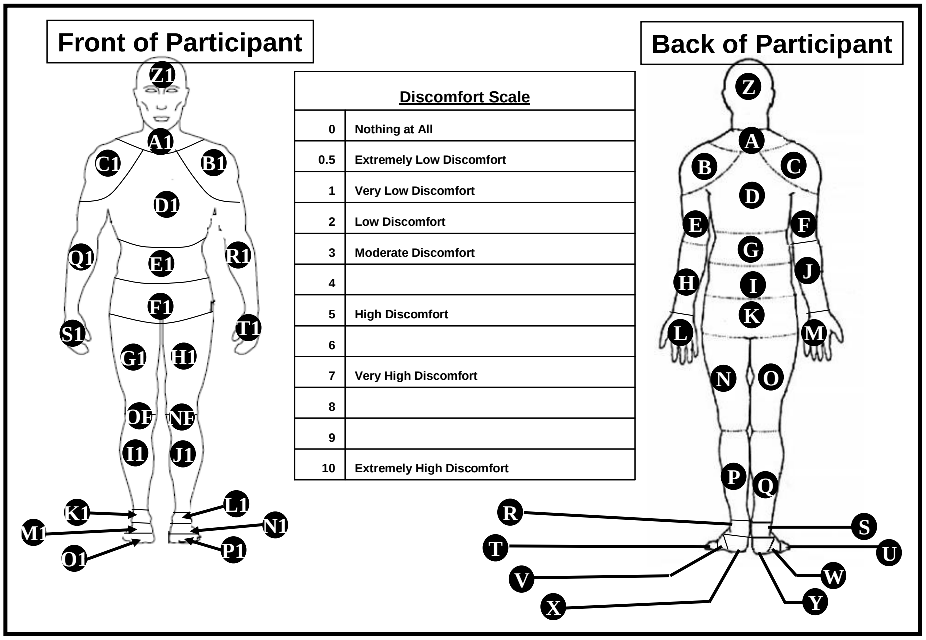

Figure 84 - Corlett & Bishop Discomfort Scale

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13. ABSTRACT *(Maximum 200 words)*

This test was a continuation of the testing series, sponsored by the Constellation Program (CxP) EVA Systems Project Office (ESPO), that is being conducted to enable development of optimized design requirements for the next-generation lunar extravehicular activity (EVA) suit. The test series is a collaborative effort of the Crew and Thermal Systems Division (CTSD), the EVA Physiology, Systems, and Performance Project (EPSP), the Anthropometry and Biomechanics Facility (ABF), and the Usability Testing and Analysis Facility (UTAF). The investigators aim to understand human performance and suit kinematics under a variety of simulated lunar EVA conditions produced by a parabolic flight aircraft. The ways in which suit kinematics, weight, mass, center of gravity (CG), and pressure affect human performance during EVA-relevant tasks are being systematically evaluated. Investigators are developing a parametric understanding of the interrelationships between suit weight, mass, pressure, CG, and crew anthropometrics and performance, while defining the limitations and correction factors associated with each environment.
This test was designed to provide data to compare with earlier human performance testing on the Space Vehicle Mockup Center's Partial Gravity Simulator (POGO) and to provide guidance for the design of other reduced-gravity simulator projects such as ARGOS (Active Response Gravity Offload System). The test was also designed to conduct new research into the effects of varied CG and varied mass on suited human performance. The results will provide insights that may drive CxP requirement definitions and suit designs that are optimized for the anthropometric range of crewmembers and for the targeted operational environment.

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