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Characterization of Partial-Gravity Analog Environments for Extravehicular Activity Suit Testing

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National Aeronautics and
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Acronyms

AP	anterior-posterior
BOS	base of support
BW	body weight
CAD	computer-aided design
CG	center of gravity
COM	center of mass
COP	center of pressure
DOF	degree of freedom
EC	end contact
EVA	extravehicular activity
GCPS	gravity compensation and performance scale
GRF	ground reaction force
HUT	hard upper torso
IC	initial contact
IST	integrated suit test
JSC	Johnson Space Center
MKIII	Mark III spacesuit technology demonstrator
ML	medial-lateral
PLSS	Portable Life Support System
POGO	partial gravity simulator
RGO	Reduced Gravity Office
SI	superior-inferior
SVMF	Space Vehicle Mockup Facility
WL	waist (joint) locked

1 Executive Summary

The primary emphasis of this report is to characterize the partial-gravity analog environments used during the integrated suit tests (ISTs) conducted between 2006 and 2009. The report will focus on how subjects performed in the two testing environments, how the test environment characteristics compared with each other, how the strengths and weaknesses associated with each environment affected the quality of the partial-gravity simulation for human performance testing, and general lessons learned on the usability and features of each environment. The primary partial-gravity analog environments discussed will be the Space Vehicle Mockup Facility's partial gravity simulator (POGO) and the Reduced Gravity Office's C-9 parabolic-flight aircraft.

POGO uses a vertically oriented, manually adjusted, servo-controlled pneumatic cylinder to create a selectable offload of a subject and allows for up to 2.4 m of vertical travel. The POGO servo system rides passively on an air-bearing track that allows for a limited amount (11.6 m) of horizontal translation along a single axis.

The C-9 aircraft can achieve lunar-gravity levels for about 25 sec during a parabolic flight pattern, and each flight typically consists of 40 to 60 parabolas total. After spacesuit and test support equipment was added to the airplane, a distance of 8 m was available on the floor of the aircraft to provide a limited area in which to complete both ambulation (~6 m) and exploration tasks (~2 m), although only 4 to 5 m of this distance was usable for ambulation because of the buffer zone needed to slow down and turn around. The height of the aircraft (2.03 m) allows a test subject to stand fully but prevents most vertical travel, and the width (2.64 m) of the aircraft allows only limited activity in that axis.

The POGO environment is without time constraints and allows for steady-state gait patterns, metered ambulation speeds, and virtually unlimited data-collection capability including full kinematic analysis and real-time metabolic rate for suited and shirtsleeve conditions. However, per the conclusions of previous ISTs, the POGO test environment seems to provide artificial stability that may allow subjects (both suited and shirtsleeve) to use less stable but more energy-efficient gait patterns. POGO also offloads the human/suit/gimbal system only at a fixed point and thus does not promote complete partial-gravity kinematics, as the limbs and other parts of the system are still at 1-g. Finally, the interaction between the offloading forces and the human subject is not yet fully understood.

The C-9 environment allows unrestrained movement in all 6 degrees of freedom (DOF) and provides a true lunar-gravity kinetic environment with all aspects of subject and suit offloaded to the same partial-gravity level. Although this may help subjects choose more realistic strategies for lunar extravehicular activity tasks and ambulation, the C-9 has volumetric restrictions that can negatively influence ambulation biomechanics (low ceiling, short walkway), task performance (low curved ceiling), and data collection capability (width of airplane does not allow full body kinematic analysis). The C-9 test environment also may contribute destabilizing effects because the acceleration provided during parabolas is variable. Finally, the C-9 environment limits the amount and type of data collection possible due to the limited continuous time of partial gravity and the high cost per unit time of testing.

A ground-based, partial-gravity analog such as POGO offers significant advantages in terms of time and cost, but offload accuracy, incomplete partial-gravity kinetics, reduced DOF, and gimbal inertia considerations limit the quality of the data. In addition, one of the original objectives of the IST series was to test the effects of mass and center of gravity on suited human performance (1). However, due to limitations on lift capacity, this test could not be performed on POGO. These factors led to the design of IST-X both to collect data that could not be collected on POGO and to compare human performance of similar tasks across both the C-9 and POGO. Some of the qualitative comparison data indicate that human performance was similar across the different environments at lunar gravity, but there was significant variability in the data as well as some important differences between how the tasks were performed on the POGO and C-9.

Given the current body of knowledge, we believe that a ground-based, partial-gravity analog that has the advantages of POGO but that also improves many of POGO's limitations would offer the best primary test bed to characterize suited human performance. Parabolic flight would then be used both for specific tests and for limited verification of the ground-based simulator.

2 Introduction

Simulating partial gravity on Earth is difficult. While many methods exist, all have significant limitations. The overarching goal of the integrated suit test (IST) series is to evaluate suited human performance in reduced gravity. To effectively complete this goal, partial-gravity analog environments would ideally need to allow unrestrained freedom of movement in all 6 degrees of freedom (DOF) while accurately simulating partial-gravity kinetics. The primary emphasis of this report is to highlight the strengths and limitations of the current partial-gravity analog environments and provide recommendations for improved simulators. Two different partial-gravity simulations were primarily used in previous studies to characterize suited human performance: 1) the Johnson Space Center (JSC) Space Vehicle Mockup Facility's (SVMF's) partial gravity simulator (POGO) and 2) JSC Reduced Gravity Office's (RGO's) C-9 parabolic flight aircraft. This report will begin with a general characterization of each environment, then will use direct comparisons to evaluate human performance metrics collected in both partial-gravity environments from subjects doing similar tasks. Next, the report will highlight indirect comparisons, which look at how human performance during partial-gravity simulation differs from expectations based on physics, models, or results from other studies. Finally, the report will close with considerations regarding the usability of each partial-gravity analog environment and suggestions for improved simulations.

3 Methods

3.1 Hardware

Full descriptions of all hardware items used are available in each of the individual study reports (2) (3) (4) (5) (1) cited at the end of this document. This report will highlight key pieces of hardware relevant to the characterization of partial-gravity analogs for clarity's sake.

3.1.1 Partial gravity simulator (POGO)

The SVMF's POGO was used to provide simulated partial-gravity conditions during IST-1 and IST-2 (Figure 3-1). POGO uses a vertically oriented, manually operated, servo-controlled pneumatic cylinder to create a constant offload of a subject. The servo system consists of the vertical servo assembly, a strain gauge, a pneumatic cylinder assembly, and a piston rod assembly. The simulator rides along a linear air-bearing rail, further allowing constant gravitational offloading in one horizontal plane (either fore/aft or left/right depending on the subject's orientation) for a distance of about 11.6 m. Further details of the POGO system are described in NASA/TP-2009-214796, the EVA Walkback Final Report (2). A gimbal support structure attached to the end of the lifting actuator supports a suited subject and provides the pitch, roll, and yaw rotational DOF during movement.

Figure 3-1. POGO support structure (left) and overhead lift column (right).

3.1.2 Mark III prototype suit

The Mark III spacesuit technology demonstrator (MKIII) was used for suited testing on both POGO and the C-9 as it represents a suit concept that provides dynamic ranges of motion considered necessary for a wide variety of planetary extravehicular activity (EVA) tasks. The MKIII also had an existing interface with POGO (Figure 3-2). This suit configuration had an attached umbilical in place of a Portable Life Support System (PLSS) during testing to provide breathing air and pressurization.

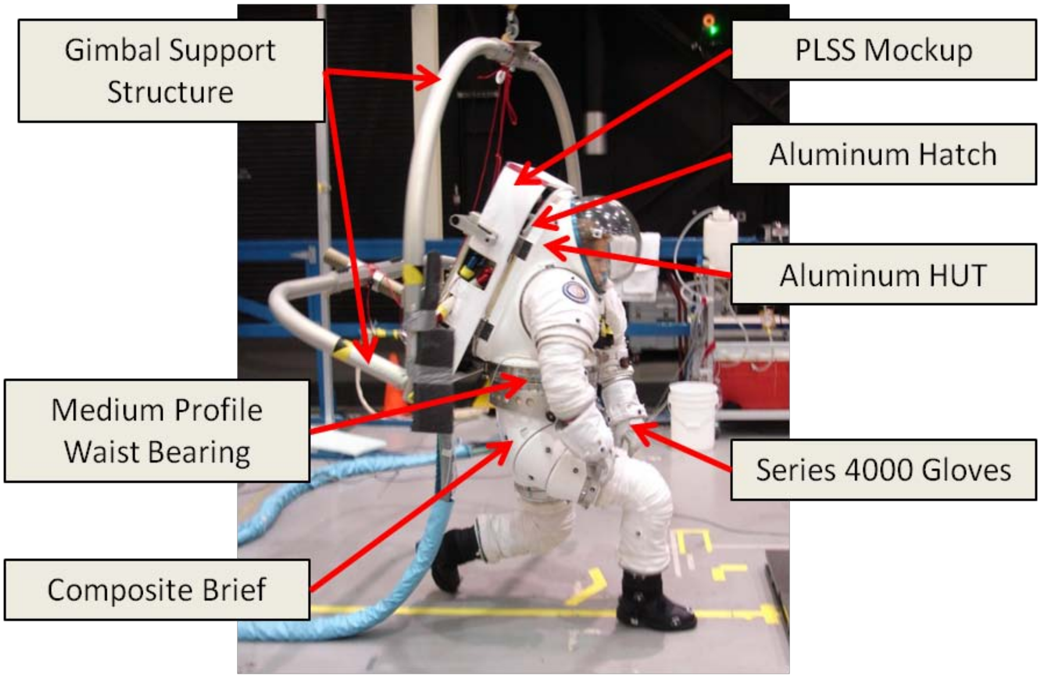

Figure 3-2. The Mark III advanced spacesuit technology demonstrator attached to the POGO gimbal.

Different hard components and soft-good materials can be used in the MKIII to achieve different test objectives and to accommodate subjects of different sizes. The MKIII configuration that was tested and compared across different partial-gravity analogs had the following components: PLSS mockup, aluminum rear-entry hatch, aluminum hard upper torso (HUT), composite brief, and medium profile waist bearing. On POGO, the gloves used during ambulation trials were the series 4000. Phase VI gloves were used during exploration tasks. Phase VI gloves were also used on the C-9.

The MKIII in the POGO configuration had a total mass of 121 kg including the suit, PLSS mockup, and gimbal support structure. The MKIII had a total mass of 120 kg in the C-9 including the suit, PLSS mockup, and center of gravity (CG)/mass rig support structure (without added weights). The suit was pressurized to 29.6 kPa (4.3 psi) above ambient in both environments.

3.1.3 Gimbal support structure

A custom gimbal support structure attached to the end of the piston on the POGO supported suited subjects and provided pitch, roll, and yaw rotational DOF during movement. Figure 3-3 shows a computer-aided design (CAD) drawing of the gimbal, which weighs about 40 kg (90 lb).

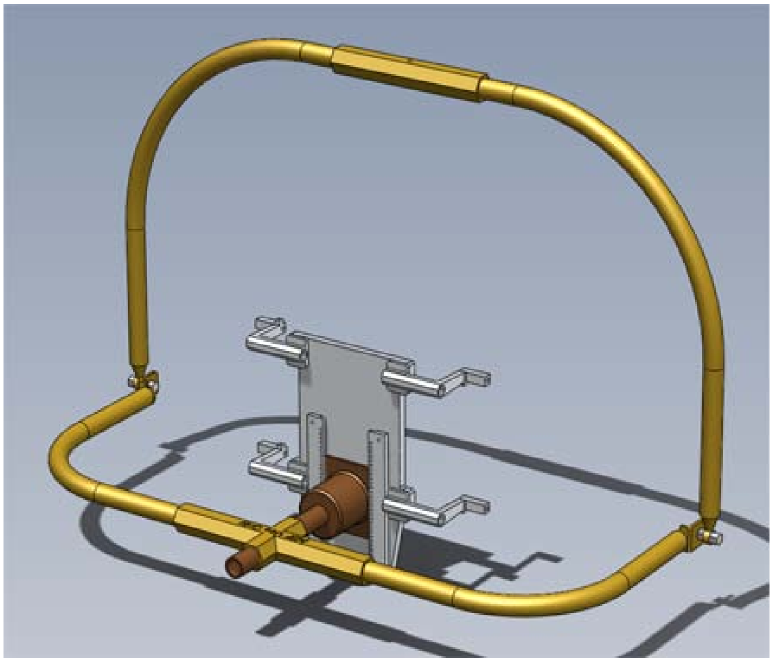

Figure 3-3. The POGO gimbal, which allows subjects to rotate about the three cardinal axes.

The gimbal attached to the suit by means of a system consisting of a "spider/stinger" combination that allowed adjustment of the fore/aft (stinger) and up/down (spider) positioning of the suited subject in relation to the gimbal axes of rotation. The spider attached to the PLSS mockup of the MKIII suit, thus allowing the POGO to partially lift (offload) the subject as shown in Figure 3-4 and simulating a reduced-gravity condition. Spider and stinger settings were adjusted until subject and test evaluators subjectively determined that the total system CG positioning allowed the subject to move and ambulate as freely as possible without pushing the subject forward or pulling the subject backward.

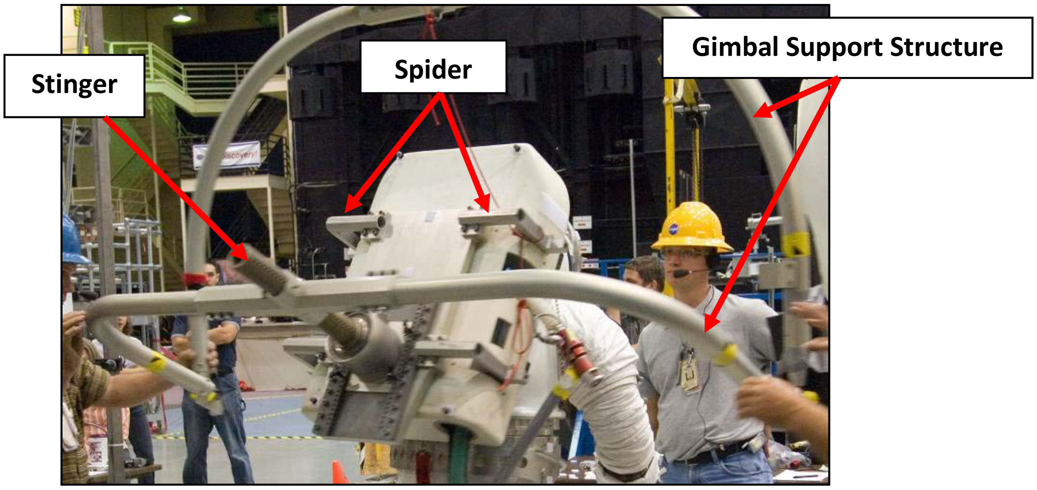

Figure 3-4. Gimbal support structure with spider and stinger attachment to MKIII suit.

In an attempt to understand how wearing a spacesuit may affect certain aspects of human performance, all tests in the IST series included unsuited testing in 1-g and partial gravity to allow for comparison of human performance data in both conditions. During unsuited testing at partial gravity, a single-axis spreader bar and harness assembly provided support to the suspended subjects (Figure 3-5) for several studies. Details on the harness assembly can be found in the individual test reports (2) (3) (4). In another study, the suited gimbal structure was modified to work with unsuited subjects (5).

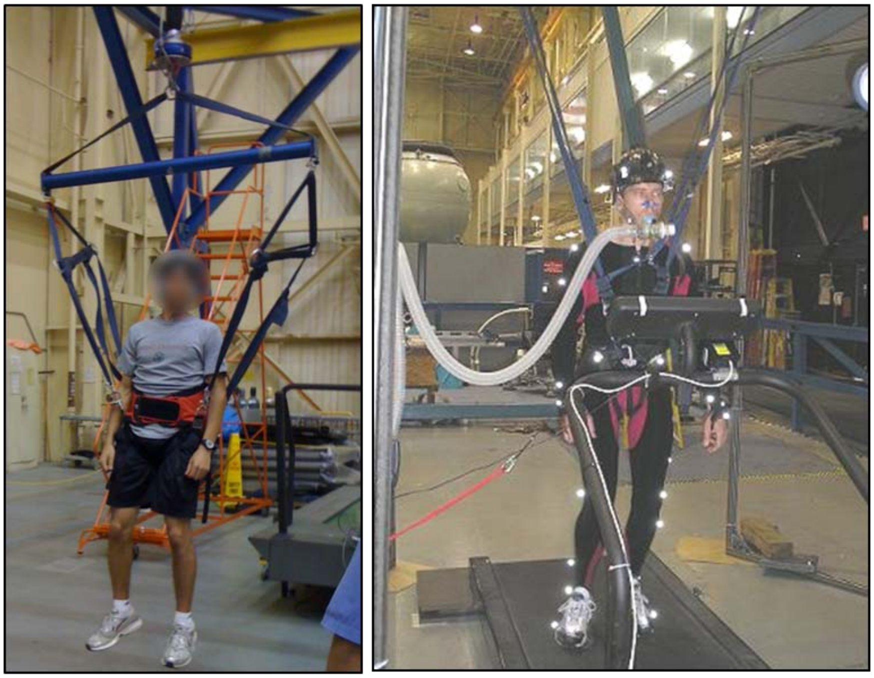

Figure 3-5. Example of spreader bar and harness assembly used for unsuited testing on POGO.

3.1.4 F-200iB Stewart Platform robot

An F-200*i*B Stewart Platform robot (FANUC, Japan) is shown in Figure 3-6. It is capable of translational motions along X, Y, and Z axes and was used during POGO characterization testing. The robot motions are limited in distance (~0.4 m) and velocity (~0.3 m•s^{-1}). Only the Z-axis translation was used during the characterization effort. A control box separate from the robot was used to control its motion.

Figure 3-6. The F-200*i*B Stewart Platform robot.

3.1.5 Reduced-gravity aircraft (C-9)

The RGO, operated by 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 Earth's orbit. This environment is ideal for testing and evaluating prototype space hardware and experimental procedures as well as for research to understand human performance in reduced gravity. A specially modified C-9 turbojet, flying parabolic arcs, produces periodic episodes of reduced gravity lasting up to 25 sec (Figure 3-7).

Figure 3-7. C-9 aircraft during parabolic maneuver.

Excluding the C-9 flight crew and the RGO test directors, the NASA C-9 aircraft has seating to accommodate 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 lightning (6). An area between 4 and 5 m long was cleared to provide a small ambulation runway (Figure 3-8). Ambulation on the C-9 does not require attachment to any equipment to provide simulated reduced gravity.

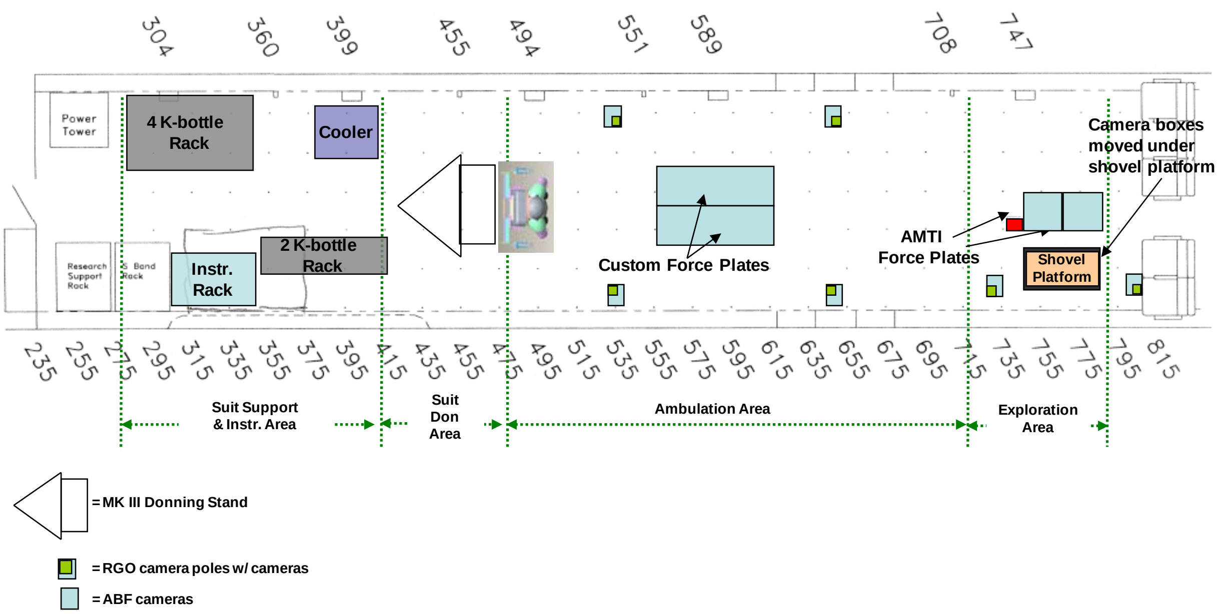

Figure 3-8. Internal layout of the C-9 airplane testing area during flight.

3.1.6 Center of gravity/mass support rig (C-9)

To enable the mass and CG of suited subjects to be changed during parabolic flight testing, a custom CG/mass support rig was designed and attached to the MKIII suit PLSS mockup during portions of the parabolic flight study. The structure was reconfigurable in that weights could be moved to different locations to achieve a desired suit mass and/or CG. Figure 3-9 shows the CG/mass support rig attached to the MKIII suit during a kneel-and-recover task. The mass of the CG/mass support rig was about 29.5 kg (65 lb) and each weight set (one on each support structure arm) was 30.6 kg (67.5 lb).

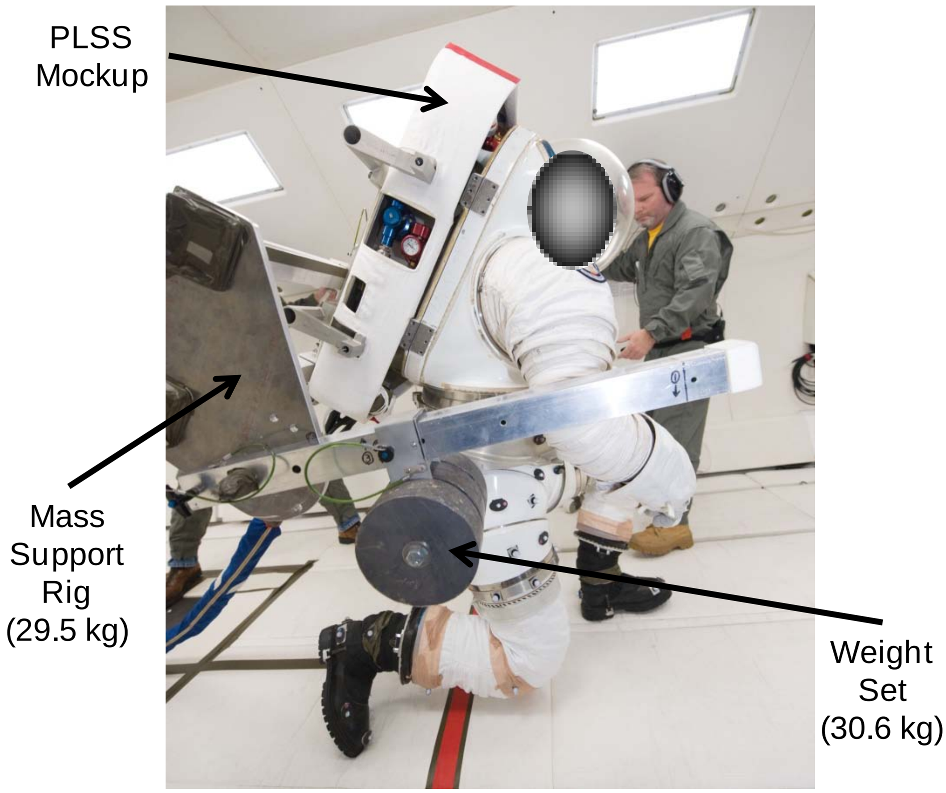

Figure 3-9. CG/mass support rig attached to the MKIII.

3.2 Test Protocols

The test protocols, described below, come from several different studies. The key elements of each of these protocols is described for this report. Table 3-1 provides a quick reference to the original study name and test report reference for these test protocols. It should also be noted that all suited POGO testing was conducted first and then subsections of those protocols were performed, to the best of our ability, later on the C-9.

Table 3-1. Study name and reference for test protocols described in this report

Test Protocol	Partial-gravity Analog Environment	Common/Short Name of Test	Reference
Nonhuman testing of environments	POGO	-	This report
	C-9	IST-X	(1)
Level ambulation	POGO	EWT, IST-1	(2) (3)
	C-9	IST-X	(1)
Incline ambulation	POGO	IST-2, IST-3	(4) (5)
	C-9	Not possible due to low height of ceiling	
Exploration tasks	POGO	IST-2	(4)
	C-9	IST-X	(1)

3.2.1 Nonhuman testing of the environments

Before doing human testing in a partial-gravity analog environment, we needed to characterize the overall accuracy and variability of the partial-gravity simulation. Data were collected on both the POGO and the C-9 to improve our basic understanding of both testing environments. Acceleration profiles for all of the C-9 parabolas were recorded by accelerometers attached to the floor of the airplane, and a subset (219) of the lunar gravity parabolas was analyzed to determine the variability of the perceived gravity effects.

Vertical displacement of the POGO system was recorded to determine its ability to achieve its desired goal of a perfect response and constant offload. The F-200*i*B Stewart Platform robot was used to mimic the vertical displacement of the human center of mass (COM) during walking at a moderate pace. POGO was attached to 68 kg (150 lb) of static weights, an amount similar to the body mass of a subject, and then the weights were offloaded to lunar gravity. The static weights rested uncoupled on the robot platform and then the robot was programmed to mimic the vertical motion of human walking.

3.2.2 Ambulation

3.2.2.1 Level Ambulation

The ambulation compared for the POGO and C-9 environments was performed on a level surface. Ambulation on the POGO was performed on a treadmill at prescribed speeds based on each subject's preferred walk-to-run transition speed (3). The time at each speed was 3 min.

Ambulation on the C-9 consisted of walking over ground on the deck of the aircraft to a clearly marked line, turning around, and walking back to the starting point (1). As was the case for all tasks, at the start of the parabola the suited subject was helped into the standing position and, before the end of the parabola, was helped into a seated position. Although the ambulation walkway was about 5 m (13 ft) long, because of volume constraints in turning around the length of walkway used was only about 3 to 4 m (~ 10 to 13 ft). Four trials of ambulation were performed under each test condition, with each trial lasting for the 15 to 20 sec of lunar gravity experienced in each parabola. Figure 3-10 shows some of the ambulation differences between environments.

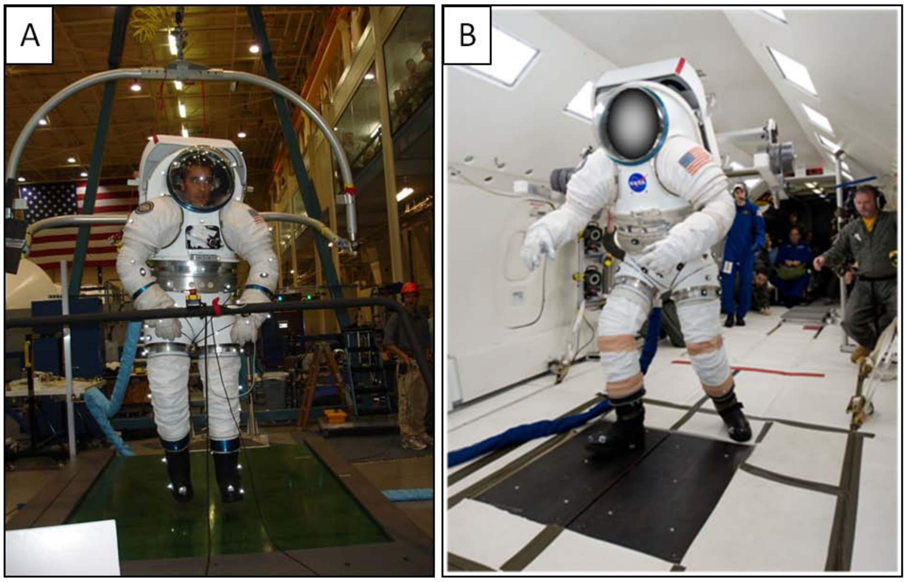

Figure 3-10. POGO ambulation on the treadmill (A) and C-9 ambulation over ground (B).

3.2.2.2 Inclined Ambulation

Inclined ambulation was performed, in both suited and unsuited conditions, only on the POGO (see Figure 3-11). Depending on the test, the grades tested were -10%, 10%, 15%, 20%, and 30% or a subset of these. All inclined ambulation was performed on a treadmill at a walking speed for a duration of 3 min per grade (4) (5). Because of height constraints, inclined ambulation was not performed on the C-9.

Figure 3-11. Suited subject performing inclined ambulation while on POGO.

3.2.3 Exploration tasks

Exploration tasks performed in both test environments were kneel and recover, rock pickup, and shoveling. The subject completed additional exploration tasks on POGO, not discussed in this report. Subjects were first instructed on proper form for each environment. On POGO, subjects completed a circuit of all the different tasks at each condition, but this was not the case with the C-9 (4). At the start of each parabola on the C-9, the suited subject was helped into the standing position. The subject would then execute the task and, before the end of the parabola, was helped into a seated position.

3.2.3.1 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 to the ground (Figure 3-12), and standing back up on both feet.

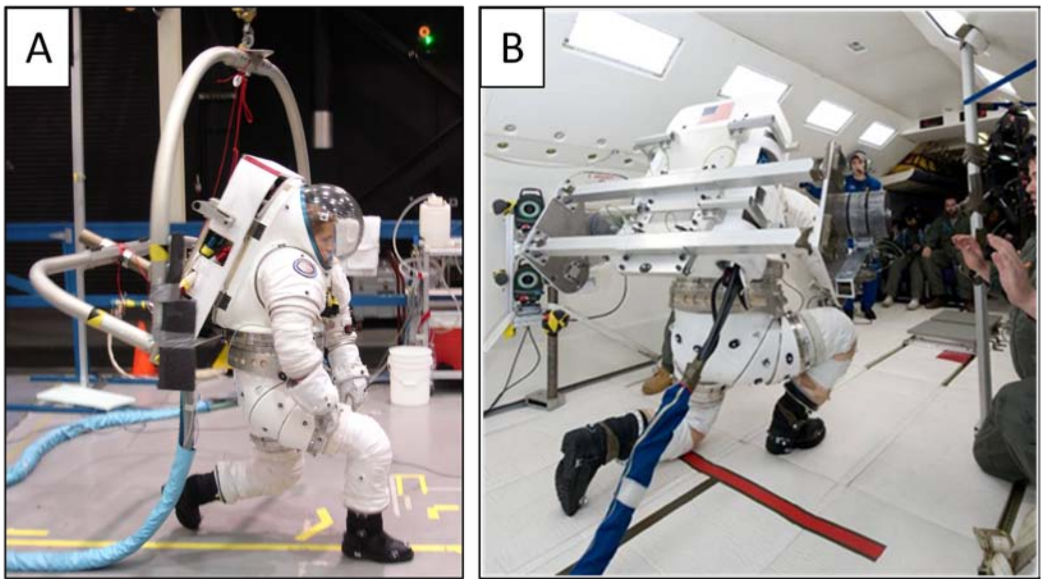

Figure 3-12. Suited subject performing kneel-and-recover task.

3.2.3.2 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. The subject flexed at the hips and knees to pick up either a lead weight (1 and 5.5 kg on POGO) or a lead-shot bag (2.7 kg on C-9), returned to a standing position, and then bent to set the “rock” back down (Figure 13). The heights of the “rocks” were set to be similar in relation to the subject’s feet in both environments, with the height on the POGO at 50 cm and the height in the C-9 at 40 cm. This task was performed three times on POGO. It was repeated at least twice on the C-9 during each parabola, whenever possible, and the task was performed during two parabolas per condition.

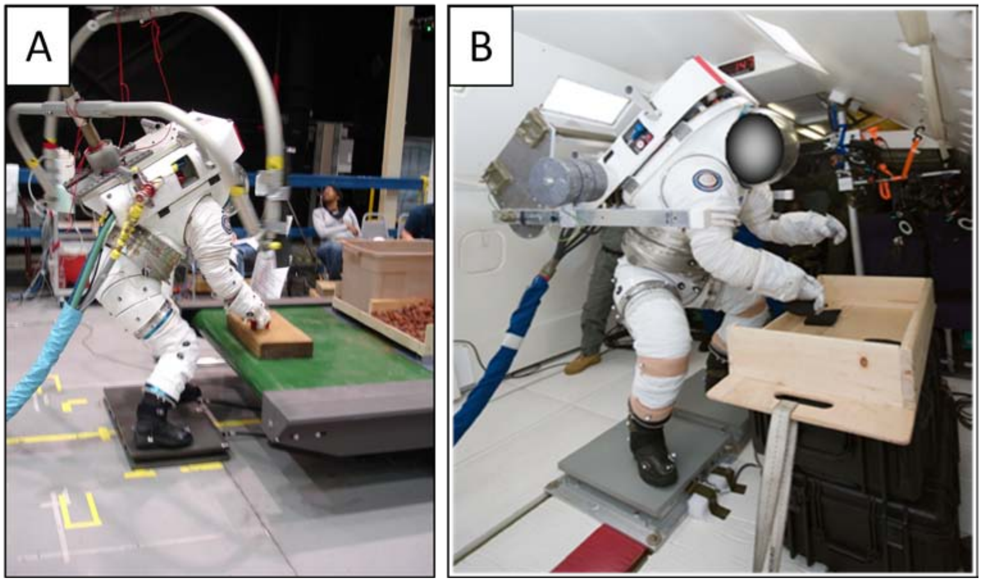

Figure 3-13. Suited subject performing rock pickup task.

3.2.3.3 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 each environment, test support personnel would hand the shovel to the test subject. The subject then scooped either a shovelful of red lava rocks (POGO) or a lead-shot bag (C-9) from the right side of the shovel platform into the shovel (Figure 3-14) and dumped it into the container on the left side (POGO) or onto the left side of the shovel platform (C-9). The heights of the shovel platforms (40 cm in both locations) were set to be the similar in relation to the subject's feet in both environments. This task was performed on POGO three times. It was repeated on the C-9 at least twice during each parabola, whenever possible, and was performed during two parabolas per condition.

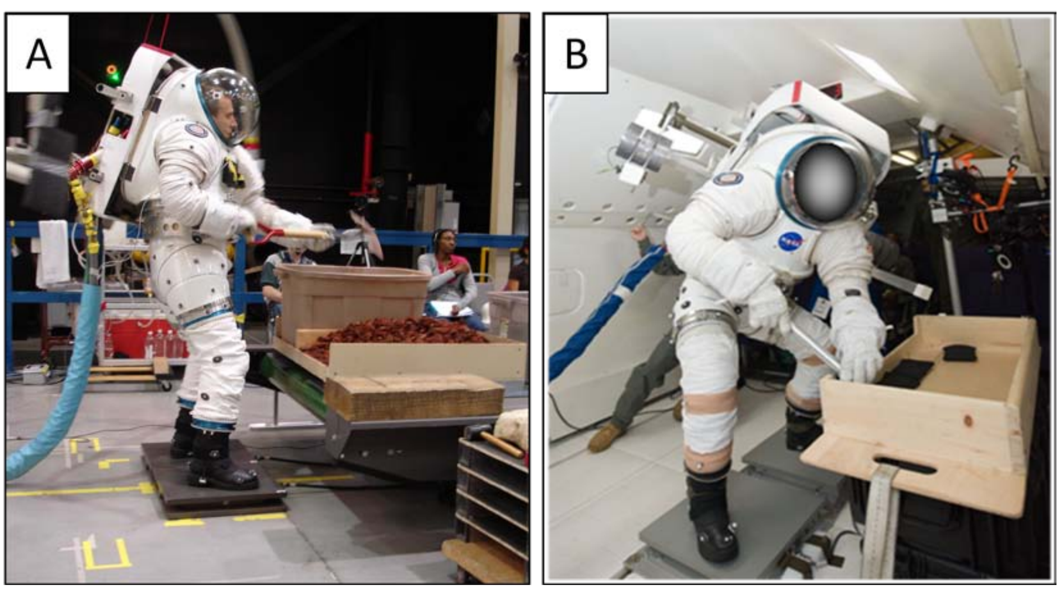

Figure 3-14. Suited subject performing shoveling task.

3.3 Biomechanical Data Collection and Analysis

3.3.1 Motion-capture data collection

A Vicon MX motion-capture system (Vicon, Oxford, England) was used to capture kinematic data in both environments. Retroreflective markers were placed on key landmarks of the body and hardware. Data were processed with custom-made inverse kinematic and dynamic models (Vicon Bodybuilder, Oxford, England) that provided additional flexibility and accuracy over previous models used by the team. The kinematic, kinetic, and temporal-spatial data output of these models included overground ambulation speed on the C-9. Overground speed was calculated using a marker on the hip as the reference point coupled with the duration it took the subject to complete the kinematic data collection area. This data collection area generally allowed for kinematic analysis of at least one full gait cycle. We have used definitions, reference frames, and reference planes commonly employed in biomechanics and prescribed by the International Society of Biomechanics (7) for this report. Appendix A contains reference materials and graphical representations of these items.

3.3.2 POGO ground reaction force data collection

Four strain-gauge-type force plates (AMTI #OR6-6-2000, Watertown, Mass.) were mounted to the frame of the treadmill under the belt and recorded normal ground reaction forces (GRFs) during ambulation trials on POGO. Shear forces were not recorded. Two additional force plates (AMTI #OR6-6-2000, Watertown, MA) were used during the exploration task trials to record GRF and center of pressure (COP). Subjects stood on the force plates while performing exploration tasks.

3.3.3 C-9 ground reaction force data collection

Because of height constraints and safety concerns on the C-9 with the regularly used force plates, JSC's Anthropometrics and Biomechanical Facility custom made two force plates. These plates consisted of a top plate and a bottom plate (A36 steel) that sandwiched 10 load cells (Transducer Techniques #THB-1K, Temecula, Calif.). These force plates only recorded GRF normal (perpendicular) to the surface of the C-9 floor. Two additional force plates (AMTI #OR6-6-2000, Watertown, Mass.) were used during exploration task trials to record GRF and center of pressure (COP). Subjects would stand on top of the force plates while performing their exploration task.

3.4 Subjective Data Collection: Gravity Compensation and Performance Scale

The gravity compensation and performance scale (GCPS) was used to assess the level of compensation needed in reduced gravity to maintain performance comparable to that achieved while unsuited at 1g (2). The scale is shown in full in Appendix C. Although the scale extends from 1 to 10 and generally functioned as a continuous scale when the data were analyzed, other groupings should be defined. GCPS ratings can be categorized into smaller groupings, with values of 1 to 3 defined 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." Because GCPS is not a continuously linear scale, a change from one category to the next, rather than a specific numerical change on the scale, is defined as a practically significant change (3).

3.5 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. Only subjects with a good suit fit were considered for inclusion in this study because of potential medical safety issues and to get the best data possible. For a direct comparison of POGO and C-9 data, the POGO data set contains data from six male crewmembers; Table 3-2 shows the subject population demographics (3) (4). IST-X also had six male crewmembers participating, and Table 3-3 shows the subject population demographics (1). Three subjects participated in testing on both the POGO and the C-9.

Table 3-2. POGO subject characteristics from IST-1 and IST-2 for *n* = 6

	Height (cm)	Body Mass (kg)	Age (years)
Average	179.1	80.7	45
Std Dev	4.8	8.5	7
Max	185.9	86.4	52
Min	174.6	68.2	37

Table 3-3. C-9 subject characteristics from IST-X for *n* = 6

	Height (cm)	Body Mass (kg)	Age (years)
Average	181.4	78.8	45
Std Dev	6.8	11.2	4
Max	189.2	97.5	52
Min	175.3	67.1	41

4 Results and Discussion

4.1 General Environmental Characterization

This section details the results and discussion pertinent to the accuracy of the partial-gravity simulation in each environment.

4.1.1 Kinetics

Kinetic analysis describes the methods the body uses for energy storage, absorption, transfer, and expenditure. By studying these processes, we can determine the nature of the interactions between the human body and its environment. Neither the POGO nor the C-9 is a purely passive environment; both will either impart some energy to or absorb energy from the human body while ambulating or performing tasks.

4.1.1.1 POGO Test Environment

The POGO system's method of simulating a reduced-gravity environment is currently the best vertical weight offload system available to NASA for suited and unsuited testing. It has some noteworthy flaws, however. The POGO system does not truly reduce the effects of gravity on the subject's entire body or suit; it offloads those body parts that are rigidly attached to POGO or are in a weight-bearing line of contact. The method of attaching the subject to POGO also creates abnormal forces, as the offload force is directed through a single point of contact.

Inertial forces are not apparent until an object with mass begins to accelerate. However, the human body is constantly accelerating and decelerating even during constant speed ambulation. Aside from the whole-body COM accelerations, each body part (except for the head) is usually in some kind of dynamic motion.

Therefore, each segment mass requires a small force to get it moving and then to slow it down again. These inertial forces are separate from the forces due to gravity field and are a property of the mass itself.

When a subject ambulates in an environment such as the POGO, the gimbal support structure adds substantial mass to the subject, which in turn affects the subject's inertia. The increase in mass alone was not a negative factor, as this was accounted for as part of the additional mass that a PLSS would add to an EVA suit, but the inertia properties differed greatly from those of a standard PLSS backpack. As the body translates and rotates, the added inertia requires the subject to compensate and change his or her normal dynamics to limit the additional energy needed. Mathematical analysis of the gimbal has shown that it substantially increased the subject's rotational moments of inertia in the transverse plane by a factor of 9 (5). Table 4-1 shows the moment-of-inertia parameters of an average human male standing, the human male torso segment, and the current POGO gimbal (5) (8). The principal axes for all three systems are located at the relative CG and are nearly coaxial to each other. The Ixx axis is anterior-posterior ([AP] frontal plane), the Iyy axis is medial-lateral ([ML] sagittal plane), and the Izz axis is superior-inferior ([SI] transverse plane).

Table 4-1. Comparison of the moments of inertia of an average human male standing, the torso segment only, and the POGO gimbal

Moment of Inertia ($kg \cdot m^2$)	*Standing*	*Torso Only*	*POGO Gimbal*
Ixx (AP, through COM)	13.40	1.62	0.03
Iyy (ML, through COM)	11.89	1.08	3.95
Izz (SI, through COM)	1.72	0.38	15.54

Testing was also performed on the POGO system using the Stewart Platform robot to examine the system's capabilities to follow human inputs while attempting to maintain a constant offload. Ideally, the system would be instantaneously responsive and adjust to match the subject's inputs exactly. Any deviations from this would cause overshoot or undershoot of trajectories, resulting in increased or decreased loading compared to the ideal.

Robotic testing showed that some overshoot of trajectories occurred throughout the profile, with the greatest amount (33 mm) occurring during descent (Figure 4-1). The profiles also showed what would be collisions between the POGO and robot just before the minimum height is obtained and then again on the ascent. If the POGO system were ideally damped, it would follow the robot's profile much more closely.

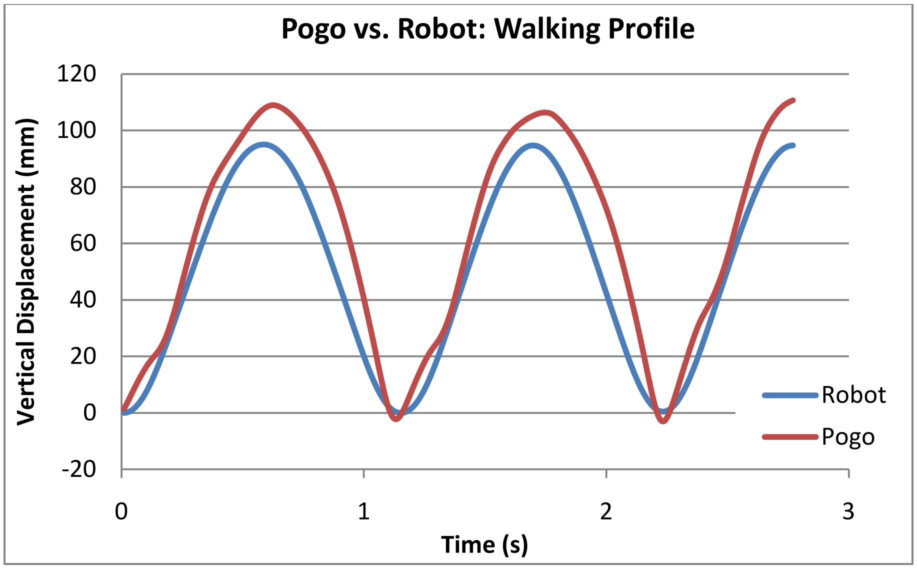

Figure 4-1. Vertical component of a human walking profile mimicked by the Stewart Platform robot and followed by the POGO system at steady state.

4.1.1.2 C-9 Test Environment

To better understand the C-9 testing environment, the Anthropometrics and Biomechanical Facility analyzed the reduced gravity levels in a subset of the parabolas flown during testing. Figure 4-2 shows the actual acceleration trace for a sample parabola (black), the mean acceleration during the parabola (dash), and the acceleration at 1/6 Earth gravity (gray). The acceleration level varied considerably with the resulting change in gravity as an induced force to the average subject possibly having considerable effects on performance. For example, the weight of an 80-kg subject at 1/6-g is about 130 N, so the minimum acceleration shown in Figure 4-2 would produce a reduction in the subject's weight of more than 30%.

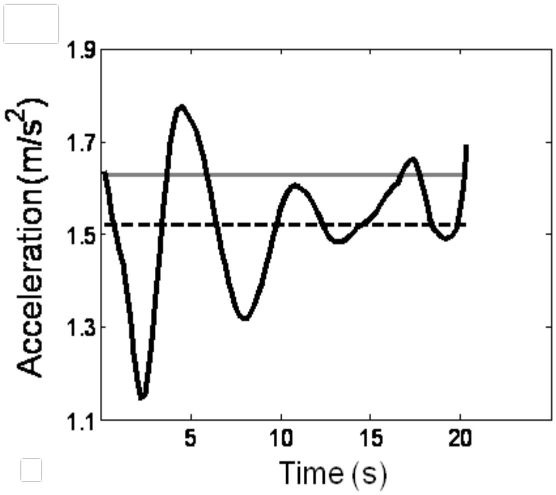

Figure 4-2. Acceleration of a sample parabola (black line) with the parabola mean acceleration (dashed line) and acceleration at 1/6-g (gray line).

By examining the full set of 219 parabolas, we calculated the mean of the mean acceleration during each parabola and the standard deviation of the parabola mean acceleration. Table 4-2 shows the summary from the collected parabola data. The 'x Acceleration' is the mean of each individual parabola's overall mean value, while the 'Δ Acceleration' is the change in acceleration from that parabola's mean to its maximum or minimum. The mean values seem to be fairly consistent, but some sizable changes in acceleration occurred during the parabolas, as seen in the example in Figure 4-2. The parabola was considered to have begun when the acceleration dipped below 2.0 $m \cdot s^{-2}$ and ended when the manual collection ended. The data were then filtered with a moving average filter with a 1-second window to eliminate electrical noise and smooth the data.

Table 4-2. The means, standard deviations, minimums, and maximums for 219 lunar parabolas. The "x Acceleration" is each individual parabola's overall mean value, while the "Δ Acceleration" is the change in acceleration from that parabola's mean

	Mean	*Std Dev*	*Max*	*Min*
Acceleration ($m \cdot s^{-2}$)	1.6	0.1	1.8	1.4
Δ Acceleration ($m \cdot s^{-2}$)			0.7	-0.5

4.2 Direct Comparison of Human Performance in Partial-gravity Analog Environments

This section presents direct comparisons of human performance metrics across similar tasks in each analog environment.

4.2.1 Known differences in task setup or performance

Because of safety, time, and volumetric restrictions, the C-9 environment is much more limited than POGO in what materials can be used in it and how tasks must be performed. These potential restrictions were not considered when determining how tasks would be performed on POGO because the full IST-X test plan had not been laid out until well after IST-2 was complete. This section describes the known differences in task setup and/or performance between the two partial-gravity analog environments. Of the four tasks, only kneel and recover had no notable differences.

4.2.1.1 Walking

Of all tasks performed, this task was the most different between environments. On POGO, the speeds were predetermined and controlled by having the subject ambulate on a treadmill, whereas the subject walked at a self-selected speed that was affected by the ambulation distance and the need to stop and turn around on the C-9. All ambulation on POGO was a steady-state activity on a treadmill with a 3-min duration at each speed. All ambulation on the C-9 was overground and not considered steady state because the trials lasted about 15 sec, which was only enough time to traverse the ambulation area in the aircraft out and back. GRF was measured via integrated force plates on POGO such that subjects could be anywhere on the treadmill belt and GRF could still be measured. A force plate was in the middle of the walkway on the C-9 and subjects were encouraged to land at least one footfall on the force plate each trip down the walkway.

4.2.1.2 Rock Pickup

Subjects picked up either a 1- or a 5.5-kg lead weight on POGO, whereas they picked up a 2.7-kg bag filled with lead shot on the C-9. In addition to the mass differences, gravitational differences should be noted. During POGO testing, only the subject, suit, and gimbal were offloaded. Therefore the weights lifted were still in 1-g. During C-9 testing, the subject, suit, and weights were all at the same partial-gravity level. It should also be noted that sometimes during the C-9 evaluation, the rock-pickup task was not completed as requested, with the subject sometimes dropping the bag back onto the surface or tossing it to test personnel if parabola time was running low. During POGO testing, the subject picked up the weight off the treadmill and was instructed to avoid leaning against the treadmill structure for additional balance support. During C-9 testing, the subject picked up the weight off an elevated surface and was instructed to avoid leaning against the body of the airplane for additional balance support.

4.2.1.3 Shoveling

The shovels used were different: the garden shovel used on POGO had a longer handle than the Apollo-style shovel used on the C-9, and it had a different handle shape as well. The type and amount of material picked up with the spade was different: subjects on POGO picked up a full load of lava rocks, but subjects on the C-9 picked up only one lead-shot bag. On POGO, the shovel and lava rocks were all in 1g, whereas on the C-9, the shovel and lead-shot bag were at the same partial-gravity level as the subject. Also, the shoveling technique required to fill the spade with lava rocks vs. scooping up one lead-shot bag was different based on visual inspection by the team and from subject comments.

4.2.2 Ground reaction force

In both environments kinetic data were collected in the form of vertical GRF, which represents the normal force acting on the subject when the subject is in contact with the walking surface (treadmill or airplane). Peak GRF values for all tested conditions were normalized to the subjects' 1-g body weight (BW).

As seen in Figure 4-3, the ability to compare the GRF in the two test environments is limited. This is due to several factors, mainly a lack of overlap and direct matching of ambulation speeds. Even in ranges in which speeds did overlap, subjects may have targeted, skimmed, or missed the force plates during ambulation passes, thus reducing the data quality. Ambulation speeds for the 0.17-g condition performed in the POGO system were different for each subject, as they were based on each subject's preferred walk-to-run transition speed. Ambulation speeds on the C-9 aircraft were freely chosen by subjects and, as seen in Figure 4-3, were more variable and did not exceed 1.0 m•s^{-1} (2.2 mph).

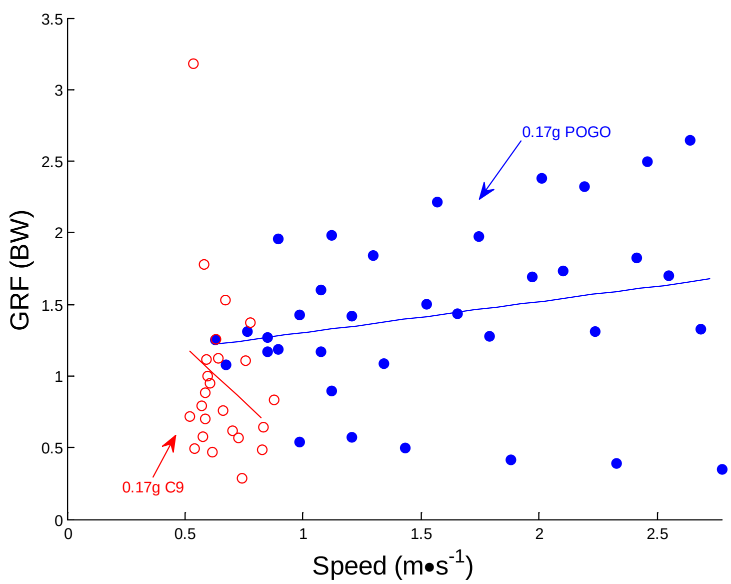

Figure 4-3. Comparison of peak GRF in POGO testing (0.17-g) and C-9 testing (0.17-g) under suited conditions.

4.2.3 Temporal-spatial characteristics

Variations in ambulation speed have a considerable effect on measured gait variables. As gait speed is directly related to temporal-spatial parameters of gait, including cadence (frequency of steps), as well as step and stride length, these metrics should proportionately change with speed. Comparison of specific suited temporal-spatial characteristics may also help to provide some insight regarding differences between testing environments. The cadence of suited subjects in the POGO and C-9 is shown in Figure 4-4. Although the absolute speeds attained on the C-9 tended to be less than those attained during POGO testing, the range of cadences used in each environment was similar.

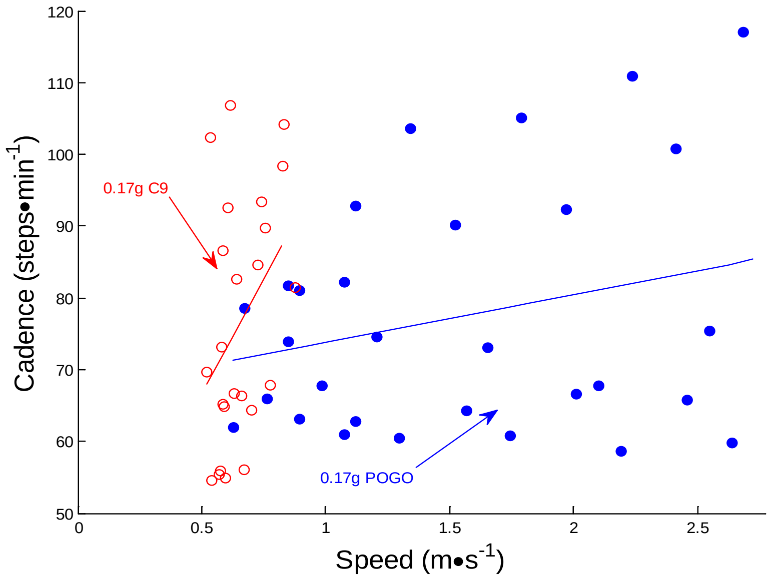

Figure 4-4. Comparison of cadence in POGO testing (0.17-g) and C-9 testing (0.17-g) under suited conditions.

As seen in Figure 4-5, the C-9 testing shows more tightly grouped results for step length than the POGO testing. Visual inspection of the data points and linear regression trend lines suggests that the C-9 results are similar to the POGO results; however, the number of data points for comparison is limited, as the speed range of the C-9 testing is at the extreme low end of the POGO range of ambulation speeds.

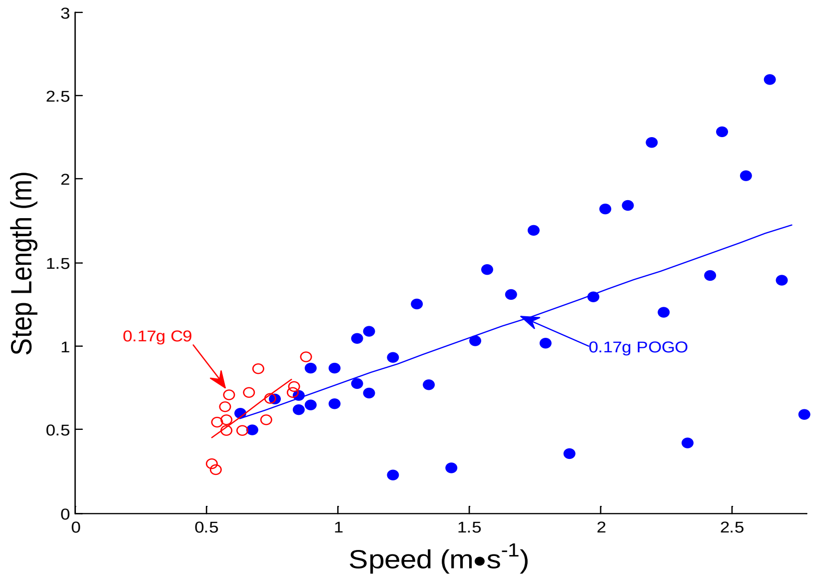

Figure 4-5. Comparison of step length in POGO testing (0.17-g) and C-9 testing (0.17-g) under suited conditions.

4.2.4 Kinematics

To be consistent with previous tests, the generic term *initial contact* (IC) is used to describe the instant at which the foot just touches the floor; conversely, at the end of the floor contact, the generic term *end contact* (EC) is used. Another consideration in the evaluation of these data is that the marker sets used during POGO testing differed from those used on the C-9. The primary reason is that the limited volume of the C-9 prevented whole-body kinematic analysis while ambulating along the length of the airplane. C-9 kinematic analysis focused on the lower body with only a few reference markers on the torso.

4.2.4.1 POGO Ambulation

Suited ambulation on POGO showed the upper torso motion being restricted to the point at which nearly all transverse rotations were made by the pelvis. This restriction was most likely a result of the increased rotational moments of inertia of the system caused by the presence of the gimbal. Figure 4-6 shows the top view relation of the MKIII HUT (yellow box) to the brief (blue box) for a left foot (A) and a right foot (B) initial contact for a typical subject. In this example, the HUT showed little to no rotation between left and right IC, whereas the brief clearly showed rotation. Figure 4-6 illustrates the locations of the HUT and brief on the MKIII.

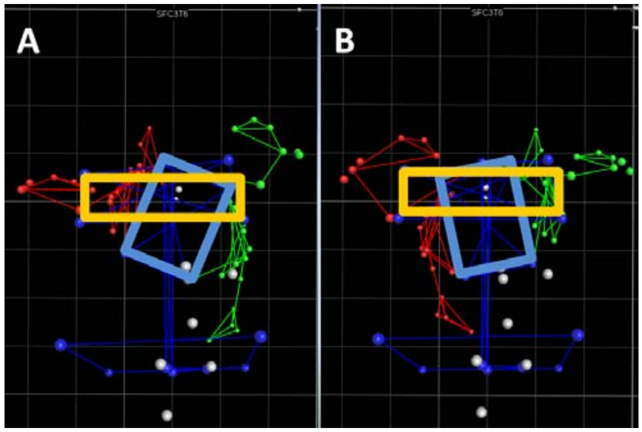

Figure 4-6. Top-view rotations of the HUT (yellow box) and brief (blue box) in the transverse plane while on the POGO for a representative subject. "A" shows positioning during IC of the left foot (red), and "B" shows positioning during IC of the right foot (green).

Many subjects also adapted their ambulation style to include a hopping motion from one foot to the other combined with a whole-body frontal plane rotation about the gimbal axis. This effect is seen in Figure 4-7, in which dotted yellow lines are drawn between the torso COM and the pelvic COM for a representative subject to show the whole-body tilt and the yellow dot shows the gimbal axis in which rotation is occurring. One effect of this motion was the capacity to keep the feet closer together during ambulation without increased lower body motion. This increased the mechanical work efficiency of the subject, which would likely lead to a decreased metabolic rate (10). The degree of this adaptation seemed to change with the subject's chosen style of ambulation.

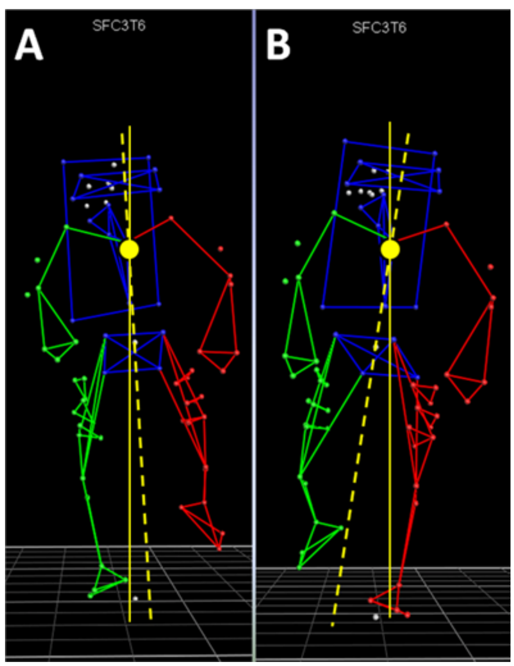

Figure 4-7. Frontal view of whole-body rotations in the frontal plane about the POGO gimbal axis of rotation (yellow dot) for a representative subject. "A" shows positioning during IC of the right foot (green), and "B" shows positioning during IC of the left foot (red). The solid yellow line runs perpendicular to the floor, and the yellow dotted line indicates whole-body rotational tilt.

A sagittal view of ambulation on the POGO is shown in Figure 4-8 for the three phases of contact during a gait cycle for the left leg (red). Notice that the knee remains straight and the foot remains in plantar flexion for the entire duration, including initial contact, where traditionally the foot is dorsiflexed.

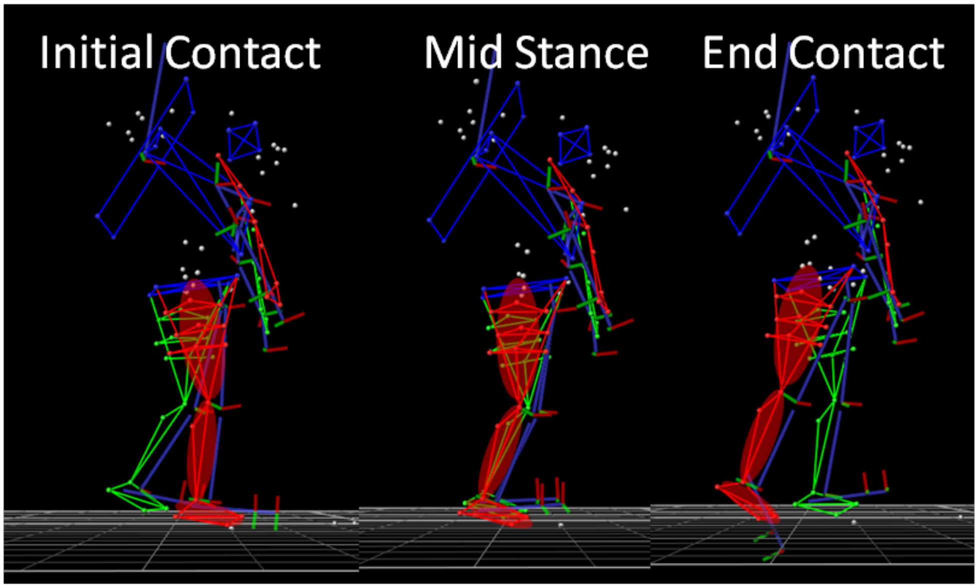

Figure 4-8. Ambulation style on the POGO for a reference subject showing limited flexion at the left (red) knee joint and consistent plantar flexion of the left (red) ankle joint throughout the gait cycle. The right (green) leg follows this same pattern, but the titles in the figure refer to left (red) leg only

4.2.4.2 C-9 Ambulation

Suited ambulation on the C-9 had the general appearance of being more crouched than that on POGO. Figure 4-9 illustrates an aspect of this crouched type of gait by showing the position of the COM squarely in the middle of the subject’s base of support. The upper torso was free to move independently of the pelvis in this environment. Notice that the pelvis and torso remain perpendicular to the floor in the frontal plane at IC.

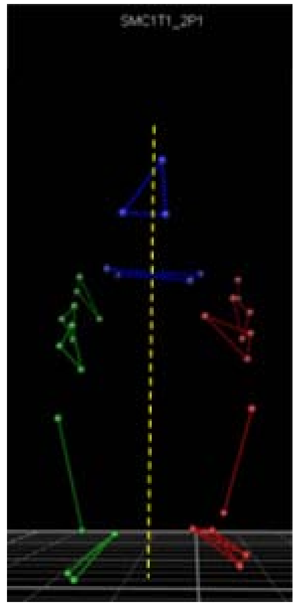

Figure 4-9. Frontal view with a representative example of the stance and posture of a subject on the C-9 at IC with the right foot (green). Yellow dotted line indicates whole-body rotational tilt, which in this example is negligible.

A view through the sagittal plane (Figure 4-10) shows that the ankle, knee, and hip joints remain flexed through the three phases of contact during a gait cycle for the right (green) leg. IC occurred on the C-9 with full contact of the foot in the neutral position.

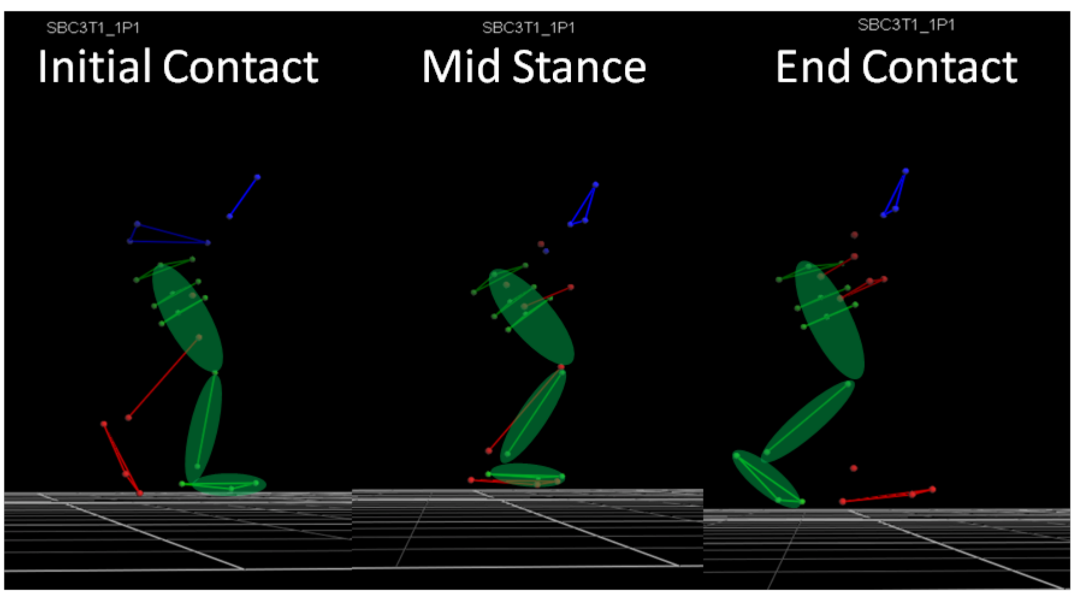

Figure 4-10. Sagittal view of a representative subject's ambulation style on the C-9 showing the hip and knee joint in constant flexion and ankle joint at constant dorsiflexion throughout the gait cycle.

Figure 4-11 shows the- large difference in use of the ankle joint between suited subjects on the POGO and the C-9. The data indicate more activity of the ankle joint on POGO than on the C-9. Ankle angles can be compared only by range and shape, not by absolute values, because different marker sets were used (that is, an angle of 0° may not be true neutral for both sets of data).

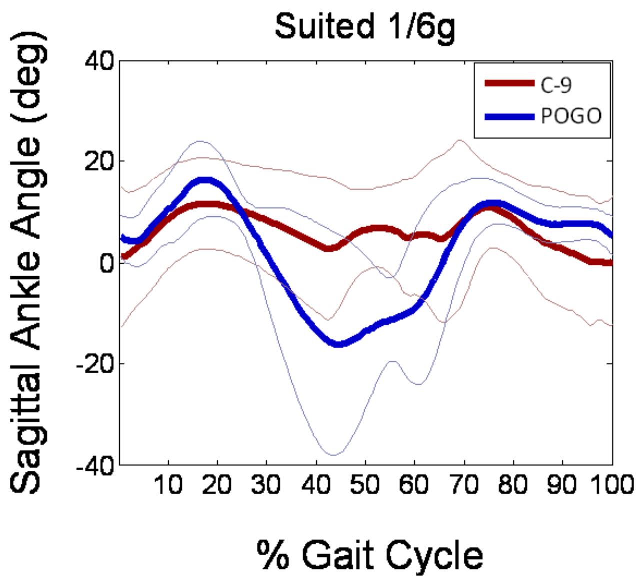

Figure 4-11. Mean sagittal ankle angles for the ground contact portion of the gait cycle for POGO (thick blue) and the C-9 (thick red). Mean sagittal ankle angle standard deviation is shown for POGO (thin blue) and the C-9 (thin red).

4.2.5 Center-of-pressure analysis

A method agreed on and considered to be a good comparison of the two analogs, before the C-9 test, was COP analysis for exploration tasks. Force-plate and motion-capture data were combined to look at the COP relative to the base of support (BOS). Four metrics were computed and analyzed to determine the effects of varying CG on COP: the percentage of time the COP was outside the BOS, the number of times the COP fell outside the BOS, the average area of the BOS, and the total distance the COP traveled during the task. All of these metrics play a role in illustrating the stability of the subject in completing a specific task. Data from IST-2 were reanalyzed to match the analysis methods for IST-X.

Figure 4-12 graphically depicts how the metrics for this analysis were computed. The red and blue lines represent the calculated COP for the right foot and left foot respectively. The combined COP total is shown as the green line. The black lines represent the subject’s BOS. Of note, data for only four subjects were collected during IST-X because of hardware problems.

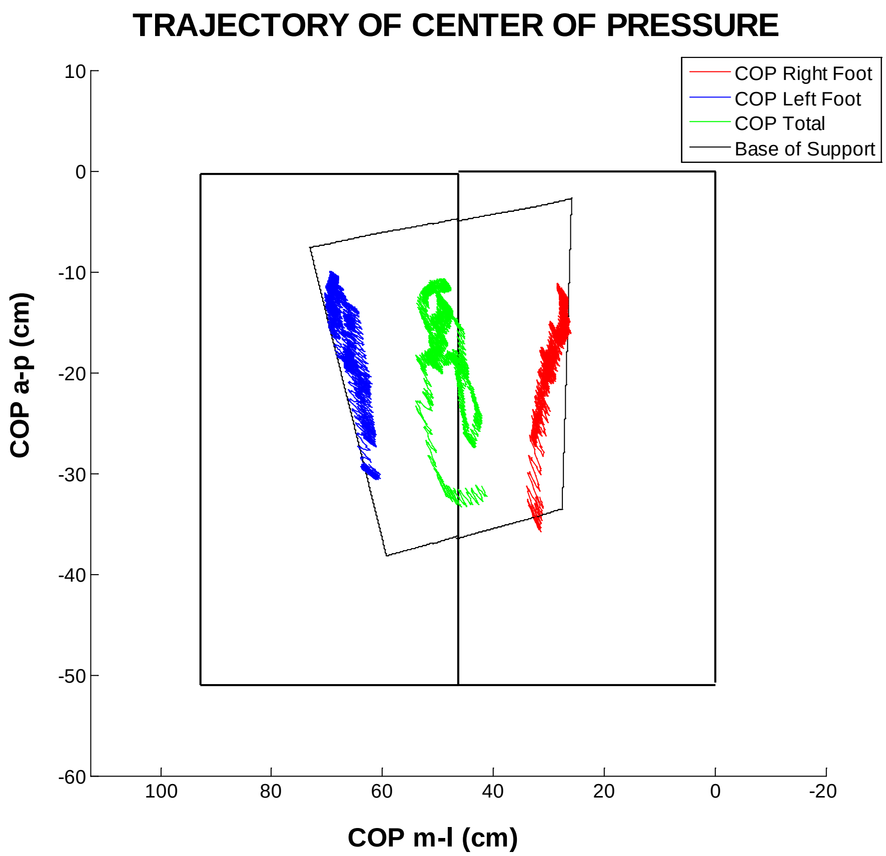

Figure 4-12. Example plot of COP trajectory while using POGO. COP can move in both the AP and the ML planes.

Figure 4-13 displays the average data from the rock-pickup tasks for each analog, with the suited lunar conditions boxed in red. The percentage of time that the COP was outside the BOS on the C-9 remained relatively constant across the conditions. The average area of the BOS was greater on the C-9 than on the POGO. The total COP travel on POGO was very small, with little variation between subjects.

Even though the COP crossed the threshold of the BOS more frequently on the C-9—a sign of instability—the subjects used a wider stance to maintain a consistent amount of time outside of the BOS, no matter the condition. The number of times outside and the total travel on POGO were much less than on the C-9 and the area of support was smaller. With these three variables, it would be assumed that stability would have been better on POGO than on the C-9, but this was not so. As the simulated gravity increased, POGO experienced a decrease in the percentage of time outside the BOS as well as a decrease in the variation. The percentage of time outside was higher than on the C-9 at lower simulated gravities, and it was lower at higher simulated gravities. Even considering only these variables, it is apparent that the two analogs affect subject performance differently.

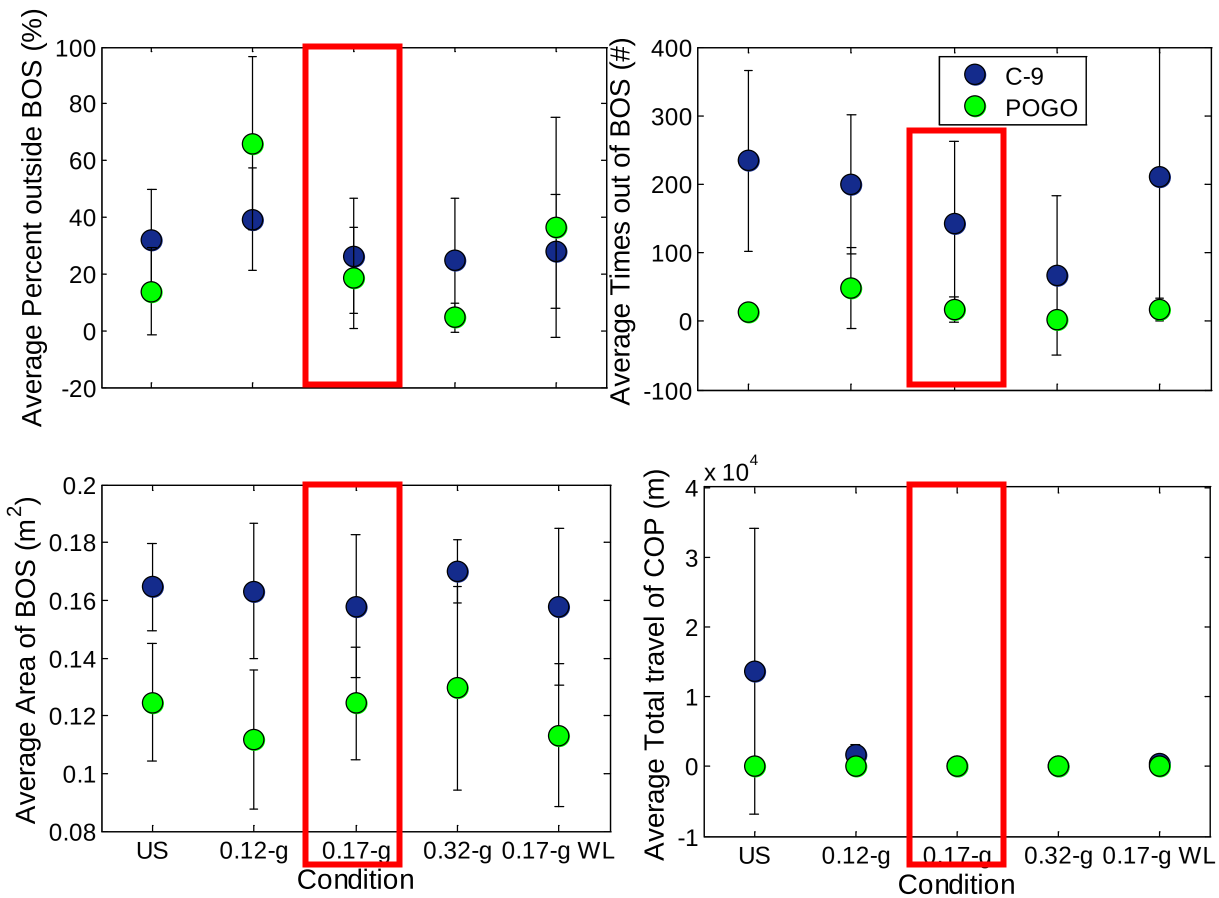

Figure 4-13. Rock-pickup task COP metrics, average ± standard deviation; suited lunar conditions are boxed in red. US refers to the unsuited condition. Data shown at 0.12g were collected at 0.10g on the C-9 and 0.12g on POGO. Data shown at 0.32g were collected at 0.30g on the C-9 and 0.32g on POGO. The 0.17g waist (joint)-locked (WL) condition refers to the suited condition with the waist joint locked.

A final consideration with respect to the differences between systems for COP analysis was that during C-9 testing, subjects were just a touch away from regaining balance if they were beginning to fall forward or laterally. Subjects could reach the top or side of the airplane with relative ease if they needed to adjust their balance. This ability to easily correct balance was not readily available in the POGO test environment.

4.2.6 Gravity compensation and performance scale

The GCPS provides a means of comparing the subjective levels of compensation required to maintain performance of these tasks across different analog environments. Given the assumption that parabolic flight is the most accurate simulation of partial gravity currently available, we expect that GCPS values during parabolic flight are more representative of true lunar performance than values from POGO. Task-to-task differences across the two environments were detailed in both Section 3.2 and Section 4.2.1 of this document. With respect to the differences in task performance between environments, a limited direct comparison of the C-9 and POGO GCPS data in lunar gravity can be made for the following three different conditions: 1) unsuited, 2) suited, and 3) suited with the waist joint locked. POGO data come from three different tests. The unsuited walking data come from the EVA Walkback Test (2); suited walking data come from IST-1 (3); and unsuited and suited data for the three remaining tasks come from IST-2 (4). Figures 4-14 through 4-16 show the GCPS values for the POGO and the C-9 for four different tasks in lunar gravity under similar test conditions.

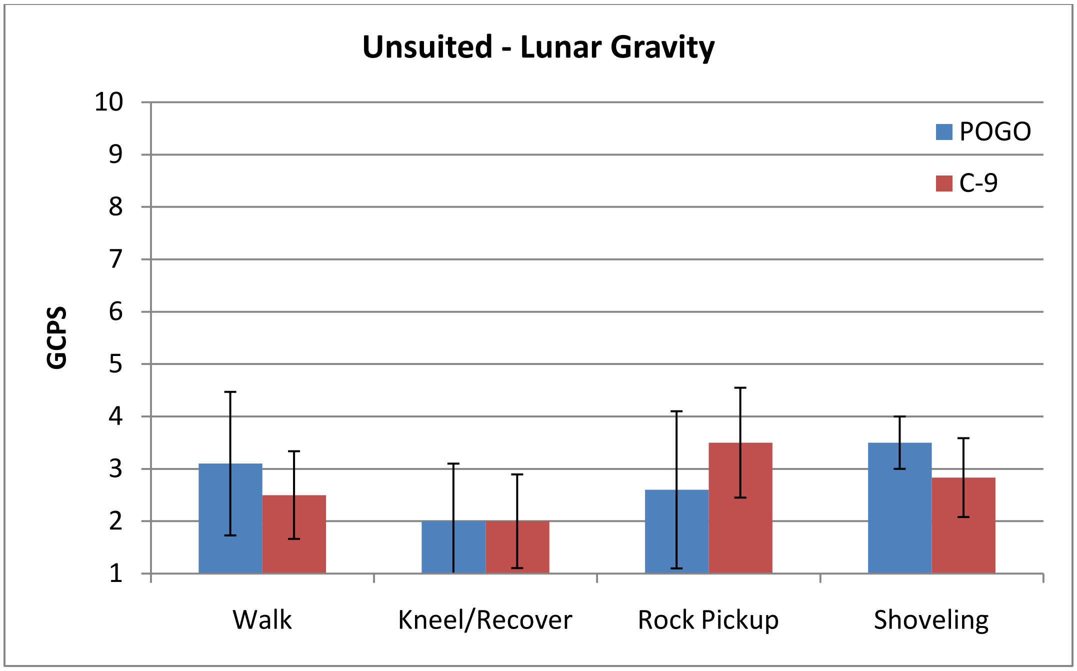

Figure 4-14. Comparison of GCPS ratings (mean ± standard deviation) for four tasks in two lunar-gravity simulations while unsuited.

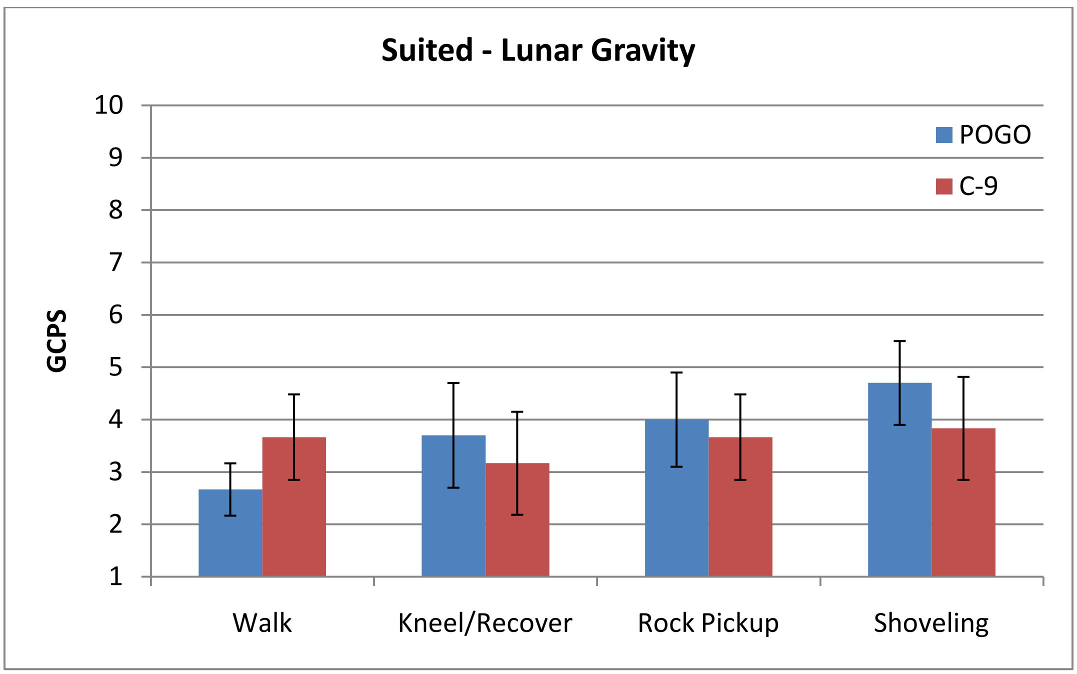

Figure 4-15. Comparison of GCPS ratings (mean ± standard deviation) for four tasks in two lunar-gravity simulations while suited.

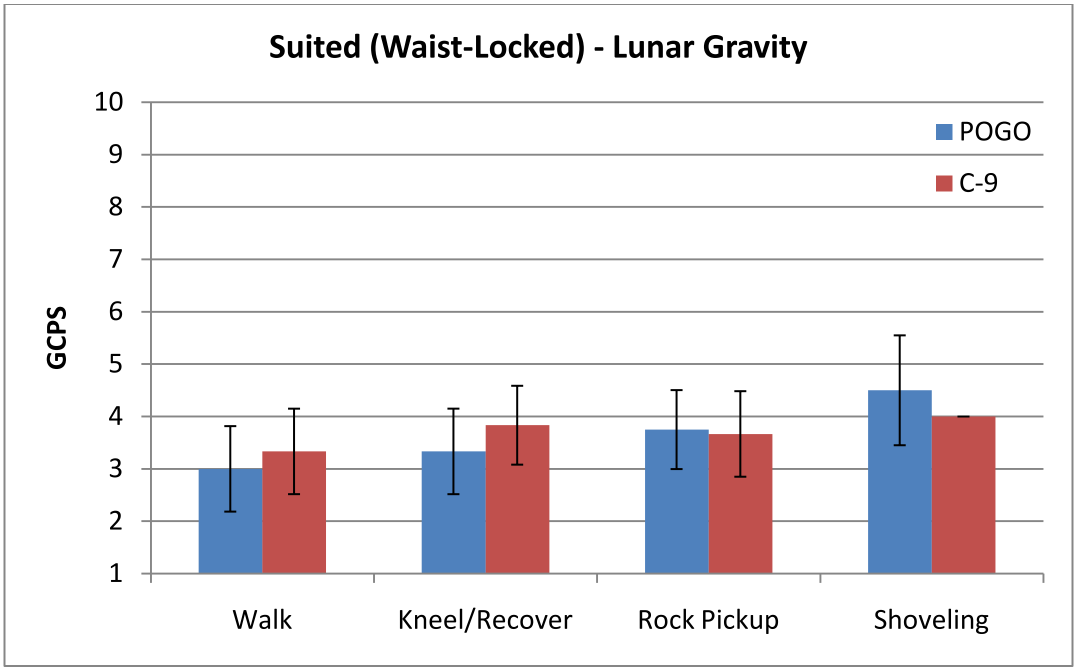

Figure 4-16. Comparison of GCPS ratings (mean ± standard deviation) for four tasks in two lunar-gravity simulations while suited with the waist joint locked.

For all three configurations (unsuited, suited, and suited with waist joint locked), there was little difference in GCPS values between the POGO and the C-9, indicating that the overall levels of compensation required to maintain performance were not different between these two partial-gravity analog environments for the limited sample size tested. In each comparison, n = 6 for the POGO and the C-9, with three subjects in common.

Because of concerns that subjective ratings can differ between subjects, data from the three common subjects are shown in Table 4-3. Cells that are not shaded showed no practically significant change (change in category; see Section 3.4.1) in GCPS rating between environments. Cells with gray shading showed what is considered a practically significant change and cells shaded yellow showed a practically significant change in GCPS rating that affected more than a one category change within the same subject between environments. Of the 36 comparisons, 22 showed no change and 14 showed a practically significant change with four of these changes greater than moving from one category to the next.

Table 4-3. Individual subject GCPS ratings under different conditions in two partial-gravity analog environments

Task	Unsuited		Suited		Suited - Waistlocked	
	C-9	POGO	C-9	POGO	C-9	POGO
Walk	3	3	3	2	3	2
	1	3	4	3	3	4
	3	3	4	3	3	3
Kneel/Recover	1	1	3	4	4	4
	3	3	3	2	3	2
	1	3	3	4	3	4
Rock Pickup	4	1	3	5	3	5
	5	4.5	4	4.5	3	3.5
	4	4	4	4	3	4
Shoveling	3	4	3	5	4	5
	4	4	5	5	4	4
	2	3	4	4	4	5

Yellow shading indicates a practically significant change of more than one category, gray shading indicates a practically significant change from one category to the next, and no shading indicates no change. Rock-pickup data for POGO are the average of the 1- and 5.5-kg trials.

In addition to the lunar-gravity test points in which there was direct crossover at the same gravity level between environments, several other conditions were tested in each analog environment. These other conditions allow a general trend comparison to be done. Figure 4-17 presents the GCPS trend comparison of POGO and C-9 across different gravity levels for four different tasks.

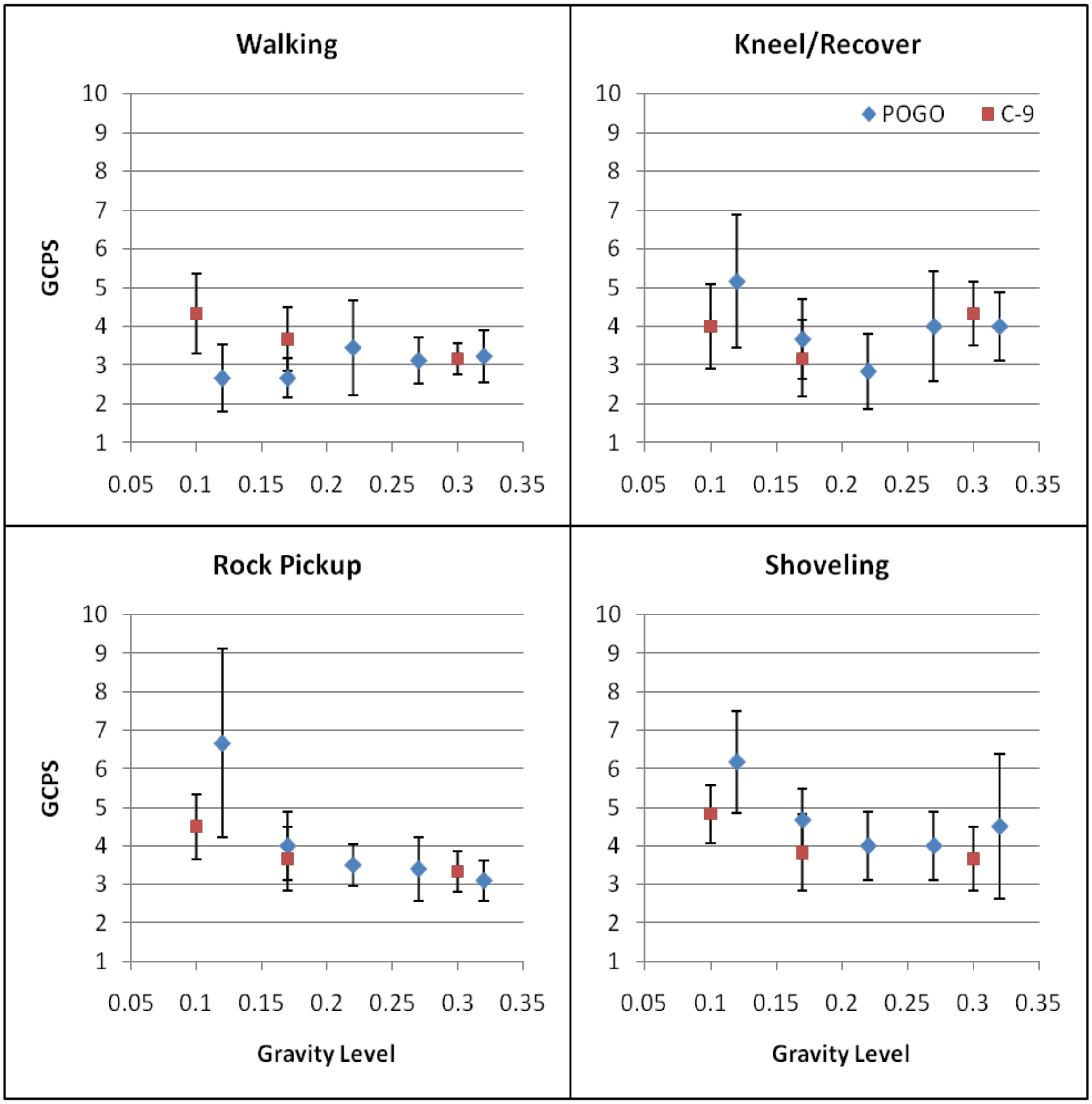

Figure 4-17. GCPS trend comparison of the POGO and C-9 analogs for four tasks at different gravity levels.

The greatest difference in GCPS trends for each task was at the lower end toward 0.1-g. Values at and above 0.17-g were remarkably similar. POGO had a lower average GCPS rating for the walking data than the C-9 had at the lowest gravity levels. Although there are several possible reasons for this, it is likely that the inertia of the POGO and gimbal artificially stabilizes the subject for treadmill ambulation and, thus, POGO does not require as much compensation as the C-9 to maintain the desired performance.

Of all the tasks, kneel and recover was the task that was performed in the manner most similar in the two environments. GCPS trends were similar for the two test environments, although, as for walking, the difference between the environments was greatest at the lowest gravity level. In this case, the GCPS rating for POGO was higher than the C-9 rating, indicating that the POGO and/or gimbal may be negatively affecting performance at lower gravity levels. Data comparison and interpretation for the shoveling tasks are virtually identical to those for the kneel-and-recover task. For both tasks, it should be noted that the variability in data demonstrates that the differences between environments could be due to random chance.

The rock-pickup task showed the greatest difference between environments at the lowest gravity levels, but GCPS ratings were remarkably similar at gravity levels ≥ 0.17-g. Judging from qualitative analysis and subject feedback about the rock-pickup task on POGO, it is likely that interactions among the POGO, gimbal, and low gravity level had a substantial negative impact on performance. At higher gravity levels that afforded increased GRF, task performance required much less compensation. The POGO/C-9 comparison suggests that it was not a low gravity level alone that led to higher GCPS values, but rather the low gravity level and the POGO/gimbal interactions. Again, even at the lowest gravity levels, the variability in data do not rule out the differences being due to random chance.

Although this comparison provides valuable feedback about the similarities and differences between POGO and the C-9, several points need to be noted. GCPS is a subjective scale with a high degree of variability, as can be seen in the error bars. Also, as noted in Section 4.2.1, there were differences between how the tasks were performed in the two environments. Finally, although there were six subjects in each group for trend comparison, only three of the subjects were the same in each group.

When looking at the trends, using only the three subjects common to both environments, the same general observations about GCPS differences exist between the environments. Figure 4-18 demonstrates these similar trends.

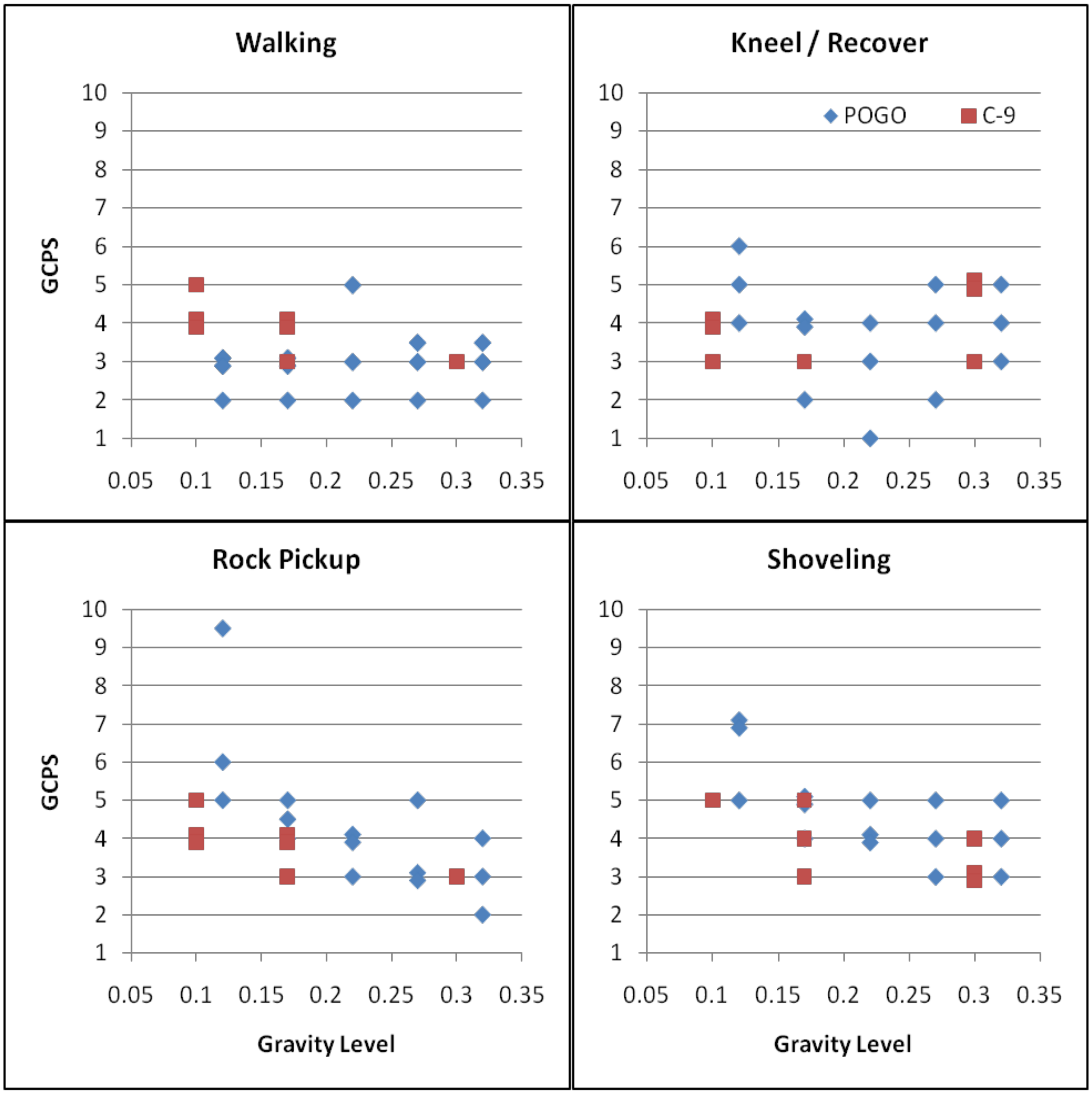

Figure 4-18. GCPS trend comparison of the POGO and C-9 analogs for four tasks at different gravity levels, using data from only the three subjects common to both environments. For each condition, three individual GCPS values were obtained. In cases in which two of three data points shared the same value, the graphical marker was stretched to indicate which GCPS value shared the two data points. If all three subjects selected the same GCPS value, only one point is shown.

The GCPS data are one of many pieces of data from which to evaluate differences between the POGO and the C-9. Although drawing conclusions from the GCPS data alone has limited validity, because of task execution differences and the limited number of subjects, the GPS data align well with the other data to support the general conclusions and recommendations in this report. For this reason, we believe these data should be shared with the greater research community so that others can build on the lessons learned from the human performance testing in both environments.

4.3 Indirect Comparisons of Partial-gravity Analog Environments

This section will focus on data collected that do not meet expectations based on literature, physics models, or physiological trends.

4.3.1 POGO offloading mechanics

This section describes the analysis that provides insight into how the POGO and gimbal/CG rig systems seem to be interacting with the human subject. This analysis was primarily performed in the sagittal plane.

Analysis from IST-3 indicated that in partial gravity, subjects may not need to impart all of the propulsive forces that are normally needed to maintain position on a treadmill operating at a constant speed (5). Rather, some evidence suggests that subjects may have been relying on the vertical offload forces to assist their upward movement while the added inertia from the overhead lift column and gimbal provided some artificial stability as the treadmill belt traveled underfoot. A portion of the possible effects attributed to the added inertial stability seen in IST-3 are likely due to the use of a CG/mass rig in that study, but the added inertia of the gimbal and POGO cylinder is still present for standard suited ambulation. Figure 4-19 shows the difference in lower limb position at EC when unsuited (left) and in the CG rig (right) from IST-3. The stance phase of the gait cycle and the contact angle of the leg in the CG rig trial have been shortened so the leg can no longer produce as much propulsive force in the forward direction. Figure 4-20 shows the difference in lower limb position at initial contact when unsuited (left) and in the CG rig (right) from IST-3. The stance phase of the gait cycle and the contact angle of the leg in the CG rig trial have been shortened so the leg absorbs only the limited energy produced by the body's forward momentum. The reduction of the stance phase of gait and leg angles over that contact period indicates that the body was not producing the necessary propulsive forces to achieve the calculated stride length. In this example, it appears that the subject was primarily hopping up and down with the treadmill belt passing underneath the feet. Other studies have shown this a possibility in 1-g (1), so we expect that with the reduced weight and increased stability from POGO, it would be easier to hop up and down on a treadmill without drifting backward and eventually falling off.

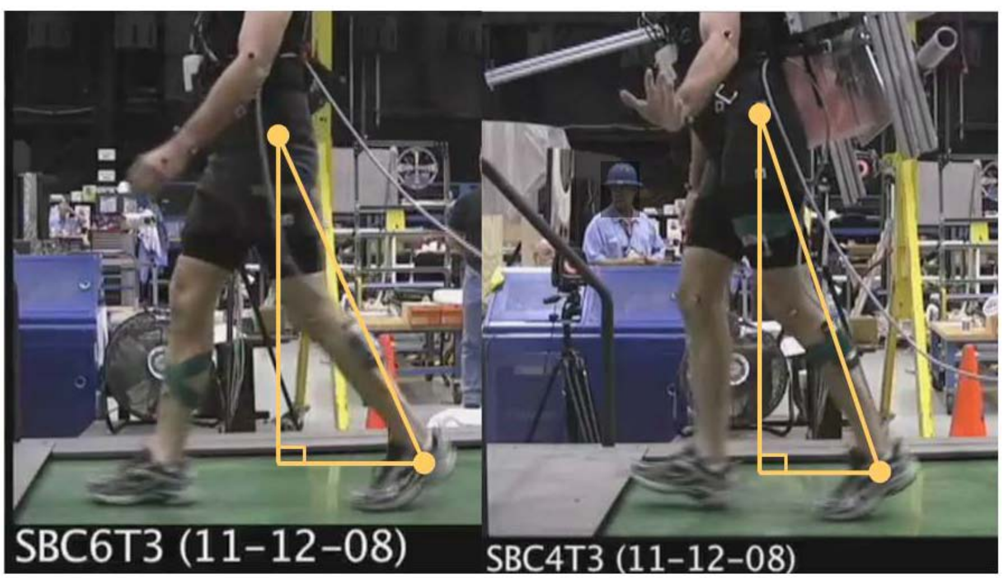

Figure 4-19. End contact shown unsuited (left) and on POGO with the IST-3 CG rig (right). Yellow lines indicate the angle of the leg with respect to vertical.

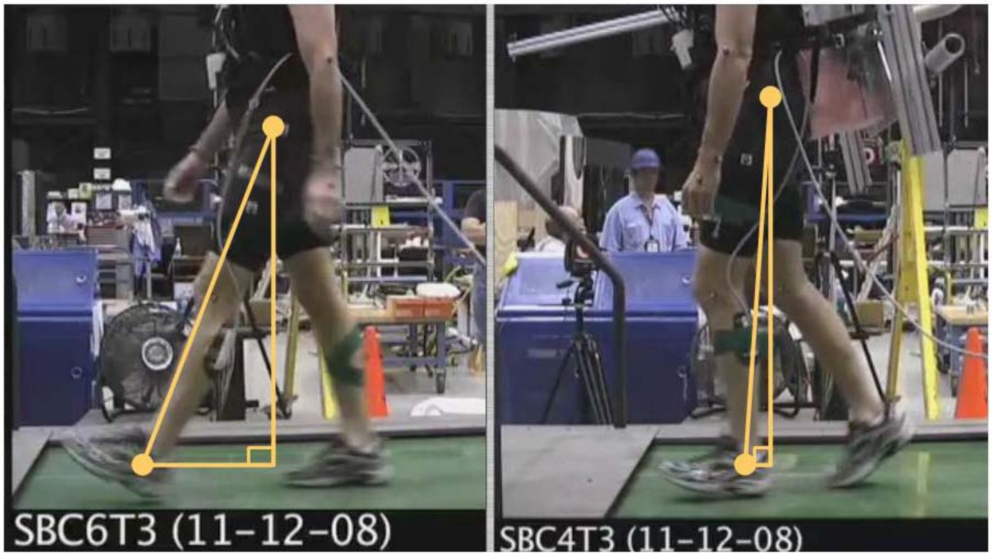

Figure 4-20. Initial contact shown unsuited (left) and on POGO with the IST-3 CG rig (right). Yellow lines indicate the angle of the leg with respect to vertical.

Certain offloading anomalies were also present with incline walking. Figure 4-21A shows an example of typical body posture when a person walks up an incline, with the torso flexed forward and increased flexion at the hip and knee (10). However, what was observed in the POGO environment was just the opposite, with the subject's trunk held upright (5) and less flexion at the hip and knee (4) (5) while walking the incline (Figure 4-21B). This posture while walking on an incline would not normally be possible without the POGO system supporting the subject.

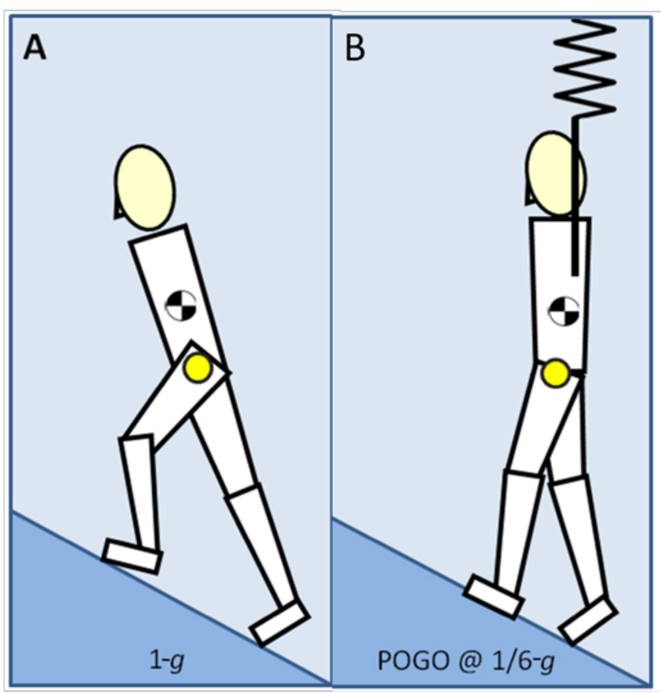

Figure 4-21. Representative posture during inclined walking in a 1-g environment (A) and the POGO 1/6-g environment (B).

4.3.2 Parabolic flight dynamic collisions

The quality of the reduced-gravity environment provided by the C-9 aircraft is a function of both the air mass the aircraft is flying through and the pilot input. Flights are planned for times and days with stable weather to the extent possible, and in all cases the airplane is flown by experienced NASA test pilots. These considerations improve the accuracy and reliability of the reduced-gravity parabolas. However, turbulence and wind shear are components of flight that cannot be eliminated. During flight, the airplane can experience shear forces that will impart forces laterally across the cabin, which imparts artificial forces into the subjects in contact with the aircraft. Variation in vertical forces can also affect parabola consistency and result in dynamic collisions with test subjects. For instance, when measuring GRF, subjects must step onto a force plate attached to the deck of the airplane. Since both the subject and the airplane are in motion, they can separately impact each other. In some cases, therefore, the resultant GRF would be overestimated because the airplane was rising at the same time the subject was contacting the force plate; in other cases, the resultant GRF could be underestimated because the airplane was dropping at the same time the subject was contacting the force plate. This can lead to increased noise in the GRF data.

4.4 Usability of Partial-gravity Analog Environments

This section will focus on both the positive and the negative usability aspects of each environment pertaining to effective suited human performance testing. Accuracy and reliability of the partial-gravity analog are not considered in this section.

4.4.1 POGO usability advantages

The POGO partial-gravity analog environment has some of the key usability characteristics that make up an ideal test environment. There is a large area around the POGO that accommodates many different forms of data collection including full biomechanical motion capture as well as standard video and photo data from unlimited angles. The large area also allows use of a treadmill to meter gait speeds and inclines as well as other test stations and mockups that can be moved in and out of the test area as needed. There is effectively no duration limit for testing, so tasks can be performed for a sufficient time to collect metabolic data. Tests can be stopped and started freely to ensure correct form and data collection procedures. Finally, access to the test environment is constrained only by resource scheduling with other users needing access to POGO.

An interface between the subject and the POGO is required to test on POGO. Currently, the gimbal support structure integrates with the MKIII suit. Other interfaces allow unsuited testing as well.

4.4.2 POGO usability disadvantages

One disadvantage of POGO is the lack of one translational DOF. Subjects can travel vertically and horizontally, but lateral translation is not possible because POGO rests on a single linear air-bearing rail. All translational DOF are limited, although the vertical and horizontal translational DOF are adequate for many different types of testing.

The large moments of inertia and mass of the POGO gimbal and overhead POGO lift column may negatively affect both static and dynamic tasks. For static tasks, the added moments of inertia may impart artificial stability. For this reason, for dynamic tasks requiring whole-body motion, there may be added resistance to changes in direction and speed over what would normally be expected.

The lift capacity of the POGO ranges from 400 to 500 lb. In most but not all cases, this is sufficient to lift a suited subject. Finally, the current interface methods for suited and unsuited subjects are quite different.

To allow better comparison of unsuited and suited human performance in reduced gravity, a gimbal that supports both configurations in the same manner is required.

4.4.3 C-9 usability advantages

One clear benefit of the C-9 and parabolic flight in general is that the human, suit, and all testing equipment are at the same reduced gravity. Since there is no need to interface the subject with the environment to simulate reduced gravity, the subject is also free to move in all 6 DOF.

4.4.4 C-9 usability disadvantages

The disadvantages of parabolic flight start with the short duration of partial gravity. Each parabola lasts 15 to 30 sec, which limits the type and quantity of data that can be collected. The cabin dimensions are also restrictive in the vertical and lateral directions and somewhat restrictive horizontally (along the length of the aircraft). The limited vertical distance currently does not accommodate suited treadmill testing in either the C-9 or Zero Gravity Corporation's (Vienna, Va.) 727 aircraft.

Time for test setup and verification is very limited. Most studies have 1 day to set up and check out all the equipment to be flown and a small amount of time for day-to-day test equipment changes. The flight schedule can have limited openings and often little flexibility for rescheduling missed test sessions.

Finally, little time is available for real-time troubleshooting or general familiarization by the subject during flight. Given the high cost of time in the air and limited fuel duration, if something goes wrong with data collection during flight, it most often means that the flight will have to land unless the problem can be fixed in a short amount of time. Also, previous studies have shown a clear need for familiarization of the suited subjects in the test environment. Due to the limited time and the cost associated with each flight, this familiarization time is often minimized.

5 General Conclusions

5.1 General Environmental Characterization

Performance of the POGO system was not ideally damped and had an overshoot when trying to follow a cyclic force profile similar to that required for support of human walking. A control system with these characteristics would likely affect subject performance because of inaccurate force returns based on subject inputs and may allow the subjects to take advantage of the system response to decrease their work load. This might lead subjects to alter their ambulation techniques and, in doing so, modify their performance.

The C-9 test environment had the ability to give the subject the experience of true reduced gravity in which all portions of the body and the suit were acted on by the same forces. This environment also allowed subjects to perform tasks unencumbered by hardware that might otherwise influence performance. The acceleration profiles of the C-9 showed that variability occurred in the acceleration provided during parabolas, although the average acceleration was fairly consistent overall. However, perturbations of this kind may lead to increased instability during task execution as the changes in aircraft acceleration are transformed into forces imparted to the subject. These forces may be considerable enough to alter the performance of subjects in reduced gravity because of their magnitude in relation to the already existing reduced GRF.

5.2 Human Performance Comparison Across Environments

5.2.1 Executing tests across different environments

One of the primary difficulties with comparing human performance across different partial-gravity analog environments was preparing for and conducting the tests in as similar a manner as possible across environments. This IST series started by using POGO and then went to the C-9. With the C-9 as a much more restrictive environment with respect to time, volume, and data collection capabilities, it was difficult to replicate the tasks performed on POGO in the C-9. One of the primary lessons learned was that the research team needs to think about how it would test in the most restrictive analog environment first and then set up testing in the other less-restrictive analogs to include this more restrictive test methodology. For example, since only overground ambulation across a short distance could be tested in the C-9, it would need to be tested in the same way on POGO to ensure the most accurate comparison. This does not preclude the research team from doing more on POGO, such as treadmill running, but ensures that the same tasks are performed in all environments.

5.2.2 Ground reaction forces

In general, with a limited range of ambulation speeds available for comparison, the GRF results from C-9 testing seem to be lower in magnitude than those from POGO testing. This may, in part, be the result of differences between testing environments, although the variability in these data make conclusive comparisons difficult. Subjects performing suited ambulation trials did so very slowly on the C-9, and the acceleration variability of the aircraft combined with a short walkway did not allow a stable suited gait to be attained. This, combined with the fact that subjects may have targeted, skimmed, or missed the force plates during ambulation passes, led to the limited data set and high variability of C-9 data seen in Figure 4-3. One can also see in Figure 4-3 the large variability in suited GRF data from the POGO tests. This is attributable, at least in part, to different gait styles adopted by subjects during those tests.

A more decisive conclusion regarding GRF differences between testing environments would require stricter control of test variables. Controlling subject ambulation speeds, for instance, would allow a more direct comparison between the POGO and the C-9 environments. This would provide a better idea of how the unsuited human is affected by the offloading system associated with ground-based partial-gravity simulators (in which limbs are not subject to reduced gravity) compared to more realistic partial-gravity conditions during parabolic flight, without the confounding factor of varied ambulation speed.

5.2.3 Temporal-spatial characteristics

The lack of overlap across a wide range of ambulation speeds prevents direct comparison of temporal-spatial characteristics and other metrics. The large variation in walking cadence seen in the C-9 data (Figure 4-4) indicates that the subjects did not reach and maintain a steady gait pattern through the capture volume, while the variation seen in POGO data indicates a lack of consistency in chosen gait style (running, hopping, loping, bounding, etc.), among other factors. It is likely that a longer walkway on the C-9, more trials, and a matching of ambulation speeds between the C-9 and the ground-based studies would facilitate a more direct comparison.

The dynamic nature of the C-9 environment, limited time per parabola available for task performance, and short walkway affected the ability of subjects to attain a stable gait pattern as they moved through the aircraft during data collection. Conversely, on the treadmill, a more controlled environment was afforded to subjects, one in which unlimited time was available to reach and maintain a steady gait pattern for data collection. Ideally, subjects would perform suited and unsuited ambulation tasks on the C-9 first, at self-selected speeds through a large (10- to 15-m length) walkway/capture volume, and subsequent testing would then be performed in ground-based partial-gravity simulators using a treadmill (and/or an instrumented walkway with a timing system for comparable over-ground ambulation trials) to match speeds for direct comparison.

5.2.4 Kinematics

Some differences are seen in gait mechanics when a person is walking over ground compared to walking on a treadmill (11). These differences are small and generally constant (although they differ for males and females), generally allowing substitution of one test environment for another when studying gait mechanics. It was assumed for the tests described here that the differences would also be relatively small for reduced-gravity environments.

Lower-body gait kinematics were expected to change in simulated reduced-gravity environments (vertical suspension and treadmill systems) as BW support was increased. These changes stem from the reduced dependence on loading to produce forward and vertical motion. Threlkeld et al. and Finch et al. showed the kinematic changes in the lower-body joints as BW support was increased from 10% to 70% (12) (13). The problem then becomes determining which changes are correct and which changes are induced by the partial-gravity analog environment.

The POGO system appears to exert a large influence on ambulation kinematics. The large rotational moments of inertia of the gimbal system seem to inhibit normal transverse plane motion. This added rotational inertia seems to require the lower body to create most of the motion needed by the subject during ambulation. Full-body rotation in the frontal plane would likely increase the efficiency of the subject as it may allow his/her stance width to be reduced. However, this type of ambulation is generally not normal, as it potentially increases the instability of the subject while decreasing his/her ability to recover from perturbations. The added stability that the POGO system and gimbal provide may be what made this adaptation method (rotation coming from the lower body) possible. There was no indication of this adaptation in the ambulation trials on the C-9, indicating that it was not likely a product of suit kinematics related only to the MKIII.

In the sagittal plane, POGO walking resembles an equine type of gait pattern, or stilt walking, that is associated with a large excursion of the COM. This gait pattern is more efficient with respect to muscular energy use, but has less inherent stability. Subjects may have been able to take advantage of the stability provided by the system and use this more economical method of ambulation. Sagittal plane kinematics on the C-9 resembled more of a “crouch gait” pattern and had very little vertical excursion of the COM. This gait pattern is less efficient with respect to muscular energy use, but has more inherent stability. Recent studies have found that reducing COM excursion in normal 1g walking did not decrease energetic cost, but actually increased it (14) (15). On the C-9 the subjects may have been concerned about stability and thus used this method of ambulation to increase their capacity to recover from perturbations. The foot in this case may have been used more as a stability platform and less as a method of propulsion, leaving the ankle joint relatively unused.

The limited volume of the C-9 affected the performance of subjects during ambulation, as they were unable to get to a steady state of ambulation due to the short walkway. The limited height of the airplane may also have contributed to the observed ambulation adaptations.

5.2.5 Center-of-pressure analysis

It is known from previous testing (4) that POGO seems to provide added stabilization to subjects while the C-9 has been shown to possibly have destabilizing effects on subjects (1). On POGO, the average number of times the COP fell outside of the BOS and the total travel of the COP was low and constant for all conditions, with little variability among subjects. Another issue from POGO data was the use of the force plates and the treadmill to assist during the task. It was evident from data that some subjects used the edge of the force plate as leverage but still had the COP within the BOS. This may have occurred because the surface area of the force plates was small. When it occurred, the frame was marked as the COP being outside the BOS. The trials with subjects leaning on the treadmill with contact by the legs were excluded from analysis, but it was difficult to discern the use of the hands or shovel for stability.

The C-9 exploration task area was limited and placed close to the fuselage wall because of seat track locations. The limited duration of the parabolas made it necessary for the tasks to be completed in a short amount of time; that is, subjects had to quickly be helped to a standing position, move to the exploration area, position themselves on the force plates, complete the tasks, and safely return to a seated position before aircraft pullout.

The plates could be lined up directly next to each other during POGO testing, but, on the C-9, they had to be spaced slightly farther apart due to the alignment of the mounting plates with the available seating track. This gave the subjects more area in which to position themselves and could be an explanation for the BOS seen on the C-9 being larger than that on POGO.

5.2.6 Gravity compensation and performance scale

GCPS ratings for the two test environments were quite similar at comparable test configurations during simulated lunar gravity. Extending the comparison to a full trend analysis showed that most of the differences were seen at the lower end of the gravity levels tested; but substantial variability in the data, coupled with differences in task performance, does not allow firm conclusions to be drawn. With subjective data, it would have been ideal to have the same subjects perform the test in both environments, but this was not possible. However, this information provides some indication that at partial-gravity levels $\geq$ 0.17g, POGO and the C-9 lead to similar levels of human compensation required to maintain desired performance of the representative EVA tasks. Also, at gravity levels $\leq$ 0.17g, there is some indication that POGO was artificially influencing performance. Even with these potential limitations, human performance testing on POGO may be relevant over a range of gravity levels when subject and macro-scale comparisons, rather than detailed biomechanical or kinematic analysis, are needed.

6 Summary

The ability to accurately and effectively characterize suited human performance is wholly contingent on understanding the accuracy, limitations, and usability of partial-gravity analog environments. Although parabolic flight may simulate partial-gravity kinetics better than any other environment, the high cost, volumetric constraints, limited parabola duration, and limited data-collection capabilities prevent the use of the C-9 or another parabolic aircraft as the primary partial-gravity analog environment for studying suited human performance.

Although POGO improves on many of the major limitations of parabolic flight, it also introduces several new sources of error including increased inertia, limited DOF, and non-optimized offload kinetics.

The ideal partial-gravity analog environment would combine the partial-gravity kinetics of parabolic flight with a large test area, advanced data collection capabilities, unlimited time, treadmill integration, and mock-up inclusion available with ground-based analogs such as POGO. We believe that many of the major limitations of the POGO can be improved after implementing the following changes:

1. Addition of lateral translational DOF
2. Increased test area space for complete EVA simulations
3. Reduction of overhead inertia of the lift column in all translational DOF

4. Improved Z-axis (vertical) offload kinetics
5. Reduced gimbal mass and inertia
6. Gimbal that supports testing with all existing planetary EVA suit concepts (MKIII and Rear Entry I-Suit)
7. Gimbal that interfaces in a similar way and allows for similar movement and data-collection capabilities for both suited and unsuited testing

If these changes are incorporated into a new, overhead suspension system, we believe that the system would provide an optimal primary test bed on which to characterize suited human performance. Even with all of these improvements, there are still limitations that cannot be removed, including how the lifting path remains only through the CG and anything outside of that lifting path, particularly the limbs and any accessories, will still operate within 1g kinetics. For this reason, parabolic flight should be used for testing that requires that all materials, including the subject, suit, tools, and mock-ups, be at the same partial gravity. Parabolic flight also remains an ideal option for limited verification of ground-based data, assuming the tasks are performed in the same way in both partial-gravity analog environments.

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Appendix A: Biomechanics Definitions and Reference Frames

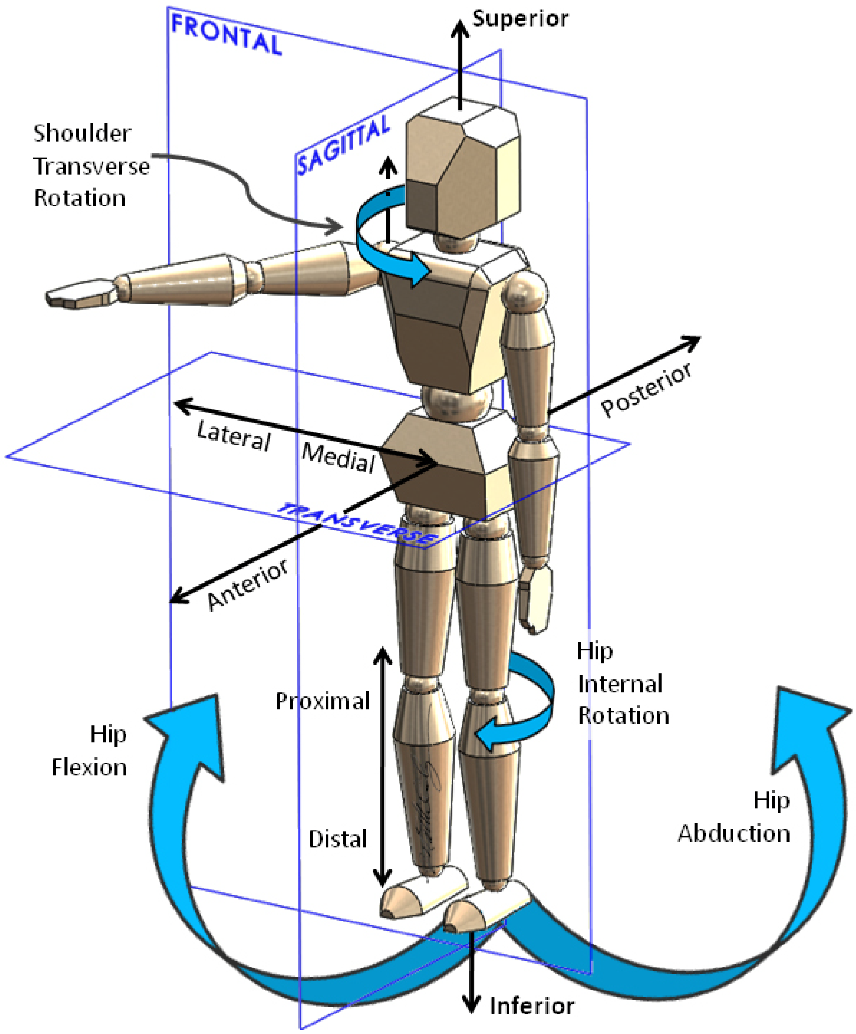

Figure A-1. Commonly used biomechanics nomenclature of the body planes, types of joint motion, and body-based directions.

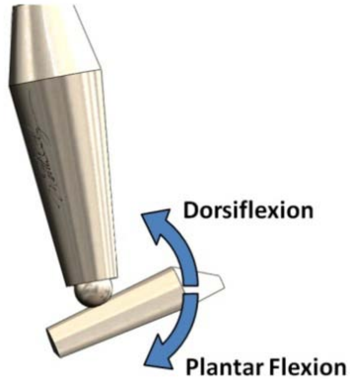

Figure A-2. Designations for the ankle joint directional rotations.

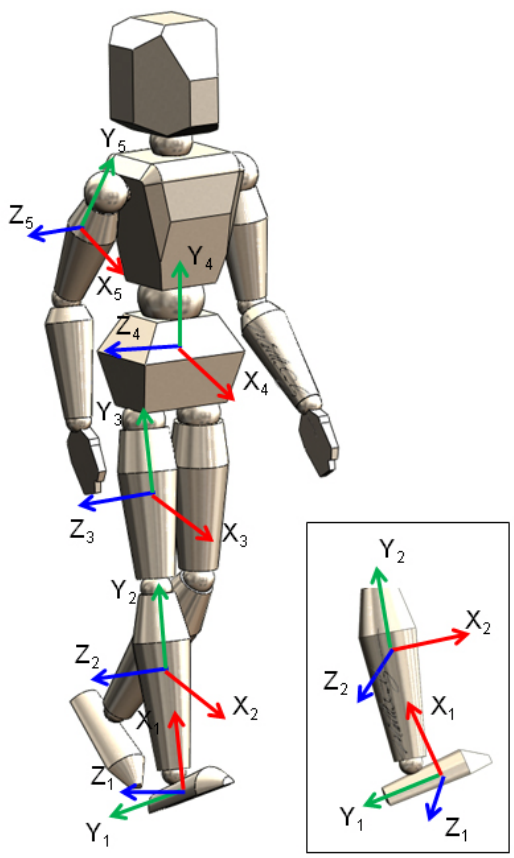

Figure A-3. Convention for local reference frames as prescribed by the International Society of Biomechanics and used by the Anthropometrics and Biomechanical Facility (16). The Y axis usually lies along the long axis of the segment.

Appendix B: List of Variables for Common Equations and Relationships

Linear Motion

Position:	x
Velocity:	v
Acceleration:	a
Mass:	m
Force:	ma
Work:	Fd
Kinetic Energy:	$\frac{1}{2} mv^2$
Power:	Fv

Rotational Motion

Angular Position:	θ
Angular Velocity:	ω
Angular Acceleration:	α
Moment of Inertia:	I
Moment/Torque:	$I\alpha, \tau$
Work:	$\tau\theta$
Kinetic Energy:	$\frac{1}{2} I\omega^2$
Power:	$\tau\omega$

Per CxP 70022-04, the NASA Constellation Interoperability Standards)document, measurements in this report are expressed in standard **SI units**. The following conversions to English units are used:

Mass:	1 kg	=	2.204 lbm
Force:	1 N	=	0.225 lb
Speed:	1 $m{\cdot}s^{-1}$	=	2.237 mph
Pressure:	1 kPa	=	0.145 psi

Appendix C: Gravity Compensation and Performance Scale

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

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13. ABSTRACT *(Maximum 200 words)*

Simulating partial gravity on Earth is difficult. Many methods exist; all have significant limitations. This report focuses on: characterizing the partial-gravity analog environments used during integrated suit tests conducted between 2006 and 2009; how subjects performed in the two testing environments; how the test environments compared with each other; how strengths and weaknesses associated with each environment affected the quality of partial-gravity simulation for human performance testing; and general lessons learned on usability and features of each environment. The primary partial-gravity analog environments discussed are: the Space Vehicle Mockup Facility partial gravity simulator (POGO), which uses a vertically oriented, manually adjusted, servo-controlled pneumatic cylinder to create a selectable offload of a subject and allows for up to 2.4 m vertical travel; and the Reduced Gravity Office C-9 parabolic-flight aircraft, which allows unrestrained movement in all 6 degrees-of-freedom and provides a true lunar-gravity kinetic environment with all aspects of subject and suit offloaded to the same partial-gravity level. We believe a ground-based, partial-gravity analog that has the advantages of POGO while improving on POGO's limitations offers the best primary test bed for characterizing suited human performance. Parabolic flight would then be used for specific tests and limited verification of ground-based simulators.

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