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Enhanced Simulation of Partial Gravity for Extravehicular Activity

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Abstract

Prior studies of human locomotion under simulated partial gravity have hypothesized that energy expenditure is increased in lunar gravity, as compared to that of Mars. This may be due to subjects having to expend excess energy for stability and posture control in the lower gravitational field. The physiological cause of this suspected "wasted energy" during locomotion in low gravity remains to be determined. This paper outlines factors to be considered for these analyses and enhancements to the simulation method that will enable assessment of inertial stability and associated metabolic cost. A novel simulation technique is proposed for assessing the effects of inertial rotation and variable mass on stability, metabolic cost, and biomechanics using a modified weight relief harness to simulate partial gravity.

Introduction

Conducting extravehicular activity (EVA) on the Moon and Mars will require an operations concept that allows scientific exploration to be carried out in as safe and efficient a manner as possible. Various astronaut safety systems may be utilized along with other components of exploration architectures, such as rovers, robotic assistants, and so on, to minimize the risks involved in exploration (Chappell & Klaus, 2004). However, the physiological impact that partial gravity exploration will have on astronaut locomotion still needs to be further researched. These physiological effects need to be understood from both the standpoint of astronaut health and performance as well as to determine the resource requirements needed for planned EVA traverses (Carr & Newman, 2003; Ross, Kosmo, Janoiko, & Eppler, 2004). EVA's conducted on the Moon during the Apollo missions required the use of more life support consumables than expected and resulted in overwork of the astronauts on some exploration traverses (Carr & Newman, 2003; Jones, 2004). A more complete understanding of the factors affecting energy expenditure will improve system design optimization that allows exploration goals to be met, maximize performance of the EVA astronauts, and minimize the rate of use of limited resources. This paper provides a summary of relevant factors associated with partial gravity locomotion energetics, compares partial gravity simulation techniques, and presents a novel reduced gravity simulation enhancement to better evaluate the metabolic cost of lunar EVA.

Background

The factors governing the energetics of partial gravity locomotion are summarized in the flowchart presented in Figure 1. Each factor is depicted as contributing to the total work in terms of kinetic or potential energy. The total work is made up of two components identified as external and internal work paradigms (Margaria, 1976). The external work is the sum of the increases in the potential energy of the body COM (center of mass), kinetic energy of the body COM, kinetic energy of the walking surface, and the kinetic energy imparted to the body rotating about its surface contact point. The internal work is the sum of the increases in the kinetic energy of the body segments relative to the body COM and the kinetic energy of the body rotating about its COM. The forces generated by isometric/opposing muscle contraction during stance, transition, and stabilization is not part of internal or external work, but the body must expend basal energy to contract and hold the muscles in opposition to one another, even though no direct work is done to move a body segment (Saibene & Minetti, 2003). Many of these factors have been investigated, except for inertial rotation about the center of mass. Significant relevant factors from Figure 1 are further discussed in the following sections. Equations describing these factors are shown following Figure 2.

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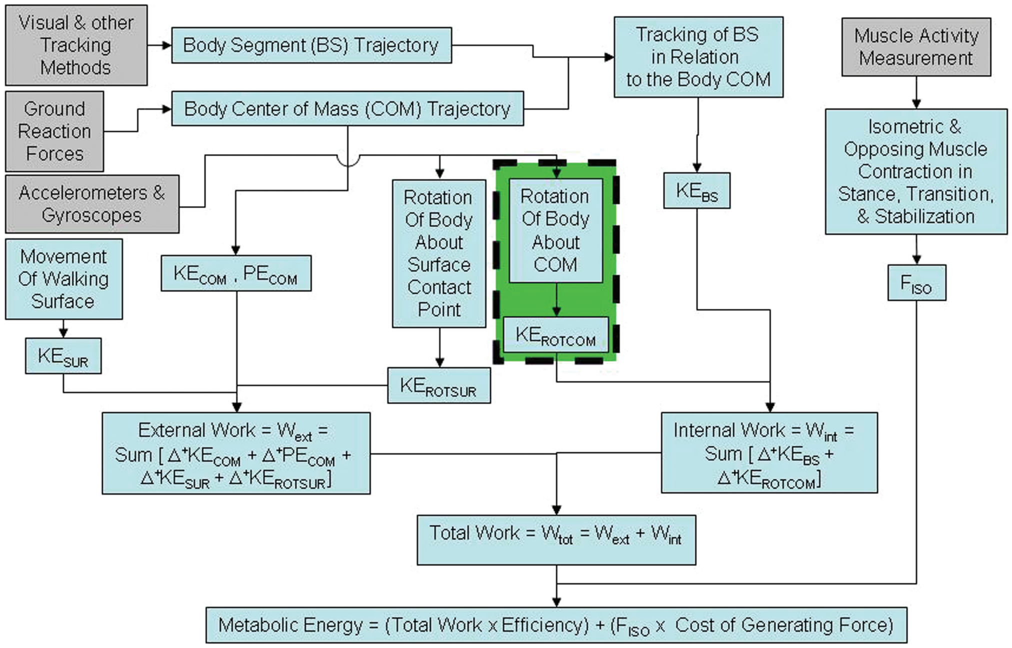

Figure 1. Summary Flowchart: Locomotion Energetics (modified from Saibene & Minetti, 2003). A bold, dotted box surrounds the rotation of the body about the COM, which is a potential contributing factor to increased metabolic cost in running locomotion.

Inertia & stability

Actions taken to maintain stability have an effect on the overall metabolic cost during locomotion and these effects may be amplified in reduced gravity. During studies of human locomotion in the gravitational environments simulating the Moon and Mars, it has been hypothesized that energy expenditure increases for lunar locomotion, as compared with Martian, may be due to subjects "wasting energy" for stability and posture control (Newman & Alexander, 1993). It was noted that further studies regarding the concept of wasted energy for stability during locomotion in low gravity levels need to be conducted.

Stability in the plane of progression is mainly controlled by foot placement in relation to the COM (Bauby & Kuo, 2000). Control of foot placement may be more difficult in reduced gravity due to longer "air time" and less precise force feedback due to insulation from the environment by an EVA suit. In addition, load carrying may increase the overall inertia of the subject, potentially increasing instability and energy expenditure required to stabilize progression in the sagittal plane. Finally, the decreased ability to sense their surroundings (visually as well as tactile force feedback) experienced by astronauts in space suits may further affect their ability to utilize this natural feedback control system, thus causing less effective stability control and associated increase in metabolic cost (Carr & Newman, 2003).

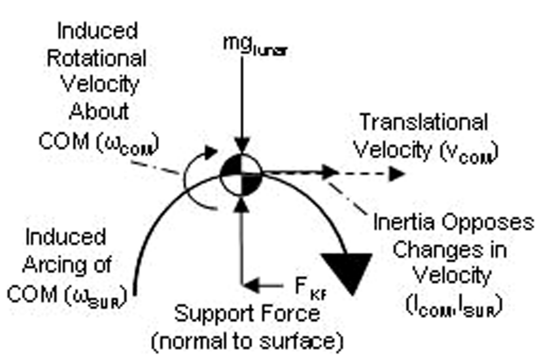

Figure 2. Free body diagram representing significant forces, velocities, and inertias for partial gravity EVA.

The minimal number of direct studies of inertia on locomotion mechanics have thus far concentrated on separating the effect of gravity induced weight and inertia. Results appear to show more of an influence of gravity induced weight over both vertical and horizontal force generation during running (Chang, Huang, Hamerski, & Kram, 2000; Grabowski, Farley, & Kram, 2005). The same studies showed that adding of additional inertia alone (by adding mass and supporting its weight) had no significant effect on the generation of peak active vertical forces on the ground. With some initial downward velocity in a hypothetical zero-gravity running situation, force would need to be exerted against the ground to reverse the direction of the body's COM and to then to raise the COM, illustrating that some of the vertical force generated on the ground by the legs does act to oppose only inertial forces (Chang et al., 2000). Additionally, inertial effects on metabolic cost may be amplified in some gravitational environments and at higher carried mass values in conjunction with the other energetics factors presented. Finally, the methods used to support the subject and added weight in reduced gravity artificially provided stabilization for the mass, thus affecting the ability to make an accurate measurement of inertia alone on ground reaction forces and metabolic cost.

Simulation Techniques

Research objectives and astronaut training are the two traditional purposes for using partial gravity simulations (Deutsch, 1969). The three main techniques that have been employed are: parabolic flight, neutral buoyancy (or partial offload) immersion, and harness suspension systems. Each simulation technique offers advantages and disadvantages as well as being good or poor at reproducing the factors associated with reduced gravity environments.

Table 1 characterizes various factors associated with the three primary simulation techniques described above. The table is gray-scale coded to indicate whether a particular simulation technique is good, moderate, or poor at replicating the conditions or physiological modifications that occur in an actual partial gravity environment. Lunar gravity was chosen for presentation purposes in the table, but the table would be similar for Mars gravity. Finally, only those reduced gravity simulation techniques allowing locomotion are included; other techniques for simulating reduced gravity effects, such as bed rest or dry immersion (Nicogossian, Huntoon, & Pool, 1993), are not included.

The first thing to note about the table is that it is divided across the top into "force and loading factors" and "physiologic/biomechanic factors". The table is also subdivided along the left side into the main simulation techniques, with harness suspension systems having the largest number of variations on the technique. The force and loading factors are the alignment of the resultant force component, resultant structural loading on the extremities, and the freedom of inertial rotation. Although the thesis in this paper is focusing on inertial effects, the other force and loading factors are included here for comparing the different techniques. The physiological/biomechanical factors included for comparison are hydrostatic gradient (decreased within the cardiovascular system), fluid shift (upward fluid shift), blood volume (decreased blood volume), red blood cell mass (decreased), gait (modified in reduced gravity), and energy expended (or metabolic cost) (Clement, 2003; Larson & Pranke, 2002; Nicogossian

Table 1
Simulation Techniques vs. Simulation Quality Factors (see text for references)

		Force and Loading Factors					Physiologic/Biomechanic Factors						
			Resultant Structural Loading on...										
Simulation Technique		Force Component Along Head to Toe Axis	Head	Arms	Legs	Inertial Rotation	Hydrostatic Gradient	Fluid Distribution	Blood Volume	Red Blood Cell Mass	Gait	Energy Expended	Description
Parabolic Flight	Parabolic Flight to 1/6-g	~1/6-g	~1/6-g	~1/6-g	~1/6-g	normal	~1/6-g	~ 1-g	1-g	1-g	~1/6-g	~1/6-g	Treadmill mounted to be horizontal during 1/6-g parabola
Neutral Buoyancy Immersion	Underwater Buoyancy Vertical Off-Load to 1/6-g	1-g	1-g	~1/6-g	~1/6-g	inertia modified due to ballast	1-g	1-g	1-g	1-g	~1/6-g (viscosity)	~1/6-g (viscosity)	Horizontal treadmill; balasting sytem for body, arms, legs to simulate 1/6-g
Harness Suspension Systems	Vertical Off-Load to 1/6-g	1-g	1-g	1-g	~1/6-g	normal	1-g	1-g	1-g	1-g	~1/6-g	~1/6-g	Waist harness only; allowing rotation
	Vertical Off-Load to 1/6-g w/ Mech. Counterpressure	1-g	1-g	1-g	~1/6-g	fully constrained	1/6-g < HG < 1-g	1/6-g < FD < 1-g	1-g	1-g	~1/6-g	~1/6-g	Waist harness; mechanical counterpressure on legs to simulate upward fluid shift
	Sloped Off-Load to 1/6-g	1/6-g	~1/6-g	~1/6-g	~1/6-g	fully constrained	~1/6-g	1/6-g < FD < 1-g	1-g	1-g	~1/6-g (con strained)	~1/6-g (con strained)	Treadmill at ~80°; waist & chest harness; head support; bungee assist for leg and arm movement and to offload weight.
	Horizontal w/ LBNP to 1/6-g	μ-g	1-g	1-g	μ-g	fully constrained	~1/6-g	~1/6-g	1-g	1-g	~1/6-g (con strained)	~1/6-g (con strained)	Treadmill at 90°; waist & chest harness; head support; bungee assist for leg and arm movement; LBNP applied to simulate 1/6-g hydrostatic gradient
	Horizontal w/ LBNP & bungee to 1/6-g	μ-g	1-g	1-g	~1/6-g	fully constrained	~1/6-g	~1/6-g	1-g	1-g	~1/6-g (con strained)	~1/6-g (con strained)	Treadmill at 90°; waist & chest harness; bungee assist for leg and arm movement; LBNP applied to simulate 1/6-g hydrostatic gradient; bungee to simulate 1/6-g structural loading
	Reference												
	Normal Earth Gravity (1-g)	1-g	1-g	1-g	1-g	normal	1-g	1-g	1-g	1-g	1-g	1-g	Earth surface; long-term exposure
	Moon (1/6-g)	1/6-g	1/6-g	1/6-g	1/6-g	normal	1/6-g	1/6-g	1/6-g	1/6-g	1/6-g	1/6-g	Moon surface; long-term exposure

Legend	
Dark Grey	Poor Simulation
Med. Grey	Moderate Simulation
White	Good Simulation

et al., 1993). Many of these effects are duration dependent, therefore, not likely in short simulation periods. Not all effects of exposure to reduced gravity are included; rather the known major effects on energy expenditure are shown.

While Table 1 provides a summary of the techniques, the following subsections describe the techniques and provide information regarding experiments that have used each method.

Parabolic flight

An effective way to create reduced gravity conditions on Earth is by employing Keplerian aircraft maneuvers. This method also induces other effects of reduced gravity such as fluid shift and reduced column pressure in the cardiovascular system (Clement, 2003). To perform these maneuvers, converted passenger jets (NASA's DC-9, Russia's Illushin 76, and the European Space Agency's (ESA) Airbus 330) fly a series of parabolas (Hawkey, 2004; Pletser, 1994). This method of replicating reduced gravity levels is quite accurate but has some limitations. First, it is expensive due to the cost of aircraft fuel and the personnel required to staff and maintain the aircraft. Second, parabolic flights can only provide short periods of reduced gravity. This limits the experiments that can be conducted to that achievable at the selected reduced gravity level (~0 g for 15 seconds, ~3/8 g for 30 seconds, ~1/6 g for 40 seconds) (Hawkey, 2004). Moran (1969) provides a complete review of the Apollo era human factors research using aircraft to simulate reduced gravity (Moran, 1969).

Comparing parabolic flight to the other techniques in Table 1, it can be seen that it is a very good method of simulating the environment, especially from a force and loading factors standpoint. Also, the gait associated with reduced gravity can be well approximated (D. Newman, 1992). The energy expended should also be quite similar to that in the actual reduced gravity environment; however, the interval nature of parabolic flight simulation does not allow for a reliable, stable approximation of energy expended using classical methods (D. Newman, 1992).

Neutral buoyancy immersion

Neutral (or partial) buoyancy involves submerging the experiment participant in a specially designed water tank. Using ballasting techniques, the buoyancy of the subject can be controlled so as to manipulate and control the 'effective weight' of the subject (Hawkey, 2004; D. Newman, 1992; Wickman & Luna, 1996). This technique has been used for over 35 years and is particularly useful for crew training for the 0 g environment of EVA; since tasks can be conducted in real-time and large objects (such as satellite or spacecraft mockups) can be submerged for environmental realism. It has also been used for zero-gravity simulation studies during the last five decades (Trout & Bruchey, 1969).

This technique is advantageous since continuous experimental time periods are available, thus allowing the assessment of biomechanics and steady-state metabolic cost. However, the major constraint that limits the realism of this simulation technique is the inherent hydrodynamic viscosity as well as the need to add ballast mass to the subjects, thus increasing inertia (D. Newman, 1992; D. J. Newman, Alexander, & Webbon, 1994). To try to insure that the ballast weights do not affect the realistic loading of the subject's body segments, an adjustable partial gravity harness can also be used along with ballasting techniques, which tries to distribute the weight on the five body segments as close to the center of mass of each segment as possible. Mathematical models have shown that the hydrodynamics associated with this technique contribute less than 6% to the overall metabolic cost measurements (D. J. Newman et al., 1994). However, studies have not been performed to determine the contribution of the added inertial mass due to ballasting and its effect on gait as well metabolic cost.

Looking at Table 1, the main advantage of the underwater technique is that, through ballasting, the resultant structural loading on the arms and legs can approximate the reduced weight associated with Martian gravity (D. Newman, 1992). However, the added mass associated with ballasting increases the inertial effects even though the weight is reduced. Additionally, the higher viscosity of the water medium as compared to air (or vacuum) causes an increased drag on the body and limbs, modifying gait and energy expenditure (Wickman & Luna, 1996). Finally, the physiological factors of hydrostatic gradient, fluid distribution, blood volume, and red blood cell mass are not simulated with this technique.

Harness suspension systems

The horizontal suspension technique suspends the subject's body parallel to the floor, thus perpendicular to the Earth's gravity vector. This technique has mainly been used to simulate microgravity conditions as are experienced in Earth orbit on the International Space Station. A complicated harness system is used to support the legs, arms, torso, and head at their approximate center of mass. Studies using this technique have shown that ground reaction forces similar to a 1-g environment can be achieved thru the use of bungee cords pulling the subject toward a vertically mounted treadmill (Davis, Cavanagh, Sommer, & Wu, 1996; McCrory, Baron, Balkin, & Cavanagh, 2002). These studies have been valuable in helping to study the effects of treadmill exercise by astronauts in low Earth orbit. Similar hydrostatic gradients and fluid distribution changes can be seen in the short-term. However, blood volume and red blood cell mass changes are only achieved over the long-term, which is not feasible with this technique due to subject discomfort. This technique is also not effective at simulating normal structural loading, inertial rotation, gait, and thus energy expenditure, due to the complex and constrained nature of the harness mechanism. The use of Lower Body Negative Pressure (LBNP) in place of bungee cords with this technique has been investigated with some successful results (Hargens, Whalen, Watenpaugh, & et al., 1991).

A variation between the vertical and horizontal techniques has been performed in several studies. Instead of purely horizontal or vertical suspension, the angle for the walking surface is picked that allows the component of the gravitational force along the body axis to match that of the Moon or Mars, 80.4 degrees and 67.8 degrees from horizontal, respectively. The harness system suspends the subject such that their right or left side faces downward, with the support forces acting laterally rather than in the sagittal plane. This technique was used in the planning and preparation for the Apollo lunar missions and allowed the astronauts to experience walking in simulated lunar gravity levels (Hewes, 1969; Sanborn, Wortz, & Wortz, 1967). Studies were performed to get a measure of the metabolic rates, balance, and stability associated with locomotion by suited astronauts in the simulated lunar gravity level (Letko, Spady, & Hewes, 1967; Robertson & Wortz, 1968). However, this variation on the suspension technique still constrained inertial rotation due to the complexity of the harness system.

Vertical suspension orients the subject so that their body is perpendicular to the floor and an attached overhead system is used to provide the weight relief associated with reduced gravity. The overhead system is generally attached to the subject via a harness system. The weight relief to the desired level of reduced gravity is provided through springs or rubber tubing and a force measurement system to determine the amount of weight compensation (Donelan & Kram, 1997; Margaria & Cavagna, 1964).

Table 1 shows that the vertical suspension technique does a good job of reproducing the reduced gravity resultant structural loading on the legs of the subject. Additionally, inertial effects are preserved and can be studied with this technique (Chang et al., 2000); however, improvements in the harness system design can be achieved and is the main theses of this paper. As in neutral buoyancy immersion, the physiological changes such as fluid distribution are not achievable with this technique.

A variation on the vertical suspension technique includes the use of mechanical or atmospheric counter pressure on the lower body. This variation helps to simulate the upward fluid shift associated with reduced gravity environments (Clement, 2003; Nicogossian et al., 1993; Whalen, Breit, & Schwandt, 1994). The upward fluid shift has effects that are noticeable on the cardiovascular system, mainly heart rate and blood pressure, that may alter the overall energy expenditure associated with exercise (Nicogossian et al., 1993). The upward fluid shift lowers the mass of the legs and increases the mass of the upper torso, thus modifying the inertial properties of the body. However, this technique artificially constrains rotational degrees of freedom so that the effects of inertial rotation cannot easily be ascertained.

Thesis

During the Apollo lunar excursions, very little of the overall EVA time was spent standing or moving at slow, steady speeds. Rather, the astronauts were nearly continuously in a loping gait, having traction problems, and starting, stopping, or changing direction while attempting to perform their planned work (Jones, 2004). Additionally, the lunar terrain was undulating and the exploration traverses took the astronauts onto sloped terrain that tended to cause large increases in the astronauts overall metabolic cost (Carr & Newman, 2003; Jones, 2004). Considering these points, the majority of the astronaut's time on the surface was spent in unstable locomotion and, thus, the factors involved in determination of metabolic cost should include the effect of overcoming inertia. Even during constant velocity locomotion, at speeds high enough to cause both feet to be off the surface, there is potential for inertial rotation about the COM to be a significant factor. The significance of inertial effects may be amplified at low gravity levels and because of increased inertia due to the weight of added EVA life support systems.

To help describe the thesis, a free-body diagram along with energy, moment, and work equations have been assembled that determine the overall energetics involved in partial gravity EVA, as shown in Figure 2. The figure shows the main forces and velocities acting on the subject, and the contribution to the internal and external work are shown in the equations that follow. Note that the key factor of rotation about the overall COM is also shown.

The potential energy (PE) and the kinetic energy (KE) associated with partial gravity EVA can be defined as follows:

$$PE = mg_{lunar}h_{COM} \tag{1}$$

$$KE = 0.5mv_{COM}^2 + 0.5m_{BS}v_{BS}^2 + 0.5m_{SUR}v_{SUR}^2 + 0.5I_{SUR}\omega_{SUR}^2 + 0.5I_{COM}\omega_{COM}^2 \tag{2}$$

The moment about the COM (M_{COM}) and the moment about the surface contact point (M_{SUR}) are as follows:

$$\Sigma M_{COM} = I_{COM}\omega_{COM} \tag{3}$$

$$\Sigma M_{SUR} = I_{SUR}\omega_{SUR} \tag{4}$$

The external work (W_{ext}) is then the changes in PE and KE associated with the COM, the work done in moving loose surface material, and the work done in rotational of the COM about the surface contact point:

$$W_{ext} = \Delta\left[mg_{lunar}h_{COM} + 0.5mv_{COM}^2 + 0.5m_{SUR}v_{SUR}^2 + 0.5I_{SUR}\omega_{SUR}^2\right] \quad (5)$$

The internal work (W_{int}) is the change in the KE of the body segments (subscript 'BS') in relation to the COM, and the rotation of the subject about the COM.

$$W_{int} = \Delta\left[0.5m_{BS}v_{BS}^2 + 0.5I_{COM}\omega_{COM}^2\right] \quad (6)$$

The total work (W_{tot}) can then be determined as the sum of the W_{ext} and the W_{int}, as follows:

$$W_{tot} = \Delta\left[mg_{lunar}h_{COM} + 0.5mv_{COM}^2 + 0.5m_{SUR}v_{SUR}^2 + 0.5I_{SUR}\omega_{SUR}^2\right] + \Delta\left[0.5m_{BS}v_{BS}^2 + 0.5I_{COM}\omega_{COM}^2\right] \quad (7)$$

with variable definitions for equations (1) through (7) of:

g_{lunar} = Acceleration due to lunar gravity,

h_{COM} = Height of COM above walking surface,

I_{COM} = Moment of inertia about the COM,

I_{SUR} = Moment of inertia about surface contact,

KE = Kinetic Energy,

m = Overall mass,

m_{BS} = Mass of the body's segments,

m_{SUR} = Mass of moving surface material,

M_{COM} = Moment about the center of mass,

M_{SUR} = Moment about the surface contact,

PE = Potential energy,

v_{BS} = Velocity of the body's segments,

v_{COM} = Velocity of the overall center of mass,

v_{SUR} = Velocity of the surface material,

ω = Angular velocity,

ω_{COM} = Angular velocity about the COM,

ω_{SUR} = Angular velocity about surface contact,

W_{ext} = External component of total work,

W_{int} = Internal component of total work,

W_{tot} = Total work.

While the sum of the moments about the COM is zero over time, during locomotion, moments are being generated in both directions in the sagittal plane with each step. The larger the moments that are generated with each step, the larger the external work may need to be to redirect the COM and maintain on overall stable moment about the center of mass of zero.

This thesis asserts that the energy expenditure during running locomotion in simulated partial gravity will be affected if rotation about the COM is allowed to freely occur vs. rotation being artificially constrained by the simulation hardware, due to the potentially higher metabolic costs incurred in overcoming this inherent instability in the real environment.

To test this thesis and more effectively reproduce the metabolic cost of partial gravity locomotion under simulation conditions, an enhanced harness suspension system has been developed. The new system has two central points of attachment, one on each side of the approximate center of mass of the subject, to allow free rotation in the sagittal plane. An overhead rectangular aluminum frame is used to support 1" tubular webbing and prevent contact with the body, thus allowing a free range of rotational motion. The webbing comes down to a central point on each side of the subject and clips through a metal ring on a waist harness. The fore/aft and up/down position of the rings can be adjusted to match the measured COM of the subject and any added mass the subject is carrying. This novel harness method is proposed to offer an improved partial gravity simulation technique for evaluating the metabolic cost of planetary surface EVA locomotion that takes into account inertial instability. The enhanced harness suspension system is shown in Figure 3.

Discussion

The four main objectives of the thesis presented in this paper toward advancing the engineering and operations knowledge required for advanced EVA operations on the Moon and Mars are summarized in Table 2.

The first objective of the proposed research is to improve the simulation capability of partial gravity locomotion

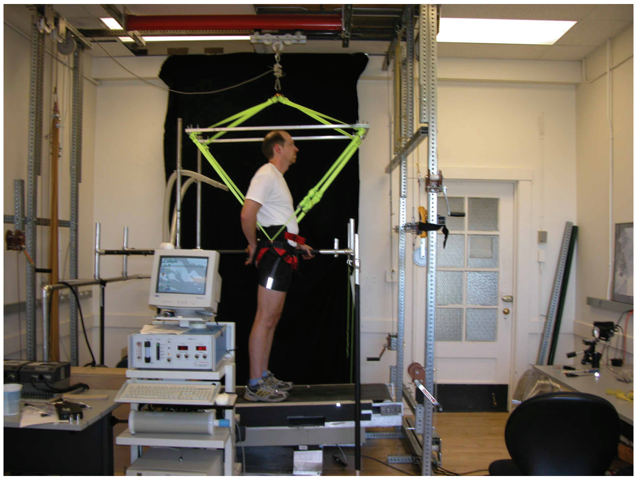

Figure 3. Novel weight offload apparatus for improved partial gravity locomotion simulation.

conditions by the introduction of an enhanced harness design to be used in conjunction with a vertical offload system. To summarize, the altered harness design will allow more realistic rotation capability about the suspended subjects center of mass in the sagittal (path of progression) plane. This increased freedom of motion is hypothesized to more accurately simulate the conditions associated with low gravity conditions by allowing inertial rotation and, thus, the natural instabilities that go along with it.

The second objective of this research is an outcome of accomplishing the first. Through the first objective, a more complete understanding of inertial effects may be obtained, leading to a better understanding of the energy requirements associated with exploration in low gravity levels.

The third objective is a natural follow-on from the first two. Recommendations and guidelines can be established to improve planetary EVA suit designs to account for inertial effects and thus optimize astronaut performance, system design, and support equipment integration.

Finally, objective four further applies the knowledge gained to fine-tuning a more accurate prediction of the ability to perform EVA tasks based upon the design of the planetary EVA suit. This will allow for EVA traverse planning that is more accurate and thus help to minimize the risks associated with complicated and sometimes ad hoc activities that may be involved in future exploration activities on the Moon and Mars.

Table 2
Objectives of thesis to EVA engineering and operations

Engineering/Operations Objectives
Improved Harness Design for Simulation of Reduced Gravity EVA
Increased Understanding of the Life Support Resource Needs for Moon & Mars EVA
Improved Design Guidelines for EVA Suit & Support Equipment
More Accurate Task Performance Predictions for Moon & Mars EVA Traverse Planning

These objectives suggest that further research of the established thesis can provide valuable engineering and science contributions to the future of space exploration.

Author note

At the time of original acceptance of this manuscript in 2005, Dr. Steven P. Chappell was a PhD candidate in Aerospace Engineering Sciences and Dr. David M. Klaus was his doctoral thesis advisor and an assistant professor in Aerospace Engineering Sciences; both were resident at the University of Colorado (CU). Due to a transition of journal editors and home institution, this article did not go to press then as was originally intended. Currently, Dr. Chappell is an exploration EVA researcher with the Wyle Science, Technology, and Engineering Group at NASA Johnson Space Center; Dr. Klaus is now an Associate Professor at CU. For any questions regarding this paper, Dr. Chappell can be reached at: Wyle Science, Technology, & Engineering Group, 2101 NASA Parkway, Mail Code Wyle/HAC/37C, Houston, TX, 77058, email: steven.p.chappell@nasa.gov.

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