A review of ambulation energy expenditure in hypogravity analogs

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INTRODUCTION

Future missions to the Moon and Mars further humanity's trek into space and simultaneously relay groundbreaking knowledge back to Earth. Equipment deployment, sustainable outpost construction, geological sampling, and mission-facilitating resource discovery are the key tasks involved in this trajectory and result in a substantial increase in the number and complexity of extravehicular activities (EVAs). In particular, planetary EVAs will be more complex than those conducted on the International Space Station due to the required ambulation between work sites on the surface [Mars Architecture Steering Group, 2009]. Gas-pressurized spacesuits, such as the current Exploration Extravehicular Mobility Unit (xEMU), can be cumbersome. High pressure, improper fit, significant mass penalties, and movement-induced volume fluctuations inhibit astronaut performance and negatively impact mission success [Anderson *et al*., 2013, Scheuring *et al*., 2009, Belobrajdic *et al*., 2021, and Kluis *et al*., 2021]. To mitigate these operational shortcomings and support mission planning, a robust metabolic model for planetary ambulation is advantageous [Márquez et al., 2008]. An accurate model for EVA ambulation will require a robust energy expenditure model for walking in hypogravity (i.e., $0 < g < 1$) environments. Unfortunately, current metabolic models for walking in Earth gravity vary widely in predictive performance and poorly account for changes in gravity level, if at all [Norcross *et al*., 2010, Carr *et al*., 2009, Márquez, 2007, Givoni *et al*., 1971, and Bobbert, 1960].

While there is an abundance of physiological, biomechanical, and computational information available regarding ambulation under gravitational acceleration equal to 1-*g*, very little is known about human movement in sustained hypogravity. In addition to comparing three hypogravity analogs, this study presents a plan to investigate ambulation in a partial gravity environment and proposes an approach to evaluate experimental and open-source data.

COMPUTATIONAL FRAMEWORK & COMPARISON

A robust metabolic model for partial gravity ambulation is a valuable tool for future EVA planning, Lunar and Martian mission operations, and spacesuit performance measurements [Sainz Ubide *et al*., 2020]. A metabolic model aids in identifying the key contributing factors to overall energy expenditure and helps determine designs and methodologies for reducing an astronaut's total metabolic cost.

Hypogravity analogs form the basis for which the computational framework is validated. A comparison can be made between the following hypogravity analogs: body weight support systems [Farley *et al*., 1992, Wortz *et al*., 1966, and Hazard, 1965], water immersion [Margaria *et* al., 1957 and Ferguson *et al*., 1963], and Lower Body Positive Pressure (LBPP) [Cutuk *et al*., 2006]. Each analog has advantages and disadvantages in the context of modeling human ambulation in partial gravity. Recognizing the key features of each will allow for a more precise and complete understanding of their contributions to the field.

The mechanical nature of body weight support systems engenders their simplistic usage. These mechanisms are typically used in conjunction with a treadmill to assess metabolic rates, gait patterns, kinetics, and general biomechanics. However, body harnesses typically used with this hypogravity analog might cause an uneven distribution of vertical force, impacting a subject's gait pattern [Mignardot *et al*., 2017]. The NASA Active Response Gravity Offload System (ARGOS) uses a body weight support system to test and evaluate spacesuits. This device is shown in Figure 1 [Bekdash *et al*., 2020]. Simpler devices may also be used for unsuited hypogravity tests, such as the "*Moonwalker III*" simulator at the Massachusetts Institute of Technology [Harvey, 2020].

Hypogravity can also be simulated with buoyant forces. Complete and partial water immersion exploits buoyant forces to offload the subject to simulate hypogravity. Unfortunately, water immersion studies entail complex testing and machinery. Additionally, the water surrounding the subject induces resistance to movement, although hydrodynamic studies have indicated that the impact of water resistance on metabolic rate may contribute as little as 6% [Newman *et al*., 1994]. NASA uses water immersion analogs for

FIGURE 1: Spacesuit testing with NASA's body weight support system ARGOS.

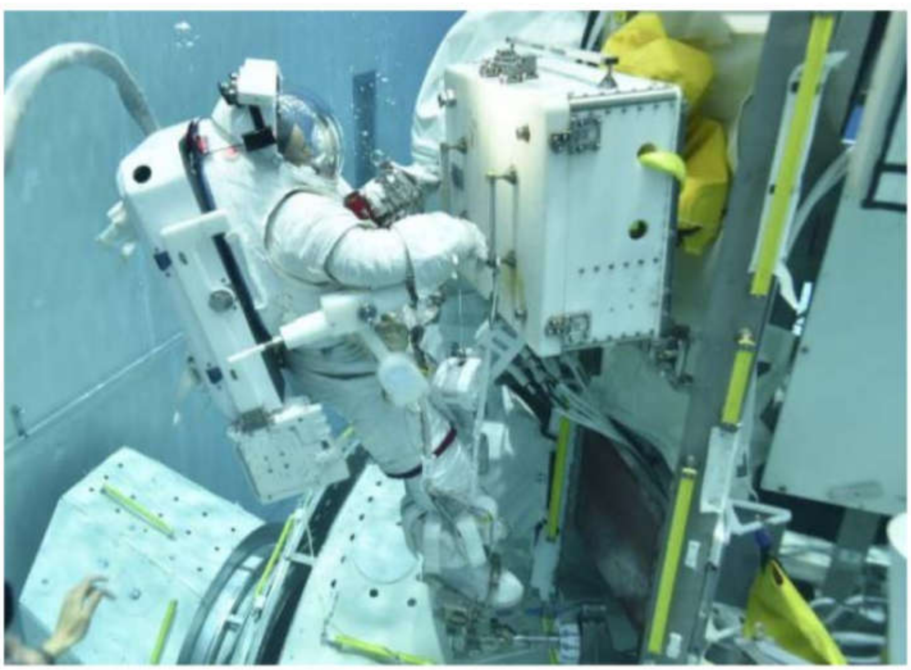

FIGURE 2: Astronaut training in the neutral buoyancy laboratory (NBL) where microgravity conditions can be simulated.

EVA training (Figure 2) [Davis *et al*., 2019], and the University of Maryland uses water immersion analogs for biomechanics testing [Mirvis, 2011].

Another analog, LBPP, increases air pressure on the lower portion of a subject, creating a lifting force with minimal disturbances to gait mechanics [Tajino *et al*., 2019]. While the positive pressure creates an even distribution of force across the lower body of the subject, there are concerns in using the device due to the high-pressure differences between upper and lower halves of the body. In addition, these systems are complex; unintended horizontal forces can arise from poor interfaces between the human and the device [Cutuk *et al*., 2006 and Grabowski *et al*., 2008]. The device used by Cutuk *et al*. capitalizes on a rigid structure with a flexible seal while the device used by Gabrowski and Kram employs a flexible pressurized tent.

FUTURE WORK

To enhance current metabolic models for partial gravity ambulation, body weight support tests will be completed on a treadmill to simulate multiple hypogravity environments. Twelve subjects between the ages of 18 and 45 will be offloaded using a crane and harness mechanism. Subject heights, weights, and leg lengths will be measured prior to testing. Each subject will walk at speeds ranging from 1 to 4 mph at gravity levels ranging from 0.12-*g* to 1-*g*. A portion of the 1-*g* trials will include walking with the addition of 25 and 50 pounds. Throughout these tests, the COSMED K5 wearable metabolic system will collect gas calorimetry data while a VICON motion capture system will collect kinematic data. In addition, ground reaction forces will be sampled with force plates located in the treadmill. The data and results from these tests will be integrated into a larger pool of metabolic data for ambulation in a variety of gravity levels, speeds, suited conditions, and hypogravity analogs. Models will then be created from this data using multiple methods including classical multivariate regression and machine learning techniques such as recurrent neural networks. These models will help with future spacesuit designs and the integration of new technologies [Kluis *et al*., 2021 and Kluis *et al*., 2021].

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