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The Metabolic Cost of Walking in Simulated Martian Gravity and its Implications

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ABSTRACT

Brown E, Russomano T, Bueno B, Bandeira L, Disiuta L, Lamadrid I, da Rosa M, de Lima JCM, Baptista RR, da Luz Dias R. The Metabolic Cost of Walking in Simulated Martian Gravity and its Implications**. JEPonline** 2018;21(1):25-35. Lower body positive pressure (LBPP) is an effective way of simulating hypogravity. This study measured the submaximal VO_2, VCO_2 and heart rate when walking on an LBPP treadmill at 1G and simulated Martian gravity (0.38G). Twelve healthy subjects with a mean age ± SD of 22.75 ± 5.38 yrs took part in this study with full consent. The LBPP box used was designed and built by the Microgravity Center. The subjects walked for 8 min at a control of 1G and then for another 8 min in simulated 0.38G 2 wks later. VO_2 was 1.00 ± 0.61 L·min^{-1} at 1G and 0.68 ± 0.33 L·min^{-1} in the simulated 0.38G ($P<0.05$). Average caloric expenditure was significantly reduced at simulated Martian gravity (4.79 ± 2.80 kcal·min^{-1}) when compared to the control (3.37 ± 1.49 Kcal·min^{-1}) ($P<0.05$). The subjects' HR was reduced from 118.49 ± 15.07 beats·min^{-1} at 1G to 106.20 ± 11.17 beats·min^{-1} at simulated 0.38G ($P<0.05$). The average respiratory exchange ratio was significantly increased from 0.83 ± 0.13 to 1.14 ± 0.19 in simulated 0.38G ($P<0.05$), with no significant difference seen in VCO_2. Energy consumption was significantly decreased when walking in LBPP simulated hypogravity. Further research into LBPP physiology can be used to calibrate EVA suits and advise on exercise regimes for future astronauts.

Key Words: Hypogravity, LBPP, VO_2 max, Walking

INTRODUCTION

The inverted pendulum theory of gait is commonly used to model walking. If the leg is assumed to be rigid during the stance phase of gait, then potential energy and kinetic energy are conserved allowing for no muscle input (5,6). However, normal walking incurs a significant metabolic cost. In healthy untrained adults, walking at a self-selected comfortable speed demands 32% of maximal oxygen consumption (VO_2 max). This significant energy expenditure can be explained by muscles in the lower limbs moving the body's center of mass both in a forward and upward direction against the force of gravity (16). Vertical ground reaction force (vGRF) quantifies the work done by the foot against the ground. When ambulating in an environment where body weight is reduced (such as the Moon, Mars, and ground-based hypogravity simulations), the metabolic cost of walking is expected to decrease. This is due to less work is being done to move the body's center of mass (6,18).

Research has shown that oxygen consumption decreases when ambulating with a reduced body weight. Ruckstalh et al. (18) demonstrated a reduction in VO_2 when walking in lower body positive pressure (LBPP) simulated Martian hypogravity. In a study conducted by Salisbury et al. (19) using a body suspension device, no significant change was observed in VO_2 during the simulation of reduced apparent body weight. The authors suggest this was due to the subjects decreasing self-selected walking speed in increasing hypogravity. Fox et al. (10) simulated hypogravity by suspending the subject's body parallel to the floor in a slowly rotating room with feet in contact with a treadmill at 90°. They reported that VO_2 per unit of mass decreased as body weight was reduced, which is in concordance with the findings of Salisbury et al. (19). However, it was noted that there was no significant difference with net VO_2 per weight, confirming that metabolic work decreases as body weight is reduced (10).

Metabolic power ($W \cdot kg^{-1}$) is another measure of physiological work performed by the body derived from respiratory data. Grabowski (11) found that as apparent body weight decreased using an LBPP box, net metabolic power (NMP) was reduced when walking at the same velocity. Therefore, at a walking pace of 1 $m \cdot sec^{-1}$, NMP is 100% when body weight is 100%. However, when it apparent body weight is reduced to 27%, NMP decreases between 40% and 60% (11).

These observations indicate that energy consumption is reduced for both walking and running in simulated hypogravity. When comparing walking and running independently, Farley et al. (8) observed that with a body weight reduction to 25% by means of a body suspension system, energy consumption was decreased by 72% when running, and 33% when walking. This suggests that running is more energetically efficient than walking in hypogravity.

When comparing Farley et al.'s (8) data to Grabowski's findings (11), the reduction in energy consumption when walking in simulated hypogravity is not as pronounced (8,11). This difference may be due to the different modalities of body weight support, as LBPP does provide some horizontal and lateral support. When walking at increased speeds in LBPP simulated hypogravity, VO_2 is maintained as similar to normal weight walking, while vGRF is significantly reduced. This principle has also been observed when running at higher speeds (11,17). As vGRF mirrors a reduction in joint loading, injured patients can exercise in simulated hypogravity with the same physiological cost, but at less detriment to their joints, muscles, and bones (22).

Measuring heart rate (HR) during ambulation gives an indication of the metabolic work performed. Using an LBPP box, walking in simulated Lunar gravity compared to walking in simulated Martian gravity incurs a significant increase in heart rate (P=0.077) (20). The observation that HR is reduced when ambulating in simulated hypogravity may be true only for low body weights like on the Moon, as Denning et al. (7) showed that at a 40% reduction in body weight using LBPP, HR was not significantly decreased. However, when observing exercise in hypogravity simulated by parallel body suspension, a decrease in HR in 0.5G and 0.25G is seen when compared to 1G (10).

These studies shed light on the effects of simulated hypogravity during locomotion. This study will use a combination of VO_2, carbon dioxide expenditure (VCO_2), and heart rate to establish a detailed picture of how metabolism changes in a simulated Martian setting. It is imperative that the limitations or benefits of ambulating in reduced gravity are well understood. The LBPP box has the potential to be used as an effective tool to aid in rehabilitation of injured orthopaedic and frail patients (22). A complete understanding of the physiological effects of unloading the body will aid in constructing exercise and rehabilitation regimes. The findings can also be applied to real hypogravity environments, such as the Moon and Mars. On long term missions, anticipating any problems before they arise will allow for a large reduction in risk for the astronauts.

This study measured submaximal VO_2 and VCO_2 when walking on a LBPP treadmill at 1G and simulated Martian gravity (0.38G). Heart rate and system data were also compared between 1G and simulated Martian gravity. These variables were measured with the objective of finding out if there is any significant difference in metabolic energy expenditure when ambulating in 1G compared to simulated Martian gravity. The purpose of this study was to investigate the difference in metabolic cost between these two conditions. The subjects' caloric expenditure and average respiratory exchange ratio (RER) were used to determine the difference.

METHODS

Subjects

This study took place at the John Ernsting Aerospace Physiology Laboratory and Aerospace Biomechanics Laboratory, MicroG Center, PURCS. Ethical approval (protocol 310.619) was granted from the Pontifícia Universidade Católica do Rio Grande do Sul (PURCS). All subjects signed a consent form prior to starting data collection, thereby providing informed consent. All 12 subjects were healthy. Trained athletes were excluded from this study.

The weight and bare-footed height of the subjects were measured at the control (1G). A Polar S610 heart rate monitor (Polar Electro Oy, Finland) was then strapped to the subjects' torso. An LBPP box treadmill, developed by the MicroG Center, Brazil, was used to simulate hypogravity. The treadmill was placed inside an inflatable plastic box within a steel frame with dimensions of 2.3 m in length, 0.97 m in width, and 1.3 m in height.

The subjects were required to wear neoprene shorts before being zipped into the box to create an airtight seal. An external motor was used to inflate the box to the specifications required to simulate hypogravity. The positive pressure inside the box created a ‘piston effect’ that decreased the apparent weight of the subject. After zipping each subject into the LBPP box, the face mask was connected to the VO2000 gas analyzer (Medical Graphics Corporation, St. Paul, Minnesota, USA), which was calibrated before each collection of data. Aerograph 4.3 Software (AeroSport Inc., Ann Arbor, MI, USA) was used to record and analyze the data collected from the VO2000.

The LBPP box was set to 1G and the treadmill at a speed of 5 $km \cdot h^{-1}$ (1.39 $m \cdot sec^{-1}$). The subject was then instructed to walk for 8 min. Heart rate data were collected every minute using the Polar S610 wrist watch. At the end of the 8-min period, the subject was helped out of the LBPP box and asked to complete a Borg Scale (3) that documented his perceived exertion. Due to operational reasons, the study design was non-randomized and, therefore, this protocol was repeated at simulated Martian gravity (0.38G) for each of the 12 subjects 2 wks after their control walk at 1G.

The subjects’ energy expenditure was determined based on the consumption of oxygen (VO_2) and the production of carbon dioxide (VCO_2). Assuming that all O_2 consumed was used for the oxidation of macronutrients and all CO_2 produced was captured during the test, it was possible to calculate the subject’s metabolic rate (9,14,15). The equation proposed by Weir (21) was used to obtain values in $kcal \cdot min^{-1}$, which does not require the use of protein metabolism by incorporating a correction factor $[(3.9 \times VO_2) + (1.1 \times VCO_2)]$ (20).

Statistical Analysis

Variable, subject, and system data were tabulated on Microsoft Excel. Caloric expenditure and average RER was calculated from the respiratory gas data. The mean ± SD was derived for each data set. Student’s *t*-test for paired samples was used to determine if the data from the two environments were significantly different from one another. Statistical significance was set at an alpha level of $P<0.05$. This was performed using the GraphPad InStat v3.00 for Windows software.

RESULTS

All 12 subjects’ with a mean age of 22.75 ± 5.38 yrs who took part in the study completed the full protocol. The mean ± SD height and weight for the subjects were 161.25 ± 7.64 cm and 58.67 ± 8.15 kg, respectively.

Oxygen Consumption

Figure 1 shows the average results of VO_2 during exercise. Mean ± SD VO_2 was 1.00 ± 0.61 $L \cdot min^{-1}$ in 1G compared to 0.68 ± 0.33 $L \cdot min^{-1}$ in simulated 0.38G, showing that oxygen consumption was significantly higher ($P=0.0036$) during terrestrial walking than the simulated Mars hypogravity environment.

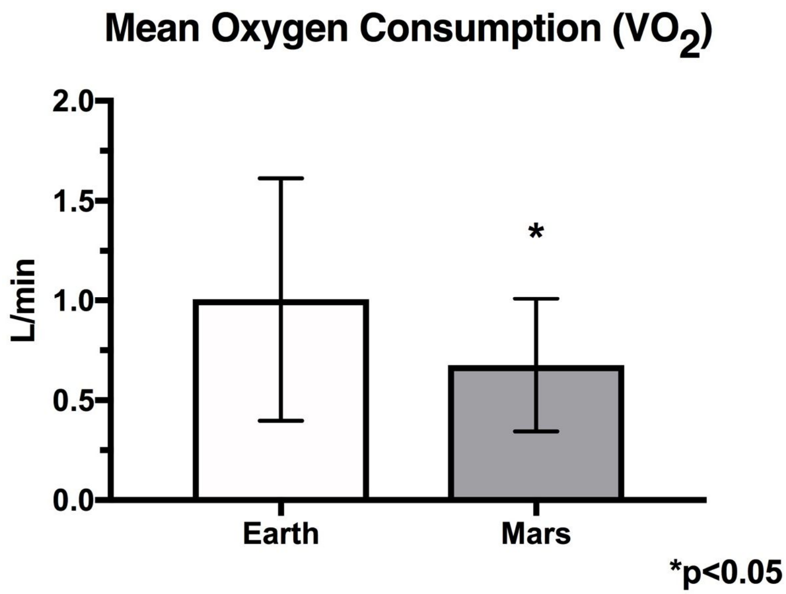

Figure 1. The Subjects' Average Oxygen Consumption (VO_2) during the 8-min Walk Performed in the Terrestrial Environment (Earth, 1G) and the Simulated Hypogravity Environment (Mars, 0.38G). *P<0.05

Heart Rate

During walking, the HR values ranged from 90 to 140 beats·min^{-1}, which is in accordance with the type of exercise performed (4). However, the mean HR decreased from 118.49 beats·min^{-1} at 1G to 106.20 beats·min^{-1} at simulated 0.38G (P=0.0037). This finding indicates less work was required from the body during simulated hypogravity (Figure 2).

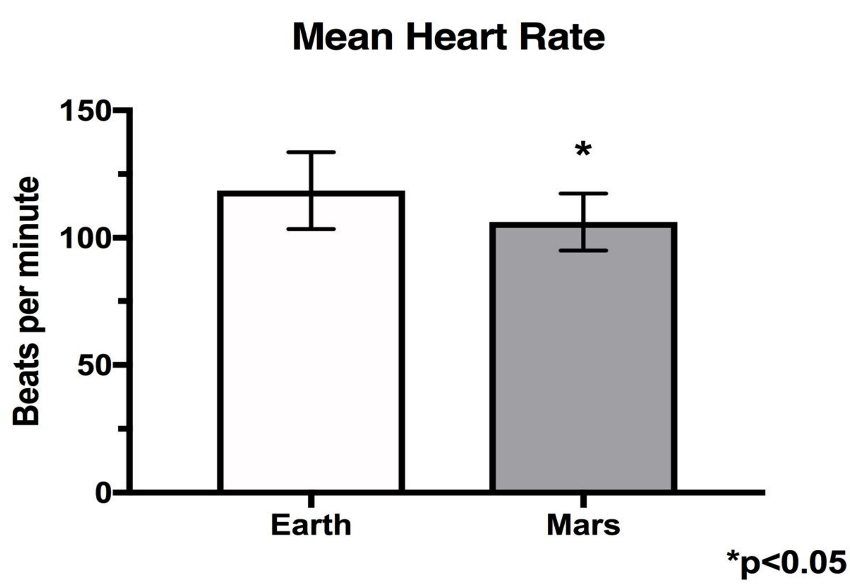

Figure 2. The Subjects' Heart Rate during the 8-min Walk in the Terrestrial Environment (Earth, 1G) and the Simulated Hypogravity Environment (Mars, 0.38G). *P<0.05

Caloric Expenditure

Calorie expenditure was calculated from the equation proposed by Weir (21), which uses the average values of VO_2 and VCO_2 ($L \cdot min^{-1}$) obtained to estimate the calorie consumption in $kcal \cdot min^{-1}$ (21). At 1G walking, the mean caloric expenditure was 4.79 ± 2.80 $kcal \cdot min^{-1}$. When body weight was unloaded to simulate 0.38G, it decreased to 3.37 ± 1.49 $kcal \cdot min^{-1}$ (P=0.045), as shown in Figure 3.

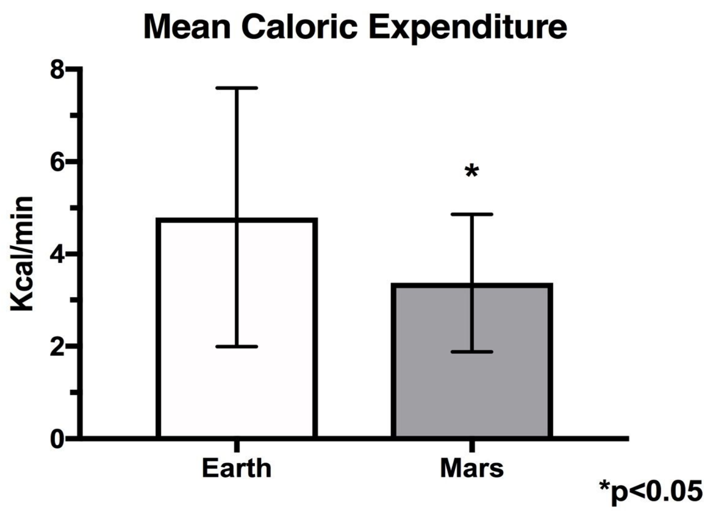

Figure 3. Caloric Expenditure during the 8-min Walk Performed in the Terrestrial Environment (Earth, 1G) and the Simulated Hypogravity Environment (Mars, 0.38G). *P<0.05

Respiratory Exchange Ratio

The data for the RER, which is related to the quantification of the use of different energy substrates during exercise, are shown in Figure 4. There was a significant difference in this variable, showing a greater RQ while walking in the simulated the Martian gravity (P<0.0042). Between the two conditions, the mean RQ increased from 0.83 ± 0.13 at 1G to 1.14 ± 0.19 at simulated 0.38G. This finding is in agreement with the results in Figure 1 that shows a lower VO_2 when walking in Martian hypogravity.

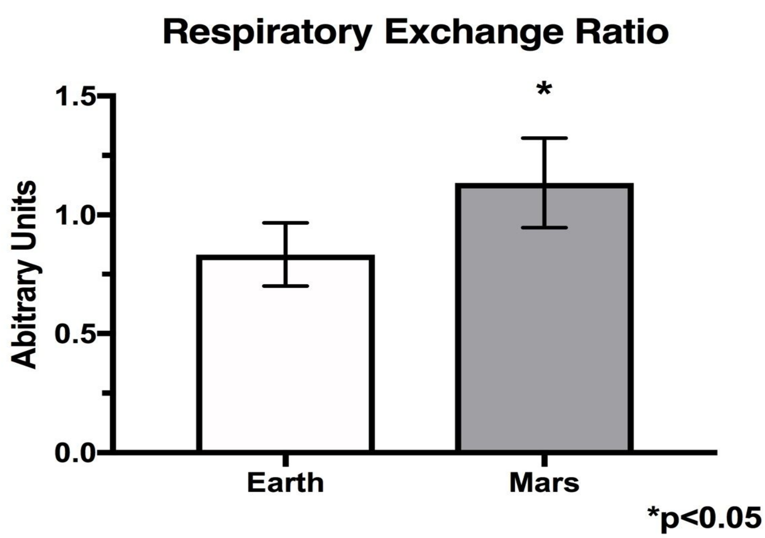

Figure 4. Respiratory Exchange Ratio during the 8-min Walk Performed in the terrestrial Environment (Earth, 1G) and the Simulated Hypogravity Environment (Mars, 0.38G). *P<0.05

Carbon Dioxide

The volume of carbon dioxide produced (VCO_2) by the lungs was a mean of 0.80 ± 0.41 $L \cdot min^{-1}$ at normal body weight and 0.67 ± 0.19 $L \cdot min^{-1}$ in simulated Martian gravity. No statistically significant difference was found between the two conditions. This finding indicates that even though VO_2 decreases, VCO_2 is not affected by reducing apparent body weight.

Borg Score

There was no significant difference in the Borg score between the two tested conditions. The average score of the control was 10.33 ± 1.15 points compared to 11.00 ± 1.35 points in simulated Martian gravity.

DISCUSSION

The results of this study indicate a clear physiological difference between walking in 1G and in simulated Martian gravity. A significant decrease in VO_2 was observed when body weight was unloaded to 0.38G. Interestingly, the effect of walking in varied states of body unloading has been previously measured. Ruckstuhl et al. (18) unloaded 10 subjects to a body weight of 33% using an LBPP box, which is comparable to Martian gravity (0.38G). Oxygen consumption significantly decreased when compared to walking at the same velocity at 1G. This relationship is more prominent when the treadmill speed is increased.

Fox et al. (10) also demonstrated a decrease in VO_2 as body weight was reduced. They used body weight suspension to simulate hypogravity. Their subjects' body weight was reduced to varying levels, with the closest approximation to Martian gravity being a decrease to 0.25G. At the walking speed of 4.7 $km \cdot h^{-1}$, which is similar to the present study's use of 5 $km \cdot h^{-1}$, VO_2 was significantly decreased (10). Given two different methods of simulated hypogravity, both produce the same physiological effect.

Given that the results of the present study are in accordance with previous research in the field, the simulation of hypogravity can be seen as accurate. The repeatable observation concerning VO_2 confirms that energy expenditure decreases when body weight is unloaded. This can be explained with the understanding that energy is used when walking to move the body's center of mass against the force of gravity. Thus, when gravity is reduced, the body's metabolism is decreased.

Caloric expenditure is a more explicit measure of energy consumption than VO_2. Following the VO_2 results, average caloric expenditure was significantly decreased when ambulating in simulated Martian hypogravity. The mean difference in nearly 2 $kcal \cdot min^{-1}$ demonstrates the extent to which less energy is being used. The electromyography measurement of the quadriceps muscle group has been identified as less active when walking in LBPP simulated hypogravity (12). This decrease in muscle activity could be the primary reason for the decrease in energy expenditure.

Grabowski's (11) measurement of net metabolic power (NMP) during walking in LBPP hypogravity reflected the observation that energy output decreases as body weight is unloaded. NMP is a measure of direct energy expenditure, so it can be compared to average caloric expenditure. When body weight was unloaded by 50% and 25% at a walking speed comparable to our study, a significant decrease was seen in NMP in both conditions (11). The expression of metabolic expenditure in calories is useful when drawing practical advice from these results. One potential application is the use of exercise regimes for recovering patients and athletes using the LBPP boxes. Calorie targets can be tailored with this information to provide controlled rehabilitation and training.

There is limited research in the analysis of how RER changes when ambulating in hypogravity, and yet RER provides important information as to which substrates are used to produce energy. The present study found a significant increase in RER between simulated Martian gravity and Earth. This is due to a significant decrease in VO_2 and no significant increase in VCO_2 when ambulating at 0.38G. The RER of 0.83 ± 0.13 at 1G indicates that a mixture of lipids and carbohydrates were oxidized; whereas, the RER of 1.14 ± 0.19 at 0.38G indicates that only carbohydrates were oxidized. An increase in RER is associated with more strenuous exercise and an RER >1 indicates that the body is in a stress state such as maximal exercise or acidosis (2). However, these results do not necessarily indicate that the body is under increased stress or oxidizing more carbohydrates. Diet, muscle fiber type, and aerobic capacity are all confounding factors that influence RER so it cannot be used to accurately determine what substrates were metabolized in this case (2).

Patients with chronic obstructive pulmonary disease using LBPP boxes for rehabilitation exercises should be aware that the respiratory burden to eliminate CO_2 is kept relatively high, even though the exercises may be perceived as easier (1,12). Maintenance of CO_2 production in low gravity will have implications when calibrating extravehicular activity (EVA) suits for excursions on Mars (13).

Considering that the age of the subjects ranged from 17 to 28 yrs, the observed HR fell in the expected interval of 90 to 140 beats·min^{-1} for moderate exercise according to the British Heart Foundation (4). Heart rate has previously been used as an indicator for metabolic output, and is useful when looked at in conjunction with other physiological variables (such as VO_2 and caloric expenditure). Therefore, the significant decrease in the subjects' HR during the hypogravity simulation gives further credence to the previous understanding of the effects of body unloading on metabolism.

A natural and unavoidable limitation of this study is that it was conducted in simulated hypogravity and not in a real Martian gravity environment. As such, the transferable nature of these results to real hypogravity is questionable. To date, there has only been surface exploration EVA on the Moon during the Apollo programme landings between 1969 and 1972 (13). Metabolism and heat dissipation data from these EVAs provides a useful insight into how metabolism changes in real hypogravity. Metabolic rate was averaged from oxygen usage and heat production derived from water coolant temperature.

When walking at a speed of 5.7 km·h^{-1} at zero incline for 1.8 min, the two astronauts of Apollo 14 had an average metabolic rate of 4.7 kcal·min^{-1} and 6.5 kcal·min^{-1} (13). This level of energy output is comparable to the subjects in the present study walking at 1G, well above what would be expected for an environment with half as much gravity as Mars. This is not surprising as a direct comparison such as this is inaccurate. The Apollo astronauts are not matched for height, weight, and sex with the subjects of the present study, as well as being encumbered by the heavy EVA suits while performing strenuous tasks. Apollo 15 astronauts performed a controlled experiment by simulating Lunar EVA tasks at 1G before flight. On average, a 70% decrease in energy expenditure was observed, as well as a 95% decrease in activities that included ambulating on the Lunar surface (13). This provides good evidence that confirms the present study's findings that metabolic output decreases in hypogravity.

CONCLUSIONS

Compared to 1G, energy expenditure is significantly decreased when walking in the LBPP boxes to simulate Martian hypogravity, as measured by VO_2 and caloric expenditure. End tidal carbon dioxide is not significantly different in the two settings. Athletes using LBPP boxes to train and avoid joint damage can be advised as to the decreased caloric intake they require. Similar recommendations can also be made to astronauts during EVA in future missions to Mars. This study also showed that further research is needed in regards to how respiratory exchange ratio changes in simulated hypogravity. This will demonstrate if there is any difference in substrate metabolism when ambulating in simulated hypogravity.

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