Prediction of Lunar- and Martian-Based Intra- and Site-to-Site Task Performance

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BACKGROUND: This study aimed to investigate the feasibility of determining the physiological parameters associated with the ability to complete simulated exploration type tasks at metabolic rates which might be expected for lunar and Martian ambulation.

METHODS: Running $\dot{V}O_{2max}$ and gas exchange threshold (GET) were measured in 21 volunteers. Two simulated extravehicular activity field tests were completed in 1 G in regular athletic apparel at two intensities designed to elicit metabolic rates of ~20.0 and ~30.0 ml · kg^{-1} · min^{-1}, which are similar to those previously reported for ambulation in simulated lunar- and Martian-based environments, respectively.

RESULTS: All subjects were able to complete the field test at the lunar intensity, but 28% were unable to complete the field test at the Martian intensity (non-Finishers). During the Martian field test there were no differences in $\dot{V}O_2$ between Finishers and non-Finishers, but the non-Finishers achieved a greater %$\dot{V}O_{2max}$ compared to Finishers (78.4 ± 4.6% vs. 64.9 ± 9.6%). Logistic regression analysis revealed fitness thresholds for a predicted probability of 0.5, at which Finishing and non-Finishing are equally likely, and 0.75, at which an individual has a 75% chance of Finishing, to be a $\dot{V}O_{2max}$ of 38.4 ml · kg^{-1} · min^{-1} and 40.0 ml · kg^{-1} · min^{-1} or a GET of 20.1 ml · kg^{-1} · min^{-1} and 25.1 ml · kg^{-1} · min^{-1}, respectively ($\chi^2 = 10.2$). Logistic regression analysis also revealed that the expected %$\dot{V}O_{2max}$ required to complete a field test could be used to successfully predict performance ($\chi^2 = 19.3$).

DISCUSSION: The results of the present investigation highlight the potential utility of $\dot{V}O_{2max}$, particularly as it relates to the metabolic demands of a surface ambulation, in defining successful completion of planetary-based exploration field tests.

KEYWORDS: endurance performance, $\dot{V}O_{2max}$, extravehicular activity, gas exchange threshold.

Ade CJ, Broxterman RM, Craig JC, Schlup SJ, Wilcox SL, Warren S, Kuehl P, Gude D, Jia C, Barstow TJ. *Prediction of lunar- and Martian-based intra- and site-to-site task performance*. Aerosp Med Hum Perform. 2016; 87(4):367–374.

The spaceflight environment elicits a cascade of physiological adaptations that, while unproblematic for life in microgravity, creates a problematic state of "spaceflight deconditioning" which manifests upon return to gravity (i.e., Earth or other planetary destinations) and may inhibit a crewmember's ability to complete extravehicular activities (EVA). As such, a concern with long-duration spaceflight is not only to survive while in space, but to also have the capacity to endure the physical demands created upon landing. Over the last several decades, it has become evident that a reduction in maximal oxygen uptake ($\dot{V}O_{2max}$) is related, in part, to the duration of microgravity exposure.[1,5,6] Recently, Moore et al.[16] demonstrated that $\dot{V}O_{2max}$ is decreased by ~15% in astronauts following International Space Station (ISS) missions ranging from 91 to 192 d with exercise countermeasures, while Capelli et al.[5] observed a ~32% decrease in $\dot{V}O_{2max}$ following 90-d bed rest. These findings highlight the potential for significant declines in aerobic capacity with long-duration microgravity exposure. Therefore, two prevailing questions exist. First, is the decreased aerobic exercise capacity following microgravity a primary concern for mission safety? Second, what is the minimum level of fitness required, particularly following long-duration missions, to complete a planetary EVA?

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This manuscript was received for review in June 2015. It was accepted for publication in December 2015.

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DOI: 10.3357/AMHP.4399.2016

Performing an EVA in a lunar or Martian environment in a pressurized space suit alters the metabolic demands of ambulation due to changes in inertial mass, suit pressure, suit weight, and suit kinematics. Of these, changes in suit weight appear to elicit the greatest differences in metabolic rate across space suit designs, with variations in suit pressure making little difference.[13] While the space suit that will be used in future lunar and Martian missions is unknown due in part to variations in factors like suit weight, strategies for evaluating astronaut physical readiness can be developed with the information that is currently available using a prototype NASA spacesuit. Using the Mark III Advanced Space Suit Technology Demonstrator EVA Suit (MKIII), Norcross et al.[21] demonstrated that suited treadmill walking at very slow speeds ($< 1\ m \cdot s^{-1}$), which is approximately the speeds expected for intra- and site-to-site EVA transitions, can elicit a $\dot{V}O_2$ of ~17-20 and ~28-30 $ml \cdot kg^{-1} \cdot min^{-1}$ for lunar and Martian gravitational environments, respectively. Given this, intra- and site-to-site EVA transitions in a space suit create a plausible EVA situation in which the metabolic cost of terrestrial ambulation may require an astronaut to work at a very high fraction of their $\dot{V}O_{2max}$, which in certain individuals may result in exhaustion and the inability to finish an EVA. Therefore, the aim of the present study was to investigate the feasibility of determining the physiological parameters associated with the ability to complete simulated exploration type tasks at metabolic rates which might be expected for intra- and site-to-site lunar and Martian ambulation based on the use of current EVA suit technology. It was hypothesized that aerobic fitness capacity and a combination of fitness capacity and EVA metabolic demand could be used as part of a predictive model to determine performance during simulated intra- and site-to-site EVA tasks. It was also hypothesized that the physiological responses to simulated intra- and site-to-site EVA tasks, particularly as they relate to $\dot{V}O_{2max}$, would show predictable patterns of tolerable exercise or impending exhaustion, discriminating between Finishers and non-Finishers of the tasks.

METHODS

Subjects

Following recruitment from advertisements in the local community, 21 healthy subjects [10 men, 11 women; 26 ± 7 yr, 171 ± 8.6 cm, 76.0 ± 15.7 kg (mean ± SD)] completed the experiments. All subjects were free of known cardiovascular, pulmonary, or metabolic disease and were nonsmokers, as determined from a medical history questionnaire. Exercise training status and fitness level were not controlled for. All subjects gave written consent to participate in the study, which was approved by the Institutional Review Board for Research Involving Human Subjects at Kansas State University, and conformed to the Declaration of Helsinki. Subjects were instructed to arrive at the laboratory rested, fully hydrated, having abstained from vigorous activity for 24 h prior to testing, and having abstained from alcohol or caffeine consumption for 10 h prior to testing.

Equipment

Each subject performed incremental exercise to exhaustion on a calibrated motor-driven treadmill (Woodway Pro, Waukesha, WI). During the incremental test breath-by-breath metabolic and ventilatory data were continuously recorded throughout each test (Ultima CPX, Medical Graphics Corp., St. Paul, MN) and converted to 15-s time-binned mean values. The system was calibrated before each test with gases of known concentration and a 3-L syringe according to manufacturer's instructions.

Throughout each field test trial breath-by-breath gas exchange and ventilation were measured using a portable system (Oxycon Mobile, CareFusion Corporation, San Diego, CA) in a subset of subjects (8 men, 4 women; 29 ± 8 yr, 172 ± 9 cm, 82.0 ± 17.0 kg). The system was calibrated before each test with gases of known concentration. The volume turbine was calibrated using the manufacturer's automated flow calibration system according to the manufacturer's instructions.

Procedures

The protocol consisted of four visits to the laboratory with at least 24 h between visits. First, each subject performed a graded treadmill exercise test for the determination of $\dot{V}O_{2max}$ and gas exchange threshold (GET). During the second visit, subjects completed a familiarization trial on a specially designed field test circuit, which was not included in the data analysis. During the following visits, in randomized order, subjects performed two constant work rate trials on the field test circuit (described below) at exercise intensities designed to elicit the metabolic rates currently estimated for ambulation in lunar (1/6-g) and Mars (3/8-g) environments in a MKIII spacesuit.[21,22]

Each subject performed an incremental exercise protocol initially consisting of 5 min walking at 2.5 km/h and a grade of 1% to simulate outside ambulation.[14] The speed was then increased to 4-6 km/h based on the subject's reported level of fitness and progressively increased 0.5 km/h each minute until the subject reached 95% predicted maximal heart rate. At this point, the speed was decreased by 1.0 km/h and the grade increased 1% every 1 min until volitional exhaustion. Subjects were given a 20-min recovery period, followed by a constant-speed test to evaluate attainment of $\dot{V}O_{2max}$ during the initial incremental test. This test consisted of a square wave transition to the highest attained treadmill speed and grade during the initial incremental test.[24] Subjects were encouraged to run to exhaustion, which in all cases was greater than 2 min. The maximum 15-s mean $\dot{V}O_2$ was considered the maximum value and $\dot{V}O_{2max}$ was considered valid if the highest $\dot{V}O_2$ during the constant-speed treadmill test was less than 200 $ml \cdot min^{-1}$ greater than the highest $\dot{V}O_2$ during the incremental test.[24] All subjects met this criterion for $\dot{V}O_{2max}$. Pilot work in our laboratory revealed that a 1 km/h increment in speed increased $\dot{V}O_2$ by ~220 $ml \cdot min^{-1}$. The $\dot{V}O_2$ corresponding to the GET was determined as the point at which $\dot{V}CO_2$ increased out of proportion with respect to $\dot{V}O_2$ and an increase in $\dot{V}_E/\dot{V}O_2$ with no increase in $\dot{V}_E/\dot{V}CO_2$.[4] Heart rate was recorded at 1-min intervals with a telemetric heart rate monitor (FT7, Polar Electro Inc., Lake Success, NY).

The field test circuit consisted of six tasks along a continuous course with approximately 10 m between each task.[2] While the actual exploration tasks requiring a high physical demand are unknown at this time, a candidate list of tasks was created in 2009 by the NASA Human Research Program.[18] Each task within the current field test was taken directly or derived from this list of potential physically demanding planetary exploration tasks. The tasks and their order within the circuit were: 1) ladder climb, where subjects ascended and descended a 12-ft ladder consisting of 10 rungs; 2) agility cones, where subjects moved forward and backward through six vertical poles spaced 6 ft apart; 3) stair climb, where subjects ascended and descended a 4.5-m set of stairs, where each step had a rise of 25 cm; 4) lateral climb, where subjects moved laterally along a vertical wall using hand and foot holds designed to simulate a climbing task; and 5) equipment lift, where subjects moved two 4.5-kg boxes from waist level to eye level and two 9-kg boxes from the floor to waist level and then back to their original positions. Only one box could be moved at a time and required both hands to be used. Waist and eye levels were determined prior to the start of each test for every individual. The final task was: 6) step-entry, where subjects moved laterally and periodically stepped over 40-cm hurdles and ducked under chest-level poles to simulate stepping over and under a habitat hatch entry. The test order was the same across all subjects and was performed in casual athletic apparel under normal (1-G) gravity.

The field test circuit was completed by each subject in 1 G and in regular athletic apparel at two different intensities designed to elicit metabolic rates of 20 $ml \cdot kg^{-1} \cdot min^{-1}$ and 30 $ml \cdot kg^{-1} \cdot min^{-1}$, which were chosen to simulate the metabolic rates reported for suited lunar (1/6-g) and Martian (3/8-g) ambulation, respectively (**Fig. 1**).[13,21,22] Thus, despite being in athletic apparel, subjects were forced to work at a metabolic rate that would be achieved if performed during suited ambulation. During each test the exercise intensity and subsequent metabolic rates were achieved by making the participants complete the tasks at a specific speed. The speed required to elicit a given target metabolic rate for each individual task was determined through pilot testing. During the field test, audio recorded feedback by means of a countdown at 1-s intervals was used to pace the subjects by informing the subjects of the time remaining to complete a given task. Subjects were also continuously given verbal feedback from an investigator regarding their field test pace. If a subject completed a task too quickly, they were slowed down or asked to pause for a short period (< 5 s in all cases).

For the Martian field test (i.e., speed associated with a sustained $\dot{V}O_2$ of 30 $ml \cdot kg^{-1} \cdot min^{-1}$), subjects were instructed to complete five laps of the field test or until they became exhausted and could no longer maintain the required field test intensity. In a similar manner for the lunar field test (i.e., speed associated with a sustained $\dot{V}O_2$ of 20 $ml \cdot kg^{-1} \cdot min^{-1}$), subjects were instructed to complete nine laps or to exhaustion. For both tests exhaustion was defined as the inability to complete two consecutive tasks within 3 s of the required time. The number of laps were chosen so that subjects would exercise for no more than 20 min for a given field test trial. While a longer test may have been more representative of a true mission scenario, it would have increased the likelihood of motivational factors contributing to subjects not finishing the field test, instead of the desired physiological factors.

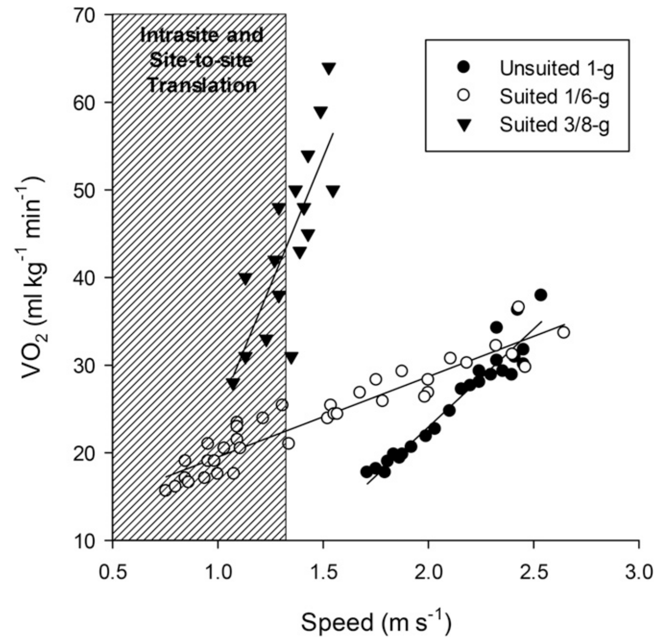

Fig. 1. $\dot{V}O_2$-to-speed relationship in subjects during 1-G unsuited treadmill ambulation (black circles) and while wearing the Mark III Advanced EVA Space Suit in simulated lunar [(1/6-g), white circles] and Mars [(3/8-g), black triangles] gravity. Shaded area represents the speeds/metabolic rates anticipated for intrasite and site-to-site translations. Adapted from Norcross and colleagues.[13,21,22]

Statistical Analysis

All analyses were performed using SPSS v.19 for Windows (SPSS, IBM Corporation, Amonk, NY). Each subject was assigned to one of two categories based on whether they finished (Finishers) the required number of Martian field test laps or not (non-Finishers). Age, height, body mass, $\dot{V}O_{2max}$, and GET were compared between groups using paired *t*-tests. Main effect for $\dot{V}O_2$ and $\%\dot{V}O_{2max}$ during each field test was tested using two-way repeated measures ANOVA (group × time). Differences were considered statistically significant when $P < 0.05$. Since subjects were paced to elicit a specific metabolic rate for each task, no comparisons between tasks were performed. To address the primary aim of determining the feasibility of setting a cardiorespiratory fitness standard, a logistic regression model was used to model the effects of $\dot{V}O_{2max}$ and GET on the likelihood of success at completing the Martian field test. A Hosmer-Lemeshow test was used to determine if the number of Finishers and non-Finishers were significantly different from those predicted by the model and then to test the overall model fit. A multiple forward logistic regression model was used to identify if $\dot{V}O_{2max}$ and GET together would provide a greater accuracy of prediction. To determine the contribution of specific components across both field tests, a multiple forward logistic regression model was also used to identify if the expected metabolic demand of a given field test, the expected

$\%\dot{V}O_{2max}$ elicited by a field test, or %GET elicited by a field test could be used to develop a predictive model to determine performance.

RESULTS

Subjects were characterized by a mean $\dot{V}O_{2max}$ of 43.4 ml $\cdot$ $kg^{-1} \cdot min^{-1}$ (range: 32.5–61.6 ml $\cdot kg^{-1} \cdot min^{-1}$) and a GET of 25.6 ml $\cdot kg^{-1} \cdot min^{-1}$ (range: 15.6 – 41.0 ml $\cdot kg^{-1} \cdot min^{-1}$). The range of $\dot{V}O_{2max}$ of subjects in the present investigation was very similar to that reported for active NASA astronauts (**Fig. 2**). Non-Finishers were characterized by a lower $\dot{V}O_{2max}$ (37.2 $\pm$ 6.7 vs. 45.8 $\pm$ 3.6 ml $\cdot kg^{-1} \cdot min^{-1}$; df = 19, P = 0.008) and GET (21.9 $\pm$ 4.3 vs. 27.1 $\pm$ 6.4 ml $\cdot kg^{-1} \cdot min^{-1}$; df = 19, P = 0.07) compared to Finishers as determined by paired t-test. On average the non-Finishers were only able to complete ~65% of the Martian field test. Two-way repeated measures ANOVA revealed a significant effect for time [F(1,30) = 67.4, $P < 0.001$], but no effect for group [F(1,10) = 0.4, P = 0.6] for $\dot{V}O_2$. There were no differences between Finishers and non-Finishers for $\dot{V}O_2$ (28.5 $\pm$ 3.8 vs. 28.6 $\pm$ 1.3 ml $\cdot kg^{-1} \cdot min^{-1}$), $\dot{V}CO_2$ (26.9 $\pm$ 4.8 vs. 28.2 $\pm$ 1.2 ml $\cdot kg^{-1} \cdot min^{-1}$; df = 10, P = 0.59), or $\dot{V}_E$ (71.8 $\pm$ 16.9 vs. 92.9 $\pm$ 22.6 L $\cdot min^{-1}$; df = 10, P = 0.09) averaged across the Martian field test. Additionally, two-way repeated measures ANOVA revealed a significant group effect for $\%\dot{V}O_{2max}$ [F(1,22) = 10.5, P = 0.009]. Compared to Finishers, the non-Finishers achieved a significantly greater $\%\dot{V}O_{2max}$ during the Martian field test (78.4 $\pm$ 4.6% vs. 64.9 $\pm$ 9.6%; **Fig. 3**; df = 10, P = 0.02). In the Finishers, the $\dot{V}O_2$ averaged across the entire Martian field test was not different than their GET (df = 6, P = 0.06). Conversely, in the non-Finishers, the average field test $\dot{V}O_2$ was significantly greater than their GET (df = 6, P = 0.005).

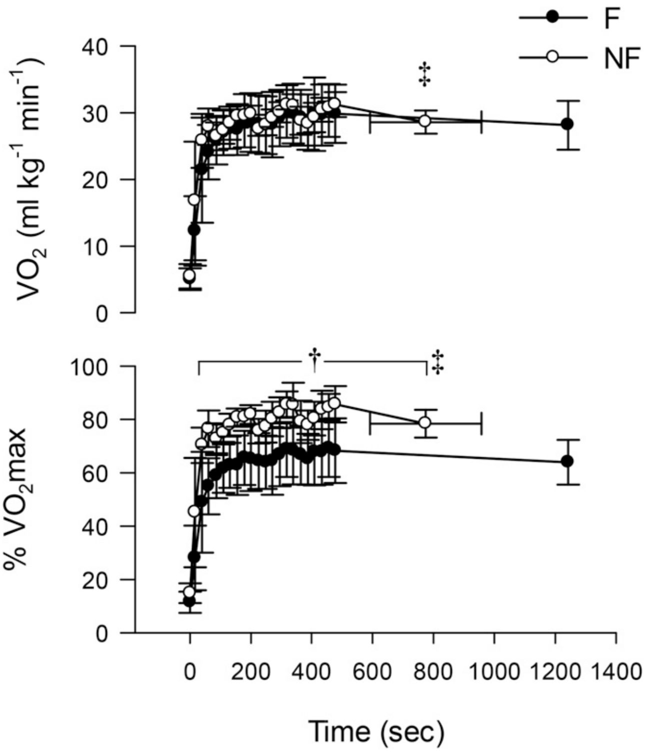

Fig. 3. Mean $\dot{V}O_2$ responses during the simulated Martian field test. Finishers, black symbols; non-Finishers, white symbols. †Significantly different from Finishers at the same time point, $P < 0.05$. ‡Significantly for time compared to Finishers, $P < 0.05$.

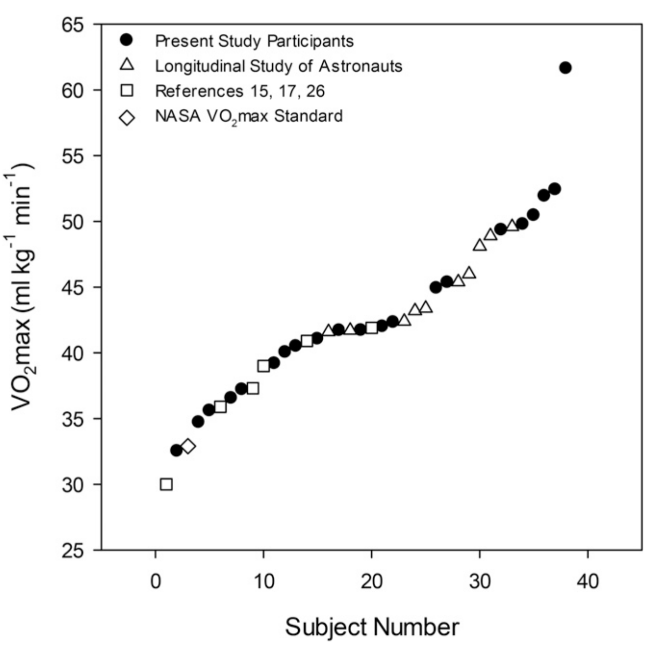

Fig. 2. The mean $\dot{V}O_{2max}$ values previously reported for NASA astronauts are used as the reference for describing the relative distribution of the current study's research subjects. The individual $\dot{V}O_{2max}$ values are plotted in a cumulative fashion for all subjects. Superimposed at the appropriate point on the distribution of $\dot{V}O_{2max}$ values are the mean values reported in the literature.[15,17,26]

Logistic regression analysis identified $\dot{V}O_{2max}$ as an independent predictor of Martian field test failure (χ^2 = 10.2, $P <$ 0.05). With this model, the probability of Martian field test success (P) is: $P = e^y/(1+e^y)$ where e = 2.72 and y = 16.6 + −0.43 × $\dot{V}O_{2max}$. The overall predictive capacity of the model was 85.7% and correctly classified 14/15 Finishers (93.3% sensitivity) and 4/6 non-Finishers (66.7% specificity). The Hosmer-Lemeshow test indicated that the number of Finishers was not significantly different from those predicted by the logistic model and that the overall model fit is good (P = 0.774). The $\dot{V}O_{2max}$ at which the predicted probability equals 0.50 (i.e., Finishing and non-Finishing are equally likely) was 38.4 ml $\cdot kg^{-1} \cdot min^{-1}$. The $\dot{V}O_{2max}$ at which the predicted probability equals 0.75 (i.e., 75% predicted probability of finishing) was 40.0 ml $\cdot kg^{-1} \cdot$ min^{-1}. **Table I** shows the predicted probability of finishing and the expected number of Finishers calculated as the predicted probability multiplied by the number of patients above and below the 40.0 ml $\cdot kg^{-1} \cdot min^{-1}$ $\dot{V}O_{2max}$ threshold. The GET was also an independent predictor of test failure (χ^2 = 4.1, P = 0.04) with an overall predictive capacity of the model of 71.4% and correct classification of 14/15 Finishers (93.3% sensitivity) and 1/6 non-Finishers (16.7% specificity). The GET at which the predicted probability equals 0.50 and 0.75 was

Table I. Relationship Between $\dot{V}O_{2max}$ and Predicted Probability of Finishing the Simulated Martian Field Test.

	NUMBER OF SUBJECTS	NUMBER OF FINISHING	PROPORTION OF FINISHING	PREDICTED PROBABILITY OF FINISHING	EXPECTED NUMBER OF FINISHING
$\dot{V}O_{2max}$ Category					
$\geq$40.0 $ml \cdot kg^{-1} \cdot min^{-1}$	13	12	92.3%	98.4%	12.8
$<$40.0 $ml \cdot kg^{-1} \cdot min^{-1}$	8	3	37.5%	38.9%	3.11
GET Category					
$\geq$25.1 $ml \cdot kg^{-1} \cdot min^{-1}$	10	9	90.0%	87.9%	8.8
$<$25.1 $ml \cdot kg^{-1} \cdot min^{-1}$	11	6	54.5%	56.2%	6.2

20.1 and 25.1 $ml \cdot kg^{-1} \cdot min^{-1}$, respectively. The predicted probability of finishing and the expected number of finishers above and below the 25.1 $ml \cdot kg^{-1} \cdot min^{-1}$ GET threshold is shown in Table I. Multiple logistic regression revealed that $\dot{V}O_{2max}$ by itself was a better predictor of performance than models containing both $\dot{V}O_{2max}$ and GET.

All 21 subjects were able to complete the lunar field test; therefore, the Finishers and non-Finishers groupings from the Martian field test were used for the lunar intensity analysis. Two-way repeated measures ANOVA revealed a significant effect for time [$F(1,22) = 70.9$, $P < 0.001$], but no effect for group [$F(1,10) = 1.7$, $P = 0.2$] for $\dot{V}O_2$. There were no differences between Finishers and non-Finishers for $\dot{V}O_2$ (18.7 ± 1.7 vs. 20.1 ± 1.7 $ml \cdot kg^{-1} \cdot min^{-1}$), $\dot{V}CO_2$ (16.6 ± 2.2 vs. 18.7 ± 1.6 $ml \cdot kg^{-1} \cdot min^{-1}$), or $\dot{V}_E$ (41.0 ± 8.5 vs. 44.8 ± 3.2 $L \cdot min^{-1}$; $P < 0.05$) averaged across the entire test as determined by paired *t*-test. The lunar field test elicited a significantly greater $\%\dot{V}O_{2max}$ in non-Finishers compared to Finishers [55.9 ± 8.6% vs. 42.5 ± 4.6%; **Fig. 4**; $F(1,10) = 12.5$, $P = 0.005$]. Further, in the Finishers, the $\dot{V}O_2$ averaged across the entire lunar field test was significantly lower than the $\dot{V}O_2$ at the GET. Conversely, in the non-Finishers the average field test $\dot{V}O_2$ was not different than the $\dot{V}O_2$ at the GET.

When the metabolic demand, the expected $\%\dot{V}O_{2max}$ elicited, and %GET elicited from both the simulated Martian and lunar field tests were combined into a multiple forward logistic regression model, it was revealed that the calculated $\%\dot{V}O_{2max}$ required to complete the field test (i.e., expected metabolic demand of the field test ÷ subject's $\dot{V}O_{2max}$) was a better predictor of performance than models containing all three field test variables ($\chi^2 = 19.3$, $P < 0.05$). With this model, the probability of field test success (P) is: $P = e^y/(1+e^y)$, where $e = 2.72$ and $y = -18.3 + 2.33 \times$ 'expected $\%\dot{V}O_{2max}$.' Thus expected $\%\dot{V}O_{2max}$ required by a simulated field test at which the predicted probability equals 0.50 (i.e., Finishing and non-Finishing are equally likely) was 78.6%. Therefore, if a field test, independent of its metabolic demand, will require >78.6% $\dot{V}O_{2max}$, there is a 50% probability of not being able to complete the required tasks.

DISCUSSION

The primary objective of the present investigation was to evaluate the feasibility of using physiological responses and laboratory-based physical performance measures to assess an individual's ability to complete a field test circuit similar to the activities and exercise intensities that might be experienced during Martian- and lunar-based exploration tasks based on the use of current EVA technology.[18,21,22] As intended, the Martian and lunar field tests elicited metabolic rates of ~28 and ~19 $ml \cdot kg^{-1} \cdot min^{-1}$, respectively, which as illustrated in Fig. 1 is similar to those reported for ambulation in a MKIII space suit simulator in these gravitational environments. Consistent with our first hypothesis, using a univariate logistic regression analysis, a fitness threshold with a predicted probability of 0.5, at which Finishing and non-Finishing are equally likely, and 0.75, at which an individual has a 75% chance of Finishing, was shown to be a $\dot{V}O_{2max}$ of 38.4 $ml \cdot kg^{-1} \cdot min^{-1}$ and 40.0 $ml \cdot kg^{-1} \cdot min^{-1}$, respectively, and a GET of 20.1 $ml \cdot kg^{-1} \cdot min^{-1}$ and 25.1 $ml \cdot kg^{-1} \cdot min^{-1}$, respectively. Thus, this analysis demonstrates the feasibility of using an aerobic fitness measurement to predict performance during simulated

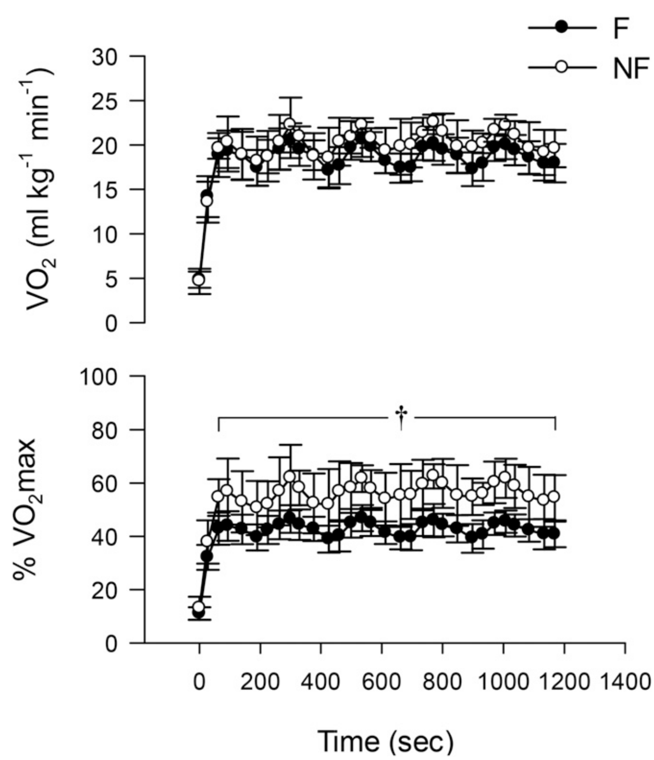

Fig. 4. Mean $\dot{V}O_2$ responses during the simulated lunar field test. Finishers, black symbols; non-Finishers, white symbols. †Significantly different from Finishers at the same time point, $P < 0.05$.

Martian-based activities developed around current suit technology. In addition, the expected % $\dot{V}O_{2max}$ required by a simulated field test, independent of the field tests absolute metabolic demand, can be used as a predictor of an individual's ability to complete a simulated EVA field test such that if a task will require >78.6% $\dot{V}O_{2max}$, there is a 50% probability of failure. The second hypothesis was also well supported by the present study's findings. Non-Finishers of the Martian-based field test achieved a greater fraction of their $\dot{V}O_{2max}$ compared to Finishers. Evaluation of pulmonary $\dot{V}O_2$ during the Martian-based field test in relation to $\dot{V}O_{2max}$ and GET revealed that non-Finishers were working at a $\dot{V}O_2$ greater than their GET.

The dynamic work reported during Shuttle and ISS EVAs primarily involved the upper body musculature[7] at a relatively low exercise intensity. As reviewed by Cowell et al.,[10] many of the Shuttle EVAs elicited a mean metabolic rate of ~0.65 L · min^{-1} or an estimated 45-50% of arm cranking $\dot{V}O_{2peak}$.[7] As many future manned missions may rely on EVAs for surface exploration, the previous Shuttle metabolic data may not accurately predict the demands of lunar or Martian exploration. In 12 Apollo astronauts, the total energy expenditure across 28 surface EVAs had a mean $\dot{V}O_2$ of 0.7 to 1.0 L · min^{-1} or ~10-14 ml · kg^{-1} · min^{-1} (assuming an average body mass of 70 kg).[27] In the Apollo 15 commander at least 20 min were spent during EVA egress and equipment deployment at a metabolic rate of ~20 ml · kg^{-1} · min^{-1}. Similar values have been observed during simulated lunar ambulation in more modern space suit designs.[19,21] In the present study, subjects were paced to elicit this target $\dot{V}O_2$ of 20 ml · kg^{-1} · min^{-1}. As shown in Fig. 4, the $\dot{V}O_2$ increased rapidly over the first 3-4 tasks, and then attained a steady state until completion of the field test. It is also important to note that all individuals, despite their level of fitness, were able to complete the lunar-based field test. This is consistent with the finding that individuals with an average $\dot{V}O_{2max}$ of 48.7 ml · kg^{-1} · min^{-1} can ambulate 10 km in a space suit in simulated lunar gravity.[21] Similarly, in the current investigation, the average metabolic rate during the simulated 10-km lunar ambulation was ~24 ml · kg^{-1} · min^{-1}, representing ~51% $\dot{V}O_{2max}$.[21] Thus there may be few physical limitations when performing EVA tasks in 1/6 g.

Unlike the low to moderate metabolic rates elicited during Shuttle and lunar EVAs, those previously measured during simulated Martian-based activities may be substantially higher when performed in the current generation of space suit designs. Suited ambulation in 3/8 g produces a $\dot{V}O_2$ which is higher than walking on Earth (Fig. 1) and which has been shown to elicit $\dot{V}O_{2max}$ in some individuals.[19,21] Thus the $\dot{V}O_2$ during even the slowest walking portions of a Martian EVA may reach or exceed 30 ml · kg^{-1} · min^{-1} and highlight an EVA situation in which reducing the pace of an activity in an attempt to reduce the physical demands of the EVA may not be a feasible option. As shown in Fig. 3, when subjects performed the field test at a target $\dot{V}O_2$ of 30 ml · kg^{-1} · min^{-1}, those individuals who maintained a % $\dot{V}O_{2max}$ of <65% were able to complete the field test, while the non-Finishers achieved >78% $\dot{V}O_{2max}$. Given that the relationship between the parameters which define each exercise intensity domain and their associated physiological responses elicited (i.e., $\dot{V}O_{2max}$ and LT/GET) are highly variable in different individuals,[25] it is apparent that a given exploration task work rate can result in dramatic variation in both the metabolic profiles and the tolerable duration of the work. As such, non-Finishers were working at a $\dot{V}O_2$ greater than their GET, while Finishers were working at an exercise intensity not different than GET. This suggests that those who could not complete the simulated Martian EVA were working very near to or in the severe exercise intensity domain (with its well-known limited exercise tolerance[18]), while those who could finish were working close to the moderate-to-heavy exercise intensity domain.[25]

Based on previous literature, it would be anticipated that aerobic exercise capacity would predict performance on the Martian-based field test.[2] In the present study, a significant relationship between the Martian-based field test performance and $\dot{V}O_{2max}$ was observed via univariate logistic regression. This is an important finding given that no study to date has established an aerobic fitness threshold that predicts successful completion of a Martian-based field test consisting of intra- and site-to-site tasks. These findings are consistent with the previous observations that $\dot{V}O_{2max}$ is strongly correlated with simulated exploration task completion time.[2] However, this early work used self-paced exploration tasks which allowed the lesser fit subjects to complete the tasks at very low metabolic rates, whereas the current investigation required all subjects to maintain a metabolic rate equivalent to that expected for actual Martian-based EVAs. $\dot{V}O_{2max}$ has also previously been shown to correlate with athletic endurance performance and firefighter work performance.[9,12,28] Similar to the present investigation, Williams-Bell et al.[28] evaluated the relationship between $\dot{V}O_{2max}$ and completion time on the firefighter Candidate Physical Abilities Test, which consisted of content-based tasks. Success in their abilities test could, in part, be predicted by a $\dot{V}O_{2max}$ of ≥~3.5 L · min^{-1}. However, it is important to note that the firefighter Candidate Physical Abilities Test consisted of tasks related to search and rescue and fire suppression, whereas the present investigation used tasks specific to intra- and site-to-site EVA work.[18] Therefore, the fitness thresholds identified for other professions where complex endurance tasks are required may not be directly applied to planetary EVA work.

The present study also extends the work of previous investigations by developing a predicative model based on the metabolic demands of simulated EVA relative to an astronaut's aerobic capacity. This model highlights that EVA performance is dependent upon both absolute demands of the required tasks, which may be largely determined by space suit limitations, and astronaut fitness. As such, this model provides a tool for exploration suit and task designers in which specific components related to exploration (i.e., suit mass, biomechanical constraints, ambulation distances, rate of ambulation, carrying requirements) can be modified to promote EVA success for crewmembers of various aerobic capacities rather than focusing solely on confining aerobic capacity to a minimum standard. This is a critical concept given that the demands placed upon astronauts in flight may need to be dictated more by the technical specifics of the mission rather than the maintenance of a minimum fitness standard.

Similar to $\dot{V}O_{2max}$, but to a lesser extent, GET significantly predicted completion of the Martian-based field test. Several investigations have shown that the gas exchange threshold and other indices of blood lactate accumulation have a strong correlation with endurance performance, particularly for distances ranging from 5 km to marathon distances.[3,11,12] These findings coupled with that of the present investigation are interesting given that bed rest deconditioning, a surrogate of spaceflight deconditioning, decreases the GET to a greater extent than $\dot{V}O_{2max}$ during supine exercise.[8]

As previously described, the field test in the current investigation replicated as closely as possible the types of exploration tasks that might be expected during Martian and lunar missions in a prototype NASA space suit.[18,19,21] It is also important that the MKIII suit is the only space suit in which the speed-to-$\dot{V}O_2$ relationship has been determined in partial gravity; therefore, certain assumptions are a consequence of this type of investigation. There are noteworthy differences between our subjects and Martian/lunar-based astronauts. Our subjects wore athletic apparel, not a pressurized space suit, and performed each test in 1 G, not a microgravity environment. To circumvent these constraints each subject was individually paced to elicit an absolute metabolic response similar to that reported for ambulation in the MKIII space suit.[21,22] In addition, while the MKIII space suit is only a prototype, previous investigations have demonstrated that variations in suit weight and suit pressure have minimal ($\sim$3-4 $ml \cdot kg^{-1} \cdot min^{-1}$) impact on the metabolic cost of activities at the slow speeds associated with intra- and site-to-site EVA transitions,[13] which is very similar to that simulated by the present study. However, unlike suit weight and pressure, suit biomechanics (i.e., suit kinematics and stability) at low speeds can significantly contribute to the metabolic cost of ambulation.[20] In addition, true ambulation on a planetary surface may elicit gait patterns different from those in which the speed-to-$\dot{V}O_2$ relationship for the MKIII was determined. In total, while the current study's methodology may limit the direct application of its findings, it does provide a strong approximation of what might be expected and the ability to predict relative success during a future planetary mission at exercise intensities expected for intra- and site-to-site EVA transitions.[13]

An additional limitation to the present study was the evaluation of only $\dot{V}O_{2max}$ and GET. Other parameters of aerobic exercise capacity would have provided possibly greater predictability and novelty to the investigation. However, $\dot{V}O_{2max}$ and GET were chosen as they represent the most common physiological measurements of cardiorespiratory fitness in NASA astronauts and spaceflight analogues.[8,16,23] Testing protocols for additional parameters of submaximal exercise performance, like critical power (highest sustainable rate of aerobic metabolism), have not yet been developed for pre- or in-flight testing of NASA astronauts. Future studies should develop additional tests of pre- and in-flight cardiorespiratory fitness followed by the in-depth evaluation of their ability to predict performance during simulated Martian-based activities.

One of the most relevant findings of the present study is the feasibility of using a standardized measurement of physical fitness, like $\dot{V}O_{2max}$, particularly as it relates to the metabolic demand, to determine an individual's ability to finish or not finish a series of simulated EVA tasks. The implications of this finding are twofold. First, for exploration EVAs that are expected to require a metabolic rate at or above 28-30 $ml \cdot kg^{-1} \cdot min^{-1}$, the probability of successfully completing the task can be calculated via logistic regression models. Second, given the assumed parameters of the present study's simulated Martian field test, a minimum fitness requirement may need to be a $\dot{V}O_{2max}$ of $>$40.0 $ml \cdot kg^{-1} \cdot min^{-1}$ and/or GET of 25.1 $ml \cdot kg^{-1} \cdot min^{-1}$. Third and most importantly, in situations in which the minimum fitness requirement cannot be met due to crew selection or severe spaceflight deconditioning, if the metabolic demands of the required tasks can be decreased (e.g., reduced rate of ambulation) such that it is below a given $\%\dot{V}O_{2max}$, task completion has a significantly higher probability of successful completion.

In summary, the results of the present investigation highlight the potential utility of $\dot{V}O_{2max}$ and GET in defining successful completion of planetary-based exploration field tests. It is our recommendation that future research investigations better evaluate the metabolic costs of suited EVA tasks so that a true aerobic fitness threshold can be developed for various mission scenarios. In addition, future in-flight testing of astronauts should continue to include measurements of $\dot{V}O_{2max}$ and that real-time monitoring of EVA metabolic rates should be scaled to $\dot{V}O_{2max}$.

ACKNOWLEDGMENTS

This study was supported by the National Aeronautics and Space Administration (NASA) research grant NNX10AK60G awarded to T. J. Barstow. R. M. Broxterman was supported by NASA EPSCOR grant KS-NNX11AM05A.

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REFERENCES

1. Ade CJ, Broxterman RM, Barstow TJ. VO2max and microgravity exposure: convective versus diffusive O2 transport. Med Sci Sports Exerc. 2015; 47(7):1351–1361.
2. Ade CJ, Broxterman RM, Craig JC, Schlup SJ, Wilcox SL, Barstow TJ. Relationship between simulated extravehicular activity tasks and measurements of physical performance. Respir Physiol Neurobiol. 2014; 203:19–27.
3. Ali Almarwaey O, Mark Jones A, Tolfrey K. Physiological correlates with endurance running performance in trained adolescents. Med Sci Sports Exerc. 2003; 35(3):480–487.
4. Beaver WL, Wasserman K, Whipp BJ. A new method for detecting anaerobic threshold by gas exchange. J Appl Physiol. 1986; 60(6): 2020–2027.

5. Capelli C, Antonutto G, Kenfack MA, Cautero M, Lador F, et al. Factors determining the time course of VO2(max) decay during bedrest: implications for VO2(max) limitation. Eur J Appl Physiol. 2006; 98(2): 152–160.
6. Convertino V. Exercise and adaptation to microgravity environments. In: Fregly MJ, Blatteis CM, eds. Handbook of physiology: section 4. Environmental physiology, vol 3. New York: Oxford University Press; 1996:815–843.
7. Convertino VA. Physiological adaptations to weightlessness: effects on exercise and work performance. Exerc Sport Sci Rev. 1990; 18:119–166.
8. Convertino VA, Karst GM, Kirby CR, Goldwater DJ. Effect of simulated weightlessness on exercise-induced anaerobic threshold. Aviat Space Environ Med. 1986; 57(4):325–331.
9. Costill DL, Thomason H, Roberts E. Fractional utilization of the aerobic capacity during distance running. Med Sci Sports. 1973; 5(4):248–252.
10. Cowell SA, Stocks JM, Evans DG, Simonson SR, Greenleaf JE. The exercise and environmental physiology of extravehicular activity. Aviat Space Environ Med. 2002; 73(1):54–67.
11. Farrell PA, Wilmore JH, Coyle EF, Billing JE, Costill DL. Plasma lactate accumulation and distance running performance. Med Sci Sports. 1979; 11(4):338–344.
12. Fay L, Londeree BR, LaFontaine TP, Volek MR. Physiological parameters related to distance running performance in female athletes. Med Sci Sports Exerc. 1989; 21(3):319–324.
13. Gernhardt ML, Jones JA, Scheuring RA, Abercromby AF, Tuxhorn JA, Norcross JR. Risk of compromised EVA performance and crew health due to inadequate EVA suit systems. 2009.
14. Jones AM, Doust JHA. 1% treadmill grade most accurately reflects the energetic cost of outdoor running. J Sports Sci. 1996; 14(4):321–327.
15. Levine BD, Lane LD, Watenpaugh DE, Gaffney FA, Buckey JC, Blomqvist CG. Maximal exercise performance after adaptation to microgravity. J Appl Physiol. 1996; 81(2):686–694.
16. Moore AD Jr, Downs ME, Lee SM, Feiveson AH, Knudsen P, Ploutz-Snyder L. Peak exercise oxygen uptake during and following long-duration spaceflight. J Appl Physiol (1985). 2014; 117(3):231–238.
17. Moore AD, Lee SM, Everett ME, Guined JR, Knudsen P. Aerobic capacity following long duration International Space Station (ISS) Missions: Preliminary results [abstract]. Aviat Space Environ Med. 2011; 82(8): 836–837.
18. NASA HRP. NASA research announcement - research and technology development to support crew health and performance in space exploration missions - NNJ09ZSA002N. Houston (TX): NASA Johnson Space Center; 2009:1-65.
19. Norcross JR, Clowers KG, Clark T, Harvill L, Morency RM, et al. Metabolic costs and biomechanics of inclined ambulation and exploration tasks in a planetary suit. Houston (TX): NASA Johnson Space Center; 2010. Report No.: NASA/TP 2010–216125.
20. Norcross JR, Clowers KG, Clark T, Harvill L, Morency RM, et al. Metabolic costs and biomechanics of level ambulation in a planetary suit. Houston (TX): NASA Johnson Space Center; 2010. Report No.: NASA/TP 2010–216115.
21. Norcross JR, Lee LR, Clowers KG, Morency RM, Desantis L, et al. In: NASA Administration, editor. Feasibility of performing a suited 10-km ambulation on the Moon - final report of the EVA Walkback Test (EWT). Hanover (MD): NASA Center for AeroSpace Information; 2009.
22. Norcross JR, Stroud LC, Schaffner G, Glass BJ, Lee PC, et al. The effects of terrain and navigation on human extravehicular activity walkback performance on the Moon [abstract]. Aviat Space Environ Med. 2008; 79(3):292–293.
23. Ploutz-Snyder LL, Downs M, Ryder J, Hackney K, Scott J, et al. Integrated resistance and aerobic exercise protects fitness during bed rest. Med Sci Sports Exerc. 2014; 46(2):358–368.
24. Poole DC, Wilkerson DP, Jones AM. Validity of criteria for establishing maximal O2 uptake during ramp exercise tests. Eur J Appl Physiol. 2008; 102(4):403–410.
25. Rossiter HB. Exercise: kinetic considerations for gas exchange. Compr Physiol. 2011; 1(1):203–244.
26. Trappe T, Trappe S, Lee G, Widrick J, Fitts R, Costill D. Cardiorespiratory responses to physical work during and following 17 days of bed rest and spaceflight. J Appl Physiol. 2006; 100(3):951–957.
27. Waligora JM, Hoorigan DJ. Metabolism and heat dissipation during Apollo EVA periods. In: Berry CA, editor. Biomedical results of Apollo. Houston (TX): NASA Johnson Space Center; 1975:115–128. Report No.: NASA SP-368.
28. Williams-Bell FM, Villar R, Sharratt MT, Hughson RL. Physiological demands of the firefighter Candidate Physical Ability Test. Med Sci Sports Exerc. 2009; 41(3):653–662.