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Relationship between simulated extravehicular activity tasks and measurements of physical performance

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ABSTRACT

The purpose was to evaluate the relationships between tests of fitness and two activities that simulate components of Lunar- and Martian-based extravehicular activities (EVA). Seventy-one subjects completed two field tests: a physical abilities test and a 10 km Walkback test. The relationships between test times and the following parameters were determined: running $\dot{V}O_{2max}$, gas exchange threshold (GET), speed at $\dot{V}O_{2max}$ (s-$\dot{V}O_{2max}$), highest sustainable rate of aerobic metabolism [critical speed (CS)], and the finite distance that could be covered above CS (D'): arm cranking $\dot{V}O_{2peak}$, GET, critical power (CP), and the finite work that can be performed above CP (W'). CS, running $\dot{V}O_{2max}$, s-$\dot{V}O_{2max}$, and arm cranking $\dot{V}O_{2peak}$ had the highest correlations with the physical abilities field test ($r = 0.66–0.82$, $P < 0.001$). For the 10 km Walkback, CS, s-$\dot{V}O_{2max}$, and running $\dot{V}O_{2max}$ were significant predictors ($r = 0.64–0.85$, $P < 0.001$). CS and to a lesser extent $\dot{V}O_{2max}$ are most strongly associated with tasks that simulate aspects of EVA performance, highlighting CS as a method for evaluating astronaut physical capacity.
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1. Introduction

During a continuous activity, like an extravehicular activity (EVA) in which astronauts work within the space environment, it is essential that the activity is completed without exhaustion and, more importantly, that the physical well-being of the astronaut is maintained. As such, if the effects of microgravity are not countered by the maintenance of physical capacity, then the physical demands of the EVA must be decreased, which for many situations may not be possible (Norcross et al., 2010; Scheuring et al., 2007). Consequently, if the effects of microgravity-induced deconditioning are severe, the EVA may now require an exercise intensity that will result in reduced exercise tolerance associated with the inability to achieve a physiological steady-state for pulmonary gas exchange, intramuscular phosphocreatine, inorganic phosphate, and hydrogen ions (Jones et al., 2008; Poole et al., 1988). Thus it is important for National Aeronautics and Space Administration (NASA) crewmembers, flight surgeons, and program managers to regularly reassess the effects of microgravity and flight duration on an astronaut's physical performance.

Performing EVAs in a partial gravity environment, in a pressurized space suit, on a Lunar/Martian-like terrain places a high physical strain on the astronaut (Gernhardt et al., 2009). As demonstrated by Norcross et al. (2009), treadmill walking at very slow speeds (<3 km h^{-1}) elicits a metabolic rate of approximately 17 and 28 ml kg^{-1} min^{-1} for suited Lunar and Martian environments, respectively. Coupled with the ~10 ml kg^{-1} min^{-1} increased $\dot{V}O_2$ required for ambulation on a Lunar/Martian-like surface (Norcross et al., 2008), this creates a plausible scenario in which $\dot{V}O_2$ during even the slowest walking portions of an EVA may reach or exceed 38 ml kg^{-1} min^{-1}. These findings highlight an EVA situation in which adapting an activity in an attempt to reduce the physical demands of the EVA may not be a feasible option.

The current NASA standard for evaluating astronaut readiness is $\dot{V}O_{2max}$, with a minimum mission readiness of 32.9 ml kg^{-1} min^{-1} (NASA, 2014). However, as highlighted in a 2009 NASA Research Announcement there is a continued need for development of pre- and in-flight standards for assessing an astronaut's ability to perform physically taxing EVAs in addition to, or in lieu of, $\dot{V}O_{2max}$ (HRP, 2009). While $\dot{V}O_{2max}$ has previously been demonstrated to correlate with endurance and work performance in fire fighters (Costill, 1970; Costill et al., 1973; Fay et al., 1989; Lindberg et al., 2013; Saltin and Astrand, 1967; von Heimburg et al., 2006;

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Williams-Bell et al., 2009) it may not adequately identify an astronaut's physical readiness. Numerous investigations have shown that the gas exchange threshold, indices of blood lactate accumulation, and critical speed (CS) often have a stronger correlation with endurance performance than $\dot{V}O_{2max}$ (Ali Almarwaey et al., 2003; Farrell et al., 1979; Fay et al., 1989; Florence and Weir, 1997; Kolbe et al., 1995; Morgan et al., 1989; Sjodin and Jacobs, 1981; Stratton et al., 2009; Svedenhag and Sjodin, 1984; Tanaka and Matsuura, 1984). Likewise, bed rest deconditioning, a surrogate of space flight deconditioning, decreases the gas exchange threshold to a greater extent than $\dot{V}O_{2max}$ during supine exercise (Convertino et al., 1986). Thus, using $\dot{V}O_{2max}$ as a standard may overestimate an astronaut's in- and post-flight physical readiness. In total these reports suggest that the current NASA standard for assessing astronaut aerobic fitness solely with $\dot{V}O_{2max}$ does not provide the fidelity required for the types of activities that may confront an astronaut working at a Lunar or Martian outpost. Therefore, the aim of the current study was to evaluate the relationships between direct laboratory tests of physical capacity and two distinctly different physically demanding tests designed to simulate the types of tasks that are expected to occur during Lunar-based or Martian-based EVAs (HRP, 2009; Norcross et al., 2009, 2010): (i) a physical abilities field test consisting of tasks requiring varying degrees of upper and lower-body strength and endurance; and (ii) a 10 km Walkback test. A key outcome of this aim is to provide a recommendation as to which laboratory tests may be the most useful for evaluating astronaut physical capacity.

2. Methods

71 subjects completed the experiments (40 men and 31 women, age 23 ± 5 yr, height 174 ± 9.8 cm, body mass 73.8 ± 15.7 kg). Each individual was free from known cardiovascular, pulmonary, or metabolic disease and were non-smokers as determined from a health history questionnaire. All subjects provided written informed consent to participate in the study. The study 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, and alcohol or caffeine for 10 h prior to testing. Each subject reported to the Human Exercise Physiology Laboratory eight times with at least 48 h between adjacent testing sessions. Testing order was determined a priori to limit the number of testing days, while minimizing testing interactions (Fig. 1).

2.1. Experimental protocols

Each subject performed incremental exercise to exhaustion on both a treadmill (Quinton Brute Q55XT Sport, WA, USA or Woodway Pro, Waukesha, WI, USA) and arm cranking ergometer (Rehab Trainer 881E, Monark) in order to determine limb specific $\dot{V}O_{2max}$ ($\dot{V}O_{2peak}$ for the upper body) and gas exchange threshold (GET). Both ergometers were calibrated prior to the beginning of the study to ensure accurate work load settings. Breath-by-breath metabolic and ventilatory data were continuously measured throughout both incremental tests (CardiO2 or Ultima CPX, Medical Graphics Corp., MN, USA) and converted to 15 s mean values. During the study the CardioO2 system became inoperable and a second system had to be used. To minimize any variability between systems, both systems were manufactured by the same company and used the same flow measuring device and gas analyzer hardware. Each system was calibrated before each testing session according to the manufacturer's instructions. The maximum 15 s mean $\dot{V}O_2$ was considered peak for a given exercise condition. The $\dot{V}O_2$ corresponding to the GET was determined as the $\dot{V}O_2$ at which $\dot{V}CO_2$ increased out of proportion with respect to $\dot{V}O_2$ and there was an increase in $\dot{V}E/\dot{V}O_2$ with no increase in $\dot{V}E/\dot{V}CO_2$ (Beaver et al., 1986). Heart rate was recorded at 1 min intervals with a telemetric heart rate monitor (FT7, Polar Electro Inc., NY, USA).

2.1.1. Running $\dot{V}O_{2max}$

Following 5 min of walking at 2.5 km h^{-1} and a grade of 1% to simulate outside running (Jones and Doust, 1996), the speed was increased to 4 km h^{-1} then 5 km h^{-1} for 3 min each. The speed was then increased to 6–10 km h^{-1}, depending on the subject's reported level of fitness, and was progressively increased 0.5 km h^{-1} each minute until the subject reached 95% predicted HR_{max} (HR_{max} = age − 220). At this point the speed was decreased by 1.0 km h^{-1} and the grade increased 1% every minute until volitional exhaustion. Following a 20 min passive recovery, subjects performed a constant-speed test to validate the attainment of $\dot{V}O_{2max}$ during the initial incremental test. This test consisted of a square-wave increase to the highest attained treadmill speed and grade during the initial incremental test. Subjects were instructed to run to exhaustion, which in all cases was >2 min. Pilot work in our laboratory revealed that a 1 km h^{-1} increment in speed increased $\dot{V}O_2$ by ∼220 ml min^{-1}. Thus, $\dot{V}O_{2max}$ was considered valid if the highest $\dot{V}O_2$ obtained during the constant-speed test was less than 200 ml min^{-1} greater than the highest $\dot{V}O_2$ during the incremental test (Poole et al., 2008). In each subject the running speeds corresponding to $\dot{V}O_{2max}$ (s-$\dot{V}O_{2max}$) and GET (s-GET) were determined by extrapolating their individual regression equation relating the sub-maximal $\dot{V}O_2$ to 1% grade running speed obtained during the early portion of the incremental test (Ali Almarwaey et al., 2003; Broxterman et al., 2013).

2.1.2. Arm $\dot{V}O_{2peak}$

During the upper-body arm cranking test subjects were seated behind the ergometer with the bottom bracket positioned at shoulder height. The ergometer set-up was recorded to ensure consistency across all testing sessions. Following 5 min of unloading cranking, the initial workload was set to 10 Watts (W) and the power output was progressively increased 10 W every minute until the subject could not maintain the cranking rate of 60 rpm for 5 consecutive revolutions. The highest power output achieved in which at least 30 s of the stage was completed was considered the peak power output (PPO). The highest 15 s mean $\dot{V}O_2$ was considered the peak metabolic response ($\dot{V}O_{2peak}$).

2.1.3. Critical speed

The speed-time relationship for treadmill running was determined via four randomly ordered square-wave transitions at speeds ranging between 90 and 120% s-$\dot{V}O_{2max}$ designed to elicit exhaustion in a range of 2–15 min periods (Broxterman et al., 2013; Smith and Jones, 2001). During each run the treadmill grade was set to 1%, to reflect outdoor running (Jones and Doust, 1996). Following 5 min of warm up walking at 2.5 km h^{-1} the subject straddled the treadmill belt while the treadmill speed was increased to the prescribed speed. The timing of each running bout was initiated when the subject started running and had let go of the handrails. The transition to exercise took <5 s. Each test was terminated when the subject grasped the handrail, signaling exhaustion, and time was recorded to the nearest second. Subjects were blinded to treadmill speed and test duration. CS and D' were calculated using the two-parameter linear speed-1/time model:

$$S = \frac{D'}{t} + CS$$

where S represents treadmill speed, t represents time-to-exhaustion, CS represents critical speed, and D' represents the finite

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