Upper Body Aerobic Exercise as a Possible Predictor of Lower Body Performance

Carl J. Ade; Ryan M. Broxterman; Jesse C. Craig; Susanna J. Schlup; Samuel L. Wilcox; Thomas J. Barstow

BACKGROUND: Aerobic exercise capacity provides information regarding cardiorespiratory health and physical capacity. However, in many populations the ability to measure whole-body or leg aerobic exercise capacity is limited due to physical disability or lack of appropriate equipment. Clinically there is a need to evaluate aerobic capacity in individuals who cannot use their legs for locomotion. In astronauts the habitable space for exercise testing in the next generation of space exploration systems may be restricted and may not support the traditional lower body testing. Therefore, the purpose was to determine if upper body physical performance could estimate lower body aerobic capacity.

METHODS: Maximal O_2 uptake ($\dot{V}O_{2max}$), gas exchange threshold (GET), and the highest sustainable rate of aerobic metabolism [arm cranking critical power ($_{A}CP$) and lower body critical speed ($_{L}CS$)] were determined in 55 conditioned men and women during arm-cranking and treadmill running.

RESULTS: $\dot{V}O_{2max}$ and GET (48.6 ± 7.6 and 29.0 ± 4.8 ml · kg^{-1} · min^{-1}, respectively) were significantly lower during arm-cranking exercise compared to running (27.1 ± 7.6 and 13.5 ± 2.6 ml · kg^{-1} · min^{-1}, respectively). The $\dot{V}O_2$ at $_{A}CP$ was significantly lower than the $\dot{V}O_2$ at the $_{L}CS$ (18.4 ± 5.01 vs. 39.5 ± 8.1 ml · kg^{-1} · min^{-1}, respectively). There was a significant correlation between arm-cranking and lower body $\dot{V}O_{2max}$, GET, and the $\dot{V}O_2$ at $_{L}CS$ and $_{A}CP$. Backward stepwise regression analyses revealed that arm-cranking physical fitness could explain 67%, 40%, and 49% of the variance in lower body $\dot{V}O_{2max}$, GET, and $_{L}CS$, respectively.

DISCUSSION: Results suggest arm-cranking exercise can be used to obtain an approximation of lower body aerobic capacity.

KEYWORDS: critical speed, $\dot{V}O_{2max}$, gas exchange threshold.

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Evaluation of aerobic exercise capacity [maximal O_2 uptake ($\dot{V}O_{2max}$)] provides detailed information regarding integrated cardiorespiratory health and the ability to complete physically demanding tasks.[1] However, in many populations the ability to measure aerobic exercise capacity is limited due to physical disability or lack of appropriate equipment, which may limit the ability to test for suspected coronary artery diseases.[14] Aerobic exercise capacity is also regularly monitored and used as a measurement of work readiness in physically challenging occupations, like firefighters.[28] In astronauts, $\dot{V}O_{2max}$ is primarily used to evaluate health and the severity of spaceflight deconditioning.[8,9,12] In addition, treadmill or cycling measurements of $\dot{V}O_{2max}$ are currently used by NASA to evaluate astronaut readiness and physical capacity.[20] Ade et al.[2] previously demonstrated that a treadmill derived $\dot{V}O_{2max}$ and, to a greater extent, critical speed (CS), the running equivalent of critical power (CP), which defines the highest sustainable rate of aerobic metabolism, are both highly correlated with simulated planetary extravehicular activity (EVA) field test performance. Therefore, the evaluation of these lower body fitness parameters pre-, in-, and postflight provide detailed information regarding an astronaut's cardiorespiratory health, general physical capacity, and the ability to complete physically challenging EVA and/or emergency maneuvers.

The main purpose of the exercise hardware currently aboard the International Space Station has been for regular exercise training, but also has a secondary role for the

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evaluation of physical performance, including lower body aerobic exercise capacity and muscular strength.[11,18,19] The next generation of space exploration systems, however, may not have the habitable space needed to support multiple large muscle mass (e.g., lower body) exercise testing and training options. Thus, the lack of a lower body exercise modality may limit lower body training, resulting in significant loss of cardiorespiratory function, as well as the ability to regularly test the efficacy of the training regimen. This creates a potential risk for loss of exercise capacity and inadequate evaluation of in-flight astronaut conditioning. Parallel to astronauts who might be limited by habitable space, many populations lack the ability to perform lower body aerobic exercise tests due to physical disabilities or athletic injury. As such there is a continued clinical need to evaluate lower body aerobic capacity in situations in which traditional lower body exercise modalities are not an option, whether it be for the in-flight astronaut, disabled clinical population, or injured athlete. Therefore, the aim of the current study was to determine if measurements of upper-body physical performance could individually, or in aggregate, estimate lower body $\dot{V}O_{2max}$ and CS. We hypothesized that, for $\dot{V}O_{2max}$, CS/CP, and the gas exchange threshold (GET), 1) absolute values for arm exercise would be less than for legs, but 2) CS/CP and GET would occur at the same %$\dot{V}O_{2max}$ for arm and leg exercise, and 3) arm and leg responses would be significantly correlated.

METHODS

Subjects

Volunteering to participate in the present study were 55 subjects (34 men, 21 women). A health history questionnaire was used to ensure that subjects were nonsmokers and free from known cardiovascular, pulmonary, or metabolic diseases. Verbal and written consent were obtained from all subjects prior to data collection. All procedures were approved by the Institutional Review Board for Research Involving Human Subjects at Kansas State University and conformed to the Declaration of Helsinki. Each subject reported to the laboratory in a rested, fully hydrated state, having abstained from alcohol, caffeine, and vigorous activity for 24 h prior to testing. Testing order was determined a priori to limit the number of testing days while minimizing testing interactions.

Equipment

Lower body $\dot{V}O_{2max}$ ($_L\dot{V}O_{2max}$), lower body gas exchange threshold ($_L$GET), and lower body critical speed ($_L$CS) were determined on a calibrated treadmill (Quinton Brute Q55XT Sport, Bothell, WA, or Woodway Pro, Waukesha, WI). Upper body exercise capacity and critical power ($_A$CP) were determined on an arm-cranking ergometer (Rehab Trainer 881E, Monark, Vansbro, Sweden). Subjects were seated behind the ergometer with the crank axis positioned at shoulder height. The seat height and distance were recorded to ensure consistency across testing sessions. All 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 via a metabolic measurement system (CardiO2 or Ultima CPX, Medical Graphics Corp., St. Paul, MN) during each exercise test and converted to 15-s binned mean values. During the study the CardioO2 system (Medical Graphics Corp.) became inoperable and a second system (Ultima CPX, Medical Graphics Corp.) had to be used on 42 of the 52 subjects. Due to the unanticipated loss of the initial system, reliability data between the two systems could not be collected. Both systems were manufactured by the same company and used the same flow measuring device and gas analyzer hardware in an attempt to minimize any variability between systems. Each system was calibrated before each testing session according to the manufacturer's instructions.

Procedures

$_L\dot{V}O_{2max}$ and $_L$GET were determined via a previously described incremental exercise test.[7] Prior to the incremental test each subject completed 5 min of walking at 2.5 km/h on a 1% grade,[15] followed by an increase to 4 km/h then 5 km/h for 3 min each. The speed was then increased to 6-10 km/h based on the subject's reported level of fitness, and then was progressively increased 0.5 km/h each minute until 95% predicted HR_{max} (HR_{max} = 220 − age) was achieved. At this point the speed was decreased by 1.0 km/h and held constant while the grade was increased 1% every minute until volitional exhaustion. Following a 20-min recovery, each subject performed a constant-speed test to volitional exhaustion, consisting of a square-wave increase to the highest attained treadmill speed and grade during the incremental test. The maximum 15-s mean $\dot{V}O_2$ was considered $\dot{V}O_{2max}$ if the highest $\dot{V}O_2$ obtained during the constant speed test was less than 200 ml · min^{-1} greater than the highest 15-s mean $\dot{V}O_2$ during the incremental test.[22] In each subject the speed at $_L\dot{V}O_{2max}$ was determined by extrapolating each subject's individual regression equation relating submaximal $\dot{V}O_2$ to 1% grade running speeds.[3,7] The $\dot{V}O_2$ corresponding to the $_L$GET was determined as the $\dot{V}O_2$ at which $\dot{V}O_2$ 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

Table I. Effects of Arm-Cranking and Lower Body Running on the Submaximal and Maximal Physiological Parameters.

VARIABLE	ARM-CRANKING	LOWER BODY RUNNING
$\dot{V}O_{2max}$ (ml · kg^{-1} · min^{-1})	27.1 7.62	48.6 ± 7.62‡
GET (ml · kg^{-1} · min^{-1})	13.5 ± 2.63	29.0 ± 4.78‡
GET (%$\dot{V}O_{2max}$)	51.1 ± 8.07	60.1 ± 8.17‡
CP/CS (ml · kg^{-1} · min^{-1})	18.4 ± 5.09	39.5 ± 8.12‡
CP/CS (%$\dot{V}O_{2max}$)	67.5 ± 8.56	81.0 ± 8.85‡
CP (W)	63.7 ± 22.1	N/A
CS (km/h)	N/A	12.0 ± 2.19

$\dot{V}O_{2max}$, maximal oxygen uptake; GET, gas exchange threshold; CP, critical power; CS, critical speed.
‡ Significantly different from arm-cranking ($P < 0.001$).

Table II. Correlation Coefficients and SEE Between Upper (Arm-Cranking) and Lower Body (Running) Parameters.

	$_L\dot{V}O_{2max}$ ($ml \cdot kg^{-1} \cdot min^{-1}$)		$_L$GET ($ml \cdot kg^{-1} \cdot min^{-1}$)		$_L$CS ($ml \cdot kg^{-1} \cdot min^{-1}$)		$_L$CS (km/h)	
VARIABLE	**R**	**SEE**	**R**	**SEE**	**R**	**SEE**	**R**	**SEE**
PPO (W)	$0.34^{\dagger}$	4.54	-	-	-	-	-	-
$_A\dot{V}O_{2max}$ ($ml \cdot kg^{-1} \cdot min^{-1}$)	$0.76^{\ddagger}$	5.04	-	-	-	-	-	-
$_A$GET ($ml \cdot kg^{-1} \cdot min^{-1}$)	-	-	$0.28^{\dagger}$	4.64	-	-	-	-
$_A$GET (%$_A\dot{V}O_{2max}$)	-	-	$0.32^{\dagger}$	4.57	-	-	-	-
$_A$CP (W)	-	-	-	-	$0.58^{\ddagger}$	6.68	$0.61^{\ddagger}$	1.75
$_A$CP ($ml \cdot kg^{-1} \cdot min^{-1}$)	-	-	-	-	$0.76^{\ddagger}$	5.30	$0.64^{\ddagger}$	1.70
$_A$CP (%$_A\dot{V}O_{2max}$)	-	-	-	-	$0.42^{\dagger}$	7.45	$0.34^{\dagger}$	2.06

PPO, arm-cranking peak power output; $_A\dot{V}O_{2max}$, arm-cranking maximal oxygen uptake; $_A$GET, arm-cranking gas exchange threshold; $_A$CP, arm-cranking critical power; $_L\dot{V}O_{2max}$, lower body maximal oxygen uptake; $_L$GET, lower body gas exchange threshold; CS, critical speed.

† Significant correlation ($P < 0.05$).

‡ Significant correlation ($P < 0.001$).

intervals with a telemetric heart rate monitor (FT7, Polar Electro Inc., North New Hyde Park, NY).

$_L$CS was determined via a series of constant speed runs on a treadmill at randomly ordered speeds ranging between 90–120% speed at $_L\dot{V}O_{2max}$ at a 1% grade,[15] selected to elicit exhaustion in 2-15 min.[6,25] Following 5 min at 2.5 km/h, the subjects straddled the treadmill belt as the treadmill was adjusted to the prescribed speed. Timing of each running bout was initiated when the subject started running and had let go of the handrails. Each test was terminated when the subject signaled exhaustion by grasping the handrail. The transition from rest-to-exercise took < 5 s and the test duration was recorded to the nearest second. Subjects were blinded to treadmill speed and test duration. $_L$CS was calculated using the two-parameter linear-1/time model:

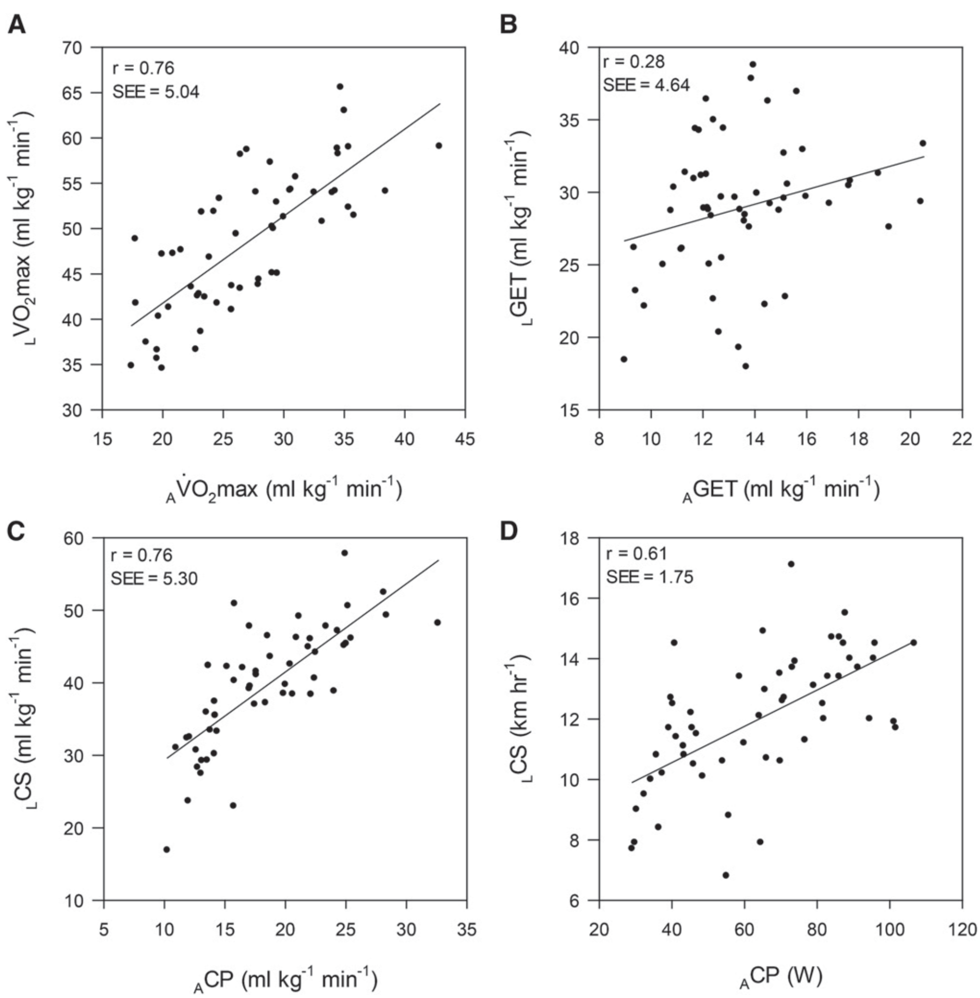

Fig. 1. Correlations between arm-cranking and lower body running. A) Maximal oxygen uptake ($\dot{V}O_{2max}$), B) gas exchange threshold (GET), C) oxygen uptake at critical speed ($_L$CS), and D) the speed at $_L$CS.

$$S = D'/t + CS \qquad \text{Eq. 1}$$

where S represents treadmill speed, t represents time-to-exhaustion, CS represents critical speed, and D' represents the finite distance that can be covered when running above CS.[6,25] In this regression analysis, $_L$CS represents the y-intercept of the relationship between treadmill speed and 1/time-to-exhaustion. In each subject $\dot{V}O_2$ at $_L$CS was determined by interpolation of each subject's individual regression equation relating submaximal $\dot{V}O_2$ to 1% grade running speeds determined from the incremental treadmill test.

Upper body exercise capacity was determined via an incremental exercise test. Following 5 min of unloaded cranking the workload was progressively increased 10 $W \cdot min^{-1}$ until the subject could not maintain the required 60 rpm for five consecutive revolutions. The highest work rate achieved in which at least 30 s of the stage was completed was considered peak power output. The maximum 15-s mean $\dot{V}O_2$ was considered the arm-cranking $\dot{V}O_{2peak}$ (${}_A\dot{V}O_{2max}$; referred to as max for clarity). The arm-cranking $\dot{V}O_2$ corresponding to the GET (${}_A$GET) was determined as the $\dot{V}O_2$ at which $\dot{V}O_2$ 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] Each GET was determined manually by a senior investigator blinded to the subject and testing modality.

${}_A$CP was determined via a series of randomly ordered square-wave transitions from rest to work rates between 70–110% peak power output. Following 5 min of unloaded cranking, the work rate was quickly increased to the prescribed power output. The test was terminated when the subject could not maintain 60 rpm for five consecutive revolutions. ${}_A$CP was calculated using the linear power-1/time model:

$$PO = W'/t + {}_A\,CP \qquad \text{Eq. 2}$$

where PO represents power output, t represents time-to-exhaustion, ${}_A$CP represents critical power, and W' represents the finite amount of work that can be performed above CP.[21] In this regression analysis, ${}_A$CP represents the y-intercept of the relationship between power output and 1/time-to-exhaustion. In each subject $\dot{V}O_2$ at ${}_A$CP was determined by interpolating each subject's individual regression equation relating submaximal $\dot{V}O_2$ to arm cranking power determined during the incremental test.

Statistical Analysis

Descriptive statistics were calculated for each arm cranking and lower body parameter of aerobic fitness. $\dot{V}O_{2max}$ and GET were compared across exercise modalities using paired *t*-tests. The relationship between arm cranking and lower body parameters were examined using Pearson product moment correlation coefficients. A multiple backward linear regression model was used to identify the arm-cranking parameters for which the majority of the variance in ${}_L\dot{V}O_{2max}$, ${}_L$GET, and ${}_L$CS could be attributed. Differences were considered statistically significant when $P < 0.05$ and all data are presented as mean ± SD.

RESULTS

Subjects were characterized by a mean age of 22 ± 4 yr, a body mass of 73.5 ± 14.3 kg, and a height of 175 ± 9 cm. **Table I** summarizes the results of the arm cranking and treadmill tests. The mean ${}_A\dot{V}O_{2max}$ was 55.6 ± 7.8% of ${}_L\dot{V}O_{2max}$, and all subjects had a lower ${}_A\dot{V}O_{2max}$ compared to ${}_L\dot{V}O_{2max}$ [$t(54) = 31.9$, $P < 0.001$]. There was a significant correlation between ${}_A\dot{V}O_{2max}$ and ${}_L\dot{V}O_{2max}$ (r = 0.76, $P <$ 0.001, **Table II** and **Fig. 1A**).

The ${}_A$GET was significantly lower than ${}_L$GET, both in absolute terms and as a percent of the respective $\dot{V}O_{2max}$ [$t(54) = -23.9$, $P < 0.001$] (Table I). In turn, both ${}_L$GET (**Fig. 2A**) and ${}_A$GET (**Fig. 2B**) were inversely related to their respective $\dot{V}O_{2max}$. There was a small but significant correlation between ${}_L$GET and ${}_A$GET (r = 0.28, $P < 0.05$, **Fig. 1B**).

The $\dot{V}O_2$ at ${}_A$CP was significantly lower than the $\dot{V}O_2$ at ${}_L$CS, both in absolute terms ($t = 9.39$, df = 54, $P < 0.001$) and as a percent [$t(54) = 29.3$, $P < 0.001$] of the respective $\dot{V}O_{2max}$ (Table I). A significant association was observed between ${}_A$CP and ${}_L$CS (**Fig. 1C** and **Fig. 1D**). ${}_L$CS varied as a function of ${}_L\dot{V}O_{2max}$ such that ${}_L$CS occurred at a greater $\%{}_L\dot{V}O_{2max}$ in individuals with a high ${}_L\dot{V}O_{2max}$ (Fig. 2A).

The stepwise regression equation for ${}_L\dot{V}O_{2max}$ was:

$$\begin{aligned} {}_{\text{pred-L}}\dot{V}O_{2max} = {} & -47.3 + \left(3.06 \times {}_A\dot{V}O_{2max}\left(\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}\right)\right) \\ & + \left(-3.10 \times {}_A CP\left(\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}\right)\right) \\ & + \left(1.04 \times {}_A CP\left(\%\,{}_A\dot{V}O_{2max}\right)\right) \end{aligned} \qquad \text{Eq. 3}$$

The standard error of the estimate (SEE) was 4.49 ml · kg^{-1} · min^{-1}, with $r^2 = 0.67$ ($P < 0.001$, power with $\alpha = 0.05$: 1.0). **Fig. 3A** illustrates the relationship between ${}_L\dot{V}O_{2max}$ and ${}_{\text{pred-L}}\dot{V}O_{2max}$ (predicted ${}_L\dot{V}O_{2max}$).

${}_{\text{pred-L}}$GET (predicted ${}_L$GET) was predicted as:

$$\begin{aligned} {}_{\text{pred-L}}GET = {} & 4.53 + \left(0.33 \times {}_A\dot{V}O_{2max}\left(\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}\right)\right) \\ & + \left(0.23 \times {}_A CP\left(\%\,{}_A\dot{V}O_{2max}\right)\right) \end{aligned} \qquad \text{Eq. 4}$$

The SEE was 3.77 ml · kg^{-1} · min^{-1}, with $r^2 = 0.40$ ($P < 0.001$, power with $\alpha = 0.05$: 1.0). **Fig. 3B** illustrates the relationship between ${}_L$GET and ${}_{\text{pred-L}}$GET.

The $\dot{V}O_2$ at ${}_L$CS (**Fig. 3C**) was predicted as:

$$\begin{aligned} {}_{\text{pred-L}}CS\left(\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}\right) = {} & -80.2 \\ & + \left(3.89 \times {}_A\dot{V}O_{2max}\left(\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}\right)\right) \\ & + \left(-4.24 \times {}_A CP\left(\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}\right)\right) \\ & + \left(1.37 \times {}_A CP\left(\%\,{}_A\dot{V}O_{2max}\right)\right) \end{aligned} \qquad \text{Eq. 5}$$

The SEE was 4.78 ml · kg^{-1} · min^{-1}, with $r^2 = 0.67$ ($P < 0.001$, power with $\alpha = 0.05$: 1.0).

Finally, the following equation predicts the speed at ${}_L$CS (**Fig. 3D**):

$$\begin{aligned} {}_{\text{pred-L}}CS\left(\text{km}\cdot\text{h}^{-1}\right) = {} & 7.15 + \left(-0.03 \times PPO(W)\right) \\ & + \left(0.13 \times {}_A\dot{V}O_{2max}\left(\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}\right)\right) \\ & + \left(0.06 \times {}_A CP(W)\right) \end{aligned} \qquad \text{Eq. 6}$$

The SEE was 1.62, with $r^2 = 0.48$ ($P < 0.001$, power with $\alpha =$ 0.05: 1.0). Figs. 3C and 3D illustrate the relationship between ${}_L$CS and ${}_{\text{pred-L}}$CS.

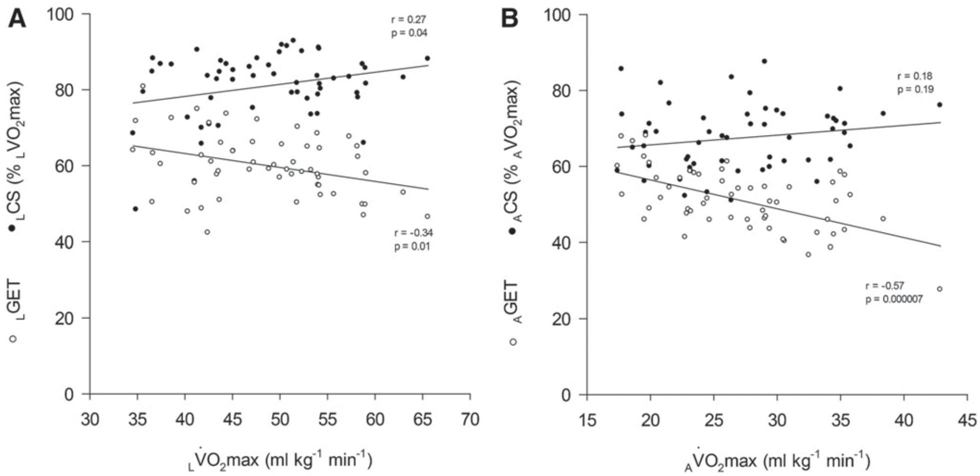

Fig. 2. GET and CS/CP (both as %$\dot{V}O_{2max}$) plotted as a function of their respective $\dot{V}O_{2max}$ for A) leg and B) arm cranking responses.

DISCUSSION

The primary aim of the present study was to determine if measurements of arm-cranking physical performance, individually or in aggregate, can be used to estimate lower-body fitness. Simple linear correlation between arm-cranking and lower body running revealed modest correlations in a large sample of low-to-well conditioned individuals. Backward stepwise regressions were capable of explaining 40–67% of the variance of $_L\dot{V}O_{2max}$, $_L$GET, and $_L$CS. Therefore, the present study demonstrates that individuals limited to arm-cranking exercise tests (e.g., in-flight astronauts) can still obtain an approximation of lower body aerobic fitness.

When compared to $_L\dot{V}O_{2max}$, $_A\dot{V}O_{2max}$ was significantly lower and represented approximately 56% of the lower body value. This finding is consistent with previous investigations comparing arm-cranking, leg-cycling, and running, in which arm-cranking $\dot{V}O_{2max}$ was between 36–89% of that achieved with leg cycling.[5,10] This variability in differences between upper and lower body aerobic capacity may be due, in part, to upper body training status. Vrijens et al.[26] demonstrated that the difference in $\dot{V}O_{2max}$ between arm and leg exercise is greater in trained controls compared to athletes whose sport depends on upper body muscular endurance (i.e., paddlers on the Belgian kayak squad). Thus, upper body trained individuals often achieve a higher fraction of their lower body $\dot{V}O_{2max}$ during arm-cranking exercise compared to sedentary individuals who attain a much lower percentage of their lower body $\dot{V}O_{2max}$.[10,11,26] Even though $_A\dot{V}O_{2max}$ is lower than $_L\dot{V}O_{2max}$, the present study observed a strong correlation between these body region-specific parameters of aerobic exercise capacity. This finding is consistent with several investigations reporting correlation coefficients between 0.70 to 0.94,[16,18,24] but diverges from some who report coefficients below 0.60.[13]

In the present study the GET was significantly lower during arm-cranking compared to running. Davis et al.[10] and Bergh et al.[5] have similarly reported that arm-cranking GET is approximately 50% of that measured during lower body exercise. However, unlike $\dot{V}O_{2max}$ and GET, the relationship between $_A$CP and running $_L$CS, to our knowledge, has not been previously investigated. In the present study, $_A$CP was correlated with running $_L$CS and significantly contributed to its estimation in the stepwise regression. The ability to evaluate running $_L$CS via either direct measurement or estimates from arm-cranking tests may provide additional information regarding physical health and performance of the long-duration astronaut. Our group has recently demonstrated that $_L$CS is the fitness parameter most strongly associated with performance on ground-based field tests designed to simulate the potentially physically demanding components of future planetary EVAs.[2] This highlights the potential use of $_L$CS as an additional measurement of astronaut readiness and the need to evaluate it in flight even when lower body-specific hardware is unavailable. However, additional work must be done to determine how $_L$CS relates to actual in-flight EVA performance. In addition, this work may have relevance for other subject groups for which job performance requires both upper and lower body fitness (e.g., military, fire, rescue, or construction).

Despite the differences in body posture and utilized muscle groups, a strong association between running and arm-cranking aerobic fitness is not unexpected. It is well established that aerobic exercise capacity, despite the modality, is dependent upon central and peripheral oxygen transport mechanisms.[23,27] Thus, any intervention that results in central adaptations would be expressed during both upper and lower body exercise stress tests, while any peripheral adaptations will be more exercise modality specific. This interaction is evident in the studies evaluating the transfer effects of exercise training with arm and legs. Lewis et al.[17] demonstrated that 11 wk of lower body training significantly increased arm-cranking $\dot{V}O_{2max}$. Conversely, Bergh et al.[5] reported that leg cycling, which significantly increased cycling $\dot{V}O_{2max}$, had no influence on arm-cranking $\dot{V}O_{2max}$ or ventilatory threshold. The different responses in these studies are likely due to differences in initial fitness level, which may have altered the degree of central versus peripheral adaptations. These disparate findings regarding transfer effects is disconcerting when discussing the use of an upper body exercise test to evaluate lower body fitness in flight, given that microgravity elicits regional adaptations, such that the lower limbs exhibit greater reductions in muscle mass and strength compared to the trunk and arms.[16] However, significant decreases in cardiac mass, ventricular volumes, plasma, and blood volumes following microgravity would likely contribute to performance during both upper and lower body exercise tests.[8] Given the central and peripheral maladaptations associated with spaceflight, estimating $_L$CS or $_L\dot{V}O_{2max}$ from

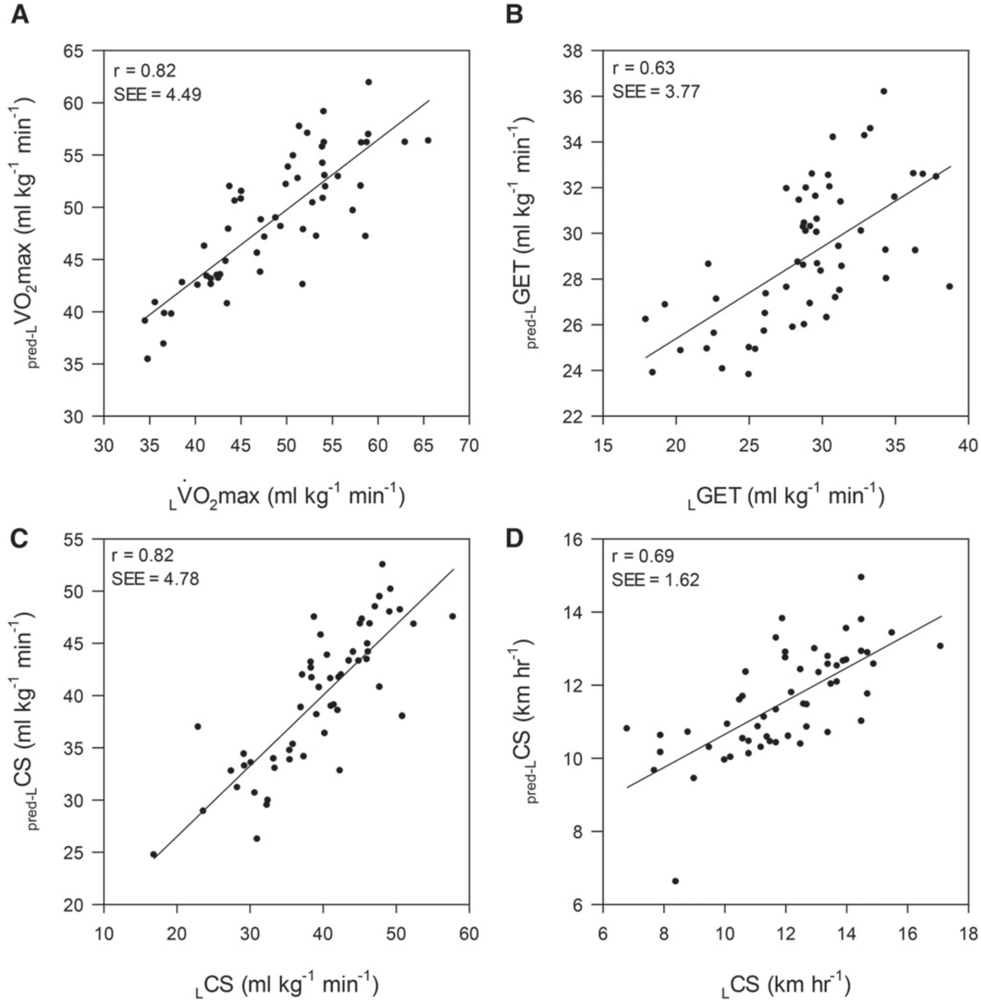

Fig. 3. Correlations between the actual and the predicted A) maximal oxygen uptake ($\dot{V}O_{2max}$), B) gas exchange threshold (GET), C) oxygen uptake at critical speed ($_{L}$CS), and D) the speed at $_{L}$CS.

arm-cranking tests should be made with caution and only used when absolutely necessary, as in the absence of appropriate testing hardware. In an attempt to improve the estimation of these key lower body fitness parameters, the present study used backward stepwise regression techniques to determine a combination of arm-cranking parameters that best calculate $_{L}\dot{V}o_{2max}$, $_{L}$GET, and $_{L}$CS. Each of the reported models was capable of explaining 67%, 40%, and 49% of the variance in $_{L}\dot{V}o_{2max}$, $_{L}$GET, and $_{L}$CS, respectively. However, it is important to note that the SEE were > 3.5 ml $\cdot$ kg^{-1} $\cdot$ min^{-1} for $_{L}\dot{V}o_{2max}$ and $_{L}$GET, while the SEE was > 1.5 km/h for $_{L}$CS. This suggests that arm cranking physical performance measurements may not be adequate in precisely predicting lower body exercise capacity. Indeed, it can be observed in Fig. 2A that an individual with a $_{\text{pred-L}}\dot{V}o_{2max}$ between 40 and 45 ml $\cdot$ kg^{-1} $\cdot$ min^{-1} could have an actual $_{L}\dot{V}o_{2max}$ of between 35.6 and 51.8 ml $\cdot$ kg^{-1} $\cdot$ min^{-1}. Therefore, while the present study demonstrates that arm-cranking exercise tests can be used to obtain an approximation of lower body aerobic capacity, this method of monitoring lower body exercise capacity should only be performed when absolutely necessary.[6]

There are a number of limitations to the present study. It is unknown if these results can be directly generalized to in-flight astronauts. Comparisons of arm and leg aerobic exercise capacity, to our knowledge, have not been performed during or following microgravity exposure. Likewise, it is unknown how arm-cranking exercise performance is altered following long-duration microgravity exposure. In an attempt to estimate these issues the present study used a cross-sectional design with a large sample size and a range in fitness similar to that observed in pre- and postflight astronauts.[8] However, some caution should be taken when cross-sectional data is used to predict physiological outcomes following microgravity exposure. An additional limitation was the testing of subjects younger than most astronauts. It is currently unknown how healthy aging affects the relationship between arm and leg aerobic exercise capacity. Future investigations may want to investigate how this relationship changes with the normal aging process.

In conclusion, the present study has shown that arm-cranking performance, specifically $\dot{V}o_{2max}$, GET, and CP, can be used to estimate lower body $\dot{V}o_{2max}$ and $_{L}$CS. These findings suggest that an upper body test may be used to estimate lower body aerobic conditioning in various populations, which may include the long-duration astronaut, athletes with lower body injuries, and patients with physical disabilities. The results also highlight that using these upper body fitness parameters in aggregate provides a better estimate of lower body performance than any one single parameter as indicated by the correlation coefficients and SEE. Therefore, while this study does not provide exact protocols that should be used, it does suggest that an upper body ergometer may be used to monitor changes in lower body aerobic capacity and performance.

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