Sweat Production During Continuous and Interval Aerobic Exercise

Jeffrey W. Ryder; J. Brent Crowell; Hee Jong Song; Michael Ewert

INTRODUCTION: Aerobic exercise within the habitable volume of small spacecraft needed for space exploration beyond low Earth orbit is expected to challenge the capacity of environmental control systems. Moisture control is a primary concern. Crewmembers will contribute moisture to the cabin environment in the form of sweat while exercising. The effects of continuous aerobic exercise for improving and maintaining aerobic capacity is well characterized. Likewise, evidence suggests that high intensity interval exercise for shorter durations is also effective in building and maintaining aerobic capacity.

METHODS: On separate days, measures of sweat and respiratory responses were made for continuous (30 min of steady state exercise at ~75% of aerobic capacity) and two interval (4 × 4 min, 8 × 30 s) exercise protocols.

RESULTS: We observed that the 4-min and 30-s interval protocols produce 16% and 66% less metabolic water loss vs. the continuous exercise protocol, respectively. These responses were highly correlated with the amount of work performed ($R^2 = 0.81$) and the amount of energy expenditure ($R^2 = 0.83$) during exercise.

DISCUSSION: These results suggest that interval exercise may be a useful alternative to continuous aerobic exercise when metabolic water production is an environmental concern. The results may inform the choices of aerobic exercise countermeasure protocols for use in deep space exploration.

KEYWORDS: exercise, sweat, interval.

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The Artemis Program is the NASA initiative to return humans to the surface of the Moon and serve as a precursor for Mars exploration. The Orion spacecraft will be the centerpiece architecture for the Artemis Program and represents one of multiple, small habitable volume spacecraft that may be used during parts of an Artemis mission. Aerobic deconditioning is a known consequence of spaceflight and aerobic exercise is currently a countermeasure against loss of aerobic capacity.[6,8,12] Aerobic exercise within the small habitable volumes of spacecraft is expected to challenge the ability of the environmental control and life support systems (ECLSS), especially moisture removal, among other challenges. Exercising humans contribute moisture to the environment by increased sweating during exercise and through increased respiration. For some crew, it is possible that standard continuous aerobic exercise may overwhelm the moisture removal capacities of the environmental control systems of small spacecraft. Evidence suggests that high intensity interval training (HIIT) is effective in building and maintaining aerobic capacity.[1] For example, studies that are comprised of HIIT alone or in combination with steady-state continuous exercise demonstrate greater improvements in aerobic capacity than those that involve continuous aerobic exercise alone.

The aim of this investigation was to determine the effect of continuous vs. interval exercise protocols on human sweat and respiratory water production responses. We hypothesized that interval protocols would result in less sweat production and be more compliant with ECLSS moisture removal capabilities.

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Interval protocols characteristically include shorter high intensity exercise but result in less total work due to the recovery periods between intervals. This investigation examined sweat responses for operationally relevant continuous and interval aerobic exercise protocols using subjects over a range of anthropometrics and fitness levels. The results will identify which protocols produce the most metabolic water loss (combined sweat and respiratory water losses), providing information as to which aerobic exercise countermeasures will be feasible to prescribe to crewmembers while remaining within humidity limits and avoiding condensation aboard small spacecraft.

METHODS

Subjects

A total of 30 subjects (18 men and 12 women) were recruited through the NASA Test Subject Support Facility. Signed informed consent for NASA Institutional Review Board-approved procedures was obtained from the subjects prior to any testing.

Procedures

Subjects completed five study sessions: two preliminary (aerobic capacity and familiarization) and three experimental. Subjects wore shorts and a t-shirt and were instructed to wear the same garments for all experimental trials. Trials were performed in an environmental chamber set to 23.9°C (75°F) and 34% relative humidity. These conditions correspond to a dew point of 7.1°C (45°F). No high-velocity fans were used to cool subjects as this capability may not be available for Artemis missions.

Aerobic capacity session. Aerobic capacity ($\dot{V}O_{2max}$) was determined by analysis of respiratory gases collected using a ParvoMedics True One 2400 Metabolic Measurements System (Sandy, UT, USA). Rowing exercise is envisioned as the mode of exercise within the Orion cabin. Therefore, subjects were tested while exercising on a Concept2 Model E rowing ergometer (Morrisville, VT, USA). An initial damper setting of 3 was used and adjusted according to subject preference and ability to achieve target workloads. Fixed workloads are not possible using a Concept2 rower; therefore, subjects were given target workloads to try to maintain based on stroke-by-stroke power output measures displayed on the Concept2 Performance Manager 5 display.

The initial workload target was 50 W for the first 3 min and increased by 25 W each minute until termination based on volitional fatigue or an inability to increase the power level for the next stage. For some individuals a "light" protocol was implemented. The "light" protocol is similar to the above, except the initial target load was 40 W and increased by 20 W every minute thereafter.

Familiarization session. During the familiarization session, target workloads were determined for each of the three experimental sessions (continuous exercise, 4-min intervals, and 30-s intervals). A linear relationship between watts and oxygen usage was used to estimate workloads and subjects were coached through abbreviated versions of the experimental session explained below.

Experimental sessions. Three aerobic training protocols were examined in a randomly balanced order on separate test days (a minimum of 2 d apart) and subjects were instructed not to perform exercise after 17:00 the day before. These protocols have previously been implemented in NASA Human Research Program (HRP)/National Space Biomedical Research Institute (NSBRI) funded research in 14-d and 70-d bed rest studies[9–11] and ISS spaceflight missions.[3] Each protocol was followed by 30 min of seated resting recovery.

- Continuous protocol: subjects rowed at a target wattage corresponding to 75% of $\dot{V}O_{2max}$ for 30 min.
- For 4-min intervals: subjects rowed for a 3-min warm-up at 50 W followed by 4 4-min intervals (120% of continuous exercise target wattage, ~85% of $\dot{V}O_{2max}$), each separated by 3 min of recovery at 50 W with a 2-min 50-W cool down (30 total min).
- For 30-s intervals: subjects performed a 3-min warm up at 50 W, followed by 8 30-s all-out intervals (~200% of continuous exercise target workload), each followed by 15 s of recovery at ~20 W of rest with a 2-min cool down at a 50-W target (11 total min).

Metabolic water loss. Subject nude dry bodyweight was recorded to the nearest 0.002 kg before exercise, following exercise, and 30 min following cessation of exercise using a Mettler Toledo PBA655 platform scale and Mettler Toledo ICS 449 display unit (Columbus, OH, USA) set to factory 5-s dynamic weight averaging. Calibration and readability were set up and certified by Mettler Toledo on site during installation and maintained by the NASA Johnson Space Center Calibration Laboratory thereafter. Total bodyweight change was calculated as the difference between each weighing, with difference between water consumption weighing added to the change in bodyweight value [(bodyweight_{pre} – bodyweight_{post}) + (water bottle_{pre} – water bottle_{post})].[4] Metabolic mass loss and respiratory water loss were calculated using respiratory gases as described.[7] Metabolic water loss was calculated as total bodyweight change – metabolic mass loss, with water volume assumed as a 1:1 ratio with mass. Sweat volume was calculated as change in total body mass – (metabolic mass loss + respiratory water loss). No subjects chose to drink water during the actual exercises. Subjects who elected to drink during the experiment all chose to drink following the postexercise weighing. Subjects had a separate set of clothes and towel for the exercise and recovery periods. Pre- to postexercise weight of clothes and towels used to dry off prior to weighing was used to estimate the amount of water that was not immediately evaporated (i.e., liquid sweat).

Power, work, and heart rate. Stroke-by-stroke power and heart rate (using a Polar H7 heart rate monitor, Polar USA, Bethpage, NY, USA) were collected via the Concept2 Performance Manager paired by Bluetooth to the Concept2 ErgData application for iPad (Apple, Inc., Cupertino, CA, USA). Work was derived from power data over time.

Metabolic measurements. Respiratory gas measurements were collected as described above using the ParvoMedics system. Continuous oxygen uptake, carbon dioxide production, respiratory exchange ratio, and energy expenditure were assessed during exercise and as soon as logistically possible during the recovery period after the postexercise weight was obtained.

Thermal measurements. Core temperature was collected using a SpotOn core temperature monitor (3M, Maplewood, MN, USA) adhered to the forehead. Skin thermistors were placed on the forehead, chest, back, thigh, calf, foot, upper arm, and forearm using ~1.5″ of Transpore tape (3M). Core temperature values were collected during exercise and as soon as logistically possible during the recovery period. Skin temperatures were collected during the exercise session only. Core temperature values were recorded manually every time the display changed by 0.1°C. Skin temperature measures were recorded using a LabView program (National Instruments, Austin, TX, USA) connected to a 1560 Black Stack thermometer (Fluke Calibration, Everett, WA, USA) readout. Individual thermistor data were recorded as the system cycled through channels such that measurements were recorded every 7–10 s. Data at 2-s intervals were derived by interpolation in order to present common time phase data for core and skin temperatures. Mean body temperature was calculated to the nearest minute using the formula $T_{body} = 0.35\ T_{skin} + 0.65\ T_{core}$ where T_{skin} = 0.3 (chest + upper arm) + 0.2 (thigh + calf).[5]

Statistical Analyses

Statistical analyses were performed using InStat statistical software package (Graphpad Software, La Jolla, CA, USA). Differences between exercise protocols were analyzed by one way analysis of variation (ANOVA), with a repeated measures approach used when there were no missing data (sweat rate variables only). Significance was accepted at $P < 0.05$. When differences occurred, they were identified using a Tukey post hoc analysis. Linear regression was used for correlation analyses. Significance vs. a slope of zero was accepted at $P < 0.05$ for regression analyses.

RESULTS

Subject characteristics reported as mean ± SD (range) were: age 37 ± 8 (26–57) yr, height 1.75 ± 0.08 (1.57–1.88) m, weight 72.9 ± 11.7 (53.7–95.9) kg, BMI 23.7 ± 2.4 (19.0–28.6) kg · m^{-2}, absolute $\dot{V}O_{2peak}$ 2.90 ± 0.62 (1.98–4.13) L · min, and relative $\dot{V}O_{2peak}$ 39.8 ± 5.2 (32.9–50.9) ml · kg^{-1} · min^{-1}.

Power and oxygen consumption were analyzed across the total exercise session and specifically during the active interval periods of the session (**Table I**). In the case of the latter, continuous exercise was considered as a single interval for comparison purposes. Peak heart rate responses during the interval phase reflect the average of peak values for all intervals completed in a session. Mean power for the total exercise session was lower on average for 4-min intervals and similar for 30-s intervals as compared to continuous exercise, respectively. However, intensity of interval exercise is evidenced by power during the interval phase. Interval phase power was 1.24 and 1.99 times greater for the 4-min intervals and 30-s intervals vs. continuous exercise, respectively. Mean HR response was significantly lower on average for interval protocols across the entire exercise session as compared to continuous but were similar when comparing interval phase values. Mean $\dot{V}O_2$ responses for each protocol are shown in **Fig. 1**. The continuous exercise protocol elicited a $\dot{V}O_2$ of 74.0 ± 2.6% of $\dot{V}O_{2peak}$, consistent with the target of 75%. Percent $\dot{V}O_2$ was significantly lower for interval protocols over the entire exercise session (66.7 ± 4.5% and 71.3 ± 4.5% for 4-min and 30-s intervals, respectively), whereas interval-phase $\dot{V}O_2$ was greater vs. continuous exercise (78.2 ± 3.8% and 91.0 ± 5.0% for 4-min and 30-s intervals, respectively). Additionally, the final 30-s plateau in oxygen uptake during the 4-min intervals averaged 86.8 ± 3.8% of $\dot{V}O_{2peak}$ ($P < 0.001$ vs. continuous exercise). Comparison of ergometer power and energy expenditure by indirect calorimetry during the steady-state continuous exercise protocol provides an estimate of rowing exercise efficiency [(energy out, i.e., mechanical power/energy in, i.e., metabolic power) × 100] of 15.9 ± 1.3%, which is lower than the reported efficiency of 20.6% (18.3–22.6%) for cycle ergometry.[2] This suggests that, at any given exercise load, more energy is lost as heat during rowing as compared to cycling.

Total work performance, energy expenditure, and accumulated oxygen uptake during each protocol was significantly less for intervals vs. continuous exercise (Table I). Furthermore, these values were lower in the 30-s vs. 4-min intervals. Total carbon dioxide production was also lower during the 30-s intervals.

Table I. Characterization of Power, Oxygen Utilization, Work, and Energy Expenditure for Each Exercise Protocol.

	CONTINUOUS (*N*)	4-min INTERVALS (*N*)	30-s INTERVALS (*N*)
Power (W)	118 ± 31 (30)	101 ± 20 (30)*	120 ± 27 (29)
Interval power (W)	118 ± 31 (30)	146 ± 36 (30)*	235 ± 62 (29)††
O2 uptake (L · min^{-1})	2.15 ± 0.46 (30)	1.92 ± 0.33 (30)	2.03 ± 0.37 (29)
Interval O2 uptake (L · min^{-1})	2.15 ± 0.46 (30)	2.26 ± 0.44 (30)	2.60 ± 0.52 (29)†
Work performed (kJ)	213 ± 56 (30)	182 ± 37 (30)*	80 ± 18 (29)††
Energy expenditure (kJ)	1328 ± 285 (30)	1189 ± 205 (30)*	472 ± 85 (29)††

Data are means ± SD.
* $P < 0.05$ vs. continuous; † $P < 0.01$; †† $P < 0.001$ vs. continuous and 4-min intervals.

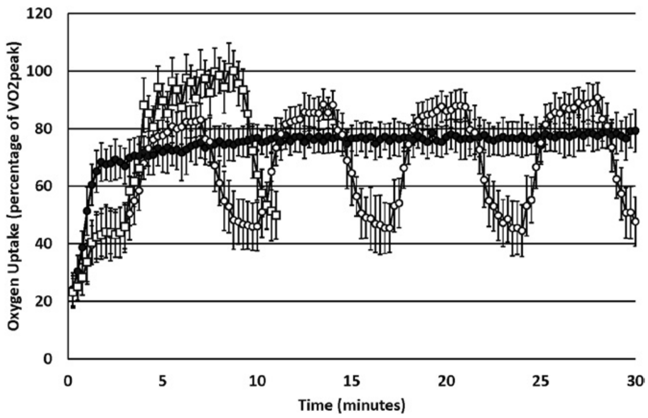

Fig. 1. $\dot{V}O_2$ responses to the experimental exercise protocols. Oxygen uptake during continuous (close circles), 4-min interval (open circles), and 30-s interval (open squares) exercise. Data are means ± SD for percentage of baseline $\dot{V}O_{2peak}$.

Mean body temperatures generally showed an initial drop followed by a gradual increase (not shown). These changes are of minimal physiological consequence as they varied only a couple of tenths of a degree from baseline. There were no differences between groups at any particular time point.

Changes to total body weight, total metabolic water, and sweat were determined for the continuous and interval exercise protocols (**Table II**). The 4-min interval protocol produced 17–18% less of these measures on average during the interval vs. continuous exercise. Likewise, the 30-s interval protocol resulted in 65–66% ($P < 0.001$) less than continuous exercise, and 59–60% (*208* $P < 0.001$) less than the 4-min protocol. No differences in responses were observed between groups during the 30-min seated recovery period. The amount of sweat that was recaptured in clothes and in the towel from drying off prior to weighing was 0.036 ± 0.023 L, 0.026 ± 0.016 L, and 0.010 ± 0.018 L for the continuous exercise, 4-min interval, and 30-s interval protocols, respectively ($P < 0.001$ for continuous vs. 30-s intervals, and for 4-min intervals vs. 30-s intervals). Recaptured sweat was below detection following the recovery period.

Total metabolic water loss in response to exercise correlated highly with total work performance and energy expenditure whether or not metabolic mass corrections were made (i.e., even if total bodyweight change is used). The coefficients of determination (R^2) values for work vs. water loss with (**Fig. 2A**) or without (**Fig. 2B**) correction for metabolic mass exercise were 0.81 ($P < 0.0001$) and 0.85 ($P < 0.0001$), respectively. Similarly, correlations were observed when analyzing for total energy expenditure instead of total work performed. The R^2 values with (**Fig. 2C**) and without (**Fig. 2D**) metabolic mass corrections were 0.83 ($P < 0.0001$) and 0.87 ($P < 0.0001$), respectively.

DISCUSSION

This investigation was conducted due to potential limitations of the moisture removal capabilities of small habitable volume vehicles that are envisioned for the Artemis lunar missions and beyond. Interval exercise characteristically involves higher intensity bouts of exercise, but with less total work compared to continuous exercise at a moderate intensity. We therefore hypothesized that the reduced total work performance associated with interval protocols would result in production of less sweat and respiratory water. Operationally, interval exercise countermeasures would presumably be more compliant with the water removal constraints of air revitalization systems.

Consistent with our hypothesis, both of the tested interval exercise protocols resulted in less metabolic water production compared with continuous exercise (Table II). Both interval protocols were also characterized by lower total work performed and lower total energy expenditure during exercise (Table I). The 30-s intervals, which resulted in the lowest sweat response, also resulted in the lowest total work performance and energy expenditure (Table I). It is worth noting that the marked reduction in the sweat response to the 30-s intervals is largely owed to the reduced exercise duration (11 min vs. 30 min). Nevertheless, the short duration 30-s interval protocol clearly resulted in the least amount of metabolic water. This was observed in all 30 subjects.

When data from all three protocols were grouped, there was a high correlation between work performance and exercise-induced loss of metabolic water (Fig. 2). Therefore, if an exercise prescription is planned where the sweat/respiratory water response is an important point of consideration, it is not critical which protocol is used, but rather the total work (and corresponding energy expenditure) that is going to drive the metabolic water production response. Given that this is predictable based on the workload profile, a variety of interval options can be prescribed beyond just those that have been measured in a laboratory. Being able to confidently prescribe a wide variety of protocols based on calculated workloads while understanding the influence on water production will

Table II. Sweat Volumes Produced for Each Protocol During the Exercise Phase.

	CONTINUOUS (*N*)	4-min INTERVALS (*N*)	30-s INTERVALS (*N*)
Total body weight loss (kg)	0.414 ± 0.133 (30)	0.347 ± 0.096 (30)**	0.139 ± 0.04 (30)†
Metabolic mass loss (kg)	0.034 ± 0.007 (30)	0.030 ± 0.005 (30)*	0.012 ± 0.002 (29)†
Total water loss (L)	0.380 ± 0.127 (30)	0.316 ± 0.092 (30)**	0.128 ± 0.044 (29)†
Respiratory water loss (L)	0.026 ± 0.006 (30)	0.024 ± 0.004 (30)*	0.009 ± 0.002 (29)†
Sweat loss (L)	0.353 ± 0.122 (30)	0.293 ± 0.088 (30)*	0.119 ± 0.042 (29)†

Data are means ± SD.
*$P < 0.05$; **$P < 0.001$ vs. continuous; †$P < 0.001$ vs. continuous and 4-min intervals.

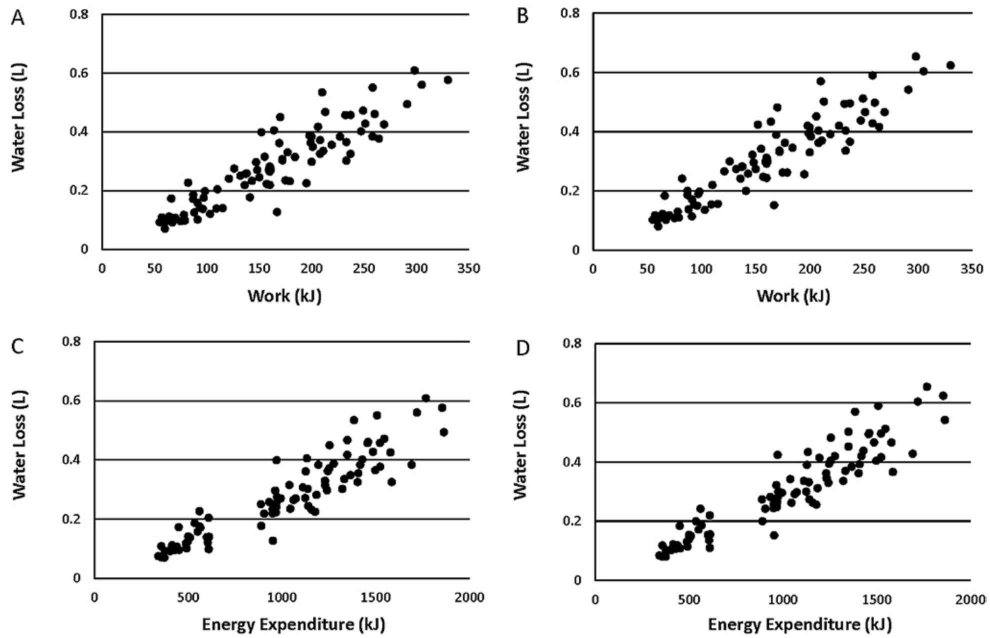

Fig. 2. Work and energy expenditure influences on sweat responses. Correlations for work performance vs. exercise water loss A) with ($R^2 = 0.81$, slope y = 0.00018× - 0.0084) and B) without ($R^2 = 0.85$, slope y = 0.00019× – 0.008) metabolic mass correction. Correlations for energy expenditure vs. exercise water loss C) with ($R^2 = 0.83$, slope y = 0.0003× – 0.023) and D) without ($R^2 = 0.87$, slope y = 0.003× – 0.024) metabolic mass correction. All correlations were significant at $P < 0.0001$.

most likely reduce instances of crew boredom from doing the same few protocols repeatedly.

Our findings here also have terrestrial applications. Competitive and recreational athletes, especially those who engage in endurance and ultra-endurance sport often look at ways to optimize hydration as part of their overall training regimen. Common field practice for measuring sweat rate is through pre-/post-exercise bodyweight changes. When accounting for consumed fluids, the change in bodyweight is used as a surrogate measure of sweat loss. Here we have completed this methodology, but further dissected out respiratory water and metabolic mass loss. Whether for stress placed upon environmental control systems, or for information to optimize hydration strategies, total body water loss is of more importance than true sweat loss per se. However, the degree to which metabolic mass loss contributes is of importance in understanding true water loss. Here we provide evidence confirming that metabolic mass contributes to less than 10% of body mass loss during exercise, at least in a cool dry environment. For athlete purposes, at home pre- to postexercise bodyweight measurements are a reasonably accurate surrogate for metabolic water loss results. This statement is made with the caveat that measurements in the current study were made in a thermal neutral environment in order to align with environmental requirements for Artemis missions.

In conclusion, we demonstrated that metabolic water loss (sweat loss + respiratory water loss) occurs in a manner related to the amount of work produced during exercise for continuous and interval exercise. These results have practical implications for providing exercise countermeasure prescriptions during space exploration where environmental control systems may have limitations in water removal.

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