Prediction of Emergency Capsule Egress Performance

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INTRODUCTION: Critical mission tasks for Martian exploration have been identified and include specific duties that astronauts will have to perform despite any adverse effects of chronic microgravity. Specifically, astronauts may have to perform an emergency capsule egress upon return to Earth, which places specific demands on compromised cardiovascular and neuromuscular systems. Therefore, the purpose of this project was to determine the relationship between cardiorespiratory fitness and simulated capsule egress time.

METHODS: There were 15 subjects who volunteered for this study. $\dot{V}O_{2peak}$ and peak power output (PPO) were determined on cycle and rowing ergometers. Critical power (CP) was determined by a 3-min all-out rowing test. Subjects then performed an emergency capsule egress on a mock-up of NASA's Orion space capsule. Peak metabolic data were compared between the cycling and rowing tests. Pearson's correlation was used to identify relationships between egress time and $\dot{V}O_{2peak}$, PPO, and CP.

RESULTS: $\dot{V}O_{2peak}$, $\dot{V}CO_{2peak}$, and minute ventilation were not different between cycling and rowing tests. Cycling elicited a greater PPO than the rowing test. Egress time was negatively correlated to rowing PPO ($r = -0.60$), but not cycling or rowing $\dot{V}O_{2peak}$, cycling PPO, or CP.

CONCLUSIONS: Rowing PPO/kg correlates with egress time. Although individuals with higher PPO/kg were able to finish the task in less time, individuals with low fitness levels ($\dot{V}O_{2peak} \leq 20$ ml · kg^{-1} · min^{-1}) could complete the egress within 2 mins. These results suggest that cardiorespiratory fitness should not limit emergency egress and that this can be assessed using rowing exercise.

KEYWORDS: critical power, $\dot{V}O_{2max}$, microgravity, spaceflight, exercise.

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The National Aeronautics and Space Administration's (NASA's) goals of long-duration missions beyond low Earth orbit will require a greater understanding of the physical requirements needed to complete specific nominal and contingency mission tasks. Prolonged spaceflight causes deficits in cardiovascular and neuromuscular function,[1,4,10] which may limit an astronaut's ability to perform physically challenging tasks in and postflight.[2,3] Thus, despite these deficits, astronauts must maintain a minimum level of cardiorespiratory fitness in order to complete all contingency mission tasks. Among the several mission tasks, astronauts must be able to perform an unaided top hatch emergency egress from the space capsule upon return to Earth as quickly as possible. This task is unique in that, in an emergency situation, it must be performed as quickly as possible while in 1 G following the total mission duration of possibly 1–3 yr.[30]

NASA's current standard for evaluating astronaut readiness is $\dot{V}O_{2peak}$, with a minimum fitness threshold of 32.9 ml · kg^{-1} · min^{-1}.[29] However, evaluation of $\dot{V}O_{2peak}$ in flight will require an onboard pulmonary gas exchange system, which may not be feasible due to space and weight limitations with future flight systems (e.g., Orion). Thus, measurements of aerobic exercise capacity using only power output are warranted. In addition to peak power output (PPO) obtained during incremental exercise, critical power (CP)—a variable that represents the highest sustainable aerobic work rate—has been shown to be a useful determinant of exercise performance.[22,35] Thus, these parameters may have physiological relevance to unaided top hatch emergency egress performance.[22,33] Therefore, the purpose of

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this study was to determine the relationships between $\dot{V}O_{2peak}$, PPO, CP, and unaided top hatch emergency egress completion time.

METHODS

Subjects

There were 15 subjects (5 men and 10 women, ages 47 ± 4 yr, weight 90 ± 23 kg, height 169 ± 10 cm) who volunteered for this study. All subjects were free from cardiovascular, pulmonary, and metabolic disease as determined by a medical history questionnaire. Prior to participation in this study, subjects were informed of all procedures and written informed consent was obtained prior to participation. Subjects were instructed to refrain from vigorous exercise 24 h prior to each session. All research components were reviewed and approved by the Institutional Review Board of Human Subjects at Kansas State University, Manhattan, KS, USA.

Procedures

Subjects visited the laboratory a minimum of four sessions, with at least 48 h between sessions. Evaluation of subject fitness included cycling and rowing tests to determine $\dot{V}O_{2peak}$, PPO, and rowing CP determined individually on separate days. Subjects were familiarized with all testing procedures and equipment prior to testing. Following the fitness evaluation phase, subjects completed an unaided top hatch emergency egress performance test using a custom-built mock-up of the Orion space capsule.

Subjects performed incremental exercise tests to exhaustion on both an electronically braked cycle ergometer (Lode, Groningen, The Netherlands) and a rowing ergometer (Concept 2 Inc., Morrisville, VT, USA) in order to determine modality specific $\dot{V}O_{2peak}$ and PPO. The test consisted of 3-min stages of 20, 50, 100, and 175 W or 20, 50, 100, and 150 W, depending on the subject's reported leisure time activity, followed by increases of 25 W · min^{-1} until task failure. Task failure was defined as the inability to maintain required cadence for 10 s. This protocol has been consistently used to evaluate $\dot{V}O_{2peak}$ in pre- and in-flight astronauts during NASA shuttle, Skylab, and International Space Station missions.[4,24] Metabolic and ventilatory data were continuously recorded using a gas exchange measurement system (True One 2400, Parvo Medics, Sandy, UT, USA) during both $\dot{V}O_{2peak}$ tests, which was calibrated prior to each test according to manufacturer's instruction. For each protocol, $\dot{V}O_{2peak}$ was defined as the highest 15-s average value achieved during exercise. PPO was defined as the duration into the final stage before task failure using the following equation:

$$PPO = WR_{peak} + Inc^{*}(T/T_{stage})$$

where WR_{peak} = work rate before that eliciting task failure, Inc = the increase of work for the last stage, T = time into the stage, and T_{stage} = total time of the stage. PPO was also normalized to body mass (W/kg). Maximal effort was confirmed and, therefore, $\dot{V}O_{2peak}$ was considered valid when at least three criteria were attained: 1) a respiratory exchange ratio > 1.1; 2) heart rate >90% of age-predicted maximum; 3) a plateau of $\dot{V}O_2$ defined as no expected increases (<150 ml · min^{-1}) in $\dot{V}O_2$ from the previous test stage; or 4) rating of perceived exertion >17 on Borg's 6–20 scale. Heart rate (HR) was measured using an HR monitor (FT7, Polar Electro Inc., Bethpage, NY, USA).

Subjects performed a 3-min all-out test on the rowing ergometer[11] during the third visit, using a protocol previously used for cycling[36] and running.[7] A 3-min warm-up at 20 W was performed on the rower followed by a 2-min rest period prior to the all-out test. Subjects began the test from a preparatory power position. Subjects were instructed to maintain maximal power output and speed for the duration of the entire test. Subjects were blinded to the time completed or remaining; however, they were verbally encouraged to provide maximum effort throughout the test. Stroke-by-stroke power output was recorded via Bluetooth link with the rowing ergometer's performance monitor. Data were analyzed post hoc on a laboratory computer, in which CP was determined as the average of the last 30 s of the all-out test. Two subjects declined to do the all-out test and therefore were not included in the CP analysis.

The capsule egress test was used to simulate an emergency exit of the capsule after landing. Subjects were asked to perform this test as quickly as possible. The test was performed on a custom-built mock-up of the NASA Orion capsule. Subjects began the test in a seated supine position. Subjects were instructed to roll from the seat to the left, move two 5-kg bags ~1 m to a marked location, and then release and attach a rope ladder to the floor of the capsule. The subjects then proceeded to carry the two packages through the top hatch; specifically, subjects were instructed that the package must be taken past the opening of the hatch and not simply handed to a researcher. The subjects would then exit the capsule through the top hatch and the time to completion was marked when the subject was seated at the top of the capsule. A minimum of two fully equipped familiarization tests were performed prior to data collection. Metabolic data were recorded using an Oxycon portable gas analyzer (Jaeger, Höchberg, Germany). The metabolic cart was calibrated prior to each test according to manufacturer's specifications. Metabolic data were averaged from the beginning of the test to the completion of the bag carry (Start-Bag), from the bag carry to the end of the test (Bag-Exit), and over the 1 min immediately following the test (Recovery). Heart rate was recorded throughout the test (BioHarness-3, Zephyr Technologies, Annapolis, MD).

Statistical Analysis

Paired *t*-tests were used to determine differences in $\dot{V}O_{2peak}$, $\dot{V}CO_{2peak}$, peak ventilation, and peak work rate between the cycle and rowing tests. A one-way ANOVA with repeated measures was used to determine changes in metabolic data throughout the egress test (Start-Bag vs. Bag-Exit and Bag-Exit vs. Recovery). Pearson's correlation was used to determine significance between egress time and $\dot{V}O_{2peak}$, CP, PPO, and PPO normalized to body mass (W/kg). Differences were considered significant when $P < 0.05$. Data are presented as mean $\pm$ SD and $N = 15$ for all comparisons unless noted otherwise.

RESULTS

All subjects met the criteria for exhibiting $\dot{V}O_{2peak}$ for both cycling and rowing. Peak metabolic data determined on the cycle and rowing ergometers are shown in **Table I**. Subjects exhibited a range of cycling $\dot{V}O_{2peak}$ of 15.5–31.7 $ml \cdot kg^{-1} \cdot min^{-1}$ and a range of rowing $\dot{V}O_{2peak}$ of 15.9 – 33.4 $ml \cdot kg^{-1} \cdot min^{-1}$. $\dot{V}O_{2peak}$ was not significantly different between cycling and rowing (df = 14, $P = 0.10$) and was significantly correlated ($r = 0.88$, $P < 0.001$). Rowing CP was 101.8 $\pm$ 30.6 W ($N = 13$) with a range of 69.6–168.5 W.

PPO was determined by the duration in the final stage of the incremental tests and the increase of resistance during that stage. The PPO was 194 $\pm$ 35 W (range: 115–291 W) for the cycle test and 177 $\pm$ 42 W (range: 100–267 W) for the rowing test. The PPO (W/kg) from the cycle test was 2.2 $\pm$ 0.4 with a range of 1.29–2.77, which was greater (df = 14, $P = 0.03$) compared to the PPO (W/kg) from the rower test (2.0 $\pm$ 0.5 with a range of 0.68–2.97).

Egress time was 54.9 $\pm$ 19.4 s, with a range of 34–114 s ($N = 15$). **Fig. 1** shows the correlation between egress time and relative $\dot{V}O_{2peak}$ and PPO (W/kg) on both the cycle and rowing $\dot{V}O_{2peak}$ tests. Two subjects, however, were beyond the 2× standardized residual for these tests and were, therefore, removed before the correlations were determined.

Egress time was not significantly correlated to age ($P = 0.96$), height ($P = 0.35$), or weight ($P = 0.11$). However, when age, height, and weight were combined in a multiple linear regression model, the result was close to significant ($P = 0.051$). Egress time was not significantly correlated to CP ($P = 0.15$) or cycling PPO (0.44), but was nearly associated with cycling and rowing $\dot{V}O_{2peak}$ ($P = 0.08$ and $P = 0.07$, respectively). Conversely, egress time showed a significant inverse correlation with rowing PPO (W/kg) ($r = -0.60$, $P = 0.03$, Fig. 1). The metabolic responses to the egress test are shown in **Fig. 2**. $\dot{V}O_2$ and $\dot{V}CO_2$ significantly increased from baseline to the bag carry and again to the end of the test [$F(2,14) = 129.1$, $P < 0.001$ and $F(2,14) = 49.5$, $P < 0.05$, respectively]. Ventilation significantly increased from 19.31 $\pm$ 9.88 $L \cdot min^{-1}$ at baseline to 31.68 $\pm$ 9.30 $L \cdot min^{-1}$ during the bag test ($P < 0.001$), but did not significantly increase further [$F(2,14) = 30.2$, $P = 0.72$]. Subjects' peak $\dot{V}O_2$ during the capsule test reached 72 $\pm$ 25% of relative $\dot{V}O_{2peak}$.

Table I. $\dot{V}O_{2peak}$ Data.

	CYCLING	ROWING
	MEAN $\pm$ SD	MEAN $\pm$ SD
Peak Power (W)	194 $\pm$ 35.2	177 $\pm$ 42.3
PPO/kg	2.2 $\pm$ 0.4	2.0 $\pm$ 0.5*
$\dot{V}O_{2peak}$ ($ml \cdot kg^{-1} \cdot min^{-1}$)	24.0 $\pm$ 4.8	25.0 $\pm$ 4.4
$\dot{V}CO_{2peak}$ ($L \cdot min^{-1}$)	2.5 $\pm$ 0.7	2.4 $\pm$ 0.5
$\dot{V}E_{peak}$ ($L \cdot min^{-1}$)	65.4 $\pm$ 18.3	63.1 $\pm$ 13.9

Metabolic responses to the cycling and rowing $\dot{V}O_{2peak}$ tests. No significant differences were found in peak power, $\dot{V}O_{2peak}$, $\dot{V}CO_{2peak}$, and peak minute ventilation ($\dot{V}E_{peak}$). However, peak power normalized to body mass (PPO/kg) was significantly higher in cycling compared to rowing ($P = 0.03$). *Different from cycling.

DISCUSSION

The major findings of this study were that simulated egress time was highly inversely correlated to rowing PPO (W/kg) and potentially $\dot{V}O_{2peak}$ determined by a cycling or rowing ergometer. Therefore, the rowing PPO should be considered as a potential factor when determining emergency egress performance. However, even individuals with a relatively low PPO and $\dot{V}O_{2peak}$ (i.e., $\dot{V}O_{2peak} \leq 20$ $ml \cdot kg^{-1} \cdot min^{-1}$) were able to perform the egress test in less than 2 min.

Previously, $\dot{V}O_{2max}$ has been used as a predictor of exercise performance, including maximal, short duration tasks,[13,21] and still remains the standard for NASA's astronauts, i.e., minimum of 32.9 $ml \cdot kg^{-1} \cdot min^{-1}$.[29] However, tracking changes in $\dot{V}O_{2peak}$ in flight is difficult and costly. Therefore, an alternative measurement of performance is necessary. The current study shows that rowing PPO has a good association with exercise performance and emergency egress (Fig. 1D). This is promising as a rowing-like ergometer is expected to be used in flight for exercising cardiovascular and muscular systems due to its small footprint and ability to stress multiple muscle groups. Additionally, CP has previously been shown to be a predictor of endurance exercise performance.[22,35,37] Although the rowing CP determined by a 3-min all-out test was not correlated with the capsule egress test, it may still be a valuable parameter when predicting performance of other contingency mission tasks.[2,3,33]

The adverse effects of prolonged microgravity have been previously studied.[4,8,24] There is evidence that the longer the exposure to microgravity, the larger the decreases in cardiovascular,[19,24] metabolic,[9,10] and muscular[5,14] function. Prolonged simulated microgravity (e.g., bedrest) has been shown to cause similar responses to actual microgravity.[10,18,34] Capelli et al.[10] provided evidence that most of the decline in $\dot{V}O_{2peak}$ occurs within the first 14 d of simulated microgravity. However, the detriments in $\dot{V}O_{2peak}$ incurred by microgravity can be lessened or negated with concurrent exercise training.[15,32]

Because PPO was correlated with egress time, we can use previous gas exchange data to estimate the likelihood of an emergency Orion capsule egress in 1 G, as work rate is linearly related with $\dot{V}O_2$.[17,23] Assuming a male astronaut begins the 18-mo Martian mission with NASA's current minimum $\dot{V}O_{2peak}$ of 32.9 $ml \cdot kg^{-1} \cdot min^{-1}$, it would be predicted to decrease through the duration of the mission due to the expected 12 mo in space and 6-mo stay on Mars (~38% Earth gravity). Previous data have shown that exercise intensity is an important countermeasure in maintaining cardiovascular and muscular function during simulated or actual microgravity.[16,27,32] However, 6 mo aboard the International Space Station (ISS) has resulted in a 15% decline in $\dot{V}O_{2peak}$, even with the use of onboard countermeasures.[1] Thus, it would be predicted that the

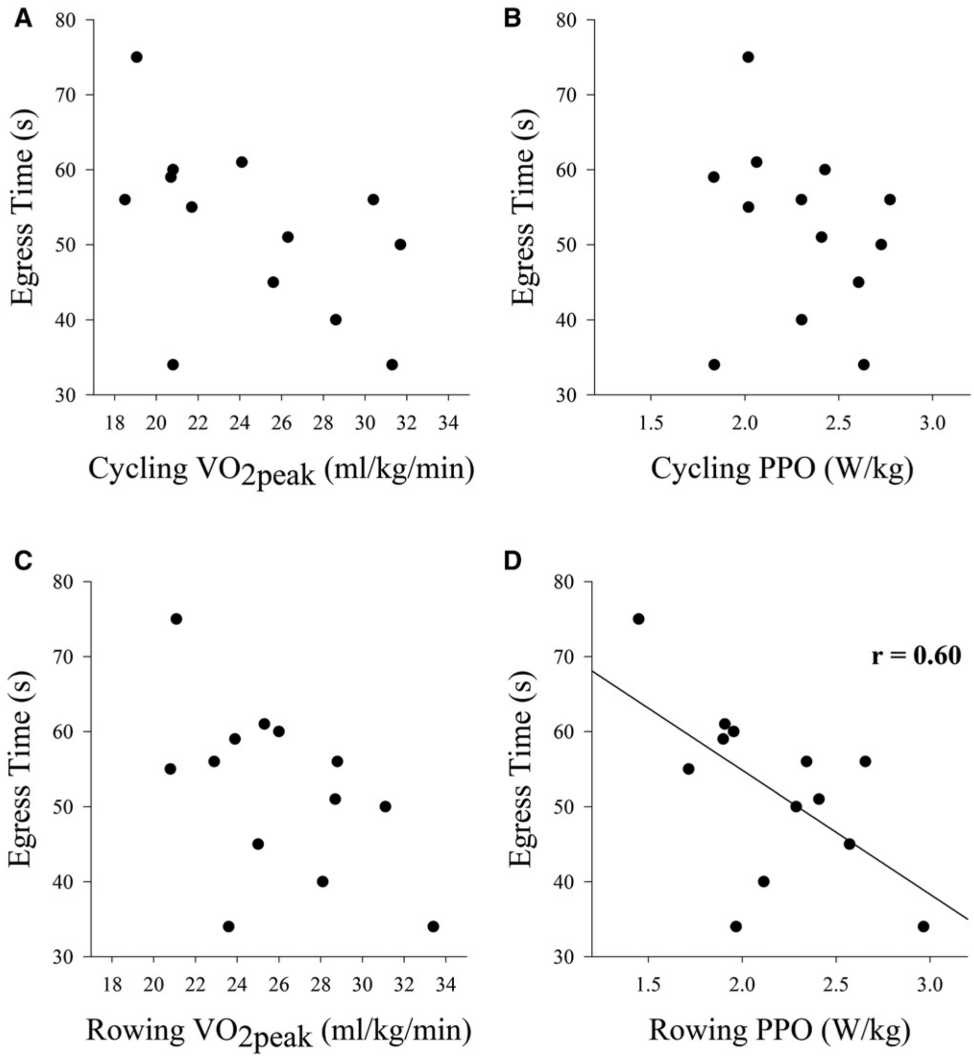

Fig. 1. Correlations of egress time as functions of A) cycling $\dot{V}O_{2peak}$, B) cycling PPO/kg, C) rowing $\dot{V}O_{2peak}$, and D) rowing PPO/kg. Cycling $\dot{V}O_{2peak}$, cycling PPO, and rowing $\dot{V}O_{2peak}$ were not significantly correlated to egress time ($P = 0.07$, $P = 0.44$, $P = 0.08$, respectively); however, egress time was significantly correlated to rowing PPO/kg ($P = 0.03$).

maximum metabolic rate of our hypothetical astronaut would be reduced from 32 to $\sim$27.9 ml $\cdot$ kg^{-1} $\cdot$ min^{-1}. Some of the decrease may be recovered during a stay on Mars, as 38% of the gravity of Earth would add some constant stress on the cardiovascular and muscular systems.[12,31] Accordingly, after 17 d of spaceflight, $\dot{V}O_{2peak}$ was 90% of preflight values on the fourth day of return to Earth, and 95% by the eighth day.[34] However, there is yet to be any data showing the recovery of $\dot{V}O_{2peak}$ during a Martian or lunar exposure. Therefore, if $\dot{V}O_{2peak}$ recovers by an arbitrary 50% by the end of the stay on Mars, $\dot{V}O_{2peak}$ would be $\sim$30.3 ml $\cdot$ kg^{-1} $\cdot$ min^{-1} at the start of the 6-mo return spaceflight. Assuming this new $\dot{V}O_{2peak}$ and recommended exercise training during the return spaceflight, $\dot{V}O_{2peak}$ may further decline to $\sim$25.8 ml $\cdot$ kg^{-1} $\cdot$ min^{-1} before reaching Earth. PPO is similarly affected by spaceflight. Antonutto et al.[5] found that peak power output is quickly reduced with microgravity exposure, but combined with our data, we would expect this individual to be able to complete the capsule egress in $<$ 90 s. This estimation is based on many assumptions and with limited data on the effects of intermittent prolonged microgravity. However, this does provide a reference point that may be beneficial in preparing for future missions to other planets.

It is also worth noting that microgravity has been shown to have a negative impact on neurovestibular components,[6,26] which can impair functional performance, which was unable to be simulated in the current study. Bacal et al. found that exercise can attenuate some of the symptoms of neurovestibular changes (i.e., clumsiness with movements and difficulty walking in straight line) and suggested that because mission duration was not correlated with any of the tested symptoms and that all symptoms were only reported as mild to moderate, they are unlikely to have a significant impact on the mission.[6] However, this is not a consistent finding. Recent data suggest that while most deficits in motor control seem to have fast recovery following short- and long-duration spaceflight upon return to Earth,[26] egress performance may still be negatively affected as body coordination and postural stability during functional tests were significantly impaired.[28]

Several experimental limitations should be considered when interpreting these results. NASA expects an ocean landing on the return to Earth, whereas these tests in the present study were performed on a flat surface. Further, an actual emergency egress would have to be performed in extreme conditions that could not be replicated in the current study. Previously, unstable surfaces compared to stable surfaces have been shown to decrease force production and alter muscle recruitment,[20,25] likely affecting $\dot{V}O_2$. However, specific effects of unstable surfaces on $\dot{V}O_2$ are currently unknown and should be investigated in the future.

Further, the relatively low $\dot{V}O_{2peak}$ of our subjects are likely to be lower than what would be predicted from astronauts with exercise training during spaceflight (see above). Though the subjects in the current study performed several familiarization trials, the extensive training and simulation protocols performed by astronauts in preparation for space travel should be sufficient to ready the astronauts for a variety of circumstances. Therefore, assuming astronauts are able to maintain a minimum

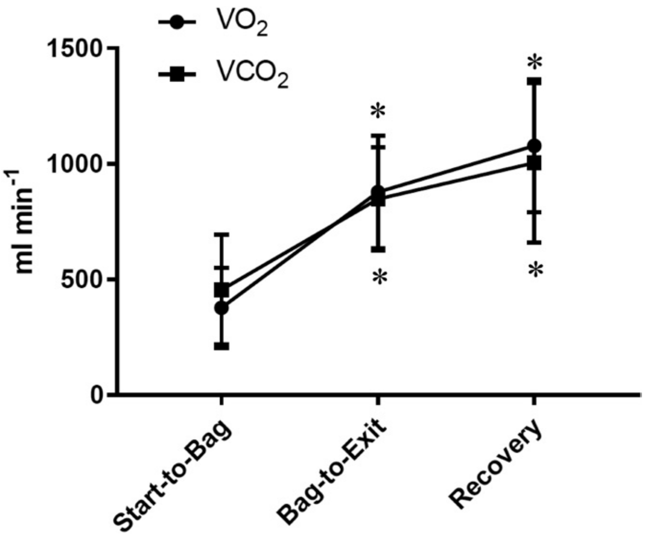

Fig. 2. Metabolic data throughout the egress test. $\dot{V}O_2$ and $\dot{V}CO_2$ significantly increased during the first transition (both $P < 0.001$) and again to recovery (both $P < 0.001$). *Different from previous stage.

PPO and/or $\dot{V}O_{2peak}$, the emergency egress task should be able to be completed in $<$ 90 s.

In conclusion, although $\dot{V}O_{2peak}$ data were not significantly correlated to the success rate for egress, PPO showed a strong correlation and, therefore, should be considered as a potential factor when examining potential task success rates following exposure to spaceflight, such as an emergency egress. More data are needed, however, to determine the minimal level of physical activity necessary to sustain an appropriate PPO for these long-duration spaceflights, as well as the effects of exercise in Martian gravity on cardiovascular and muscular performance.

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