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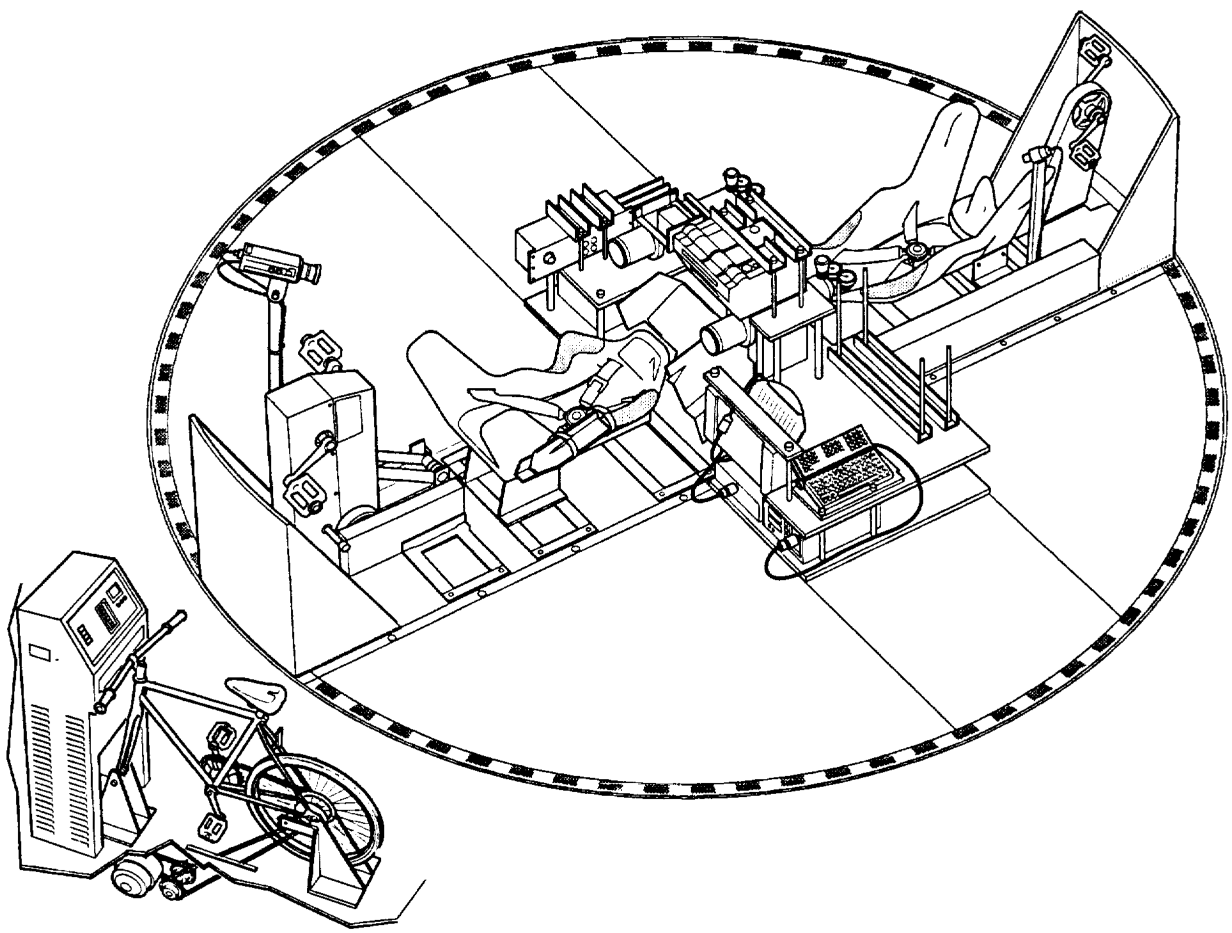

September 1998

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Summary

Spaceflight and bed-rest deconditioning decrease maximal oxygen uptake (aerobic power), strength, endurance capacity, and orthostatic tolerance. In addition to extensive use of muscular exercise conditioning as a countermeasure for the reduction in aerobic power ($\dot{V}O_{2\,max}$), stimuli from some form of +Gz acceleration conditioning may be necessary to attenuate the orthostatic intolerance component of this deconditioning. **Hypothesis**: There will be no significant difference in the physiological responses (oxygen uptake, heart rate, ventilation, or respiratory exchange ratio) during supine exercise with moderate +Gz acceleration. **Methods**: Seven male subjects (24-39 yrs.) exercised supine on the human powered centrifuge (HPC). Each subject performed maximal oxygen uptake ($\dot{V}O_{2\,max}$) and submaximal exercise tests at 42%, 61% and 89% of $\dot{V}O_{2\,max}$ under two conditions: exercise and exercise + acceleration. During exercise + acceleration the subjects accelerated on the HPC at a mean (±SE) level of +2.20 ± 0.02 Gz (50% of max Gz) while exercising. **Results**: There were no significant differences in $\dot{V}O_2$, HR, or $\dot{V}_{E\,BTPS}$ during the submaximal or maximal exercise runs with added acceleration. Mean (±SE) $\dot{V}O_{2\,max}$ for exercise was $2.86 \pm 0.12\ L \bullet min^{-1}$ ($34.8 \pm 2.3\ ml \bullet min^{-1} \bullet kg^{-1}$) and for exercise + acceleration was $3.09 \pm 0.14\ L \bullet min^{-1}$ ($37.3 \pm 1.7\ ml \bullet min^{-1} \bullet kg^{-1}$). The respiratory exchange ratio (R_E) was significantly different at 61% ($p<0.05$) and 89% ($p<0.01$) of $\dot{V}O_{2\,max}$. **Conclusion**: There were no significant positive or negative effects among the tested parameters when moderate (+2.2 Gz) acceleration accompanied exercise. It is concluded that moderate acceleration does not affect the normal relationships between oxygen uptake, heart rate, ventilation, or respiratory exchange ratio in relation to a relative exercise load.

Introduction

With the increasing probability of a human mission to Mars and the increased duration and number of Space Shuttle flights to construct the space station, it is now more important than ever to find optimal countermeasures for attenuation or elimination of the adverse physiological effects during and after spaceflight. The question of type, intensity, and duration of countermeasures for use by astronauts in flight has been debated for years (Fortney et al.1996).

Exposure to spaceflight significantly impairs physiological responses and physical performance of astronauts during and after reentry into Earth's gravitational field (Buckey et al. 1996; Convertino 1996; Fortney et al. 1998). Fortney et al. (1998) found 3 cosmonauts so debilitated after a 115-day mission that they were not allowed to perform even moderate submaximal exercise until five days after landing. Some physiological effects of long-term spaceflight (decreased aerobic power, muscular strength, and endurance capacity; and accentuated orthostatic intolerance) become functionally manifest when astronauts are re-exposed to gravitational fields. Countermeasures, such as exercise and acceleration, have been studied separately and in combination. Studies have been conducted with separate treatments (Greenleaf et al. 1989a; Greenleaf 1997; Levine et al. 1996; Rosenhamer 1968; Shvartz 1996; White et al. 1966), and with combined treatments (Bjurstedt et al. 1968; Greenleaf et al. 1997; Rosenhamer 1967; Vil-Vilyams 1994; Vil-Vilyams and Shul'zhenko 1980). Even now, use of many of these treatments separately as countermeasures has had only moderate success for attenuating all the adverse physiological effects of spaceflight.

Based on physical work requirements for astronauts during spaceflight and re-entry, and from bed-rest deconditioning (reduction of physical fitness) studies that utilized exercise conditioning as a countermeasure for the reduction of aerobic power and deterioration of muscular strength and endurance, it is clear that exercise conditioning protocols are necessary. However, exercise conditioning alone does not overcome the problem of orthostatic intolerance (Greenleaf et al. 1989c; White et al. 1965), defined as the time a subject can tolerate standing or the head-up posture when the physiological system can no longer compensate for the stress resulting in adverse presyncopal signs and symptoms leading to fainting (Geelen and Greenleaf 1993). Intermittent +Gz acceleration conditioning during bed rest can significantly attenuate the decreased orthostatic (tilt) tolerance after bed rest (White et al. 1965). Bjurstedt et al. (1968) and Rosenhamer (1967) have investigated cardiovascular and respiratory responses during acceleration combined with exercise on a long-arm centrifuge. Vil-Vilyams (1994) and Vil-Vilyams and Shul'zhenko (1980) utilized combined exercise and +Gz acceleration conditioning on a short-arm centrifuge to attenuate the decreased work capacity and orthostatic tolerance associated with deconditioning. Therefore, it is possible, by combining exercise and +Gz acceleration conditioning simultaneously on a human powered centrifuge, that we could significantly reduce the astronauts' exercise time in space while counteracting adverse effects of spaceflight deconditioning.

Thus, the purpose of this study was to determine the effect of additional +Gz acceleration on selected physiological responses (oxygen uptake, ventilation, heart rate, and respiratory exchange ratio) during exercise on normal, ambulatory, unconditioned men. The hypothesis was that there would be no significant differences in these physiological responses during exercise with moderate +Gz acceleration.

Literature Review

Introduction

The purpose for countermeasures is to ameliorate the adaptive responses of astronauts induced by spaceflight and to allow them to function productively during and especially after flight. Major factors that can impair performance during flight are decreases in aerobic power and muscular strength and endurance (Greenleaf et al. 1989b). Countermeasures used by astronauts include physical exercise conditioning during flight, and fluid loading and G-suit inflation before reentry (Greenleaf et al. 1989c). It was not until the mid 1960's that +Gz acceleration conditioning was studied as a possible countermeasure for orthostatic tolerance (White et al. 1965; White et al. 1966). Greenleaf et al. (1997), Vil-Vilyams (1994), and Vil-Vilyams and Shul'zhenko (1980) have reported some effects of combining exercise and acceleration for use as countermeasures.

Deconditioning

Confinement to bed rest (BR) in the 6^0 head-down position is a valuable analog for simulating some of the effects of spaceflight as it induces similar physiological changes in human cardiovascular, musculoskeletal, and neuroendocrine systems (Convertino 1996). Many adaptive cardiovascular responses during BR have significant impact on exercise endurance capacity and aerobic power. The maximal oxygen uptake ($\dot{V}O_{2\ max}$), defined as the point at which no further increase in $\dot{V}O_2$ is possible with increasing exercise intensity (Brooks et al. 1996), is usually decreased after BR (Fortney et al. 1996). Most factors which enhance $\dot{V}O_{2\ max}$ such as hypervolemia, increased red cell mass, increased strength, muscle hypertrophy, and increased arterial baroreceptor sensitivity, are affected negatively by BR deconditioning (Fortney et al. 1996).

At a given oxygen uptake the cardiovascular responses to exercise are exaggerated after BR deconditioning; these include increases in heart rate, cardiovascular peripheral resistance, diastolic blood pressures, and the respiratory exchange ratio (Fortney et al. 1996, Geelen and Greenleaf 1993). These responses facilitate the increased stroke volume to help counteract the reduced maximal cardiac output, the reduced exercise endurance, and the unchanged systolic blood pressure (Fortney et al. 1996).

Physiological responses to head-up tilt, passive standing, and +Gz acceleration are also altered after exposure to BR (Convertino 1996). Multiple factors influence post-BR orthostatic function which include decreased blood volume, decreased baroreceptor sensitivity, and altered autonomic function (Fortney et al. 1996); as well as increased venous distensibility (Leftheriotis et al. 1998), and decreased cerebral autoregulation (Zhang et al. 1997). The control of orthostatic tolerance resides in the neuroendocrine system which controls the cardiovascular system to maintain adequate arterial pressure and blood flow to the tissues, especially the brain (Convertino et al. 1984). Reentry from space into the Earth's gravitational field usually results in multiple symptoms, termed the gravitational reentry syndrome, part of which is manifested by decreased orthostatic tolerance (Burton and Smith 1996).

Greenleaf (1997) found that orthostatic (tilt-table) tolerance was decreased significantly by 19-43%, after 30 days of -6^0 head-down BR and White et al. (1996) found tolerance to +Gz acceleration decreased by 33% to 55% (G-units) after 10 days of horizontal BR. There are no reports of significantly increased acceleration tolerance following prolonged exposure to BR or immersion deconditioning.

Countermeasures

Exercise. The decline in aerobic exercise capacity and power during BR deconditioning can be restored by intermittent exercise conditioning. Changes in $\dot{V}O_{2\ max}$ have been measured many times before and after prolonged BR (Convertino 1996). Chase et al. (1966) reported positive conditioning responses such that peak aerobic power was actually higher after BR. Four untrained subjects, who exercised for 30 min • day^{-1} on a horizontal bed that moved laterally between two vertical trampolines, had a mean increase in $\dot{V}O_{2\ max}$ of 16%; while a second group of untrained subjects, who exercised in the horizontal-supine position on a cycle ergometer, increased their $\dot{V}O_{2\ max}$ by only 8.5%.

Greenleaf et al. (1989a, 1989b) designed and tested intensive exercise-conditioning protocols that maintained $\dot{V}O_{2\ max}$ and muscular strength and endurance at ambulatory-control levels during 30 days of −6^0 head-down BR deconditioning. The protocol consisted of intermittent isotonic leg exercise conditioning for 30 min twice a day in the horizontal-supine position, and maximal isokinetic knee flexion and extension also supine for 2 x 30 min • day^{-1}. These exercise conditioning protocols were designed to maximize intensity and minimize duration and risk of overtraining. The subjects warmed up on the cycle ergometer for 7 min at a relative intensity of 40% $\dot{V}O_{2\ max}$, which was followed by 2 min of exercise at 60, 70, 80, 90, and 80% $\dot{V}O_{2\ max}$, with each bout separated by 2 min at 40%, and a final 5-min cool-down period. The near-peak, variable intensity, isotonic leg exercise training in moderately trained subjects dur-

during BR maintained $\dot{V}O_{2\,max}$ at pre-bed rest levels, while the no-exercise control group decreased their $\dot{V}O_{2\,max}$ significantly by about 18%. However, exercise conditioning has little effect, if any, on reducing orthostatic (tilt) intolerance after BR. Greenleaf et al. (1989b) found no effect of either isotonic or isokinetic exercise conditioning during BR on the expected reduction of orthostatic (tilt) tolerance with significant increases in $\dot{V}O_{2\,max}$ of 20%. Results from short term (12 days, isotonic exercise conditioning) and long term (6 months, isotonic and isometric exercise conditioning) studies in ambulatory subjects indicate no significant change in orthostatic (tilt) tolerance of subjects with increased $\dot{V}O_{2\,max}$ (Greenleaf et al. 1988). Results from spaceflight and ground-based studies suggest that repeated endurance exercise designed to restore aerobic power has not been able to provide appropriate stimuli to affect the mechanism that underlies orthostatic intolerance (Greenleaf 1997).

Acceleration. Intermittent, passive (no exercise or muscular contraction) +Gz acceleration not only restores the reduced orthostatic tolerance that occurs after BR deconditioning (White et al. 1965), but also redistributes and retains blood in the venous system of the lower extremities similar to that during standing (Convertino 1996). White et al. (1965) reported that the expected deterioration in the ability to tolerate 90^0 head-up tilt for 20 min was largely alleviated with intermittent exposure to +1Gz and +4Gz (at the subjects feet) acceleration conditioning 4 x 20 min • day^{-1} on a 1.8 m centrifuge during 41 days of horizontal BR. White et al. (1966) also studied the influence of acceleration on a 1.8 m centrifuge during 10 days of BR. The subjects were accelerated 4 x 20 min • day^{-1} at +1.75Gz measured at the heart; the expected deterioration in the ability to tolerate 70^0 head-up tilt for 20 min was alleviated with this periodic acceleration. These data indicate the validity of acceleration as a positive countermeasure for the adverse effects of BR on orthostatic tolerance, and suggest that such countermeasures could also ameliorate the adverse physiological effects during and after spaceflight.

Exercise + acceleration: long-arm centrifuge with radius > 2.0 m. By combining exercise with +Gz acceleration, Bjurstedt et al. (1968) and Rosenhamer (1967, 1968) measured physiological responses during exercise at 300, 600, and 900 kpm • min^{-1} at 1Gz (centrifuge stationary) and during +3Gz acceleration on a long-arm centrifuge (radius 7.4 m). Bjurstedt et al. (1968) and Rosenhamer (1967) found significant increases in heart rate, oxygen uptake, and pulmonary minute ventilation with a change from rest to exercise at +3Gz at 300, 600, and 900 kpm • min^{-1} compared to rest and exercise at +1Gz (normal gravity).

Exercise + acceleration: short-arm centrifuge with radius < 2.0 m. Vil-Vilyams and Shulzhenko (1980) investigated cardiovascular responses and G tolerances with combined short-arm centrifuge acceleration and exercise after 28-days of dry immersion with subjects wrapped in plastic. Use of periodic rotation on the short-arm centrifuge at +1 to +2Gz for up to 60 min twice a day, combined with concomitant exercise on a cycle ergometer, attenuated the effects of immersion deconditioning on the cardiovascular system. Vil-Vilyams (1994) tested subjects at different levels of +Gz acceleration exposure alone at 0.8, 1.2, and 1.6 Gz on a short-arm (radius = 2.0 m) centrifuge before and after immersion, and combined with exercise. After 7 days of immersion without countermeasures the mean acceleration tolerance of the subjects was decreased by 28%. However, performance of exercise + acceleration (+0.8 to +1.6 Gz) intermittently during immersion led to restoration of the pre-immersion level of acceleration tolerance.

These results indicate that combined exercise + acceleration, on long- or short-arm centrifuges, can attenuate or eliminate the decreases in aerobic power and orthostatic tolerance during prolonged BR and immersion deconditioning.

Summary

Intensive exercise conditioning during BR can counteract the usual decreases in aerobic power, muscular strength, and endurance. However, there is little evidence to indicate that exercise conditioning can overcome orthostatic intolerance after deconditioning. Some data indicate intermittent acceleration conditioning as an efficient countermeasure for orthostatic intolerance. Combined use of acceleration (+0.8 to +1.6Gz on a short-arm centrifuge) and moderate levels of cycle ergometer exercise attenuated some effects of deconditioning, thus pointing the way for future studies to examine the effect of acceleration plus exercise on orthostatic tolerance and work capacity during and after spaceflight. There appear to be no data on the effect of short-arm +Gz acceleration + exercise conditioning on oxygen uptake capacity and orthostatic tolerance during deconditioning, thus emphasizing the practical importance of the present study to provide basic data for design of future studies to test these countermeasures.

Methods

Centrifuge design and operation. The human powered centrifuge (HPC) was designed and fabricated in the model and machine shop at Ames Research Center (Greenleaf et al. 1997). The supine test subjects are oriented in the horizontal supine position, with the top of their head at the level of the middle cerebral artery located 19 cm from the center of rotation, and their feet about 1.7 m from the center (Figure 1). There are three pedaling stations on the HPC; two on the platform at the outer end of each seat, and the third on the operator's off-platform stationary cycle. One on-platform pedaling station and the off-platform stationary cycle are linked by bicycle chains and sprockets to the center hub, and rotation of the HPC can be generated from these stations. The second on-platform pedaling station is a basic isolated cycle ergometer (model 845, Quinton Ergometer, Seattle, WA) not connected with centrifuge rotation. For rotation to occur while exercising at this station, one of the other pedaling stations must be engaged. In the present study the off-platform pedaling station was used to power the centrifuge, while the subjects used the Quinton Ergometer for exercise on the HPC; this allowed the subjects to exercise with and without acceleration on the same ergometer.

Subjects. Seven healthy men (24-40 yrs, Table 1) provided written informed consent and received a thorough medical examination including medical history, ECG, and blood and urine tests. This study was approved by the Human Research Review Boards at Ames Research Center and San Francisco State University. All subjects were asked to abstain from alcohol and caffeine 24 hours before their tests. Subjects who were tested in the morning were asked not to eat breakfast, while subjects tested in the afternoon were asked not to eat lunch: all complied.

Procedure. Each subject participated in both exercise and exercise + acceleration tests consisting first of a maximal oxygen uptake ($\dot{V}O_{2\,max}$) determination followed by submaximal loads of 25%, 50% and 75% of the maximal load. Acceleration levels for the exercise + acceleration tests were arbitrarily selected at 50% of the subjects maximum +Gz (rpm) acceleration on the HPC. Maximal +Gz (rpm) levels were determined while the subject exercised in the horizontal supine body position at the on-platform pedaling station. The 50% +Gz (rpm) levels were used by the off-platform operator to rotate the centrifuge during the exercise + acceleration phase.

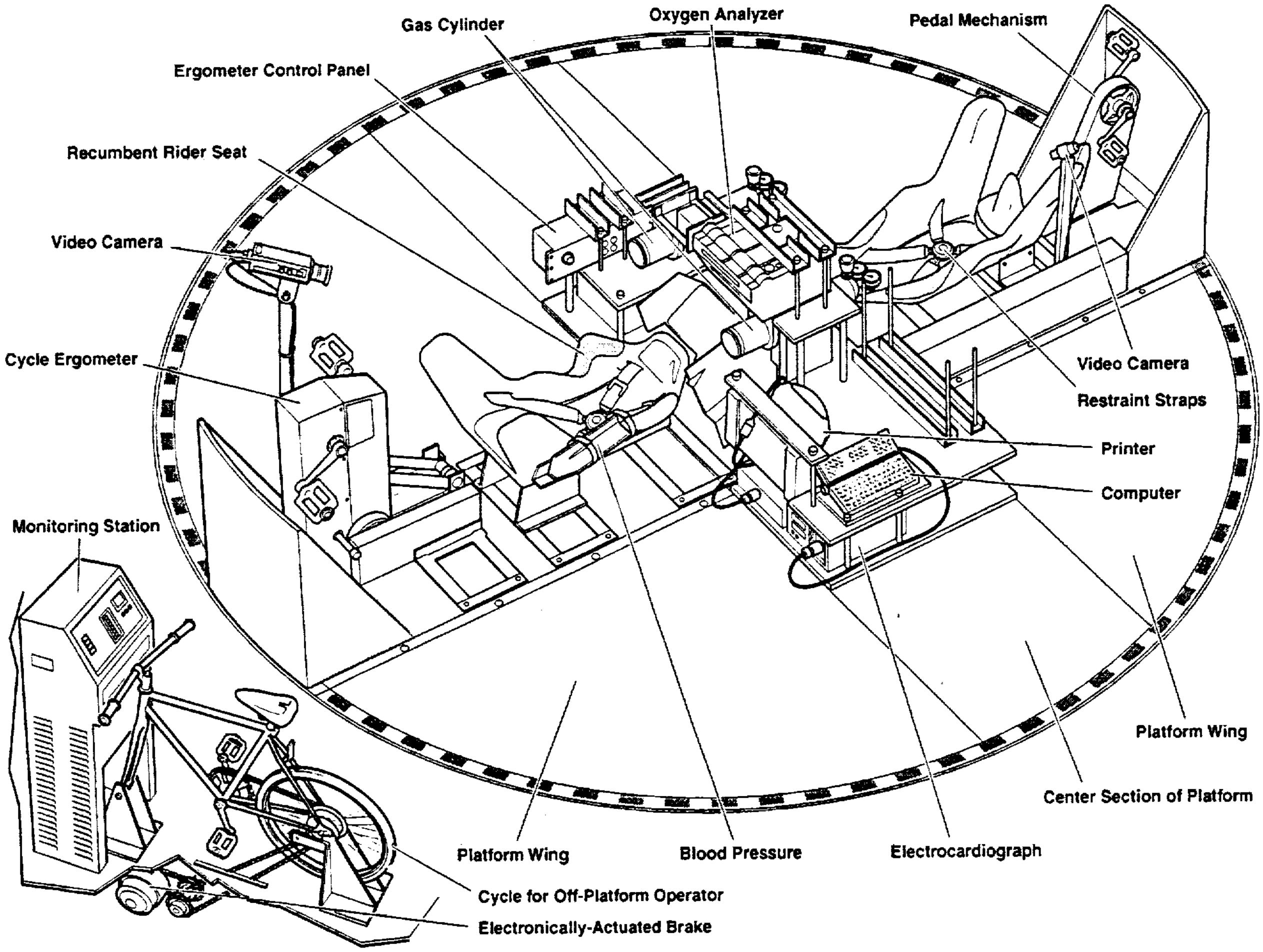

Figure 1. Human-powered short-arm centrifuge schematic.

Leg exercise was performed with the subject supine on the HPC with the cycle ergometer. For the maximal test the subjects had warm-up periods of 2 min at 400 kpm • min^{-1} and 1 min at 800 kpm • min^{-1}, with a rest period of approximately 2 min between tests (Table 2). The maximal test began with a warm-up at 800 kpm • min^{-1} for 30 sec. This was followed with 1 min exercise loads of 1000 kpm • min^{-1}, then 1200 kpm • min^{-1}, and continuing with 100 kpm • min^{-1} increases until the subject could no longer keep the pace of 60 rpm, or stopped due to exhaustion (Table 2).

The submaximal tests with exercise and exercise + acceleration consisted of two warm-up phases; first for 2 min at 400 kpm • min^{-1}, and second for 1 min at 800 kpm • min^{-1}. Both warm up periods were followed by 2-min rest periods. The submaximal test followed with 4-min exercise bouts at 25%, 50% and 75% of the maximal exercise load

Table 1. Subject anthropometric data.

Anthropometry				
Subject	Age, yr.	Height, cm	Weight, kg	Surface Area, m^2
Mbar	24	177.0	82.77	2.03
Bar	31	185.8	86.55	2.12
Guf	40	168.5	59.82	1.68
Mor	33	185.0	93.00	2.20
Oku	24	174.0	76.77	1.94
Rea	38	178.6	95.40	2.20
Sav	39	183.5	88.85	2.14
Mean	33	178.9	83.31	2.04
SD	7	6.3	12.08	0.19
SE	3	2.4	4.57	0.07

Table 2. Exercise and exercise + acceleration maximal and submaximal exercise tests protocols.

				Maximal VO_2 test				
warm up	rest	warm up	rest	exercise				
2 min 400 kpm/min		1 min 800 kpm/min		30 sec 800kpm/min	1 min 1000kpm/min	1 min 1200kpm/min	1 min 1300kpm/min	continue increasing at 100kpm/min increments for 1 min until exhaustion

				Submaximal VO_2 test				
warm up	rest	warm up	rest	exercise	rest	exercise	rest	exercise
2 min 400 kpm/min		1 min 800 kpm/min		4 min 42% $\dot{V}O_{2\,max}$ 25% max load (kpm/min)		4 min 61% $\dot{V}O_{2\,max}$ 50% max load (kpm/min)		4 min 89% $\dot{V}O_{2\,max}$ 75% max load (kpm/min)

with a 2-min rest period between each bout (Table 2). Timing for exercise + acceleration did not start until the off-platform operator reached the appropriate +Gz level. Five of the 7 subjects had 24 hr recovery periods between their maximal test and the subsequent submaximal tests. Two subjects completed their submaximal and maximal tests the same day, with at least 3 hr rest between tests so that their heart rates and $\dot{V}O_2$ had returned to pre-exercise levels. The order of the exercise and exercise + acceleration tests was assigned randomly.

Instrumentation. The subjects were monitored with an electrocardiogram (model 78203A, Hewlett-Packard, Waltham MA) for wave form and heart rate. The ECG was displayed, processed, and stored on a Gateway 2000 personal computer (model 4DX2-66V, North Sioux City, SD) for the medical monitor and investigators.

The oxygen uptake ($\dot{V}O_2$), pulmonary minute ventilation ($\dot{V}_{E_{BTPS}}$), and respiratory exchange ratio (R_E) were measured and calculated with the CPX Express System (model 762035, Medical Graphics Corp., St. Paul, MN) and processed and stored on a laptop computer (Power Note 3000 Media, Zenon Inc., Los Angeles, CA).

Voice communication was maintained among the medical monitor, centrifuge operator, research assistants, and the test subject. Video coverage of the entire centrifuge room including the operator, and coverage from the onboard camera focused on the subject, was displayed in the control room for the medical monitor and investigators.

Data analysis. All data were analyzed with one-way analysis of variance (MINITAB version 11.12, Minitab Inc., State College, PA). Level of significance was $p<0.05$ and non-significant differences were indicated by NS. The null hypothesis was rejected when $p<0.05$.

Results

Because oxygen uptake had not been measured previously in supine subjects using the leg ergometer on the HPC, a standard curve for $\dot{V}O_2$ vs. absolute exercise load (with and without acceleration) was constructed (Figure 2). The relative exercise loads (which reduce variability) were not equivalent to comparable percentages of $\dot{V}O_{2\ max}$. The mean arbitrary 25% of maximal ergometer exercise load (421 ± 15 kpm • min^{-1}) was 42 ± 3% of $\dot{V}O_{2\ max}$; the 50% load (828 ± 22 kpm • min^{-1}) was 61 ± 1% $\dot{V}O_{2\ max}$, and the 75% load (1,236 ± 37 kpm • min^{-1}) was 89 ± 2% $\dot{V}O_{2\ max}$ (Table 3). Thus these results can be given in percentage of $\dot{V}O_{2\ max}$.

Exercise load and acceleration level. The mean (±SE) loads for the exercise tests and the rpm and +Gz levels for the exercise + acceleration tests are also reported in Table 3: for exercise + acceleration +Gz = 2.20 ± 0.02 and rpm = 33 ± 1.

Oxygen uptake ($\dot{V}O_2$): Mean (± SE) $\dot{V}O_2$ for the exercise tests were: rest = 0.28 ± 0.02 L • min^{-1}, 42% = 1.22 ± 0.09 L • min^{-1}, 61% = 1.80 ± 0.08 L • min^{-1}, 89% = 2.63 ± 0.12 L • min^{-1}, and 100% = 2.86 ± 0.12 L • min^{-1} (Figure 3). Mean (± SE) $\dot{V}O_2$ for exercise + acceleration were: rest = 0.21 ± 0.02 L • min^{-1}, 42% = 1.23 ± 0.06 L • min^{-1}, 61% = 1.86 ± 0.06 L • min^{-1}, 89% = 2.66 ± 0.14 L • min^{-1} and 100% = 3.09 ± 0.14 L • min^{-1} (Figure 3). Comparison of exercise vs. exercise + acceleration conditions indicated no significant differences in $\dot{V}O_2$ at rest ($p = 0.10$), or at 42% ($p = 0.90$), 61% ($p = 0.50$), 89% ($p = 0.80$), or 100% ($p = 0.20$) of $\dot{V}O_{2\ max}$.

Heart rate (HR): Mean (±SE) heart rates for exercise tests were: rest = 65 ± 2 bpm, 42% = 101 ± 3 bpm, 61% = 121 ± 3 bpm, 89% = 155 ± 4 bpm, and 100% = 169 ± 6 bpm, while those during exercise + acceleration were: rest = 68 ± 2 bpm, 42% = 109 ± 3 bpm, 61% = 132 ± 5 bpm, 89% = 157 ± 5 bpm and 100% = 180 ± 5 bpm (Figure 4). When comparing results from the two conditions, there were no significant differences in HR at rest ($p = 0.40$), or at 42% ($p = 0.09$), 61% ($p = 0.08$), 89% ($p = 0.70$), or 100% ($p = 0.10$) of $\dot{V}O_{2\ max}$. While not statistically significant, HR during exercise tended to be lower than that during exercise + acceleration at all levels of $\dot{V}O_{2\ max}$.

Pulmonary minute ventilation ($\dot{V}_{E_{BTPS}}$): Mean (±SE) ventilations for exercise were: rest = 8.84 ± 0.84 L • min^{-1}, 42% = 29.09 ± 1.90 L • min^{-1}, 61% = 47.87 ± 2.88 L • min^{-1}, 89%= 87.79 ± 7.82 L • min^{-1}, and 100% = 119.57 ± 6.85 L • min^{-1}; those for exercise + acceleration were: rest = 11.17 ± 0.79 L • min^{-1}, 42% = 28.27 ± 1.8 L • min^{-1}, 61% = 47.60 ± 2.5 L • min^{-1}, 89% = 77.90 ± 7.52 L • min^{-1} and 100% = 134.86 ± 8.00 L • min^{-1} (Figure 5). There were no significant differences at rest ($p = 0.06$), or at 42% ($p = 0.80$), 61% ($p = 0.90$), 89% ($p = 0.40$) or 100% ($p = 0.20$) of $\dot{V}O_{2\ max}$ between the two conditions.

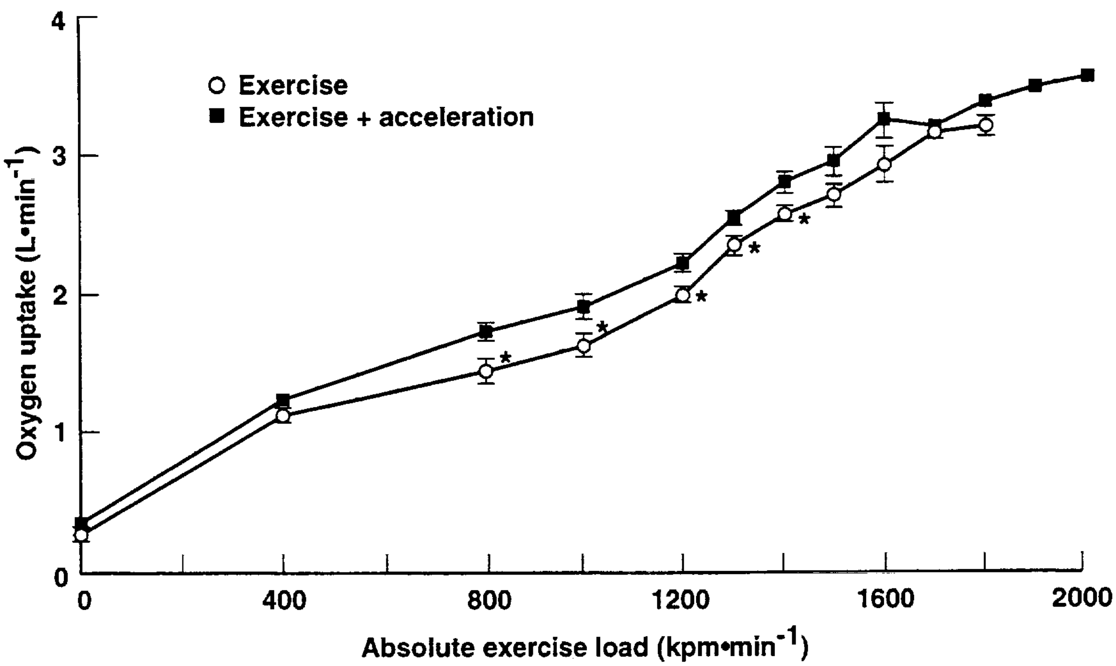

Figure 2. Supine oxygen uptake on HPC vs. exercise load with exercise and exercise + acceleration. *p<0.05.

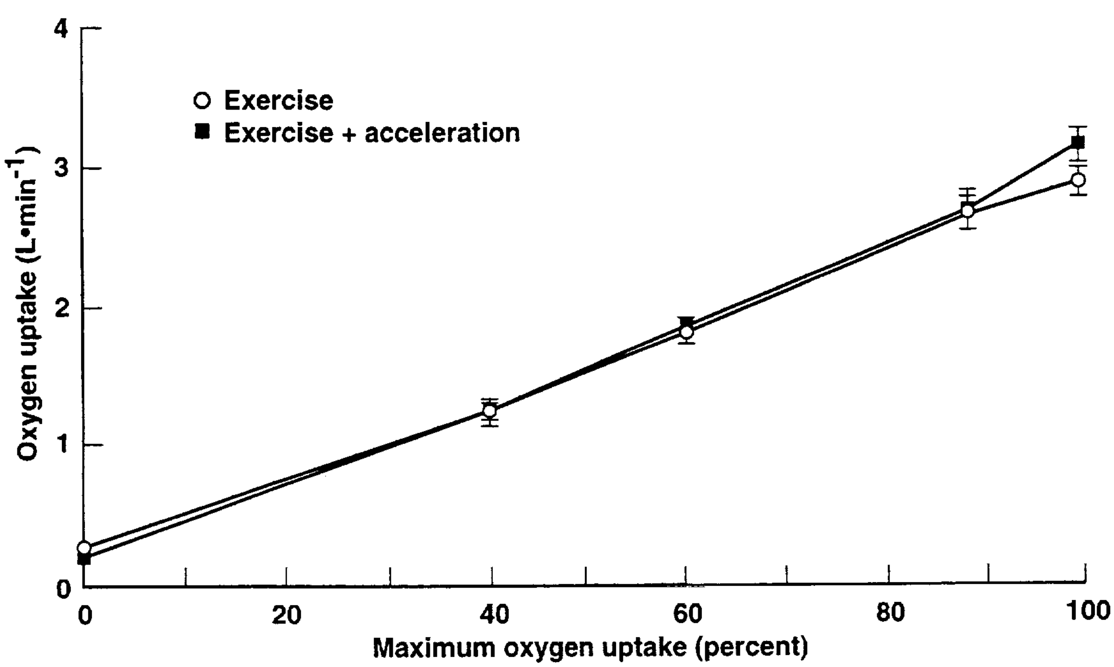

Figure 3. Mean (±SE) oxygen uptake in relation to percentage of maximum oxygen uptake with exercise and exercise + acceleration. *p<0.05.

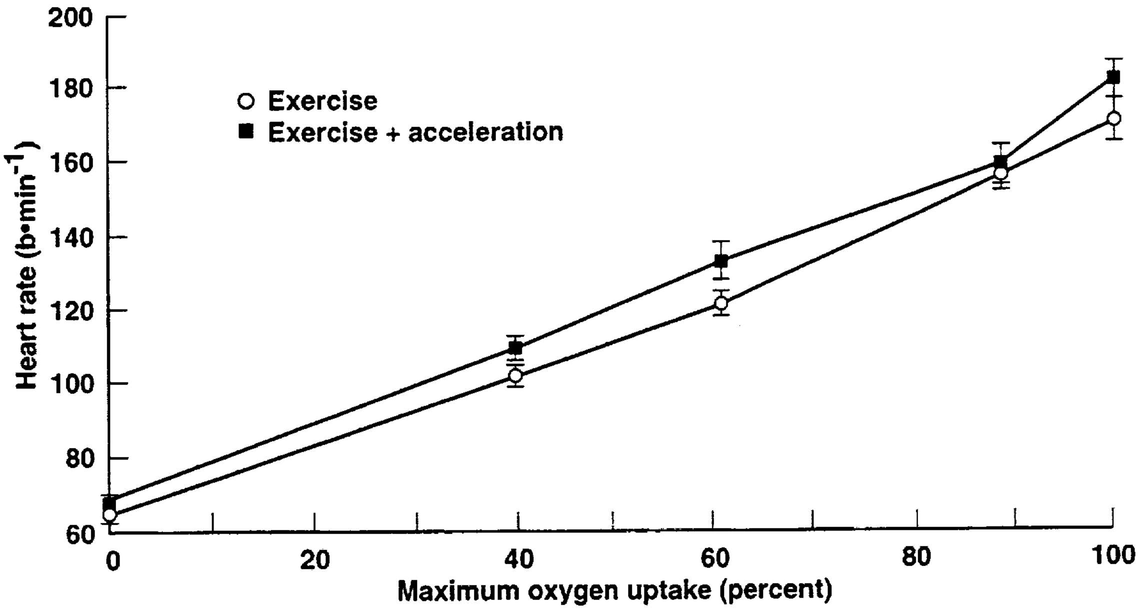

Figure 4. Mean (±SE) heart rate in relation to percentage of maximum oxygen uptake with exercise and exercise + acceleration. *p<0.05.

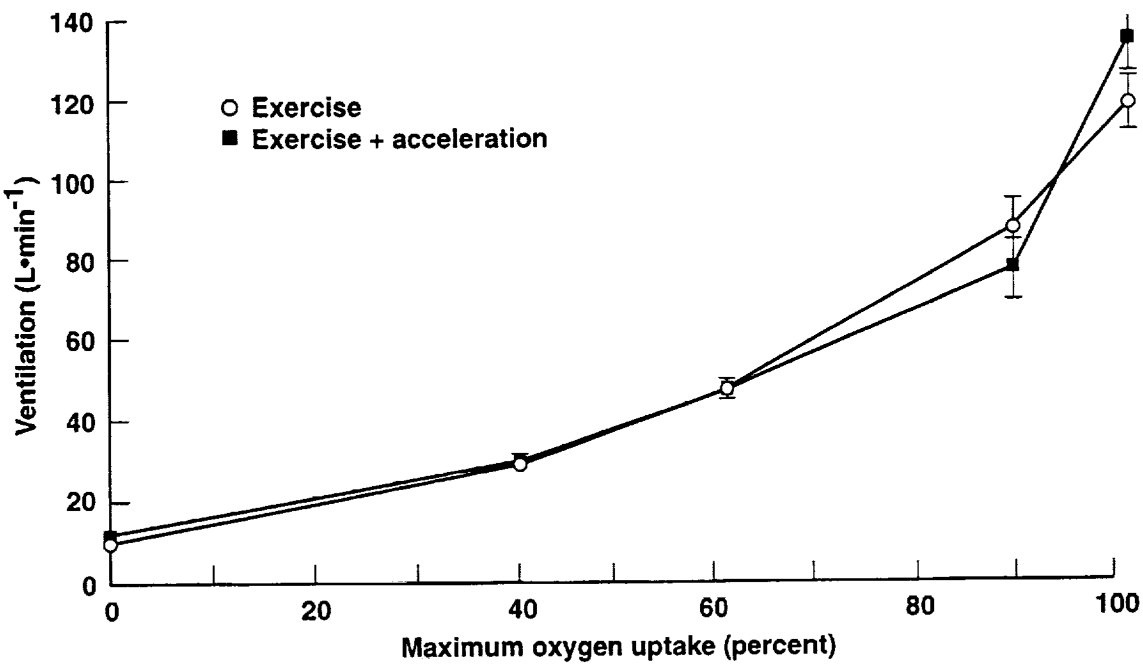

Figure 5. Mean (±SE) pulmonary minute ventilation in relation to percentage of maximum oxygen uptake with exercise and exercise + acceleration. *p<0.05.

Respiratory exchange ratio (R_E): Mean (±SE) R_E for exercise were: rest = 0.94 ± 0.03, 42% = 0.92 ± 0.02, 61% = 1.04 ± 0.01, 89% = 1.18 ± 0.02, and 100% = 1.3 ± 0.03; while those for exercise + acceleration were: rest = 0.98 ± 0.05, 42% = 0.89 ± 0.02, 61% = 1.0 ± 0.02, 89% = 1.1 ± 0.02 and 100% = 1.3 ± 0.03 (Figure 6). The R_E during exercise was significantly higher than that of exercise + acceleration at 61% ($p<0.05$) and 89% ($p<0.01$) of $\dot{V}O_{2\,max}$; there were non-significant differences at rest ($p = 0.50$), 42% ($p = 0.50$), and 100% ($p = 1.00$) of $\dot{V}O_{2\,max}$.

Discussion

The purpose of this study was to study some basic physiological responses ($\dot{V}O_2$, $\dot{V}O_{2\,max}$, HR, $\dot{V}_{E_{BTPS}}$, and R_E) when utilizing exercise alone plus combining it with moderate acceleration on a short-arm centrifuge to test the null hypothesis that there would be no significant differences in these physiological responses during exercise with added +Gz acceleration. With the exception of the R_E, this null hypothesis was confirmed.

One advantage of combining these two countermeasures is that exercise + acceleration attenuates possible adverse symptoms of passive acceleration alone such as nausea, blurred vision, and syncope. Thus, most negative physiological effects of acceleration can be eliminated with addition of exercise thereby allowing for longer and safer exposure to +Gz acceleration if necessary. Bjurstedt et al. (1968)

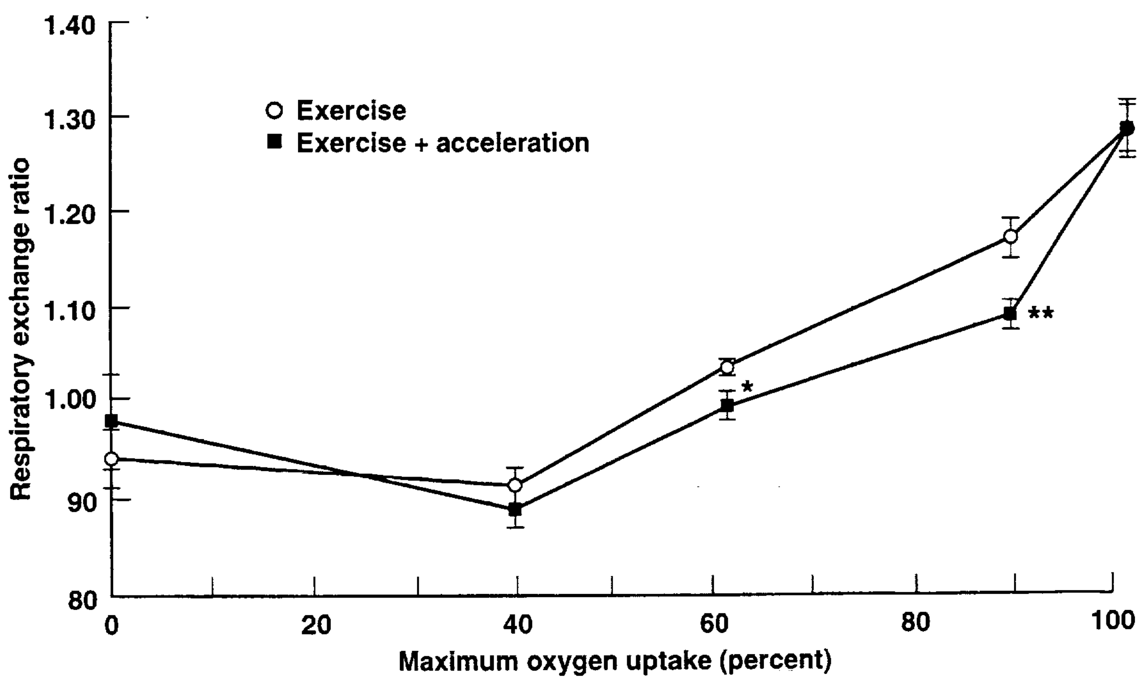

Figure 6. Mean (±SE) respiratory exchange ratio on relation to percentage of maximum oxygen uptake with exercise and exercise + acceleration. *p<0.05, **p<0.01.

Table 3. Exercise loads at each percentage of oxygen uptake for exercise and for exercise + acceleration tests. Insert is +Gz and rpm for exercise + acceleration run.

Subject	42% $\dot{V}O_{2max}$ load (kpm·min^{-1})	61% $\dot{V}O_{2max}$ load (kpm·min^{-1})	89% $\dot{V}O_{2max}$ load (kpm·min^{-1})	100% $\dot{V}O_{2max}$ load (kpm·min^{-1})	100% $\dot{V}O_{2max}$ (L·min^{-1})	100% $\dot{V}O_{2max}$ (ml·min^{-1}·kg^{-1})	Acceleration rpm	Acceleration Gz
Exercise								
Mbar	500	900	1400	1800	3.05	36.6		
Bar	400	700	1100	1400	2.55	29.3		
Guf	400	800	1200	1500	2.56	42.6		
Mor	500	900	1400	1900	3.24	34.3		
Oku	500	900	1400	1800	3.27	42.4		
Rea	400	800	1200	1600	2.55	26.8		
Sav	300	800	1100	1500	2.82	31.7		
Mean	429	829	1257	1643	2.86	34.8		
SD	76	76	140	190	0.32	6.1		
SE	29	29	53	72	0.12	2.3		
Exercise + acceleration								
Mbar	400	800	1200	1600	3.47	41.8	36	2.6
Bar	400	800	1100	1500	2.74	31.5	34	2.4
Guf	400	800	1100	1500	2.54	41.6	31	2.0
Mor	500	1000	1500	2000	3.54	38.1	36	2.6
Oku	400	900	1300	1700	3.19	41.4	34	2.3
Rea	400	800	1200	1500	3.11	32.7	26	1.4
Sav	400	700	1100	1400	3.04	34.2	34	2.3
Mean	414	829	1214	1600	3.09	37.3	33	2.2
SD	38	95	146	200	0.36	4.5	4	0.4
SE	14	36	55	76	0.14	1.7	1	0.2

and Rosenhamer (1968) conducted their experiments on a long-arm centrifuge, thus negating direct comparisons with the present data. Long-arm acceleration places the entire body at the end of the arm at the desired acceleration level. It is this acceleration force distributed over the entire body that creates increased work for returning blood back to the heart (Burton and Smith 1996), thus increasing $\dot{V}O_2$, $\dot{V}_E$, and HR significantly. With short-arm acceleration there is an acceleration gradient ranging from about zero at the head nearest the center of rotation increasing progressively towards the feet. Because the thorax is at a lower G level than the feet, this gradient allows for easier venous return from below the heart and less impact on the physiological responses.

Oxygen uptake: There were no statistically significant changes in $\dot{V}O_2$ with addition of acceleration to exercise at submaximal or maximal levels; i.e., there were linear relationships between $\dot{V}O_2$ and absolute and relative exercise loads. Thus, moderate short-arm acceleration does not alter the well-established $\dot{V}O_2$ versus exercise load relationship.

Heart rate: Mean HR for all $\dot{V}O_2$ levels tended to increase progressively during both the exercise and the exercise + acceleration tests; all values for the later tended to be higher (NS) than with those of exercise alone, possibly resulting from the increased hydrostatic pressure with added acceleration.

Pulmonary minute ventilation: As exercise loads increased from resting levels, $\dot{V}_E$ increases linearly; thereafter, as exercise intensity increases the $\dot{V}_E$ increases nonlinearly. This turn point (between 40 and 60% $\dot{V}O_{2\ max}$) has been referred to as the ventilatory threshold, and the nonlinear increments are usually associated with an increase in blood lactate levels (Brooks et al. 1996). These exercise $\dot{V}_E$ data indicate no effect of the added +Gz acceleration.

Respiratory exchange ratio: An R_E value of 1.00 indicates body utilization of mainly carbohydrates for fuel, and above 1.00 an increase in blood lactate levels is suspected with enhanced production of CO_2 (Brooks et al. 1996). Thus, the significantly higher R_E values during the exercise test could be due to an increase in lactate production, which would be consistent with the increased ventilatory threshold.

Conclusion and Practical Applications

Results of the present study indicate that addition of +2.2 Gz short-arm acceleration does not significantly influence oxygen uptake, heart rate, or ventilation during maximal or submaximal exercise. The effects of added acceleration on R_E, however, need further study.

With data from the present and past studies it can now be hypothesized, when combining exercise training and acceleration training, that attenuation of orthostatic intolerance can be attributed mainly to the +Gz acceleration conditioning. Testing of this hypothesis will require additional exercise + acceleration studies on short-arm centrifuges. For the centrifuge to be used aboard the Space Station it must fit within a 2.0 m radius; therefore data from short-arm centrifuge studies have practical importance.

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Appendix 1. Oxygen uptake ($L \cdot min^{-1}$) for exercise and exercise + acceleration tests.

Subject	**Exercise**						
	Resting $\dot{V}O_2$	$\dot{V}O_2$ at 25% load	Exercise load	% of $\dot{V}O_{2max}$	$\dot{V}O_2$ at 50% load	Exercise load	% of $\dot{V}O_{2max}$
Mbar	0.34	1.17	500	38%	1.75	900	57%
Bar	0.27	1.42	400	55%	1.58	700	62%
Guf	0.17	0.97	400	38%	1.58	800	62%
Moo	0.36	1.43	500	44%	2.16	900	67%
Oku	0.28	1.50	500	46%	1.87	900	57%
Rea	0.25	1.15	400	56%	1.79	800	70%
Sav	0.31	0.92	300	33%	1.84	800	65%
Mean	0.28	1.22	429	44%	1.80	829	63%
SD	0.06	0.23	76	9%	0.20	76	5%
SE	0.02	0.09	29	3%	0.08	29	2%

Subject	**Exercise + acceleration**						
	Resting $\dot{V}O_2$	$\dot{V}O_2$ at 25% load	Exercise load	% of $\dot{V}O_{2max}$	$\dot{V}O_2$ at 50% load	Exercise load	% of $\dot{V}O_{2max}$
Mbar	0.32	1.41	400	40%	2.06	800	59%
Bar	0.31	1.09	400	40%	1.75	800	64%
Guf	0.27	1.03	400	41%	1.65	800	65%
Moo	0.30	1.38	500	39%	2.06	1000	58%
Oku	0.33	1.15	400	36%	1.78	900	56%
Rea	0.38	1.15	400	37%	1.75	800	56%
Sav	0.39	1.39	400	46%	1.89	700	62%
Mean	0.33	1.23	414	40%	1.85	829	60%
SD	0.04	0.16	38	3%	0.16	95	4%
SE	0.02	0.06	14	5%	0.06	36	2%

Appendix 1. Oxygen uptake ($L \cdot min^{-1}$) for exercise and exercise + acceleration tests. (continued)

Subject	Exercise					
	$\dot{V}O_2$ at 75% load	Exercise load	% of $\dot{V}O_{2\,max}$	$\dot{V}O_{2\,max}$ ($L \cdot min^{-1}$)	Max exercise load	$\dot{V}O_{2\,max}$ ($ml \cdot min^{-1} \cdot kg^{-1}$)
Mbar	2.64	1400	86%	3.05	1800	36.6
Bar	2.37	1100	95%	2.55	1400	29.3
Guf	2.39	1200	93%	2.56	1500	42.6
Moo	3.21	1400	99%	3.24	1900	34.3
Oku	2.87	1400	88%	3.27	1800	42.4
Rea	2.61	1200	102%	2.55	1600	26.8
Sav	2.33	1100	83%	2.82	1400	31.7
Mean	2.63	1257	92%	2.86	1629	34.8
SD	0.32	140	7%	0.32	206	6.1
SE	0.12	53	3%	0.12	78	2.3

Subject	Exercise + acceleration					
	$\dot{V}O_2$ at 75% load	Exercise load	% of $\dot{V}O_{2\,max}$	$\dot{V}O_{2\,max}$ ($L \cdot min^{-1}$)	Max exercise load	$\dot{V}O_{2\,max}$ ($ml \cdot min^{-1} \cdot kg^{-1}$)
Mbar	2.93	1200	84%	3.47	1600	41.8
Bar	2.37	1100	86%	2.74	1500	31.5
Guf	2.01	1100	79%	2.54	1500	41.6
Moo	3.14	1500	88%	3.54	2000	38.1
Oku	2.80	1300	88%	3.19	1700	41.4
Rea	2.73	1200	88%	3.11	1500	32.7
Sav	2.61	1100	86%	3.04	1400	34.2
Mean	2.66	1214	86%	3.09	1600	37.3
SD	0.37	146	3%	0.36	200	4.5
SE	0.14	55	1%	0.14	76	1.7

Appendix 2. Ventilation (BTPS, $L \cdot min^{-1}$) for exercise and exercise + acceleration tests.

Subject	**Exercise**				
	Resting $\dot{V}e$	25% $\dot{V}e$	50% $\dot{V}e$	75% $\dot{V}e$	Max $\dot{V}e$
Mbar	10.4	28.9	41.9	78.1	122
Bar	8.8	31.9	40.9	76.3	109
Guf	5.0	22.6	42.9	79.1	117
Moo	11.0	36.4	62.8	120.5	134
Oku	6.9	32.6	47.4	107.6	148
Rea	9.0	28.0	52.0	93.0	116
Sav	10.8	23.2	47.2	59.9	91
Mean	8.8	29.1	47.9	87.8	120
SD	2.2	5.0	7.6	20.7	18
SE	0.8	1.9	2.9	7.8	7

Subject	**Exercise + acceleration**				
	Resting $\dot{V}e$	25% $\dot{V}e$	50% $\dot{V}e$	75% $\dot{V}e$	Max $\dot{V}e$
Mbar	11.2	32.1	46.2	69.0	131
Bar	10.4	27.6	47.0	73.7	138
Guf	7.9	19.3	42.9	55.1	119
Moo	9.8	34.6	56.5	108.9	155
Oku	13.3	27.4	43.0	94.0	156
Rea	11.6	28.2	57.0	87.7	147
Sav	14.0	28.7	40.6	56.9	101
Mean	11.2	28.3	47.6	77.9	135
SD	2.1	4.8	6.6	19.9	20
SE	0.8	1.8	2.5	7.5	8

Appendix 3. Heart rates ($b \cdot min^{-1}$)) for exercise and exercise + acceleration tests.

Subject	**Exercise**					
	Resting HR	25% max	50% max	75% max	100% max HR	Max workload
Mbar	60	99	125	172	187	1800
Bar	71	112	131	157	178	1400
Guf	59	92	112	140	156	1500
Moo	73	109	124	164	187	1800
Oku	57	102	120	156	171	1800
Rea	64	93	106	150	150	1600
Sav	69	100	126	144	153	1400
Mean	65	101	121	155	169	1614
SD	6	7	9	11	16	186
SE	2	3	3	4	6	70

Subject	**Exercise + acceleration**					
	Resting HR	25% max	50% max	75% max	100% max HR	Max workload
Mbar	61	110	141	175	193	1600
Bar	72	108	137	161	185	1500
Guf	57	92	111	132	161	1500
Moo	72	106	127	161	198	2000
Oku	69	114	125	155	175	1700
Rea	72	116	154	167	169	1500
Sav	70	115	130	151	180	1400
Mean	68	109	132	157	180	1600
SD	6	8	14	14	13	200
SE	2	3	5	5	5	76

Appendix 4. Respiratory exchange ratio for exercise and exercise + acceleration tests.

Subject	Exercise				
	Resting R_E	25% max	50% max	75% max	100% max R_E
Mbar	0.91	0.98	1.03	1.23	1.31
Bar	0.97	1.00	1.02	1.19	1.37
Guf	1.00	0.91	1.07	1.15	1.34
Moo	0.88	0.92	1.05	1.25	1.21
Oku	0.85	0.87	1.02	1.18	1.20
Rea	0.92	0.83	1.04	1.18	1.31
Sav	1.04	0.90	1.07	1.10	1.35
Mean	0.94	0.92	1.04	1.18	1.30
SD	0.07	0.06	0.02	0.05	0.07
SE	0.03	0.02	0.01	0.02	0.03

Subject	Exercise + acceleration				
	Resting R_E	25% max	50% max	75% max	100% max R_E
Mbar	0.98	0.90	0.99	1.06	1.28
Bar	0.92	0.93	1.05	1.17	1.43
Guf	0.91	0.95	1.05	1.09	1.35
Moo	0.87	0.90	0.97	1.13	1.21
Oku	1.17	0.92	1.00	1.12	1.24
Rea	0.82	0.79	1.02	1.11	1.25
Sav	1.17	0.86	0.94	1.04	1.33
Mean	0.98	0.89	1.00	1.10	1.30
SD	0.14	0.05	0.04	0.04	0.08
SE	0.05	0.02	0.02	0.02	0.03

Appendix 5. Oxygen uptake ($L \cdot min^{-1}$) for absolute exercise loads during exercise and exercise + acceleration tests.

Workload ($kpm \cdot min^{-1}$)	0	400	800	1000	1200	1300	1400	1500	1600	1700	1800	1900	2000
Subject	**Exercise**												
Mbar	0.35	1.07	1.42	1.52	1.92	2.08	2.44	2.55	2.92	3.02	3.05		
Bar	0.25	1.12	1.38	1.61	1.88	2.32	2.55						
Guf	0.15	0.97	1.06	1.44	1.87	2.25	2.43	2.56					
Moo	0.36	1.13	1.52	1.82	2.18	2.35	2.71	2.88	3.10	3.23	3.24		
Oku	0.31	1.20	1.64	1.77	2.05	2.35	2.63	2.78	3.08	3.18	3.27		
Rea	0.25	1.05	1.32	1.25	1.76		2.34		2.55				
Sav	0.27	1.29	1.63	1.83	2.19	2.57	2.82						
Mean	0.28	1.12	1.42	1.61	1.98	2.32	2.56	2.69	2.91	3.14	3.19		
SD	0.07	0.10	0.20	0.22	0.16	0.16	0.17	0.16	0.25	0.11	0.12		
SE	0.03	0.04	0.08	0.08	0.06	0.07	0.06	0.08	0.13	0.06	0.07		
Subject	**Exercise + Acceleration**												
Mbar	0.29	1.30	1.75	2.05	2.34	2.65	2.99	3.32	3.47				
Bar	0.29	1.17	1.64	1.81	2.17	2.51	2.67	2.75					
Guf	0.23	1.07	1.51	1.66	1.96	2.28	2.52	2.54					
Moo	0.29	1.24	1.91	2.04	2.23	2.49	2.69	2.93	3.06	3.17	3.37	3.47	3.54
Oku	0.34	1.25	1.73	1.87	2.1	2.52	2.79	2.95	3.15	3.19			
Rea	0.49	1.17	1.46	1.58	2.19	2.5	2.85	3.11					
Sav	0.39	1.35	1.94	2.23	2.48	2.74	3.04						
Mean	0.33	1.22	1.71	1.89	2.21	2.53	2.79	2.93	3.23	3.18	3.37	3.47	3.54
SD	0.09	0.09	0.18	0.23	0.17	0.14	0.18	0.27	0.22	0.01			
SE	0.03	0.03	0.07	0.09	0.06	0.05	0.07	0.11	0.13	0.007			

Appendix 6. Ventilation ($L \cdot min^{-1}$) and absolute workloads for exercise and exercise + acceleration tests.

Workload ($kpm \cdot min^{-1}$)	0	400	800	1000	1200	1300	1400	1500	1600	1700	1800	1900	2000
Subject	**Exercise**												
Mbar	10.6	23.7	25.5	28.8	44.4	53.4	68.3	74.0	97.6	114.4	121.9		
Bar	7.2	27.4	33.0	36.8	58.5	81.6	109.0						
Guf	4.7	20.7	20.9	28.1	50.3	74.0	99.2	117.6					
Moo	11.1	27.8	39.1	45.1	65.7	75.8	95.4	103.6	120.1	127.5	135.1		
Oku	7.0	25.5	27.5	34.6	45.8	61.5	69.8	85.8	119.6	134.1	148.8		
Rea	9.0	25.6	30.2	26.4	48.3		82.2		116.4	2.55			
Sav	10.6	29.9	32.2	36.4	49.6	70.0	90.9						
Mean	8.6	25.8	29.8	33.7	51.8	69.4	87.8	95.3	113.4	125.3	135.3		
SD	2.4	3.0	5.9	7.0	7.6	10.3	15.2	19.2	10.7	10.0	13.5		
SE	0.9	1.1	2.2	2.7	2.9	4.2	5.7	9.6	5.4	5.8	7.8		
Subject	**Exercise + Acceleration**												
Mbar	9.7	29.9	34.1	44.5	56.9	68.4	85.8	106.4	131.5				
Bar	9.8	25.9	34.1	44.5	60.2	84.8	116.0						
Guf	4.6	22.5	28.9	34.7	52.8	73.9	104.2	119.0					
Moo	8.6	32.5	49.7	56.4	72.6	81.3	88.0	107.1	115.5	120.2	135.7	142.4	154.8
Oku	13.6	26.3	35.3	50.2	58.9	81.2	104.3	123.9	151.3	156.4			
Rea	13.1	30.1	36.5	37.6	66.6	93.1	119.9	146.7					
Sav	14.2	30.3	39.5	47.7	58.7	69.0	101.1						
Mean	10.5	28.2	36.9	45.1	61.0	78.8	102.8	120.6	132.8	138.3	135.7	142.4	154.8
SD	3.4	3.4	6.5	7.4	6.6	9.0	12.8	16.4	17.9	25.6			
SE	1.3	1.3	2.5	2.8	2.5	3.4	4.8	7.3	10.3	18.1			

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13. ABSTRACT *(Maximum 200 words)*
Spaceflight and bed-rest deconditioning decrease maximal oxygen uptake (aerobic power), strength, endurance capacity, and orthostatic tolerance. In addition to extensive use of muscular exercise conditioning as a countermeasure for the reduction in aerobic power ($\dot{V}O_{2max}$), stimuli from some form of +Gz acceleration conditioning may be necessary to attenuate the orthostatic intolerance component of this deconditioning. **Hypothesis:** There will be no significant difference in the physiological responses (oxygen uptake, heart rate, ventilation, or respiratory exchange ratio) during supine exercise with moderate +Gz acceleration. **Methods:** Seven male subjects (24–39 yrs.) exercised supine on the human powered centrifuge (HPC). Each subject performed maximal oxygen uptake ($\dot{V}O_{2max}$) and submaximal exercise tests at 42%, 61% and 89% of $\dot{V}O_{2max}$ under two conditions: exercise and exercise + acceleration. During exercise + acceleration the subjects accelerated on the HPC at a mean (±SE) level of +2.20 ± 0.02 Gz (50% of max Gz) while exercising. **Results:** There were no significant differences in $\dot{V}O_2$, HR, or $\dot{V}_{EBTPS}$ during the submaximal or maximal exercise runs with added acceleration. Mean (±SE) $\dot{V}O_{2max}$ for exercise was 2.86 ± 0.12 L • min^{-1} (34.8 ± 2.3 ml • min^{-1} • kg^{-1}) and for exercise + acceleration was 3.09 ± 0.14 L • min^{-1} (37.3 ± 1.7 ml • min^{-1} • kg^{-1}). The respiratory exchange ratio (R_E) was significantly different at 61% ($p<0.05$) and 89% ($p<0.01$) of $\dot{V}O_{2max}$. **Conclusion:** There were no significant positive or negative effects among the tested parameters when moderate (+2.2 Gz) acceleration accompanied exercise. It is concluded that moderate acceleration does not affect the normal relationships between oxygen uptake, heart rate, ventilation, or respiratory exchange ratio in relation to a relative exercise load.

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