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Comparison of the U.S. and Russian Cycle Ergometers

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Acronyms

ANOVA	Analysis of Variance
BP	Blood Pressure
CEVIS	Cycle Ergometer with Vibration Isolation System
EVA	Extra Vehicular Activity
HR	Heart Rate
ISS	International Space Station
MO-5	Russian submaximal cycle exercise test protocol
PFE	Periodic Fitness Evaluation, U.S. submaximal cycle exercise test protocol
RER	Respiratory Exchange Ratio
RPE	Rating of Perceived Exertion
VCO_2	Carbon dioxide production
VE	Expired Ventilation
Velo	Veloergometer
VO_2	Oxygen consumption
VO_2pk	Peak oxygen consumption
W	watts

Abstract

Purpose: The purpose of this study was to compare the U.S. and Russian cycle ergometers, focusing on the mechanical differences of the devices and the physiological differences observed while using the devices. **Methods**: First, the mechanical loads provided by the U.S. Cycle Ergometer with Vibration Isolation System (CEVIS) and the Russian Veloergometer were measured using a calibration dynamometer. Results were compared and conversion equations were modeled to determine the actual load provided by each device. Second, 10 male subjects (32.9 ± 6.5 yrs, 180.6 ± 4.4 cm; 81.9 ± 6.9 kg) experienced with both cycling and exercise testing completed a standardized submaximal exercise test protocol on CEVIS and Veloergometer. The exercise protocol involved eight submaximal workloads each lasting three minutes for a total of 24 minutes per session, or until the end of the stage when the subject reached 85% of peak oxygen consumption or age-predicted maximum heart rate (220 - age). The workload started at 50 watts (W), increased to 100 W, and then increased 25 W every three minutes until reaching a peak workload of 250 W. Physiological variables were then compared at each workload by repeated measures Analysis of Variance (ANOVA) or paired t-tests ($p<0.05$). **Results:** While both CEVIS and Veloergometer produced significantly lower workloads than the displayed workload, CEVIS produced even lower loads than Veloergometer ($p<0.05$) at each indicated workload. Despite this fact, the only physiological variables that showed a significant difference between the ergometers were expired ventilation (VE) (125 – 250W), oxygen consumption (VO_2) (175 and 250 W), and carbon dioxide production (VCO_2) (175 W). All other physiological data were not statistically different between CEVIS and Veloergometer. **Conclusion**: Although workloads were different between ergometers, relatively few physiological differences were observed. Therefore, CEVIS workloads of 87.5 – 262.5 W can be rounded to the nearest 25 W increment and performed on the Veloergometer.

1.0 Introduction

Physiological testing of the astronaut crew is essential to understand the physiological changes that occur with microgravity and to assess if current countermeasures effectively combat any negative changes. Beyond tracking changes in aerobic capacity, the Periodic Fitness Evaluation (PFE) cycle ergometer test is conducted to determine if any changes are needed for the Extra Vehicular Activity (EVA) exercise prebreathe protocol. The EVA exercise prebreathe protocol uses a 10-minute period of exercise to increase the purging of nitrogen from body tissues while breathing 100% oxygen (5, MR087L). Having the correct workload prescription is critical to the success of the prebreathe protocol as validated by ground-based studies[2,13,15] and established by the NASA EVA-Integrated Product Team.

There are two different cycle ergometers onboard the International Space Station (ISS): the U.S.-designed Cycle Ergometer with Vibration Isolation System (CEVIS); and the Russian-designed Veloergometer. These devices provide controlled workloads, quantified in watts (W), for crew exercise countermeasures prescriptions, exercise prebreathe prescriptions, and exercise testing purposes. The capabilities of each ergometer are listed in Table 1.

Table 1: Specifications of Veloergometer and CEVIS.

Parameter	Veloergometer	CEVIS
Pedal Speed Range for Controlled Workloads	40-120 rpm	50-120 rpm
Controlled Workload Range	100-250 W*	25-350 W
Workload Increments	25 W	1 W

* Veloergometer also has a setting “XX” which is less than 50 W.

Prior to this evaluation, there was evidence from multiple ISS crew member comments and from a small amount of heart rate (HR) data from a single crew member that, at similar indicated workload settings, the two devices were not delivering the same workload to an exercising crew member (Figure 1). From examination of the HR data, it appeared that the Veloergometer yielded lower actual loads (resulting in lower HRs) than CEVIS at displayed workloads below approximately 170 W and higher actual loads than CEVIS at displayed workloads over 170 W.

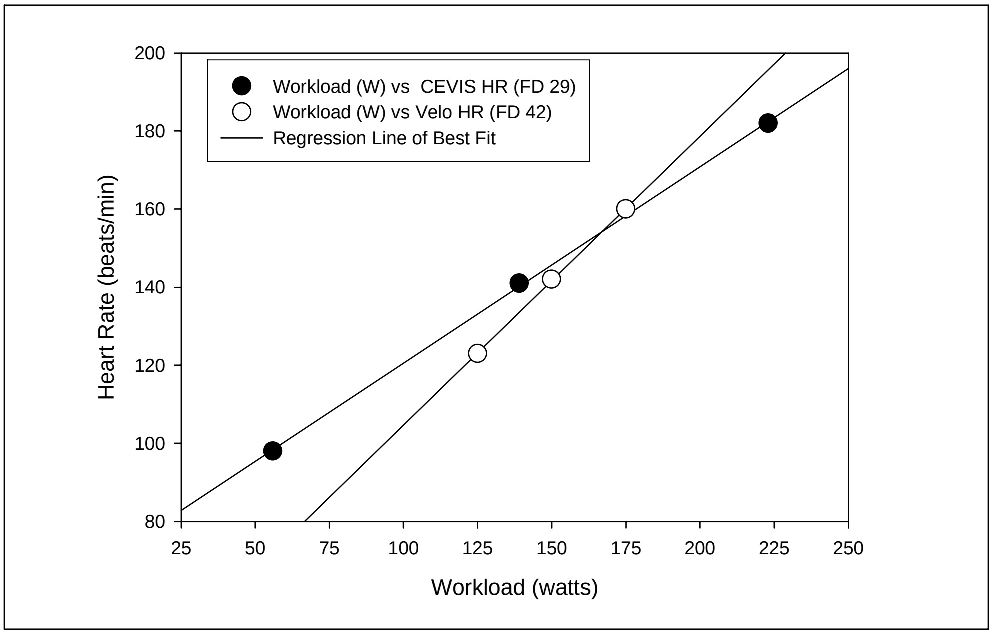

Figure 1: Heart rate data for single subject on Veloergometer and CEVIS.

Ideally, both ergometers would be compatible, affording crew members the utmost flexibility; thus, this evaluation will determine if CEVIS and Veloergometer provide similar workloads at similar wattage settings.

Furthermore, the history of ISS operations indicates a high likelihood that an exercise device may be unusable for a period of time. This can cause problems in obtaining medical information regarding the crew's fitness levels and cardiovascular status. Lack of an exercise device on the ISS also negatively impacts nominal countermeasures programs. Therefore, it is imperative that redundancy and backup capability be present with as much fidelity as possible to provide exercise countermeasures and in-flight medical testing.

2.0 Goal and Hypothesis

The goal of this study was to compare the ground-based differences of CEVIS and Veloergometer in order to evaluate the potential flexibility available on the ISS for fitness testing and exercise countermeasures. The hypothesis is that power output and physiological data will not differ between CEVIS and Veloergometer.

3.0 Methods

For the mechanical load verification test, CEVIS and Veloergometer were attached to a calibration dynamometer (Damec, Odense, Denmark, Part # IED-0110-0000-DA). The dynamometer measured the true output workload of each ergometer at 80 revolutions per minute (RPM). True output was measured on both ergometers at displayed workloads of 100, 125, 150, 175, 200, 225 and 250 W. In addition, CEVIS was measured at 50 W and Veloergometer was measured at XX (idle) mode, which is listed as supplying less than 50 W.[11] Although results from the XX setting were measured, for comparison purposes, only the results from 100-250 W measurements were analyzed. The results from each ergometer were compared to displayed workloads using repeated measures Analysis of Variance (ANOVA) ($p<0.05$ with Tukey post hoc test).

Following the mechanical load verification tests, 10 male subjects (32.9 ± 6.5 yrs, 180.6 ± 4.4 cm; 81.9 ± 6.9 kg) completed the physiological portion of this evaluation. Each subject had previous experience with respiratory gas analysis, cycling and exercise testing. Subjects were free from injuries and pathological conditions which could have potentially affected the results of the study. Prior to participation, all subjects signed an informed consent document. The study was given approval by the Johnson Space Center (JSC) Committee for the Protection of Human Subjects.

Each subject completed two exercise sessions in random order: one on CEVIS (Figure 2A); the other on the Veloergometer (Figure 2B). Subjects exercised at submaximal workloads for a total of 24 minutes per session. Each exercise session contained eight stages lasting three minutes each. These stages started at 50 W, increased to 100 W and then increased sequentially by 25 W per stage until reaching a peak workload of 250 W (Figure 3). Target cadence was 80 RPM because it is similar to the cadence chosen by crew members and was the cadence used for the mechanical load verification tests.

A **B**

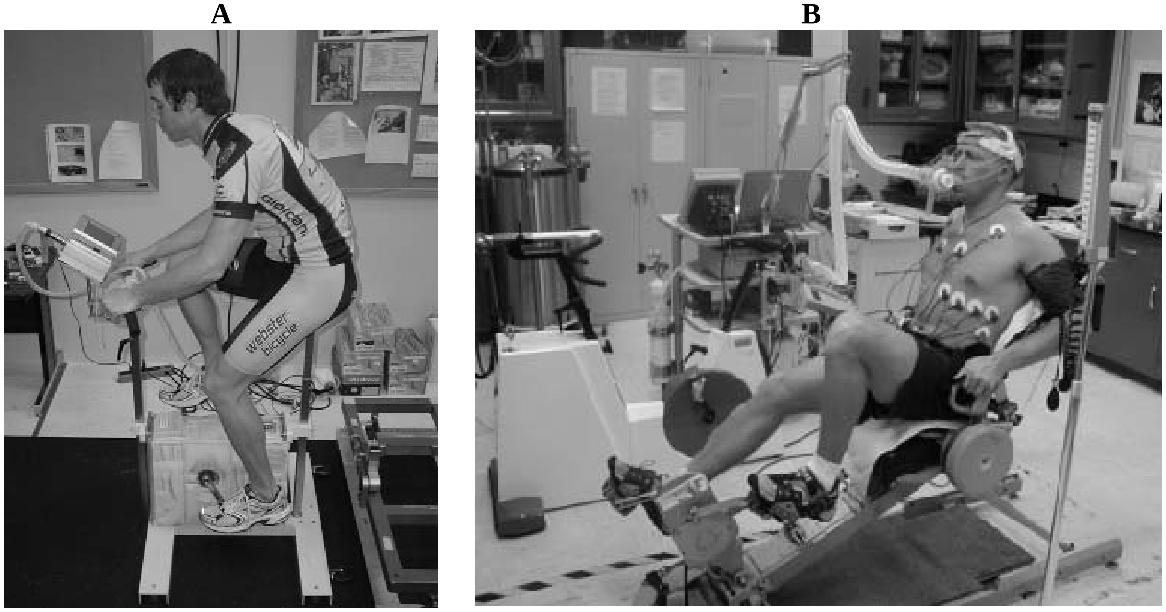

Figure 2: (A) Subject using CEVIS; (B) Subject using Veloergometer.

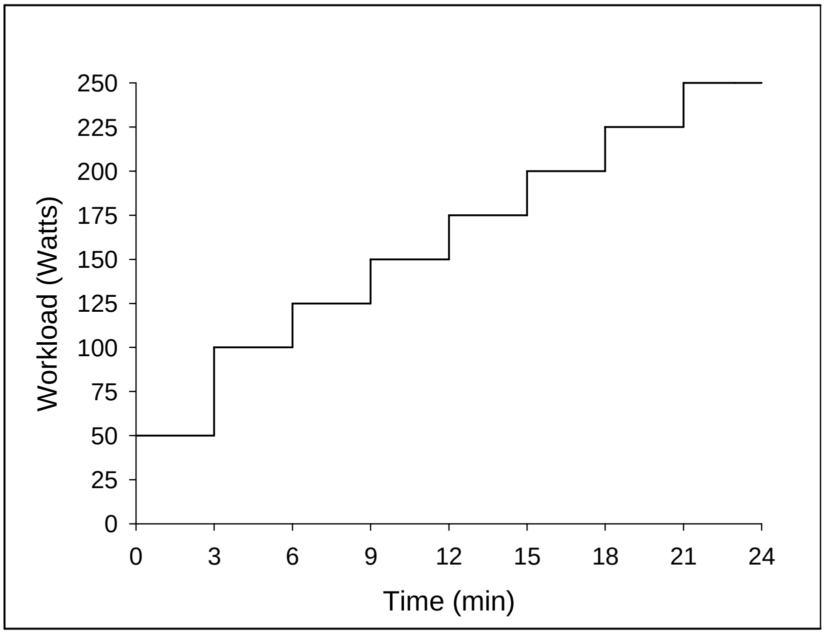

Figure 3: Submaximal exercise protocol for ergometer comparison.

For these tests, HR and rhythm were obtained through continuous monitoring of the electrocardiogram (ECG; Q-Stress, Quinton Cardiology, Inc., Bothell, WA). Respiratory gas analysis was measured continuously with a metabolic cart (TrueOne® 2400, Parvo-Medics, Salt Lake City, UT). Blood pressure (BP) and ratings of perceived exertion (RPE, Borg 6-20 scale) were recorded for each stage, and the subject was monitored for signs and symptoms of exertional intolerance.

If results from a peak oxygen consumption (VO_2pk) test performed within the past year in the JSC Exercise Physiology Laboratory were available, then testing was terminated at the end of the stage when the subject reached 85% of VO_2pk. If no VO_2pk test was on file, then the test was terminated at the end of the stage when the subject attained 85% of age-predicted maximum HR (220 - age). Although encouraged to attain this level, subjects were able to voluntarily terminate the test at any time.

Repeated measures ANOVA were used to compare oxygen consumption (VO_2), carbon dioxide production (VCO_2), ventilation (VE), respiratory exchange ratio (RER), HR and rating of perceived exertion (RPE) at each independent workload. Regression analysis was used for the calibration dynamometer data to create correction factors between displayed workloads on the ergometers.

4.0 Results

4.1 Mechanical Testing

Both CEVIS ($p<0.001$) and Veloergometer ($p = 0.013$) measured significantly different workloads than the displayed workloads (Figure 4). Also, CEVIS was statistically lower than Veloergometer at all workloads 100 W and above ($p<0.001$).

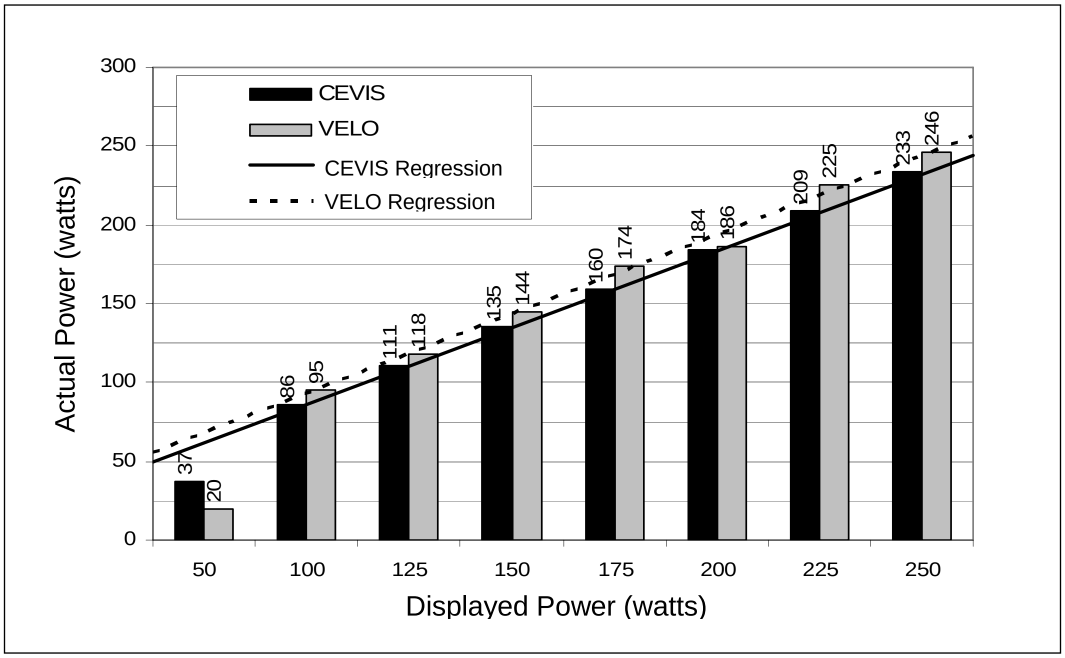

Figure 4: Actual power output vs. displayed power.

Although Veloergometer and CEVIS were almost identical at 200 W, Veloergometer averaged 9.1 W higher than CEVIS (range 2.5 - 16.9 W) at displayed power settings of 100 W and above. A linear regression was used to derive an equation to convert displayed wattage to actual wattage:

$$\text{CEVIS Actual W} = (0.98 \cdot \text{CEVIS Displayed W}) - 11.8$$

$$\text{Velo Actual W} = (1.01 \cdot \text{Velo Displayed W}) - 7.7$$

4.2 ***Physiological Testing***

Although 10 subjects completed the protocol, one subject was removed from data analysis due to anomalous data. Of the remaining nine subjects, five subjects completed all workloads, three subjects completed the protocol through 225 W, and one subject completed the protocol through 200 W. Sessions were terminated due to the subject exceeding the predetermined HR test termination criteria. No sessions were voluntarily terminated by the subjects.

In general, CEVIS tended to produce lower VO_2 values than Veloergometer at each displayed wattage level (Figure 5). This is similar to the work rate data obtained from dynamometer testing. Although clearly the trend, statistically significant differences were seen only between CEVIS and Veloergometer at 175 W ($p = 0.030$) and 250 W ($p = 0.029$).

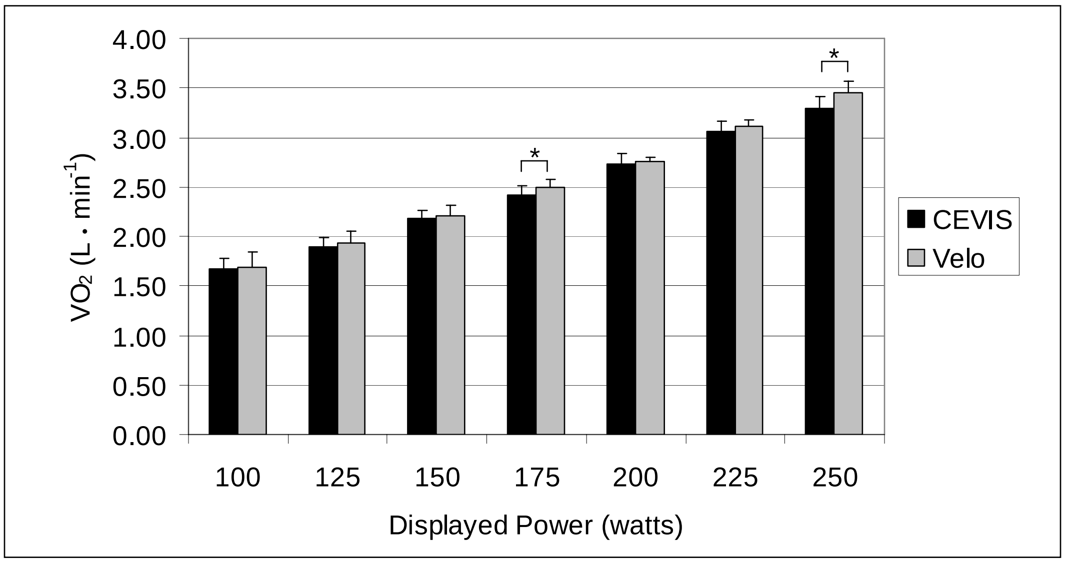

Figure 5: Mean (±SD) VO_2 from CEVIS and Veloergometer.
*** p<0.05**

VCO_2 followed a similar trend to VO_2 (Figure 6), although a significant difference was seen between CEVIS and Veloergometer only at 175 W ($p = 0.035$).

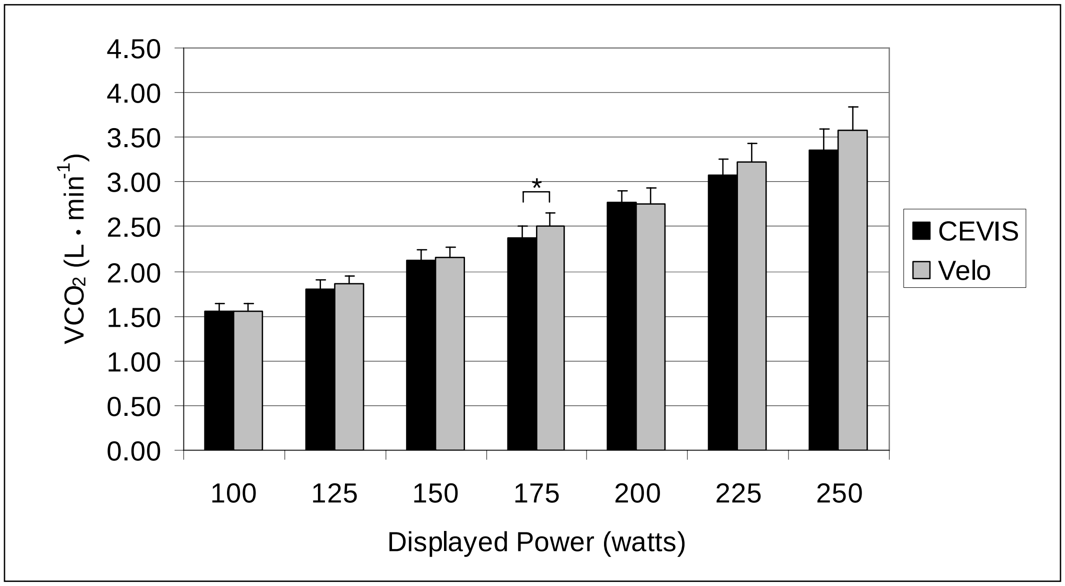

Figure 6: Mean (±SD) VCO_2 from CEVIS and Veloergometer.
*** p<0.05**

Ventilation (VE) showed the greatest differences of all variables examined (Figure 7). Ventilation while exercising on Veloergometer was significantly higher than CEVIS at all workloads except 50 and 100 W.

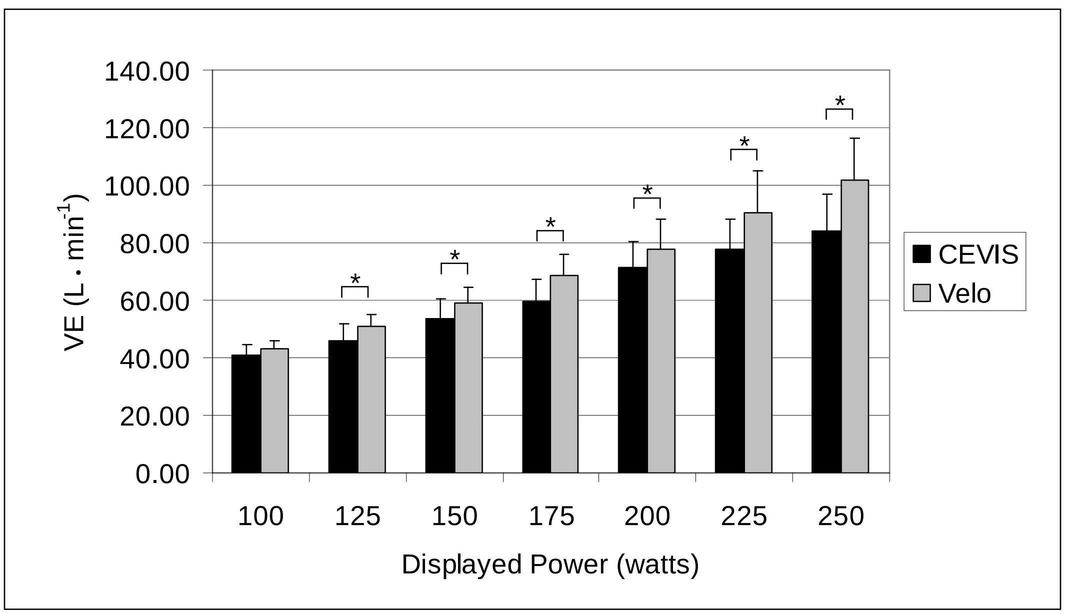

Figure 7: Mean (±SD) VE from CEVIS and Veloergometer.
*** p<0.05**

There were no significant differences in RER between CEVIS and Veloergometer (Figure 8).

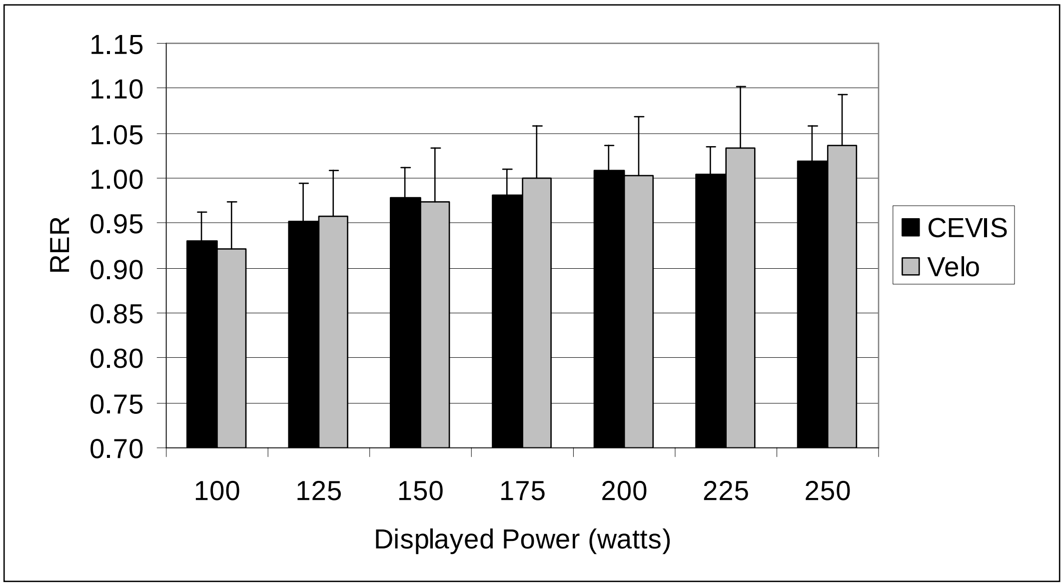

Figure 8: Mean (±SD) RER from CEVIS and Veloergometer.

HR followed a similar trend seen with VO_2, where HR observed while exercising on CEVIS appears less than Veloergometer at each workload (Figure 9). Although this trend is clearly seen, there were no significant differences.

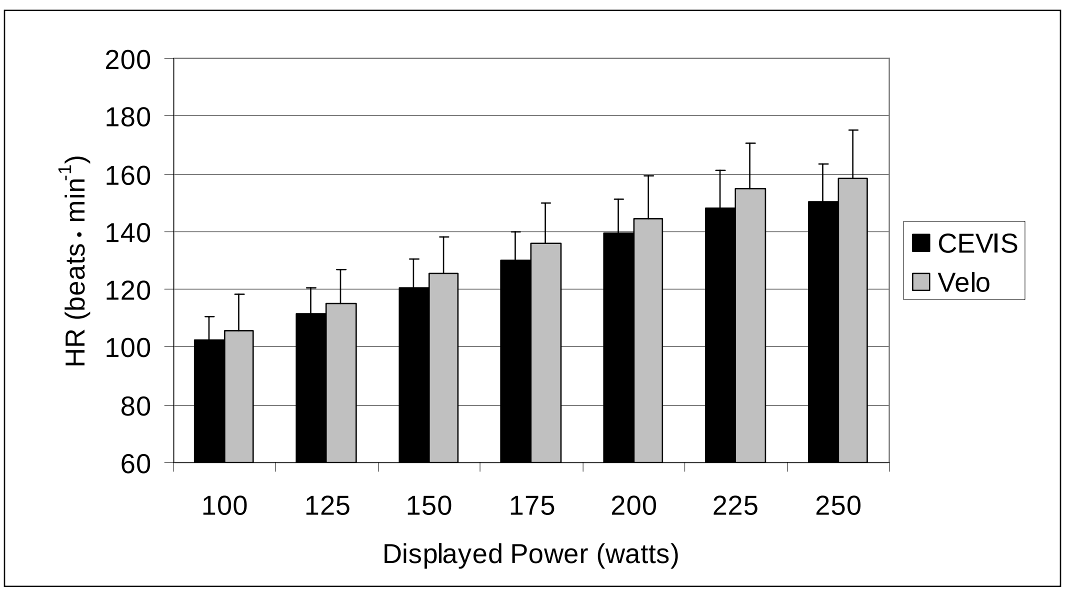

Figure 9: Mean (±SD) HR from CEVIS and Veloergometer.

RPE also followed a similar pattern to that seen with VO_2 and HR, although no significant differences were observed at any workload (Figure 10).

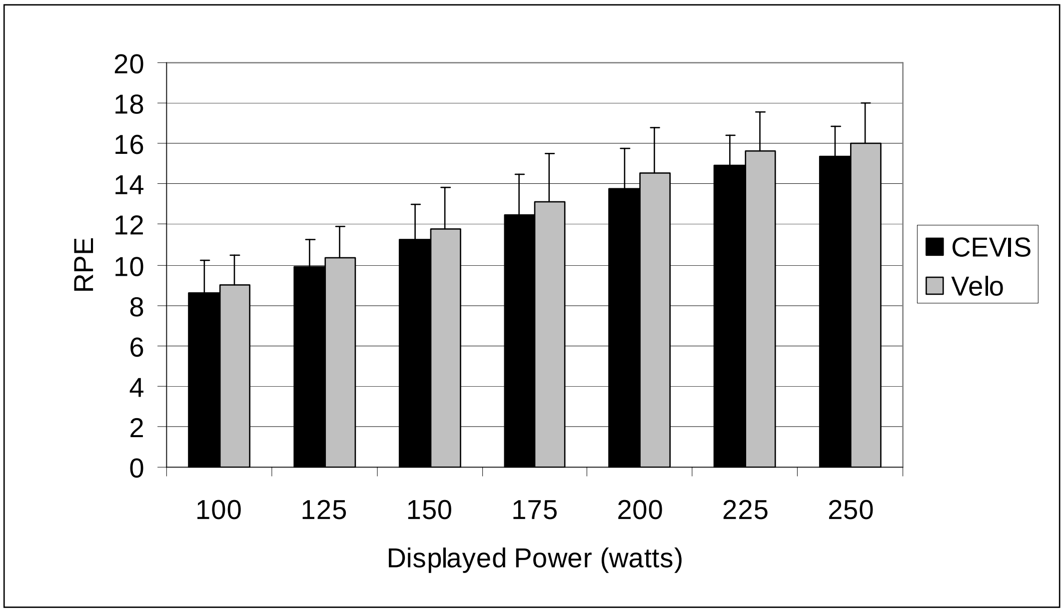

Figure 10: Mean (±SD) RPE from CEVIS and Veloergometer.

5.0 Discussion

Mechanical verification showed some pre-existing differences between the ergometers. Both the Veloergometer and CEVIS provided an average of 5 and 14 W lower workloads, respectively, than the displayed workloads between 100 and 250 W. In addition, the Veloergometer provided an average of 9 W greater resistances than CEVIS at each displayed workload.

Significant differences between the cycles were observed in VO_2, VCO_2 and VE for some, but not all, exercise stages. In the case of VO_2, differences were observed at only two workloads (175 and 250 W). For VCO_2, statistical differences were only observed at one workload (175 W). This displayed workload also had one of the largest actual workload differences between devices (160 W for CEVIS and 174 W for Veloergometer), which may account for the differences observed.

Interestingly, the physiological variable that showed the most significant differences was VE. At six of eight displayed workloads (125 – 250 W), VE was statistically higher on the Veloergometer. While some of the differences may have been due to actual workload differences between devices, differences in subject positioning (Veloergometer was utilized in a more recumbent position than CEVIS) may have had a greater impact on VE than other physiological variables. However, results from published literature where recumbent cycling was physiologically compared to upright cycling showed similar VO_2, VE and HR values.[3,7] Another study showed VO_2, HR and RPE values were similar between recumbent and upright cycling, but workloads were not deemed interchangeable because physiological variables were slightly higher in upright cycling.[1] This is similar to the higher HR seen with upright cycling compared to recumbent.[14] Only at very low workloads (<70 W) has recumbent cycling produced higher VO_2, VCO_2 and VE values than upright cycling.[10]

A biomechanical comparison of recumbent versus upright cycling showed similar trends. The functional roles of leg muscles were similar as measured by percent of integrated activation in crank cycle regions in upright and recumbent cycling.[4] Lower extremity kinematics were not different between recumbent and upright cycling, but anterior/posterior forces were different between the two conditions.[8] Another study used inverse dynamics to determine that the amount of energy transferred from the upper body to lower extremities was significantly reduced in the recumbent position and although total work at the knee was not different, the amount of knee flexion work increased significantly.[9] Therefore, something beyond body position or biomechanics must be playing a role in the increased VE observed while riding Veloergometer.

The lack of a flywheel in Veloergometer may have contributed to the increased VE. Flywheels allow for energy storage in the ergometer which propels the subject's legs through dead spots in the pedal stroke. Both CEVIS and most ground-based ergometers (such as the Lode Excalibur Sport [Lode B.V., Groningen, The Netherlands] used for preflight and postflight testing) contain a flywheel. It is interesting, though, that VE would be the main variable affected by this design difference.

Since the Veloergometer is designed for use in microgravity, another possible contribution to the physiological differences observed was the lack of a supportive, non-slip seat. The 1-G configuration used for this testing is intended for usage training purposes only. Although finding a comfortable seating position was attempted by both subjects and test operators, all subjects had to exert some amount of force just to prevent them from sliding downward on the seat of the ergometer. Subjectively, most subjects reported that Veloergometer was the most difficult ergometer to use when exercising, even though analysis of RPE showed no consistent trend. This difficulty was the primary complaint of one subject and the ultimate reason why, after careful consideration, the subject was dropped from data analysis. This subject completed 250 W on CEVIS with physiological data consistent with other subjects but struggled to finish 200 W on Veloergometer. The subject continued to slip and had to visibly exert force on the Veloergometer handles to maintain position. For this subject, VO_2 and all other physiological variables were markedly higher at all workloads on Veloergometer and was an extreme outlier when compared to the data from the other nine subjects. The cause of this was most likely related to positional discomfort.

It is important to consider that body position and biomechanics are very different in the microgravity environment. For example, while CEVIS was ridden in the upright position for this study, it is configured very similar to Veloergometer on the ISS. It is therefore unlikely that body position would have a significant impact on any potential physiological differences in microgravity.

In general, greater VE values as well as the limited differences in VO_2 and VCO_2 indicate that Veloergometer was the most difficult ergometer to use; however, a global view of all observed data indicates few statistical differences between Veloergometer and CEVIS. Therefore, the intended use of the ergometers should be the determinant of how much variance is acceptable. The ISS cycle ergometers have three primary uses:

- Exercise countermeasures
- EVA exercise prebreathe protocol
- Submaximal exercise testing

To examine each of these individual conditions, one can assume the following:

1. Workloads will be adjusted using the previously described equations when alternating between CEVIS and Veloergometer.
2. Workloads will be rounded to the nearest 25 W between 100 – 250 W when moving from CEVIS to Veloergometer. Therefore, the greatest difference between the CEVIS and Veloergometer workload would be 12.5 W.
3. Workloads less than 87.5 W and greater than 262.5 W will require the use of CEVIS.

For exercise countermeasures, differences between the cycle ergometers would have the largest acceptable range. The primary goal of the cycle ergometer exercise countermeasure is to protect the cardiorespiratory system. With feedback such as HR and RPE, workload is just one of the options available when attempting to regulate exercise intensity to obtain an adequate exercise stimulus.

For the EVA exercise prebreathe protocol, the workload needs to be more rigorously controlled. The final and most important workload is prescribed at the workload required to elicit 75% of the crew member's preflight VO_2pk. Without using a metabolic analyzer, crew members use HR to monitor proper exercise intensity with RPE as a backup. Should the prescribed workload push the crew member over a predetermined HR, the workload is decreased by 20 W. Thus, a certain safety margin is built into the exercise prebreathe protocol. When performing the EVA exercise prebreathe workloads, the crew member must be ± 10% of the target VO_2. The maximal 12.5 W difference between ergometers leads to a proposed change in the VO_2 of less than 0.2 l/min, which is less than 10% of the average crew member VO_2pk of 2.83 ± 0.45 l/min for females and 3.69 ± 0.42 l/min for males.[6] This difference may be within the noise of day-to-day variation of VO_2 at a given submaximal workload.[12,16,17,18]

Submaximal exercise testing, such as the PFE and MO-5, also require specific workloads. The PFE contains four stages, each lasting five minutes, with workloads based on the results of the VO_2pk test. The stages consist of the workload required to elicit 25%, 50% and 75% of the crew member's preflight VO_2pk. A fourth cool down stage is performed at the initial workload. The MO-5 protocol contains three stages, each lasting three minutes, with standard workloads of 125, 150 and 175 W. Currently, there is no difficulty maintaining the appropriate workload for the MO-5 on either cycle ergometer. When considering the correct loads to use during a PFE on Veloergometer, it is necessary to round the workload to the nearest 25 W increment. However, since HR and workload are known, analysis of a HR/W regression is possible.

6.0 Conclusion

Although workloads were statistically different between ergometers, only minor physiological differences were observed in VE, VO_2 and VCO_2. Therefore, both CEVIS and Veloergometer can be interchangeable for all purposes including exercise countermeasures, EVA exercise prebreathe protocols and submaximal exercise testing, assuming the workload range is 87.5 – 262.5 W.

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13. ABSTRACT *(Maximum 200 words)*

The purpose of this study was to compare the U.S. and Russian cycle ergometers, focusing on the mechanical differences of the devices and the physiological differences observed while using the devices. First, the mechanical loads provided by the U.S. Cycle Ergometer with Vibration Isolation System (CEVIS) and the Russian Veloergometer were measured using a calibration dynamometer. Results were compared and conversion equations were modeled to determine the actual load provided by each device. Second, 10 male subjects experienced with both cycling and exercise testing completed a standardized submaximal exercise test protocol on CEVIS and Veloergometer. The exercise protocol involved eight submaximal workloads each lasting three minutes for a total of 24 minutes per session, or until the end of the stage when the subject reached 85% of peak oxygen consumption or age-predicted maximum heart rate. The workload started at 50 watts (W), increased to 100 W, and then increased 25 W every three minutes until reaching a peak workload of 250 W. Physiological variables were then compared at each workload by repeated measures Analysis of Variance (ANOVA) or paired t-tests ($p<0.05$). While both CEVIS and Veloergometer produced significantly lower workloads than the displayed workload, CEVIS produced even lower loads than Veloergometer ($p<0.05$) at each indicated workload. Despite this fact, the only physiological variables that showed a significant difference between the ergometers were expired ventilation (125 – 250W), oxygen consumption (175 and 250 W), and carbon dioxide production (175 W). All other physiological data were not statistically different between CEVIS and Veloergometer.

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