1993

Cardiovascular Responses of Trained Cyclists to Different Pedaling Rates at a Constant Power Output on a Cycle Ergometer

David C. Immke

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Cardiovascular Responses of Trained Cyclists to Different

Pedaling Rates at a Constant Power Output on a Cycle

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David C. Immke

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ABSTRACT

Cardiovascular Responses of Trained Cyclists
to Different Pedaling Rates at a Constant Power
Output on a Cycle Ergometer

David Immke

Previous research has not resolved the issue as to which pedaling rate is the most efficient in terms of oxygen uptake (VO_2) for competitive cyclists. The purpose of this study was to determine the most efficient pedaling rate (30, 60, or 90 rpm) at steady state submaximal cycling (720 kpm/min) for trained cyclists. Eight healthy subjects (all male) were examined during steady state exercise for each of the three trials for which work rate was kept constant with varying pedal rate and resistance. Variables included oxygen uptake, cardiac output, heart rate, stroke volume, arterio-venous O_2 difference, respiratory exchange ratio, and respiratory rate. Basic descriptive statistics (mean, standard deviation, etc.) and one-factor analysis of variance with repeated measures were used to analyze the data. Significance was set at 95% ($p<0.05$) for the data. Results showed that VO_2 (L/min and ml/kg/min), heart rate, and VCO_2 were significantly lower ($p<0.05$) for 60 rpm compared to 30 rpm and 90 rpm. Minute ventilatory volume was significantly lower ($p<0.05$) for 60 rpm compared to 90 rpm. Respiratory exchange ratio was significantly lower ($p<0.05$) for 30 rpm and 60

rpm compared to 90 rpm. It is hypothesized that at low pedal rates the muscle fibers are in a longer period of contraction and at high pedal rates more muscle fibers are recruited to stabilize the trunk. Each of these will result in a decrease in efficiency for the competitive cyclist. The results indicate that 60 rpm is more efficient for the competitive cyclist when compared to the low pedal rate of 30 rpm and the high pedal rate of 90 rpm at an absolute steady state work rate of 720 kpm/min.

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CHAPTER 1

INTRODUCTION

Identification of the Problem

Competitive cycling is a unique human powered sport because athletes can attain similar velocities at markedly different rates of limb movements, by varying gear ratios. Other competitive sports, such as running, swimming, and speedskating rely on standard rate of limb movements to attain certain velocities and not force applied to a mechanical device as in cycling (Hagberg, Mullin, Giese,& Spitznagel, 1981). Road-racing cyclists can vary their pedaling rate to as low as 30 rpm or as high as 120 rpm and attain the same speed by altering resistance by gear ratios. However, cyclists routinely use high pedal rates in the range of 80-110 rpm (Hagberg, Mullin, Bahrke,& Limburg, 1979). Contrary to the high pedal rates used by competitive cyclists, laboratory testing frequently uses the range of 50-60 rpm.

Many studies have addressed the question of the optimal pedal rate. The problem that has occurred with the research is that many of the subjects were either noncyclists or recreational cyclists and the results have been inferred to aid the competitive cyclist (Ramey, 1977). These studies and others have shown that the most efficient pedaling rate ranges from 50-80 rpm, well below the range used by competitive cyclists.

The criteria to determine which pedaling rate is most efficient is the rate at which oxygen uptake (VO_2) is lowest at an absolute submaximal test or the highest at a maximal test. VO_2 is the gold standard that has worldwide

acceptance for measuring the ability of humans to perform prolonged exercise. Oxygen uptake is determined by the product of cardiac output (Q) and arterio-venous O_2 difference (a-v O_2 diff.). Since VO_2 is a product of two variables there are different means for achieving the same VO_2 value. Cardiac output can be low with a high a-v O_2 diff., or vice verca. This is important because there is discussion as to which of the two variables, Q or a-v O_2 diff., is the limiting factor for VO_{2max}. Since, the ability for an athlete to increase exercise capacity following training depends partially on the magnitude of the increase in oxygen uptake. Although resting oxygen uptake is very similar in trained and untrained individuals there can be a one and a half to twofold higher maximal oxygen uptake in the trained versus the untrained individual (Sutton, 1991). Therefore, studies that have not used competitive cyclists for subjects should not apply results to all populations, namely, noncyclists, recreational cyclists, and competitive cyclists.

Oxygen consumption itself, though, has several different variables that have not been widely studied when researching pedaling rates. The component that usually is reported is heart rate. This is useful since heart rate response is known to parallel that of VO_2 during exercise. However, the limiting variables for oxygen consumption where little research has been done in connection with pedal rate are stroke volume and a-v O_2 diff. These two variables are the central and peripheral limiting factors, respectively. Measuring these variables at different pedaling rates could possibly explain why different efficiencies at different pedaling rates are reported in the literature.

Various results have been reported when investigating which pedaling rates to use when measuring VO_{2max}. Pivarnik and associates (1988) showed less than three percent difference in absolute peak oxygen consumption when comparing 50 rpm versus 90 rpm. In contrast, McKay and Bannister (1976) found that 80 rpm and 100 rpm produced a greater VO_{2max} than did 60 and 120 rpm. Additionally, both of these studies (Pivarnik, et al., 1988; McKay, et al., 1976) differ from Hermansen and Saltin (1969) who reported that 60 rpm elicited the highest VO_{2max}. The confusion concerning which pedaling rate is most efficient for maximal values has carried over to submaximal efforts of competitive cyclists. However, few studies measure the variables that determine oxygen consumption at submaximal levels: cardiac output (heart rate x stroke volume) and arterio-venous oxygen difference.

One reason for the lack of data for this type of testing is because until the last twenty years there was no non-invasive yet accurate and reliable method of determining cardiac output during exercise. Because of the risks and technical complications of the Direct Fick and Indicator Dye Dilution methods of determining cardiac output, testing in this area had not often been previously attempted. However, now that the consistency and accuracy of the non-invasive carbon dioxide rebreathing technique to determine cardiac output during exercise has been verified, testing can now be accomplished for competitive cyclists at submaximal levels (Knowlton & Adams, 1974).

Statement of the Problem

The purpose of this study was to determine the most efficient pedaling rate (30, 60, or 90 rpm) at steady state submaximal cycling (720 kpm/min, 120 W) for trained cyclists in terms of oxygen uptake, heart rate, stroke volume, cardiac output, and arterio-venous oxygen difference. The results of this study will have practical applications regarding the pedal rate which trained cyclists may compete.

Hypotheses

1. There is no difference in the oxygen uptake among the three pedal rates (30, 60, and 90 rpms) at a steady state submaximal work rate of 720 kpm/min (120 Watts).

2. There is no difference in the central (cardiac output, heart rate, and stroke volume) or peripheral (a-v O_2 diff.) limiting factors of oxygen uptake among the three pedal rates (30, 60, and 90 rpms) at a steady state submaximal work rate of 720 kpm/min (120 Watts)

Limitations

1. This study was limited to eight subjects. It was difficult to find subjects who were competitive cyclists and willing to participate in the study during the summer months when races normally take place.

2. Because of time constraints for the subjects, testing was done at random throughout the day and not at an established time of day.

3. It was assumed that physiological responses were due to exercise and not influenced by any other factors such as medications, caffeine, diet, or prior exercise. It would have been to difficult to control for these variables due to the different time of day when testing took place.

4. The subjects used the ergometer as provided from the research laboratory and were not allowed to use their own bicycle or any of its components.

5. Due to time constraints the researcher did not test the maximal oxygen consumption for each subject. The work load was the same for each subject regardless of fitness. This did not enable the researcher to determine the percent of VO_{2max} the subjects were utilizing.

Definition of terms

Arterio-venous Oxygen Difference (a-v O_2 diff). The average difference between the oxygen content of arterial and mixed venous blood. (McArdle, Katch,& Katch, 1986, page 269)

Cardiac Output (Q). The amount of blood determined by the hearts rate of pumping and the quantity of blood ejected with each stroke. (McArdle, et al., 1986, page 269)

Central Limitation. The limitation of oxygen uptake by the cardiorespiratory system involving cardiac output (HR x SV) or maximal arterial oxygen content. (Sutton, 1991, page 26)

Competitive Cyclist. The level of each of the subjects was at Category 3 or better.

Fick Equation. VO_2 = Cardiac Output x Arterio-Venous Oxygen Difference. (McArdle, et al., 1986, page 269)

Peripheral Limitation. The limitation of oxygen uptake by the degree of extraction and utilization of oxygen from the arterial blood by the muscle cells. Described as arterio-venous oxygen difference. (Sutton, page 26)

Revolutions Per Minute (rpm). The number of cycles per unit of time on an ergometer.

Stroke Volume (SV). The quantity of blood ejected from the heart with each beat. (McArdle, et al., page 269)

Oxygen Uptake (VO_2). The volume of oxygen (STPD) extracted from the inspired air, usually expressed in liters per minute. (Astrand & Rodahl, 1986, page 738)

CHAPTER II

REVIEW OF LITERATURE

The research in the literature that is pertinent to this investigation will be described in this chapter. Included will be the following topics: 1) Physiological changes due to different pedal rates; 2) Effect of pedal rate on endurance; 3) Techniques for measuring cardiac output during exercise; 4) Cardiac output - oxygen uptake relationship during cycle ergometry.

Physiological Changes Due To Different Pedal Rates

In theory, in cardiovascular, respiratory, metabolic, or perceptual responses during different bouts of submaximal exercise at absolute work rates should be similar. For competitive cyclists there are many ways in which to attain a submaximal work rate. By varying pedal rate versus gear ratio to either extreme the cyclist can attain the same velocity if the resulting power output are equal. The cyclist, therefore, has a large number of combinations of pedal rates versus resistance in order to attain the same speed.

Researchers have found that in unloaded cycling exercise, responses are not the same at different pedal rates. Differences were noted within the cardiovascular system, respiratory system, metabolically, and even the perception of effort by the cyclist. Hagberg, et al., (1981) found that unloaded

cycling at different pedal rates in seven road-racing cyclists that had just completed their competitive year, differences do occur. VO_2, ventilation (Ve), and HR were all significantly greater for each increase in unloaded pedal rate. On the other hand, there were no significant changes seen with the respiratory exchange ratio, lactic acid, or perceived exertion parameters. They reported, however, that the relationship between the parameters and the pedal rates during unloaded cycling is somewhat more complex than simply the additional work required to move the legs more rapidly, insomuch as VO_2 and Ve increases exponentially with increasing pedal rates while HR increases linearly. The possible explanation for these changes at the lower pedal rates is a less uniform pattern of blood flow caused by increasing the force requirement per pedal stroke. Meanwhile at the higher pedal rates, the difference could be due to the recruitment of additional musculature to stabilize the trunk.

Hagberg, et. al, (1981) also investigated the effects of the physiological parameters under differing pedal rates at a work load requiring 80% of their maximal O_2 uptake. The researchers showed that VO_2, Ve, Respiratory Exchange Ratio (RER), and lactic acid (LA) were best fit by quadratic models. Perceived exertion and heart rate increased linearly with an increase in pedal rate, supporting the original contention of Borg (1962), that perceived exertion is best related to heart rate. Hagberg, et al., (1981) speculated as pedal rate increases, less absolute power (and therefore force) is required per pedal stroke. Since blood flow during the time of contraction is known to be related to the relative force of the contraction (Barcroft and Millen, 1930), an increased pedal rate may cause less occlusion of blood flow during the contraction period.

Hagberg, et al., (1981) noted 91 rpm as the most efficient pedal rate as judged by VO_2, Ve, RER, and LA. A study similar to Hagberg, et al, (1981) but used 50% of peak power instead of 80% (Bolonchuk et al. 1992). All three of their tests were set at a mean of 731± 149 kpm/min at pedaling rates of 25, 50, and 75, and external resistance of 3.0, 1.5, and 1.0, respectively. The study used eight college age males for subjects. The results concluded that although work and power were held constant for pedal rates of 25, 50, and 75, physiological changes did occur. Mean VO_2, VCO_2, CNO_2 debt and VO_2/kg for the 25 rpm test were significantly greater than those values for 50 and 75 rpm. Heart rates were significantly different for 25 rpm also. There were no significant differences found for the heart rate and respiratory variables (Ve, F, VT or ratios). The anaerobic component was greater for the 25 rpm (8%) than the 50 rpm (4%) and the 75 rpm (5%) despite an absolute power output.

Buchanan & Weltman (1985) examined the effects of three pedal rates (60,90, 120 rpm) on VO_{2max} and lactate threshold in competitive cyclists. Nine competitive road racing cyclists were tested using a continuous incremental protocol on a Monark ergometer which was equipped with toe clips. At submaximal work rates from 0 kpm/min to 1300 kpm/min oxygen uptake values were significantly higher at 120 rpm as compared to 60 and 90 rpm. There were no statistically significant differences in VO_2 at these work outputs when 60 and 90 rpm were examined. At higher submaximal levels (from 1300 kpm/min to 2000 kpm/min) both 60 and 120 rpm resulted in higher VO_2 than observed at 90 rpm. The data at higher submaximal levels are similar to and different from other reports. Pandolf & Noble (1973) noted no difference in VO_2

at power outputs of 550, 775, and 1075 kpm/min when 40, 60, and 80 rpm were compared. However, Lollgen, Graham, and Sjogaerd (1980) reported that 100 rpm resulted in the highest VO_2 when compared to 40, 60, and 80 rpm at 70% of VO_2. Additionally, Hughes, Turner, and Brooks (1982) reported that VO_2 values at 90 rpm were significantly greater than VO_2 values at 50 rpm and work rates from 300 kpm/min to 2100 kpm/min. Hughes, et al., (1982) suggested that pedaling at faster rates increases the caloric cost thus elevating the VO_2 at a given work load. Buchanan and Weltman (1985) do not support this suggestion since no difference in VO_2 was seen for 60 versus 90 rpm for work rates of 0 kpm/min to 1300 kpm/min and a higher VO_2 was observed at 60 rpm as compared to 90 rpm from work rates of 1300 to 2000 kpm/min.

In the comparison of 50 rpm and 90 rpm, Pivarnik, Montain, Graves, and Pollock (1988), sought to determine whether there were differences in peak VO_2 values, at any of the metabolic, ventilatory, or perceived exertion variables during the submaximal stages of a maximal cycle test. Eleven male subjects underwent two incremental cycle ergometer tests designed to elicit maximal aerobic capacity (VO_{2max}). The speeds were set at 50 and 90 rpm and the power output was increased every two minutes by 300 kpm/min. Their results included a non-significant difference of 3% due to pedal speed for absolute peak VO_2. There was a significant main effect of pedal speed as average values of VO_2, VCO_2, RER, Ve, and HR were all greater at 90 rpm for submaximal levels. In this study, however, there were no significant interactions within the respiratory rate (RR) or perceived exertion (RPE). The fact that there was no change with perceived exertion is different from many studies that found

that there is a lower perception of exertion as pedal rate increases (Coast, Cox, & Welch, 1986; Lollgen, et al., 1980). Gaesser and Brooks (1975) studied the differences between the traditional and theoretical exercise efficiency calculations. They defined that gross efficiency was not corrected, net efficiency was corrected for resting metabolism at base-line, work efficiency was defined by correcting for unloaded cycling, and finally delta efficiency was computed by adjusting for measurable work rate as a base-line correction. Twelve well-conditioned male subjects exercised at 40, 60, 80, and 100 rpm at work rates of 0, 200, 400, 600, and 800 kpm/min. Their results stated that all definitions for efficiency (gross, net, work, and delta) yielded decreasing efficiency with increments in speed.

Many submaximal exercise studies suffer from the drawback that only low work rates are measured when competitive cyclists perform at relatively high work rates was noticed by Boning, Gonen, and Maassen (1984). Another problem they felt needed to be looked into was the difference between trained and untrained cyclists. They exercised nine well-trained amateur road-racing cyclists and six untrained medical students at work loads of 50, 100, and 200 W each at pedaling rates of 40, 60, 70, 80, and 100 rpm. Their results showed significantly higher oxygen uptake, ventilatory minute volume, and heart rate for the untrained group versus the trained group. The most important finding of this study was that the "optimal" pedaling rate shifted from 40 rpm at 50 W to 70 rpm at 200 W. This study is similar to others (Lollgen, et al., 1980, and Pugh, 1974) in that the dependence of VO_2 on pedaling rate disappears when approaching maximal oxygen uptake. One of the suggestions that the authors make is that

"efficiency must be reduced when using numerous muscle fibers as well as when using few fibers frequently for a given load. Also, additional effects may come from the difficulty of pedaling regularly at high work loads with low rate; thus, acceleration and auxiliary movements increase energy expenditure." (Boning, et al., 1986, page 96)

The Effect Of Pedal Rate On Endurance

One aspect of cycling at high rates is that endurance could be compromised. Carnevale and Gaesser (1991) reported the effects of pedaling rate on the power-duration relationship for high-intensity exercise. Their subjects included seven males who performed eight exhaustive bouts (four at 60 rpm and four at 100 rpm). Their report conclude that the power asymptote (capacity for sustained power output) at 60 rpm bout of exercise (235 ± 8W) was significantly greater than at 100 rpm (204 ± 11W). The power asymptote reflects an inherent characteristic of aerobic energy production during exercise, above which only a finite amount of work can be performed, regardless of the rate at which the work is performed. Their data demonstrates that there is a greater cardiorespiratory and blood/muscle lactate response during constant-power exercise while cycling at high versus low rpm. It also indicates that the theoretical maximum sustainable power during cycle ergometry in untrained males is greater at 60 rpm than at 100 rpm. In essence, endurance is

compromised at higher pedaling rates for untrained versus trained cyclists. Similar to this study Jones, et al., (1985) found that the fatigue index of subjects are different at different pedal rates without affecting the changes in muscle metabolites.

In summary, many exercise laboratories have addressed the question of which pedal rate is most efficient. There have been studies utilizing maximal and submaximal levels of exercise and no definite answer has emerged. Due to the differing opinions on the subject research needs to be expanded to show how the central (Q, HR, SV) and peripheral factors (a-v O_2 diff.) of VO_2 are affected by pedaling rate. Due to the difficulty of determining cardiac output during exercise it has rarely been measured. Three laboratory procedures can be used to determine cardiac output: Direct Fick method, dye dilution method, and carbon dioxide rebreathing technique. But, carbon dioxide rebreathing is the only non-invasive yet reliable means of determining cardiac output during exercise.

Techniques For Measuring Cardiac Output During Exercise

In 1870 Fick devised a formula expressing the relationship between cardiac output, oxygen consumption, and arterio-venous difference: cardiac output = oxygen consumption / arterio-venous difference. The difficulty in determining cardiac output with this theory ,directly, is that the arterio-venous

difference must be calculated from samples of arterial and venous blood. Although the arteries needed are easily located, the actual arterial puncture can be traumatic to the subject. In addition, the most accurate assessment of oxygen content in venous blood is from the right atrium, right ventricle, or pulmonary artery taken by catheterization. This is needed because if the sample is taken from a peripheral vein its oxygen content will only reflect the metabolic activity from the area it drains. The Direct Fick method is generally the standard by which other techniques are validated but its use as a laboratory technique is criticized for its invasive nature to subjects.

The second method of determining cardiac output is the indicator dye dilution method. Like the direct Fick method of determining cardiac output the indicator dye dilution involves both venous and arterial punctures, but does not require cardiac catheterization. A harmless dye is injected into the venous system of a subject where it usually binds to plasma proteins on red blood cells. Arterial blood samples are then continuously measured with a radioactive counter. The area under the dilution-concentration curve obtained by this repetitive sampling indicates the average concentration of indicator material as blood is pumped from the heart. Cardiac output would then be calculated as follows: cardiac output = quantity of dye injected / average concentration of dye in blood for duration of curve x duration of curve(McArdle, et al., 1986).

These two techniques can be more traumatic to the subject than the value of the information received. It is for that reason that the carbon dioxide rebreathing technique was established. With this method, steady state exercise is needed while the subject "rebreathes" a certain mixture of oxygen and carbon

dioxide from an anesthetic bag. This combination of gases mixes with the air in the lungs and results in an indication of venous carbon dioxide. The measurement of end tidal CO_2 represents arterial CO_2. After calculations are made from the values of carbon dioxide from the plateau technique of Collier (1950) or the extrapolation technique of Defares (1958) estimates of $PvCO_2$ are established. From this $PvCO_2$ critical measurements permit the useful estimation of the CO_2 content in the mixed venous and arterial blood. After this is known cardiac output can be calculated from equations ($Q = VCO_2$ / a-v CO_2 diff.).

Because of the many assumptions and indirect calculations made for the carbon dioxide rebreathing technique studies needed to be done to verify its validity and reliability. Comparisons of the rebreathing technique versus the dye dilution and have been performed. Ferguson, et al., (1968) showed that the validity of the rebreathing method correlated well with the dye dilution method. Also in 1968, Muiesan, et al., showed that when compared to the gold standard, the Direct Fick method, the rebreathing technique was a reliable non-invasive clinical testing device for determining cardiac output.

The consistency of carbon dioxide rebreathing as a non-invasive method to determine exercise cardiac output was investigated by Knowlton and Adams (1974). The researchers performed cardiac output studies on 15 college age volunteers from the student body. Four separate bouts of exercise were conducted on consecutive days. The first and second days the bicycle ergometer resistance was set at 600 kpm/min and the third and fourth days it was set at 900 kpm/min. Each subject rode for twelve minutes with steady state usually occurring near minute seven. $PvCO_2$ and $PaCO_2$ were calculated from

the extrapolation method and Bohr equation, respectively. The mean cardiac output for the 600 kpm/min workload was 11.1L/min for the first day, 10.9 L/min for the second day and at the heavier workload 13.7 L/min and 13.5 L/min for the third and fourth days. Their data showed a 5.5% error and and 4.2% error for variability for the 600 and 900 kpm/min, respectively. This variability compares favorably with duplicate Direct Fick determinations obtained under the same conditions. However, mean cardiac output values seem to appear low when related to oxygen consumption values at both workloads. The authors attributed this to the fact that all subjects were well-trained and at least half were experienced bicycle riders. Knowlton and Adams (1974) state that the carbon dioxide rebreathing method of determining cardiac output at steady state exercise was reliable and well correlated to the Direct Fick method. Clausen (1969) and Holmgren (1967) both showed pre- and post-training studies, that at a given level of submaximal oxygen consumption that post-training cardiac output values are lower than pre-trained. Knowing the linear relationship of cardiac output to oxygen consumption the authors pointed out that one would expect the "conservation of energy" for the central circulation to be most significant for physically trained and skilled subjects.

In 1991 Auchincloss, et al., studied the effect of the carbon dioxide rebreathing technique in terms of steady state versus progressive exercise. Two separate testing sessions were included in their data set along with data from a study done earlier. In the testing session I two men and seven women participated and in session II six men and two women participated. In the

previous study there were 18 men between the ages of 21-64 who were tested only in the steady state. Four determinations were done in the steady state for the first two sessions and averages of cardiac output and oxygen consumption were taken. For the steady state cardiac output - oxygen consumption relationship the data from the previous studies was added and relation slope was linear with a slope of 5.2. For the unsteady state the relationship was curvilinear and the comparison was much more complex. The authors results further depicted that the rebreathing method at steady state is viable, but at progressive exercise nearing maximal levels the reliability of the results diminishes.

Cardiac Output - Oxygen Uptake Relationship During Cycle Ergometry

As previously stated Auchincloss, et al., (1991) reported the steady state cardiac output - oxygen consumption relationship as linear with a slope of 5.2. Similar results come from Faulkner, Heigenhauser, and Schork (1977). In a study which included 50 normal healthy males between the ages of 17 to 71 a slope of 5.2 was also reported. This study exercised the the volunteers on a bicycle pedaling at 50 rpm for 5 min with an increase of 25 or 50 W after a rest of five minutes. The magnitude of increase was based on a previously obtained VO_{2max}. Since this study was large (n=50) differences could be ascertained

between ages and body sizes. No significant differences were observed in the intercepts or slopes of the relationship between light weight men compared to heavy men, young men compared to old men, and men with low VO_{2max} compared to men with high VO_{2max}. The results did show significance difference in cardiac output and VO_2 due to age differences, as expected.

The authors noted that assuming the relationship is not significantly different from linear, the cardiac output/kg - VO_2/kg relation may be expressed as the equation, $y = mx+b$ where y = cardiac output (ml/kg/min), $x = VO_2$ (ml/kg/min), m = slope of 5.2, and b = intercept (66 ml/kg/min). This equation could be used as a predictor of cardiac output at given levels of VO_2.

Since this study utilized submaximal exercise on a bicycle ergometer at a pedaling rate of 50 rpm, it remains to answer whether the slope of the cardiac output - VO_2 relationship change at the same submaximal level with different pedal rates?

CHAPTER III

METHODOLOGY

Introduction

In theory, oxygen uptake during submaximal cycle ergometry should not change at different pedal rates if the resistance is adjusted to elicit the same work rate. It has been well documented, though, that there are different levels of oxygen uptake for cyclists at different pedal rates even when the work rate is the same. This study was designed to determine which pedal rate (30, 60, or 90 rpm) at a work rate of 720 kpm/min elicits the most efficient means of oxygen uptake. In addition, cardiac output was measured during each exercise bout by carbon dioxide rebreathing. A description of the subjects, the experimental setting, equipment used, treatments, and treatment of data are included in this chapter.

Subjects

Eight male subjects were selected for the study. Subjects were selected from competitive cyclists (minimum of Catgeroy 3) and triathletes in the area. Six of the subjects had been competitive cyclists for at least three years, one

was a triathlete, and one was a trained cyclist not in competition. Prior to participation an informed consent was signed by each volunteer. Physical characteristics of the subjects are shown in Table 1.

Table 1: Individual anthropometric data of the subjects

Subject	Age (yr)	Height (cm)	Weight (kg)	Body Mass Index (kg/m^2)
1	23	190.5	79.5	21.9
2	47	174.0	76.3	25.2
3	17	172.7	65.0	21.8
4	21	167.6	60.0	21.4
5	33	172.7	78.5	26.3
6	35	182.9	73.5	22.0
7	21	170.2	74.7	25.8
8	26	180.3	72.3	22.2

Setting

Investigations took place at the Eastern Illinois University Human Performance Laboratory. The room temperature ranged from 23-25 degrees

Celcius with a humidity of 53-60%. As these two factors could not be altered, a large fan was used to help cool all subjects during exercise.

Experimental Design

Each subject came to the Human Performance Laboratory on one occasion only. The time of day varied due to each of the subjects schedules. Subjects signed an informed consent prior to the preliminary measurements of height and weight. A detailed explanation of the protocol was given to the subjects and questions were answered at this time. Each subject performed all three exercise bouts (30, 60, and 90 rpm) with a rest period of 15 minutes between bouts.

Prior to coming into the laboratory each subject was provided with information detailing the purpose of the study and the procedures for the investigation.

Submaximal Exercise Protocol

Each submaximal bout of exercise on the Monark 881ergometer was performed at 720 kpm/min (120 Watts) accomplished by 30 rpm at a resistance of four kiloponds (KP), 60 rpm at a resistance of two KP, and 90 rpm at a resistance of 1.33 KP. The subject was able to keep a constant pedal rate by

keeping rhythm with an electric metronome. Each subject was assigned, according to a table of random numbers, corresponding to which test would be performed first, second, and third. After correctly positioning the seat height and toe clips each subject pedaled for five minutes to be used as a warm-up period. Each bout was a maximum of seven minutes in length. During each submaximal bout HR, VO_2, Ve, VCO_2, and RR were recorded at 30 second intervals. Oxygen uptake was determined by using standard open circuit spirometry procedures. Nose clips were used and gas was collected through the Hans Rudolph three way respiratory valve with modification for carbon dioxide rebreathing technique. Inspired minute ventilation was calculated with the Rayfield Ram 9200 air flow meter. Expired gases were analyzed with the Applied Electrochemistry SA-3 oxygen Analyzer and Applied Electrochemistry CD-3A Carbon Dioxide Analyzer. The data was automatically collected and analyzed by the REP-2000 B Data Acquisition System developed by Rayfield Equipment Ltd for use with an Apple IIe microcomputer. A hard copy of oxygen consumptions, respiratory exchange ratios, VCO_2, and respiratory rates was printed every 30 seconds during the cycle ergometer test.

Heart rate was recorded every 30 seconds with the Polar Pacer heart rate monitor. All heart rate records were stored in its memory and each 30 second interval was recorded on the data sheet to note when steady state was achieved by the subject.

The subjects were declared to be at steady state when four consecutive thirty second heart rates were within ± 2 bpm. No steady states were reached prior to five minutes exercise time and none longer than seven minutes.

After steady state heart rates were noted one additional 30 second interval was measured and final HR, VO_2, VE, RER, and RR values were recorded. At this time the carbon dioxide rebreathing technique was started to indirectly determine cardiac output.

Carbon Dioxide Rebreathing Protocol

Prior to the start of exercise an anesthetic (rebreathing) bag which was connected to the Hans Rudolph valve and filled with a mixture of oxygen and carbon dioxide. The percentage (%) of carbon dioxide was set between 13.75 and 14.25. This percentage was set as a result of a pilot study done prior to the start of the research (Emmett, McClung, and Immke, unpublished data). It was found that this percentage provided a steady state CO_2 value without eliciting lightheadedness. After steady state had been reached the end tidal volume of carbon dioxide was measured. Ten consecutive end tidal volumes were recorded. The high and low values were discarded and the remaining eight values were averaged.

During the submaximal exercise bout the rebreathing bag hung below the Hans Rudolph valve with the subject breathing room air. At the point when steady state VO_2 had been reached and the final data was collected the subject was instructed to continue to pedal at the same rate. Following an exhalation the subject then pushed in a plunger on the Hans Rudolph valve which switched the breathing from open circuit to the closed circuit system containing

the 5 liter anaesthetic bag. At the same time when the plunger was pushed the computer plotted a $FeCO_2$ versus time curve. The subject continued to pedal until a plateau was obtained (typically 15 seconds) based on the technique by Collier (1950) for estimating $PvCO_2$.

Analysis of Data

Basic descriptive statistics (mean, standard deviation, etc.) were used to describe the population. A one-factor analysis of variance with repeated measures was performed on the dependent variables comparing the three pedal frequencies. The dependent variables include: heart rate, stroke volume, cardiac output, oxygen uptake (absolute and relative), respiratory rate, and arterio-venous difference. A Scheffe post-hoc analysis was to determine differences between groups. The alpha level of $p<0.05$ was used to determine significant differences.

CHAPTER IV

RESULTS

Introduction

This study was designed to evaluate the differences of efficiency for pedaling rates of 30, 60, and 90 rpm at a resistance level of 720 kpm/min. The relationship of the variables (VO_2, HR, SV, Q, a-v O_2 difference, VCO_2, RR, RER, and Ve) were compared for each of the three pedaling rates.

Subject Data

Table 2 shows the descriptive statistics for the subjects that participated in the study. Six of the subjects were competitive cyclists (Cat 3) for at least three years, one was a trained triathlete, and one subject was a trained cyclist not currently in competition. The subject pool had a variation of ages, cycling experience (though all were trained cyclists), and body surface area.

Table 2: Descriptive statistics for subject characteristics

(n=8)

	Mean	Std. Dev.	Minimum	Maximum	S. Err
Age (yr)	27.88	9.88	17	47	3.49
Height (cm)	176.36	7.61	167.6	190.5	2.69
Weight (kg)	72.47	6.74	60.0	79.5	2.38
Surface area (kg/cm^2)	23.32	2.06	21.4	26.3	0.73

Descriptive data for each pedal rate

Tables 3, 4, and 5 shows the descriptive statistics for 30, 60, and 90 rpm, respectively. Mean, standard deviation, minimum, maximum, and standard error are included for each pedal rate. All of the variables are taken for the same time period for each subject during which steady state exercise was attained. The variables were averaged for the two minute steady state exercise period.

Table 3. Cardiovascular and metabolic values from trained subjects while cycling at an absolute power level of 720 kpm/min at 30 rpm (n=8).

	Mean	Std. D.	Minimum	Maximum	Std. Err
VO_2 (L)	2.03	0.09	1.91	2.22	0.03
VO_2 (ml)	28.18	2.52	24.45	32.44	0.89
HR (bpm)	125.6	11.69	105.5	143.5	4.13
SV (ml)	125.6	11.7	110.6	144.7	4.14
Q (L/m)	15.70	1.13	14.40	17.26	0.40
a-v O_2 diff.	0.13	0.01	0.12	0.14	0.0028
VCO_2 (L/m)	1.89	0.13	1.74	2.12	0.05
RER	0.94	0.04	0.86	0.99	0.01
Ve (L/m)	42.15	3.46	38.1	48.26	1.22
RR (b/m)	25.19	3.31	20.5	31.0	1.17

Table 4. Cardiovascular and metabolic values from trained subjects while cycling at an absolute power level of 720 kpm/min at 60 rpm (n=8).

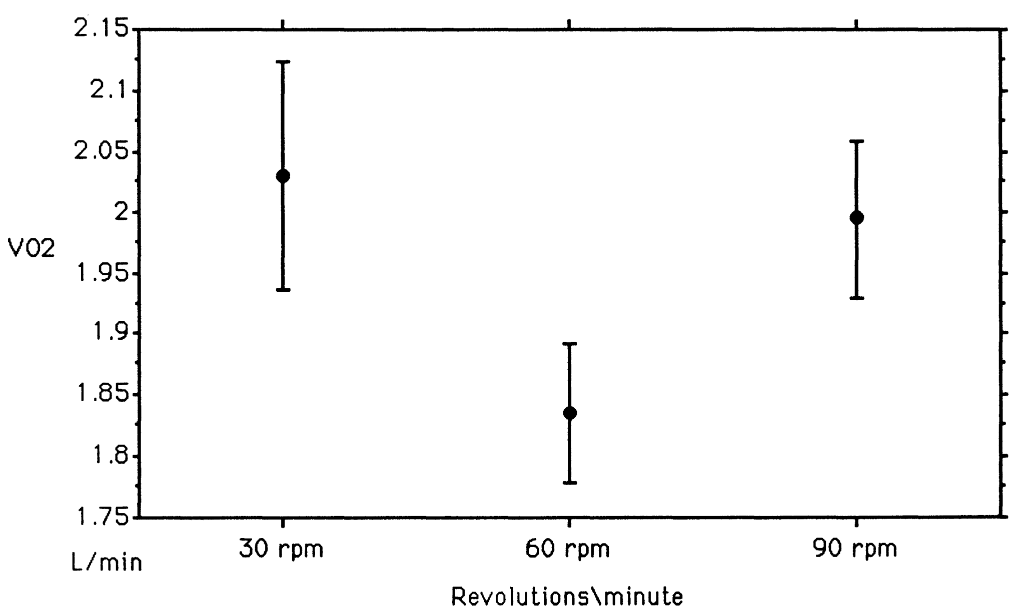
	Mean	Std. D.	Minimum	Maximum	Std. Err
VO_2 (L)	1.83	0.06	1.74	1.91	0.02
VO_2 (ml)	25.63	3.01	22.2	31.0	1.06
HR (bpm)	120.4	12.29	102	144	4.35
SV (ml)	126.27	14.92	112.5	157.2	5.28
Q (L/m)	15.09	1.15	13.46	16.67	0.41
a-v O_2 diff.	0.12	0.01	0.11	0.13	0.0026
VCO_2 (L/m)	1.74	0.07	1.6	1.82	0.02
RER	0.94	0.04	0.87	0.98	0.01
Ve (L/m)	38.08	3.69	32.38	41.89	1.30
RR (b/m)	23.59	4.6	16	30	1.63

Table 5. Cardiovascular and metabolic values from trained subjects while cycling at an absolute power level of 720 kpm/min at 90 rpm (n=8).

	Mean	Std. D.	Minimum	Maximum	Std. Err
VO_2 (L)	1.99	0.07	1.93	2.10	0.02
VO_2 (ml)	27.77	3.28	24.43	34.0	1.16
HR (bpm)	126.7	11.78	109.5	149	4.16
SV (ml)	126.2	18.84	108.82	161.29	6.66
Q (L/m)	15.83	1.22	14.47	17.66	0.43
a-v O_2 diff.	0.13	0.01	0.11	0.15	0.0041
VCO_2 (L/m)	1.96	0.17	1.73	2.24	0.06
RER	0.98	0.07	0.89	1.06	0.02
Ve (L/m)	44.19	6.78	34.68	56.85	2.40
RR (b/m)	25.44	4.69	16.5	31.0	1.66

Comparison of Oxygen Uptake

The relationship among VO_2 (L/min) at the three pedal rates. The mean values for 30, 60, and 90 rpm are 2.03, 1.83, and 1.99 (L/min), respectively. One standard deviation for each value is indicated by the bars. Statistical significance was seen between 60 rpm and both 30 and 90 rpm. No significance was seen between 30 and 90 rpm.

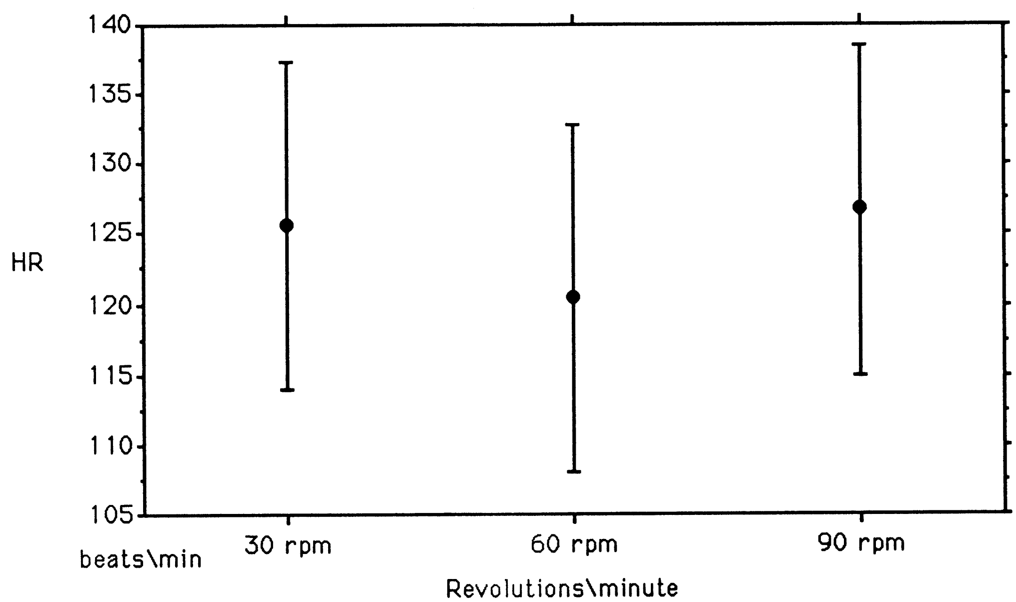


* $p < 0.05$ for 60 rpm compared to 30 rpm and 90 rpm

Figure 1. Oxygen uptake versus each of the three different exercise trials at 30, 60, and 90 rpm at a work rate of 720 kpm/min. (n=8)

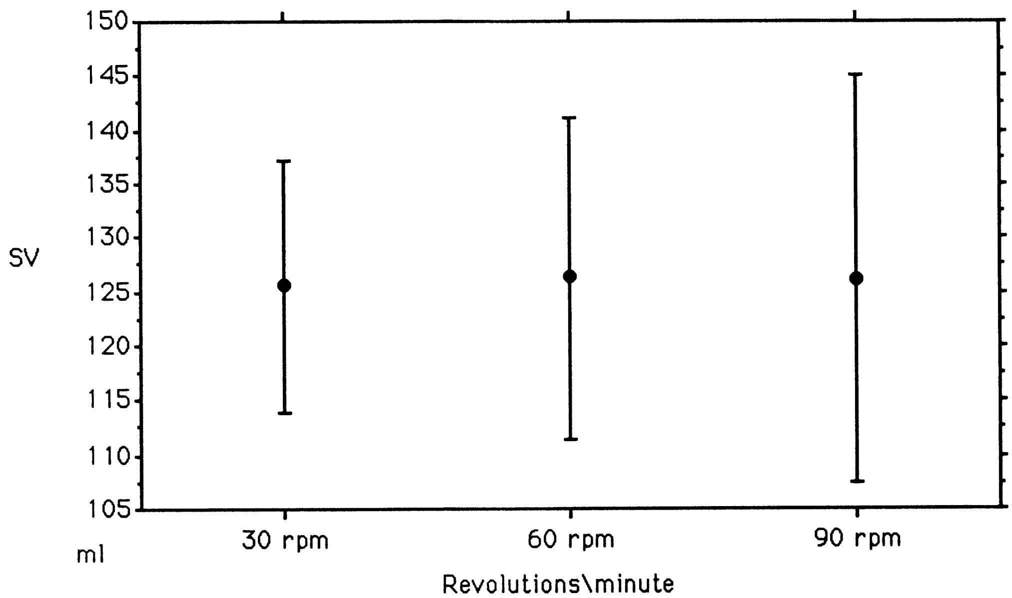
Comparison of the Central Limitations of Oxygen Uptake

The central limitation of VO_2 as affected by the differing pedal rates is depicted in figures 2, 3, and 4. Figure 2 shows the relationship of heart rate (bpm) for the three pedal rates. The mean values for 30, 60, and 90 rpm are 125.6, 120.4, and 126.7 (bpm), respectively. Figure 3 shows the relationship of stroke volume (ml) for the three pedal rates. The mean values for 30, 60, and 90 rpm were 125.6, 126.3, and 126.2 (ml), respectively. Figure 4 shows the relationship of cardiac output (L/min) for the three pedal rates. The mean values for 30, 60, and 90 rpm were 15.7, 15.09, and 15.83 (L/min), respectively. One standard deviation is indicated by the bars for each figure.



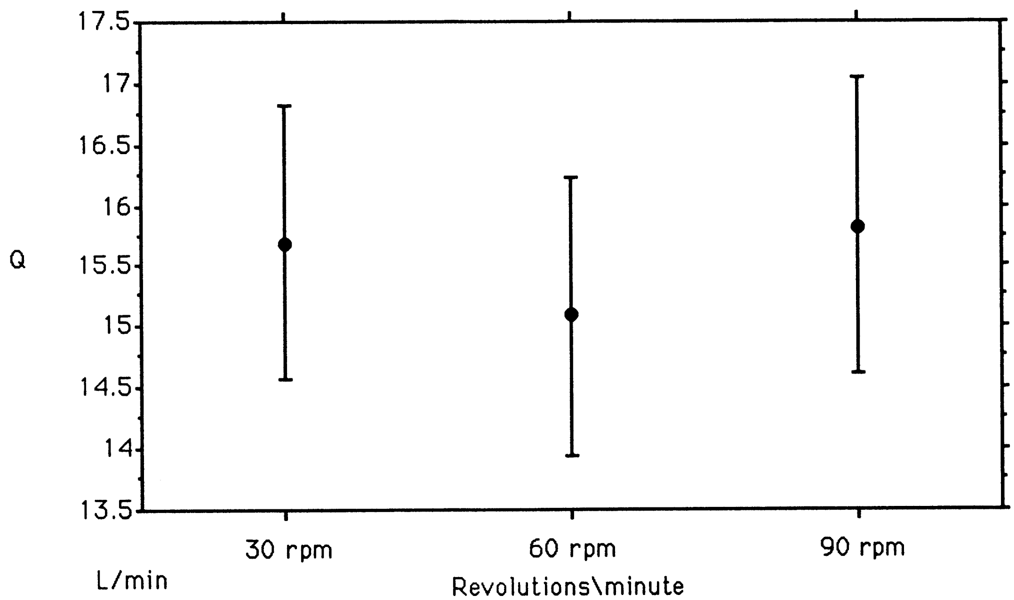
* $p < 0.05$ for 60 rpm compared to 30 rpm and 90 rpm

Figure 2. Heart rate compared between each of the three separate exercise trials at 30, 60, and 90 rpm at a work rate of 720 kpm/min. (n=8)



* No significance was seen at the p<0.05 level between exercise levels

Figure 3. Stroke volume comparison between each of the three separate exercise trials at 30, 60, and 90 rpm at a work rate of 720 kpm/min. (n=8)

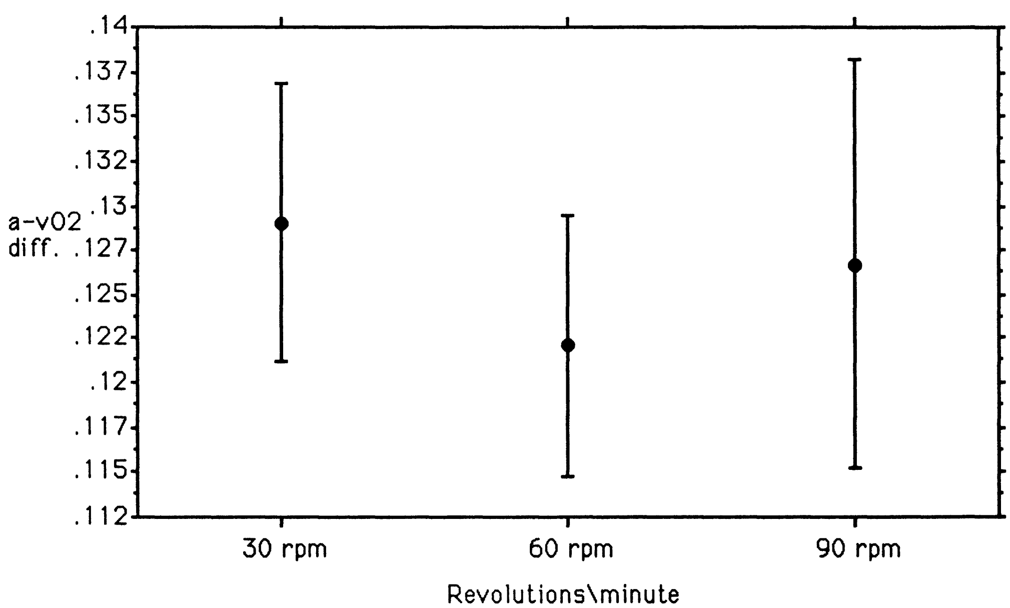


* No significance was seen at the p<0.05 level between the exercise levels

Figure 4. Cardiac output compared between each of the three separate exercise trials at 30, 60, and 90 rpm at a work rate of 720 kpm/min. (n=8)

Comparison of the Peripheral Limitation of Oxygen Uptake

Figure 5 shows the relationship of a-v O_2 difference for the three pedal frequencies. The mean values for 30, 60, and 90 rpm are .13, .12, and .13, respectively. One standard deviation is shown in the figure by the bars.

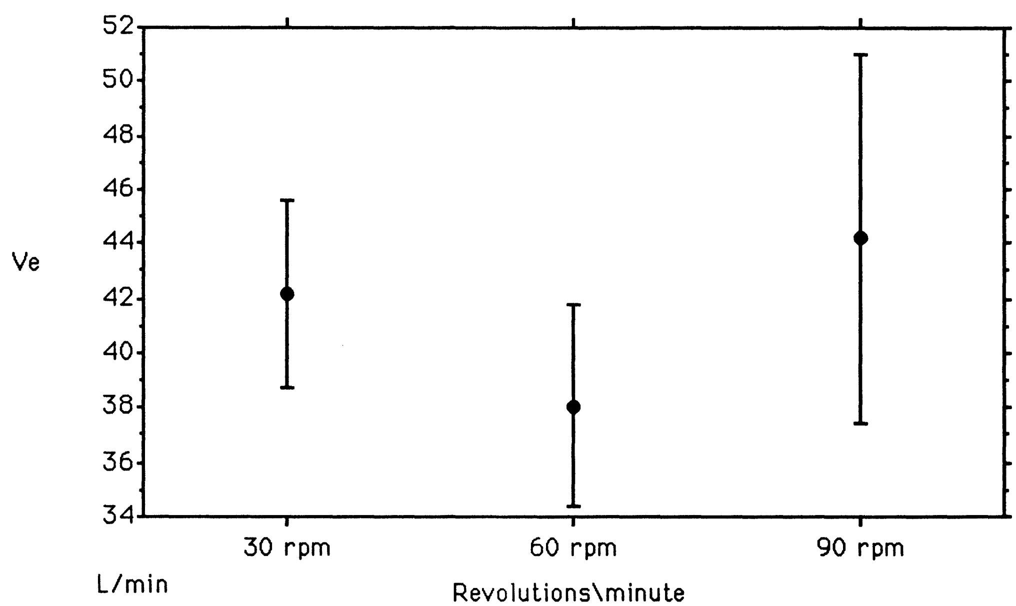


* No significance was seen at the p<0.05 level between the exercise levels

Figure 5. a-v O_2 diff. compared between each of the three separate exercise trials at 30, 60, and 90 rpm at a work rate of 720 kpm/min. (n=8)

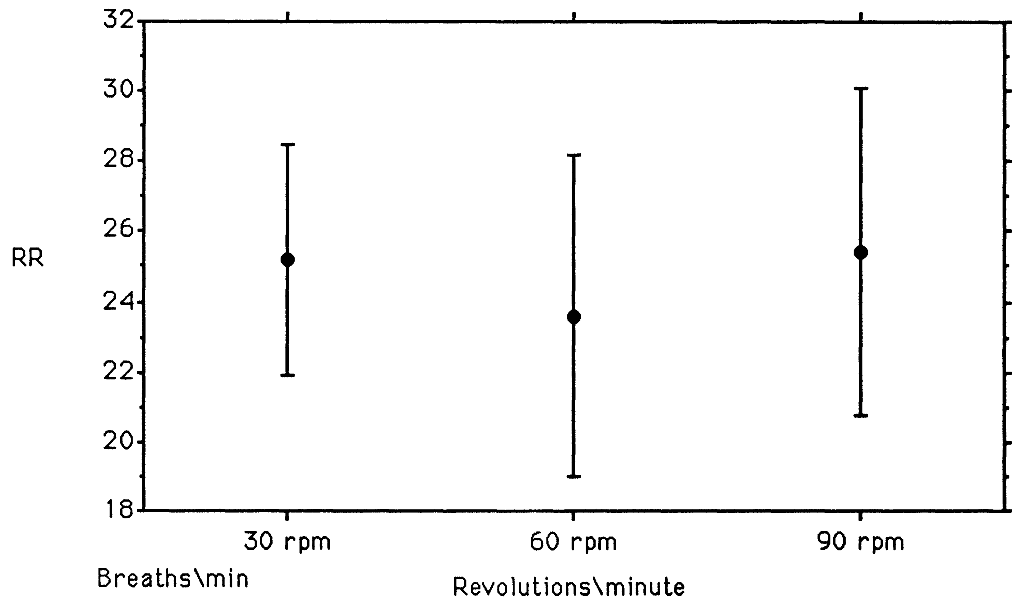
Comparison of Respiratory Function

Figures 6 and 7 show the relationship of ventilation and respiratory rate for the three pedal rates. Figure 6 shows the means for ventilation (L/min) at 30, 60, and 90 rpm to be 42.15, 38.08, and 44.19, respectively.



* p<0.05 for 60 rpm compared to 90 rpm

Figure 6. Minute ventilatory volume (L/min) compared between each of the three separate exercise trials at 30, 60, and 90 rpm at a work rate of 720 kpm/min. (n=8)



* $p<0.05$ for 60 rpm versus 90 rpm, $p<0.05$ for 30 rpm versus 90 rpm

Figure 7. Respiratory rate compared between each of the three separate exercise trials at 30, 60, and 90 rpm at a work rate of 720 kpm/min.

Figure 7 shows the means for respiratory rate (breaths/min) to be 25.19, 23.59, and 25.44 for 30, 60, and 90 rpm, respectively. Standard deviation is shown by the bars on the figure.

Statistical Analysis of Differences Between Groups

A one-way analysis of variance with repeated measures was used to determine differences between groups for the dependent variables. A post-hoc Scheffe F-test was used to determine significance at the 95% level. Table 6 shows the dependent variables along with the appropriate F-test and p value. The level of significance was set at a 95% confidence interval so any p value less than (<) .05 will show significance. Table 7 shows the results of the Scheffe post-hoc analysis for significance, if any, between each of the three groups.

Table 6. Summary of the one-factor ANOVA with repeated measures for the dependent variables. (n=8)

Variable	F	p
VO_2 (L/min)	18.662	0.0001
VO_2 (ml/kg/min)	19.168	0.0001
Q (L/min)	0.894	0.431
HR (bpm)	8.563	0.0037
SV (ml)	0.011	0.9892
a-v O_2 diff.	1.38	0.2842
Ve (L/min)	6.14	0.0121
RR (b/min)	1.25	0.317
RER	5.24	0.020
VCO_2 (L/min)	8.02	0.0048

Table 7. Scheffe F-test determination of significance

Dependent Variable	30 vs. 60	30 vs. 90	60 vs. 90
VO_2 (L/min)	16.492*	0.57	10.93*
VO_2 (ml/kg/min)	16.594*	0.419	11.739*
Q (L/min)	0.532	0.025	0.785
HR (bpm)	5.126*	0.224	7.494*
SV (ml)	0.009	0.007	0.0002
a-v O_2 diff.	1.33	0.15	0.58
Ve (L/min)	2.64	0.66	5.92*
RR (b/min)	0.79	0.02	1.06
RER	0.0013	4.05*	3.8*
VCO_2 (L/min)	3.95*	0.56	7.51*

* Significance at 95% ($p < 0.05$)

As shown by Table 7 significance was shown at the $p<0.05$ level for several dependent variables. For the 30 versus 60 rpm comparison significance was seen at VO_2 (L/min and ml/kg/min), heart rate, and VCO_2. All other variables did not meet the significance level. For the 30 versus 90 rpm comparison significance was only seen at RER variable. And finally, the 60 versus 90 rpm comparison showed significance for VO_2 (L/min and ml/kg/min), HR, Ve, RER, and VCO_2. No significant differences were seen at Q, SV, a-v 0_2 diff., or RR.

CHAPTER V

DISCUSSION, CONCLUSIONS, AND RECOMMENDATIONS

Discussion

The present study examined whether any differences would occur in oxygen consumption at three separate pedaling rates (30, 60 90 rpm) performed at a submaximal workload of 720 kpm/min. Also, this study examined whether there was a difference in the central or peripheral limitations of oxygen uptake due to the different pedal rates. Results from this study indicate that 60 rpm is the most oxygen efficient pedaling rate and there is little difference between the 30 rpm and 90 rpm pedal rates . These findings support some previous studies (Hermansen, et al. 1969; Bolonchuk, et al. 1992; Pivarnik, et al. 1988; Boning, et al. 1984; Hughes, et al. 1982) but contradicts others (McKay, et al. 1976; Hagberg, et al. 1981; Buchanan, et al., 1985; Pandolf & Noble, 1973). Due to study design differences, opinions about the most efficient pedal rates is debated. Some studies are compared although there are various fitness levels and cycling experience of the subjects. Studies have shown there were differences in VO_2 when comparing trained versus untrained individuals at different pedal rates. This study, however, tried to minimize this possibility of error by recruiting trained subjects . Other theories suggest that as submaximal levels increase towards maximal levels that the differences in oxygen consumption become less to a point of no significance (Boning, et al., 1985). Because competitive cyclists train and race at

submaximal levels a resistance setting of 720 kpm/min (120 W) was decided upon.

The oxygen uptake for the 60 rpm stage (x = 1.83 L/min) is significantly lower ($p<0.05$) than both the 30 rpm stage (x = 2.03 L/min) and the 90 rpm stage (x = 1.99 L/min). Differing results came from Buchanan, et al. (1985) who found no difference between 60 and 90 rpm at submaximal values from 0 kpm/min to 1300 kpm/min. Similar to Buchanan, et al. (1985), Pandolf and Noble (1973) noted no differences in VO_2 at power outputs of 550,775, and 1075 kpm/min when 40, 60, and 80 rpm were compared. However, Hughes, et al. (1982), presented data that is similar to the results of this study. They found that VO_2 values at 90 rpm were significantly greater than VO_2 values at 50 rpm at work rates from 300 kpm/min to 2100 kpm/min. Hughes, et al. (1982), suggested that pedaling at a faster rate causes the body to use more muscles to move the legs more rapidly and extra abdominal muscles to stabilize the trunk. In effect, the more muscles recruited increases the caloric cost and therefore results in an elevation of VO_2 at a given work load. Buchanan, et al. (1985), disagrees with this idea because no differences in their study were found between 60 and 90 rpm. However, the data presented in this study supports Hughes' suggestion.

If the theory of Hughes, et al. (1982), is accurate the difference in VO_2 between 60 and 90 rpm is explained, but, the difference in VO_2 between 30 and 60 rpm is not. Bolonchuk, et al. (1992), examined the difference between 25, 50, and 75 rpm at 50% of peak power (731 kpm/min ±149 kpm/min). The authors noted that although work and power were held constant for all three exercise bouts HR, mean VO_2, VCO_2, and VO_2/kg were significantly greater

($p<0.05$) for 25 rpm compared to 50 and 75 rpm. The anaerobic component was greater for 25 rpm (8%) than 50 rpm (4%) and 75 rpm (5%), also. The authors suggest the 25 rpm stage utilizes a greater dependence on anaerobic metabolism than the 50 and 75 rpm stages even though the anaerobic components were not significantly different because the trend is consistent with the increased VO_2 and CO_2. The data in this study follows the same pattern as the data from Bolonchuk, et al., (1992). Along with the values of VO_2 being significant for the three different stages, HR was also significantly different. Bolonchuk, et al., found that HR at 50 rpm was significantly lower than those at 25 and 75 rpm. In this study HR values were significantly different ($p<0.05$) 30 rpm (125.6 bpm), 60 rpm (120.4 bpm), and 90 rpm (126.7 bpm). The fact that HR is linearly related to VO_2 is shown in both of the studies.

As discussed earlier VO_2 is controlled by central (cardiac output) and peripheral (a-v O_2 diff.) factors. According to Pirnay, et al., (1972) "VO_2 in the muscles during general exercise seems to be limited by the carrying power of the circulatory system, ... whether this limitation is cardiac or peripheral remains to be investigated." Astrand (1952) and Taylor, Buskirk, and Henschel (1955) supported the idea that the muscles become unable to accept a supplementary blood flow. Opposing views come from Stenberg, Astrand, Ekblom, Royce, and Saltin (1967) who found while studying exercises carried out by different muscular groups, concluded that the cardiac output was the limiting factor. This study indirectly measured cardiac output by carbon dioxide rebreathing and calculated stroke volume and a-v O_2 difference. Significant differences between groups were found for VO_2 and HR but no differences were found for Q, SV, or a-v O_2 difference. The data by Stenberg, et al., (1967) found that

there was no leveling off of the peripheral factors that limit VO_2 in any of there subjects. Therefore, it was their estimation that the limitation of VO_2 by peripheral factors was hardly probable.

The VO_2 versus Q relationship was studied by Faulkner, et al., (1977). The authors reported that the VO_2-Q relationship is not significantly different from linear. This is supported by Ekblom and Hermansen (1968). Faulkner, et al., (1977) had their subjects at pedal rate of 50 rpm and plotted the change of Q compared to the rise in VO_2. The data of the present study show different VO_2 for different pedal rates without significant change of Q. But, in this study there is a trend for Q to follow the changes of VO_2 with a change in HR and not in SV. The results from this study show a trend that the linear relationship of VO_2 and Q is the result of the change in HR not in SV.

The change in VO_2 between 30 and 60 rpm seems to be due to the fact that the length of time the legs are needed to contract increases the amount of anaerobic work. The change in VO_2 between 60 and 90 rpm seems to be due to the fact that at the higher pedal rate more muscles are needed to stabilize the trunk, thus using more caloric output. For all three of the pedal rates VO_2 seems to be centrally controlled by HR (and Q) with no change in SV and not by peripheral factors (a-v O_2 diff.).

Summary

Eight male competitive cyclists were examined during steady state submaximal exercise on a cycle ergometer at three separate pedal rates. Each subject pedaled at frequencies of 30, 60, and 90 rpm at a resistance of 720 kpm/min. Variables measured included VO_2 (L/min and ml/kg/min), Q, HR, SV, a-v O_2 diff., VCO_2, RR, RER, and Ve. Previous research reports differing findings regarding which pedal rate is the most efficient in terms of VO_2. The purpose of this study was to examine the differences of VO_2 for competitive cyclists at submaximal exercise for differing rpm. Second, it was to determine if there were any central or peripheral limitations of VO_2 at submaximal exercise. Descriptive statistics and one way analysis of variance with repeated measures were used to analyze the data. Results showed that VO_2 and HR for 60 rpm was significantly different ($p<0.05$) than those for 30 and 90 rpm. Significance ($p<0.05$) was also seen for Ve, RER, and VCO_2 for 60 versus 90 rpm, and RER and VCO_2 for 30 versus 90 rpm. The results indicate that the most efficient pedaling rate at 720 kpm/min for competitive cyclists (Category 3) to be 60 rpm when compared to 30 and 90 rpm. The differences in VO_2 seem to be as a result of the longer period of time that the muscles stay contracted in the 30 rpm bout and the acquisition of more muscles to stabilize the trunk for the 90 rpm bout.

Conclusions

The findings of the study do not support the first null hypothesis that there is no difference in the VO_2 among three pedal rates at a steady state submaximal work rate of 720 kpm/min. Competitive cyclists will use less energy and thus have more endurance if 60 rpm is used rather than the popular rate of 90-100 rpm.

The findings of the study do support the second null hypothesis that there is no difference in the central or peripheral limiting factors of VO_2. Even though the VO_2 changed between the groups the cause of the change is directly related to the HR. Since all three groups changed because of the same variable there were no differences in the central or peripheral limiting factors of VO_2.

Recommendations

1. For studies similar to this VO_{2max} is recommended to show the percentage of peak effort the cyclists were exercising. The closer the percentage is to actual racing conditions the more meaningful the results will be.

2. Studies need to show at what percent of VO_{2max} cyclists compete for different races and then develop a protocol around those results. Cyclists have various types of races ranging from sprints to long endurance trials and the proper pedaling rate may be different for each of these races.

3. As with other sports competitive cyclists have varying degrees of fitness. Studies should be done to show if there are any efficiency differences when differing levels of competitive cyclists are used. The proper pedaling rate could be different for amateur versus professional cyclists.

4. Borg's Rating of Perceived Exertion should be used to determine how hard the subjects feel they are working at various work rates. It is possible that VO_2 is lower at a submaximal level for a certain pedal rate but the cyclists perceives to be working harder.

5. A larger sample size is needed to make the results of cycling studies stronger. In order for a detailed examination of the proper pedal rate to be addressed a large population is needed to verify the results.

6. Studies need to done showing how much of the total energy expenditure during cycling is a direct result of pedal rate. Most studies that have researched pedal rate have data resulting from clinical testing within a laboratory and not where training and races take place. The cyclists need to be tested in their environment when other factors are introduced, such as wind resistance.

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