To the Graduate Council:

I am submitting herewith a dissertation written by J. Richard Coast entitled "Changes in Efficiency and Exertion With Changes in Pedal Rate in Cycling." I recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Life Sciences.

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CHANGES IN EFFICIENCY AND EXERTION WITH CHANGES IN PEDAL RATE IN CYCLING

A Dissertation

Presented for the

Doctor of Philosophy

Degree

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J. Richard Coast

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ABSTRACT

This study consisted of two sets of experiments. It was designed to determine if an optimal or most efficient pedal rate in cycling exists, and if so what variables determine the optimal pedal rate. Five trained bicycle racers were used as subjects for the study. The first experiment was a series of five maximal ergometer tests at different pedal rates (40, 60, 80, 100, and 120 RPM). The subjects rode to exhaustion at progressive loads while heart rate and oxygen uptake were measured. From the tests heart rate and energy cost were interpolated for power outputs of 100, 150, 200, 250, and 300W. When compared with pedal rate, both heart rate and energy cost varied as a quadratic function at a given power output. The low point in the curve was used as the optimal pedal rate. When plotted against power output, optimal pedal rate varied linearly, i.e. as power output increased, so did optimal pedal rate. The second experiment consisted of five 30-min tests at about 85% of the subjects' maximum. The same pedal rates were used. In this experiment, energy cost, heart rate, perceived exertion, blood lactate concentration, and plasma levels of epinephrine, norepinephrine, and B-endorphin were measured. When compared across pedal rates, energy cost, heart rate, and perceived exertion all were minimal at 80 RPM at each sampling period. Blood lactate showed the same relationship with pedal rate as the preceding variables at 10-min of exercise, but not late in the test. The catecholamine values appeared to follow the same trend but not significantly. B-endorphin showed no differences.

The two experiments show that in this group of cyclists an optimal pedal rate exists, and that it shows up in measures of both stress and efficiency. It also shows that the most efficient pedal rate changes with power output. These experiments indicate that the choice of pedal rate is an important one for both researchers and bicyclists who use high power outputs. They also indicate that a need exists for a more individual type of testing for different types of subjects.

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Chapter I

INTRODUCTION

A great number of researchers in work physiology laboratories use the bicycle ergometer as a major mode of testing subjects, whether as the test itself or as a preliminary test to determine work capacity. For this reason, it is very important to design the test to both duplicate a subject's activity and to get the most accurate determination of work capacity. One important aspect of an ergometer test is the pedalling rate at which the subject rides. Many studies have examined pedal cadence as a variable in itself (11, 15, 27, 29, 38, 44, 46, 53, 61, 68, 69, 73, 74, 79, 91, 94). Most researchers pick a pedal rate of 50 or 60 RPM because that is what others before them have used (3, 4, 51, 87). On the other hand, bicycle racers normally pedal at rates of 80-100 RPM (32, 44, 46, 89, 106). They too do this just because others before them used these rates with success.

Several studies (15, 21, 28, 35, 61) have shown that mechanical efficiency decreases with increased pedal rate; so why do racers - even time trial riders whose objective is to be very steady in their pacing - try and maintain a fast cadence? Other studies (45, 73) have shown that maximal oxygen uptake (VO_2 max) is achieved on an ergometer at higher pedal rates (80-100 RPM); so why is 50 or 60 RPM still the chosen pedal rate for maximal tests?

The choice of pedal rates should not be an arbitrary one. If, as some have shown (11, 46), there is a difference of 5-10% in the energy cost of pedalling at different rates, cyclists should take the time to decide which rate is their most efficient one. Researchers too should determine which is the best pedal rate to use for a given group of subjects. At slow pedal rates with high power outputs, there may be selective recruitment of fast twitch fibers (96), thereby producing more lactate and lowering performance. There is also speculation (45) that at slow pedal rates a lot of energy may be used to overcome the inertia of the ergometer. Other problems may exist with high pedal rates.

It is my objective with this research to answer some of these questions. Is there an optimum pedal rate, one at which the rider gets the highest power output for a given energy expenditure? Is it the same for different types of work? What determines optimum pedal rate?

The study is divided into two parts. The first is an incremental maximal test at different pedal rates. I believe that this will be similar to most tests conducted in that the times at each work rate are short and the subject goes to his maximum. This should show if an optimum pedal rate exists and if it changes when work rates range from very low to very high.

The second series of experiments is a series of prolonged bouts at different pedal rates. They are somewhat nearer to what an athlete undergoes in a contest. They are designed to exhaust the subject in 20-30 minutes. While a race is hard to duplicate in the laboratory, these conditions were as near to a steady rate race as they could be designed. Measures of stress in addition to energy cost and heart rate were taken to determine if other factors influence pedalling rate.

Between the two sets of experiments I hope to answer both the researchers who usually use a relatively low pedal rate, and the cyclists who generally work at a faster cadence. I also hope to find out if the two types of tests are similar with regards to pedal rate optima.

I believe that this disparity between the experimental and real situations can be serious. With the cyclists riding one way and scientists testing them in another manner, it is quite difficult to see how a rider reacts to a real situation that might be encountered (Cyclists tend to use a fast cadence over long distances. Researchers often use slower pedal rates, short work periods, and bicycles that do not fit the rider). These tests can both provide the researchers with a more realistic situation in which to test subjects on the ergometer, and possibly help the cyclist to improve his performance by choosing a more efficient pedal rate.

Chapter II

LITERATURE REVIEW

Because of the number of variables measured during the course of this study, an exhaustive review of the literature dealing with each would be extremely long and cumbersome, both for the writer and the reader. With this in mind, an abbreviated review of the most important literature dealing with each of the variables will follow. Along with that, a more extensive treatment will be given the literature that deals specifically with previous studies of cycling and pedal frequency.

VARIABLES

Oxygen Uptake and Energy Cost of Exercise

Early researchers realized that a relationship existed between work done and the amount of heat produced. Count Rumford's experiments in which he boiled water with the heat produced by a horse-powered cannon borer were among the first to show this. It has long been known that calorimetry could be used to determine the amount of heat given off by a person doing a task. This could then be equated to the physical amount of work the person had done to obtain a measure of efficiency (6, 12, 13, 14, 110). Scoresby and Joule (90) did this when they measured how much work a horse did in a 24-hr period and how many bushels of corn and hay it ate in the same time. They came up with a value of about 20% as its efficiency. (see 15 for review of others).

Indirect calorimetry can also be used to calculate efficiency. Since the time of Zuntz (110), oxygen uptake has been linked to energy cost by the respiratory quotient. Physiologists of the late 19th and early 20th centuries determined that the amount of energy obtained from protein very seldom exceeded 15% at rest. The absolute amount of protein used remained the same during exercise as in rest, so that in exercise the relative protein usage dropped to one to two percent of the total and the respiratory quotient could safely be used without including protein (non-protein R, 5) (see 15 for review). This allows the simple conversion of oxygen uptake to energy cost with minimal error. These scientists (12) established, through the meticulous weighing of metabolic products and reactants of exercising humans, and very careful simultaneous temperature measurements, that the caloric cost of burning a given fuel to do work is absolutely related to the amount of oxygen the subject uses and carbon dioxide he produces doing that work. By relying on the values they calculated for the caloric cost of using a volume of oxygen at a given R, we can now easily determine how much energy a person uses as he works.

The methods we now use for measuring $\dot{V}O_2$ and $\dot{V}CO_2$ have been used for many years and are now well established as being accurate (4, 108). Analysing gas fractions in a volume of air enables investigators to measure VO_2 for short periods of time (one minute or less) by only collecting a small volume of expired air (88). With these measurements, it is a relatively simple matter to obtain values of efficiency during various activities.

Dickinson (27) calculated efficiency on the bicycle ergometer and obtained values of 15-23%. Garry and Wishart (38) found much the same relationship between the power output and the energy cost of producing the power. They went a step beyond that and calculated the efficiency of cycling after removing the cost of pedalling an unloaded ergometer - presumably this took out the cost of moving the legs, so that what remained was the cost of turning the crank with the load on it. This yielded higher efficiency values that increased with increased pedal rate. That was because unloaded pedalling cost was also higher at higher pedal rates. Cathcart et al. (21) used an arm ergometer to measure mechanical efficiency and also got values of 20-25%. Whipp and Wasserman (107) compared the amount of free energy from the breakdown of ATP (7 kcal/mole) with mechanical work output on an ergometer to see if the theoretical efficiency was similar to that calculated using VO_2. Their values were around 29%, which is similar to those obtained by others when subtracting the cost of unloaded cycling.

Gaesser and Brooks (35) undertook a more systematic study of efficiency when they compared different methods of calculating mechanical efficiency. They found that their most appropriate estimate of muscular efficiency, which they called delta efficiency, decreased with both increased speed of movement at a given load and with increased load at a maintained pedal cadence. Delta efficiency measures small increases in energy cost associated with equally small increases in work rate (delta work accomplished/delta energy expended x 100 = delta efficiency). They postulated that an increased recruitment of FT fibers with increased speed and/or load could be the cause of the decreased efficiency.

By the use of the above studies it can be seen that even without calculating actual values for efficiency, an estimate of the relative efficiency can be determined. If a subject performs a series of tests at equal power outputs, the test that requires the lowest $\dot{V}O_2$ to accomplish the task is the most efficient. Technically that is a measure of gross efficiency, but it is sufficient as a comparative measure with a given subject.

Lactate

Another of the variables being studied, lactate, is known to occur in the body following hard work, and is used as a relative measure of muscle metabolism and fatigue. Liljestrand and Wilsson (67) showed that lactate was found in the urine of exercising humans. Long (70) found lactate in the blood of resting man. His values were near 1.0 mM, similar to values we find in current studies. Himwich et al. (55) proposed a cycle which proceeded as follows: the muscle released lactate into the blood and the liver took it up and converted it to glucose. That was then released back into the circulatory system and used by muscle. This is better known as the Cori cycle. Himwich et al. also found that lactate was produced at rest.

Bang (8) used a series of studies to examine the blood lactate response to exercise on the bicycle ergometer. His studies indicated an initial rise in the blood lactate concentration upon onset of exercise. This was generally followed by a steady decrease over time whether the person was exercising during this time or resting. Some of his tests showed a secondary lactate peak and a few showed a lactate plateau during exercise. His overall explanation was that lactate is produced only when the tissues are working anaerobically - either at the start of exercise or during strenuous exertion. This explanation has been forwarded by many as the reason for lactate production in exercise. Bang also found that, to some extent, blood lactate concentration was determined by the level of exercise performed.

Many others have reported results which differed from those of Bang. Costill (24), using highly trained distance runners, found only a slight increase in lactate over time until the work rate exceeded that which demanded over 80% of maximum oxygen uptake. Hermansen and Stensvold (52) found much the same thing, indicating that lactate did not increase greatly until the subject reached 75-80% $\dot{V}O_2$ max. Nagle et al. (76) and Hagberg et al. (47) showed in their subjects that at about 80% $\dot{V}O_2$ max, lactate concentration increased over time. These more recent results almost all contradict those of Bang. Whether that is the result of errors in the methods of Bang, or an improvement in technique in recent years is open to speculation.

In contrast to Bang, Nagle et al. (76) and others (59, 60, 93) state that not all lactate production may be due to anaerobic work of the muscles, but may be in part because of the fact that pyruvate can be produced from glucose faster than it can be converted to acetyl Co-A and used in the Krebs cycle. Jöbsis and Duffield (59), using frog muscle and Jöbsis and Stainsby (60) studying dog muscle showed that oxygen was never limiting, indicating that instead of being formed only in response to limited oxygen, lactate is often produced because of a rapid increase in glycolysis, substantiating the hypothesis in the previous sentence.

Lactate concentration in the blood has been used for years as an indicator of muscle fatigue. For that reason, I am using lactate concentration as an objective indicator of not only the metabolic cost of a test, but also of the stress of doing a particular bout of work.

Several authors have found a differential rate of lactate formation in FT and ST fibers (98). Because of this we can expect that with differential recruitment of muscle fibers, as may be found at low pedal rates during a high power output, different levels of lactate could be found.

Perceived Exertion

Perceived exertion ratings, subjective evaluations of how a subject feels during work, can be useful tools in determining the differences between tests in a given subject. The idea was first put forth quantitatively by Weber and by Fechner independently in the mid-nineteenth century (see 9 for review). The actual rating of perceived exertion (RPE) as is used today was devised by Borg (16). He first proposed a 21-point scale from three to 19. This was changed to a 15-point scale from six to 20, with six being extremely light work or no work at all, and 20 being maximal or supramaximal work. This scale was designed to correlate with heart rate, where the heart rate divided by 10 is the perceived exertion. He calculated correlations between heart rate and RPE. The correlation coefficients were very high (r=.80) indicating that RPE can be used as a subjective measure of exertion with some relationships to physiological measures.

Others have undertaken studies to validate the work of Borg and to expand upon his work (19, 69, 75, 92). Morgan (69) showed that in normal subjects, RPE mirrored the energy cost of the work task. He also found that people who were neurotic, anxious, or depressed had different perceptions of work. Skinner et al. (92) showed that RPE was very closely related to both heart rate and percent $\dot{V}O_2$ max in both lean and obese subjects. Gamberale (37) used several different modes of work - lifting weights, pushing a wheelbarrow, and riding a cycle ergometer - to assess RPE. He also differentiated between overall RPE and perception of effort of different muscle groups. He found that overall RPE was closely related to heart rate regardless of the mode of work, but that the perception in the arms or legs varied with the work. He attributed this in part to build-up of lactate in the individual muscles.

Stamford and Noble (94) had subjects ride an ergometer at a constant power output using 40, 60, and 80 RPM pedalling rates. They found no difference in heart rate, $\dot{V}O_2$, or ventilation, but did find that RPE was highest at 40 RPM and lowest at 60 RPM. They concluded that RPE did not necessarily follow metabolic cost but that limb feedback may have had an input into the rating.

Cafarelli (19) found that at 35, 50, 65, and 80% VO_2 max, with no difference in ventilation or $\dot{V}O_2$ between 30 and 60 RPM pedal rates, RPE was always higher at 30 RPM than 60 RPM. The inference is that RPE was affected by inputs other than heart rate or $\dot{V}O_2$. He postulated a combined central and peripheral (muscle or joint receptor) input to RPE.

Robertson et al. (83, 84) used differentiated RPE values (chest and leg) in order to determine which of them had the most input into the overall RPE value. They used work on a bicycle ergometer at different pedalling frequencies as their model. RPE from the legs was taken as the localized RPE, while that from the chest was used as the central RPE. They found that each rating was higher at 40 RPM than 60 or 80 RPM, as were metabolic cost and heart rate. They also found that the overall RPE was lower than the average of the chest and leg RPE values, indicating that the central and local signals underwent some kind of weighting to form the overall RPE.

The studies cited above show that even though it is not known for sure what factors influence RPE, the rating is still a reasonably accurate measure of how a subject feels during a test. While the overall RPE may be more influenced by local inputs (muscle or joint receptors) at lower pedal rates it can still be used as a good indicator of the relative difficulty of a work task.

Catecholamines

Research involving catecholamine (CA) secretion in response to various stresses has progressed in the last quarter century from studies that could best be characterized as descriptive to the present-day investigations that quantitatively measure the response of CA to increments of work and other stresses. Among the early researchers in the area was von Euler. In his review (103) he discussed the synthesis of the catecholamines and their localization in the nervous system. In another paper (104) he described the different types of stresses and the catecholamine responses to them. Generally he said that gravitational stress and response to cold stimulated the secretion of norepinephrine; and emotional or aggressive states elicited an epinephrine response. He believed that CA analysis might lead to an objective measure of stress.

Elmadjian et al. (30) also observed various types of stress to determine the CA response. They measured CA in healthy people and psychiatric patients under varying physical and/or emotional stresses and psychiatric patients under psychotomimetic drugs. They agreed with the theory that norepinephrine was more related to physical stress while epinephrine was released as a result of passive emotional stress.

After the development of more quantitative assays for blood and urine levels of catecholamines (31, 48, 80, 100, 101, 102), numerous studies were undertaken to determine how CA levels varied with different levels of exercise. Howley et al. (58) measured urinary CA excretion at different intensities of treadmill running. They found that CA excretion correlated best with the percent of maximum oxygen uptake rather than the absolute power output at which the subject was working, although it was not a precise indicator of the level of stress when comparing subjects. They did not differentiate between epinephrine and norepinephrine.

Banister and Griffiths (10) measured plasma catecholamines at different work rates and found that both epinephrine and norepinephrine varied with work rate and $\dot{V}O_2$. This is a different result from that found by other researchers (36, 49, 50, 57, 65). Hartley et al. (49, 50) found that while norepinephrine increased with increased load, epinephrine only increased at the highest loads, or near exhaustion.

Howley (57) showed that while norepinephrine increased with load from 49-82% $\dot{V}O_2$ max, epinephrine did not vary consistently. Kindermann et al. (65) found that epinephrine increased during short term, very intense work, but did not in work that could be maintained for 50 min. Norepinephrine increased in both types of work. The latter findings are the predominant ones. This probably indicates that Banister and Griffiths did not use methods that were as quantitatively accurate as others.

These studies all indicate that norepinephrine is responsive to power output or metabolic rate. Several of them argue for an increase in epinephrine only at very high loads or near exhaustion, suggesting as von Euler (104) did that norepinephrine is more a hormone of physical stress and epinephrine of mental stress or anxiety. The studies also lead to the conclusion that CA levels in the plasma, at least those of norepinephrine, are a reasonable objective indicator of the physical stress of a bout of work.

<u>B-Endorphins</u>

Endorphin, which is a contraction of the words endogenous morphine, is just as it sounds. It is a morphine-like substance produced by the body, which binds with morphine receptors in the brain (39). The discovery of specific receptors for morphine in the brain (40) led many investigators to look for a substance produced by the body that had the properties of morphine. This was found by several groups in the mid-1970's (25, 97, 99). Terenius and Wahlstrom (97) found a factor in the cerebrospinal fluid which had the analgesic properties of morphine. They called it "morphine-like factor." Teschemacher et al. (99) found a substance in pituitary extracts that also had the analgesic properties of morphine, but they did not know its physiologic role. Cox et al. (25) reported that they, too, had found this substance in the pituitary and went about the purification of it.

At that time, two assays were being used for B-endorphin. One was a naloxone reversible bio-assay on guinea pig ileum. The other was an opiate receptor binding assay (39). Already, groups were looking at the effect of endorphins on performance. Appenzeller et al. (2) conducted a study on endurance running in which they reported a doubling of normal endorphin levels by the end of a 28-mile run at a high altitude (>1800 M). They concluded by saying that they were not sure whether this had anything to do with "runner's high" or not.

Radioimmunoassays (RIA) were soon developed to detect the presence of endorphin in tissue fluids (1, 41, 105, 109). Guilleman et al. (41) reported developing an RIA to detect endorphins at the level of 0.05 to 5ng. The assay had a high cross-reactivity to other substances, meaning that assays for B-endorphin were measuring other compounds as well as B-endorphin. Wilkes et al. (109) developed an RIA technique which has a better sensitivity to endorphin alone.

Many groups have shown that endorphins are released in response to both acute and chronic stresses (2, 17, 23, 42, 56, 64, 71, 77, 85). Rossier et al. (85) found that rats, when subjected to foot-shock stress had increased endorphin levels. Madden et al. (71) reported similar results.

The question then arose as to whether endorphin occurred under normal conditions in humans. Suda et al. (95) said that endorphin was not found in the plasma of humans under normal conditions or after vasopressin was administered. They did detect it in patients with endocrine disorders who also had elevated levels of ACTH. Nakao et al. (78) determined that, with more sensitive detection, endorphins were present in plasma of normal humans. The same group (77) also reported that endorphin levels increased with insulin-induced hypoglycemia. Akil et al. (1) also found endorphins in blood.

With the knowledge that endorphin was a normally occurring peptide in the blood, groups started to look at what happened to it with exercise. Carr et al. (20) found that in women in endurance training, the levels of endorphin increased with acute exercise, and that training enhanced the acute effect. Their endorphin concentrations ranged from 23-63 pg/ml. Colt et al. (23) found that running increased the endorphin levels in the plasma. Their values ranged from <7 to 86 pg/ml, but not all increased with exercise. Fraioli et al. (34) found also that endorphins increased with exercise, but their values were in the range of 300-1600 pg/ml.

Generally, the studies find that the endorphin concentration increases with exercise. There are some contradictory figures though. In the study by Colt et al. (23), after an easy run, over 50% of the subjects showed no change or a decrease in endorphin concentration. After a hard run, 20% of the subjects showed no increase. The values given by Fraoli et al. (34) and those by Carr et al. (20) and Colt et al. (23) differ by more than 10 fold.

Although endorphin levels in the plasma do tend to increase with stress (1, 2, 20, 23, 72), the values seem to differ tremendously; and there is as yet no clear indication as to their physiological significance in exercise or training (33). But as an indicator of stress levels, they may be useful.

BICYCLING EFFICIENCY AND PEDAL RATE

The early studies of cycling efficiency were carried out at the turn of the century by two major groups. Zuntz calculated gross efficiencies in the range of 20%, with net efficiencies (resting energy cost subtracted) around 28% (110). After 1900 the group led by F.G. Benedict was the most prolific of those calculating cycling pedalling efficiency. They used an electrically braked ergometer that they calibrated in a calorimeter - finding the energy cost of one pedal revolution by the heat given off (13, 14, 15). They found gross efficiencies in the range of 15-20% and net efficiencies around 15-25%. They made an argument for deducting either resting energy cost or no-load work energy cost from the total in order to get an efficiency value that most closely indicates the cost of doing only the mechanical work and not day-to-day body maintenance.

That group (15) further examined the efficiency of using different pedalling rates. Their subject was a professional cyclist on whom they did over 50 tests during a period of more than four months. They determined that his gross efficiency decreased with increased pedal speed. His highest efficiency was 20.6% at 70 RPM, the lowest pedal rate used. Duffield and MacDonald (28) used pedal rates of 40, 63, and

85 RPM and found efficiency to decrease with increased pedal rate. Cathcart et al. (21) found much the same thing using a hand ergometer.

In a widely cited study, Dickinson (27) used pedalling rates from about 25 to 120 RPM. She calculated maximum efficiencies of about 21%. These were obtained at 33 RPM. She was the first to show that efficiency decreased with low pedal rate as well as with increased pedal rate. On the other hand, she - like several others - used only one subject. The subject was also too short for the bicycle, which casts doubt as to the usefulness of this particular study specific to cycling.

Garry and Wishart (38) also found that the efficiency decreased at both high and low pedalling rates. Their calculated optimum cadence was 53 RPM.

Interest in pedal rate was renewed in the 1960's and 1970's, as investigators tried to determine the best ways to do maximal oxygen uptake tests (11, 53). Hess and Seusing (53) found that $\dot{V}O_2$ at a fixed power output increased with increased pedal rate. They used power outputs of only 30W at pedal rates of 30, 60, and 90 RPM. When power output was this low, it ensured that a steady state was maintained (108), but it was not very useful in performance studies. Eckermann and Millahn (29) used somewhat higher power outputs and found that heart rate and $\dot{V}O_2$ were lowest at 45-50 RPM.

Banister and Jackson (11) showed that the oxygen cost of pedalling at a power output of 360 kgm/min at 120 RPM was equivalent in energy cost to riding at 1000 kgm/min at 50-80 RPM, indicating that in their subjects 120 RPM pedalling rates were terribly inefficient. By measuring oxygen uptake or heart rate, they as well as others (29, 53) were essentially measuring gross efficiency; that is work done/energy cost x 100, with no correction for resting or no-load work metabolism.

Numerous studies have recently tried to ascertain which is the optimum pedalling rate using different variables including - but not limited to - oxygen uptake. Hagberg et al. (44, 46) tested seven national class riders who rode their own bicycles on a treadmill. The riders picked what was the most comfortable rate for them. They then rode at 20 RPM higher or lower than their preferred pedal rate. When graphed against pedal rate, $\dot{V}O_2$, $\dot{V}_E$, RPE, heart rate, and lactate were in a U-shaped curve with the low point at the preferred pedal rate. They found optimum pedal rate to be between 90 and 100 RPM. They reported the results of another study (46) that showed much the same thing, an optimum pedal rate of 91 RPM. However, graphs that they provide seem to indicate that heart rate and perceived exertion increase linearly with pedal rate, and that $\dot{V}O_2$, $\dot{V}_E$, and lactate all have low points or optima at somewhere between 20 and 40% lower pedal rates that what was preferred. These results hint that even in national class cyclists, 90 RPM may be higher than the most efficient cadence.

Jordan and Merrill (61) came to a similar conclusion when they tested five world class cyclists. They found that from 60-135 RPM at 75% $\dot{V}O_2$ max, heart rate and $\dot{V}O_2$ were the lowest at the low pedal rate and highest at the high pedal rate, and increased steadily in between.

Other studies have been undertaken that did not observe pedal rate as such, but the researchers changed pedal rate to see its influence on another variable. In looking for the factors which determine perceived exertion values, several groups have used varying pedal rate to see if movement speed may have an effect. Pandolf and Noble (79) found that RPE was lower with a higher pedal rate. Stamford and Noble (94) showed that at equivalent power outputs using different pedal rates, $\dot{V}O_2$ and heart rate were identical, but RPE was lower at 60 RPM than at 40 or 80 RPM. They believed that a combination of factors rather than just metabolic rate influenced RPE. Lollgen et al. (68, 69) in two studies examining the inputs into RPE, found that while RPE changed with pedal rate - with a low at 60 or 80 RPM - it is not reflected particularly in heart rate, $\dot{V}O_2$, $\dot{V}_E$, or several muscle metabolites. They conclude that it is a combination of the physical factors (load and speed) and physiological factors that influence RPE.

Cavanagh and Williams (22) found that the relationships of speed and force optima held not only for cycling but also in running. They varied the runners' stride length by 20% of leg length from their freely chosen stride length. This would also have the effect of varying frequency when the pace was kept constant. Their findings showed that when compared to stride length, $\dot{V}O_2$ varied in the form of a quadratic function, with a minimum which they called the optimum.

Kushmerick and Davies (66) have shown that the property of an optimum rate of movement may not be just one of whole limbs, but also of isolated muscle. They found in frog sartorius muscle that there was a speed of shortening at which the muscle broke down the most ATP and was also most efficient. Their conclusion was that the change in efficiency was mainly due to the properties of the contraction coupling of myosin and actin, and not to a differential rate of ATP splitting.

Seabury et al. (91) carried out a study in which they calculated the optimum pedal rate of cycling at increasing loads. They found that at increasing power outputs up to 200W, the optimal pedal rate increased. Above 200W the optimal rate increased, but only slightly. Their optima went from 42 RPM at 40W to 62 RPM at 327W, all still in the general range of the optima found in most other studies. As in the other studies, they also used non-cyclists.

This change of pedal rate optima with change in power output would help explain the high frequencies reported in the Hagberg studies (44, 46). That group was the only one that found pedal rate optima as high as 91 RPM. Part of their findings would seem to be influenced by the fact that most cyclists train at very high pedal rates (32) and are thus accustomed to that type of work. The subjects in the Hagberg study were also working at 330W, a very high power output. There may also have been a tendency in the Hagberg group to overestimate the optima, as discussed above.

So far, all the studies show that not all pedal rates are equivalent with respect to one or more physiological or stress measurements. Most point to an optimum pedal rate somewhere in the range of 45-80 RPM. Many of the people who found $\dot{V}O_2$ and heart rate to increase with increased pedalling rate attributed that to the fact that unloaded pedalling showed the same relationships (35, 38), i.e. it cost more just to move the legs faster. For the type of study that is interested in overall performance though, the cost of unloaded cycling is to some extent irrelevant since it also contributes to the overall cost of cycling. In other words, if a work task is more than a person can handle, it matters little to the person if that is because he cannot move that fast or because he cannot push with enough force; he still cannot do the task. The thing that matters the most in his performance is finding the combination of force and speed at which he can actually do the most work in a given amount of time. So for this kind of experimental series, gross cost of work curves and heart rate curves would probably be the most meaningful.

Conclusions

From the studies cited, an optimum pedal rate does appear to exist but there is disagreement over what the optimum is and if it changes with power output. There is also disagreement over the appropriate method of calculating efficiency. Some studies were done using gross efficiency or $\dot{V}O_2$. Others used efficiency when resting metabolic rate or no-load energy cost was subtracted from the total. Most have shown that energy cost changes with pedal rate at equivalent loads.

Various metabolic and psychological indicators have also been shown to differ among pedal rates. There seems to be a place in these studies for other indicators of stress. Norepinephrine, being an indicator of physical stress, may be an appropriate assay to perform on a group in order to see the effects of rate of movement. Epinephrine may also have a place in a series of studies as an indicator of emotional stress - "Can I even finish this test?" B-endorphin, as an indicator of pain may be as good a measure of the stress of an event as is possible to find although this is still speculation and remains to be seen. It has the possibility of integrating the physical and physiological factors as well as RPE, but without the subjective input.

Room still exists in the literature to integrate all of these factors into a study involving pedal rate. Both physiological measures of efficiency and various measures of stress can show the best pedal rate to use. By the use of these indicators, an answer to the question of the existence of optimal pedal rates and the inputs into them may be available.

CHAPTER III

STUDY ONE

INTRODUCTION

When work is done on the bicycle ergometer in the laboratory, it is assumed that 50 or 60 RPM is the best pedal rate at which to work (4, 51, 87). Many investigators have found optimum pedal rates of 30 to 60 RPM (27, 29, 53) using relatively low power outputs. Others have determined optimum pedal rates in terms of power output or efficiency in the range of 80 to 90 RPM (44, 46, 73). Still another found that optimum pedal rate varied with power output (91).

Estimates of optimum pedal rate as widely varied as these make it difficult to decide on the protocol of a maximum test as regards pedal rate. One of the objectives of this study was to see if an optimum pedal rate does indeed exist for this group of cyclists, and if so, if it stays the same through widely varied work rates.

Others have argued that the ergometer is not the best way to test cyclists (45). They seem to say that with its heavy flywheel, the forces required to overcome the inertia in pedalling may affect the measurements during cycle ergometry. In light of this, another objective of the experiments was to see if there is something built in to an ergometer that might make it less useful at very high or very low pedal rates. With this in mind, a series of tests on an ergometer was compared with a similar series of tests using a bicycle on a treadmill. These were used to show whether the energy cost curve on an ergometer closely approximated that of a bicycle: does an ergometer elicit the same physiological responses during work as a bicycle?

METHODS

For this study five male volunteers participated after having been told the nature of the experiment and its possible risks and after signing an informed consent statement that also gave these details. All subjects were experienced bicyclists with one or more seasons of racing experience. The ages of the subjects ranged from 22 to 31 yrs and the $\dot{V}O_2$ max ranged from 56 to 73 ml/min per kg. The characteristics of the subjects are shown in Table 1.

Table 1: Physical characteristics of the subjects used in the study.

Subject	Age	Weight (kg)	$\dot{V}O_2$ max (l/min)	$\dot{V}O_2$ max (ml/kg.min)	Years Racing Experience
1	28	77.7	4.32	55.6	2
2	31	70.0	4.53	64.7	3
3	24	78.2	5.37	68.7	5
4	23	73.3	5.38	73.4	1
5	22	66.0	4.40	66.7	1

The subjects each completed five progressive maximal tests on the bicycle ergometer (Monark). Each test was performed at one of five pedal rates (40, 60, 80, 100, and 120 RPM) with resistance being increased 10N every three minutes until a heart rate of 150 beats per minute was reached; then increments of 5N were used until exhaustion. We used this protocol in order to measure $\dot{V}O_2$ values during a steady rate and still avoid undue fatigue from the previous power output. Maximal values were taken as those achieved at the last power output that the subject was able to complete the full three minutes. The order of the tests was randomized to prevent an ordering effect.

The ergometer was equipped with racing style handlebars and seat, each fully adjustable to duplicate the measurements of the subject's own racing bicycle. The ergometer also had racing pedals with toe clips and straps; and the subjects used cycling shoes with cleats in order to allow for application of power to the full pedal stroke.

During the third minute at each load, the following variables were measured: heart rate, F_EO_2, F_ECO_2, and $\dot{V}_I$ or $\dot{V}_E$. Heart rate was measured using a conventional bipolar lead system attached to a cardiotachometer (Narco Biosystems BT 1200). It was then recorded as a rate by attachment to an ink writing oscillograph (Narco Biosystems DMP-4B).

Ventilation was measured with a Parkinson-Cowan dry gas meter which had been calibrated with a Collins 120-liter spirometer. O_2 uptake and CO_2 output were measured by conventional open circuit spirometry using a Koegel low resistance valve and meteorological balloons. An Applied Electrochemistry S-3A O_2 analyzer and Beckman LB-2 CO_2 analyzer were used to measure gas fractions of expired air. Both had been calibrated with known gases standardized by the Scholander technique.

Pedal rate was constantly monitored with a mechanical counter attached to a tachometer coupler on the oscillograph.

From the $\dot{V}O_2$, R, and heart rate values obtained above, an energy cost of cycling and a heart rate line were calculated for each rider at each pedal rate. The energy and heart rate cost of riding at power outputs of 100, 150, 200, 250, and 300W were taken from each of the lines. These were the values used for the subsequent calculations (see

Fig. 1 for sample graph).

One subject then did five tests in which he rode his racing bicycle on a treadmill. These tests were done at 40, 60, 80, 100, and 115 RPM. This was done in order to ascertain whether there was an inherent difference in the energy cost of riding an ergometer and riding a bicycle at the same power output and pedal rate. An energy cost of cycling line was also made from these tests.

From the cost of cycling lines, values were taken to compare the cost of riding at a given power output at one pedal rate with riding at the same power output at each other pedal rate. This was done for each power output. The value used was the average of five subjects. It was done in this manner rather than making curves for each subject since the theoretical cost of riding at the same power output is the same for each rider regardless of size (i.e. Energy cost = 300 ml O_2 + 2 ml O_2/kpm. ref 2, p. 341).

Using nonlinear regression, a curve of best fit was determined for pedal rate vs. energy cost at each power output. The point where the first derivative of the equation was equal to zero was found in order to determine the point in the curve where the slope was zero - that is, the low point in the curve or that point where the energy cost or heart rate was lowest for a given power output. These low points were considered the optimum pedal rates for the respective power output. Optimum pedal rate was then plotted against power output to determine how the two were related.

Analysis of variance for repeated measures was used to determine overall differences between costs for each pedal rate. Newman-Keuls

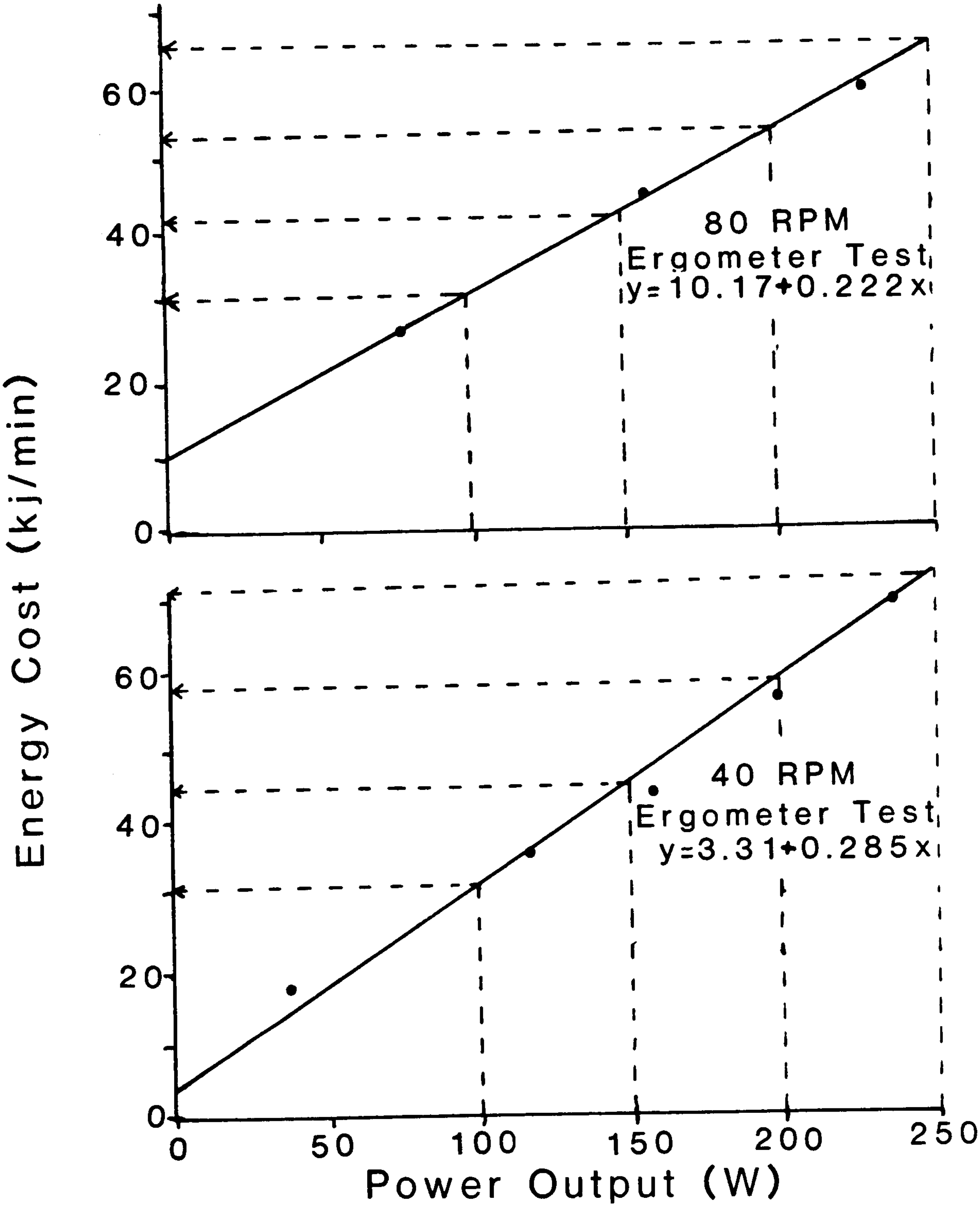

Figure 1: Sample graphs showing the cost of cycling lines computed from two of the ergometer tests. This shows how the energy cost values were interpolated for use in the remainder of the study. Each line represents one test for one subject.

Multiple-Range a posteriori tests were employed to detect which pedal rates were different. Regression analysis was used to find the equations of the lines and curves. Analysis of regression coefficients and adjusted means were used to detect differences between lines.

RESULTS

The results of the progressive tests showed that both heart rate and energy cost increased linearly with power output at each pedal rate. The correlation coefficients for either the heart rate or energy cost of cycling lines vs. power output were all above 0.95. From these lines, the energy cost and the heart rate were determined for the previously mentioned power outputs (Figure 1).

Analysis of variance showed that both energy cost and heart rate differed significantly between pedal rates at equal power outputs ($p<.001$ Tables 2,3, Appendix). Although the energy cost or heart rate at 60 RPM appears lower, there was never a significant difference between the energy cost or heart rate at 60 and 80 RPM pedal rates, as shown by the Newman-Keuls test (Appendix, Tables 4,5).

When energy cost or heart rate was plotted against pedal rate at equal power outputs, each line could be described by a quadratic equation (Fig. 2, 3). Correlation coefficients for the curves varied from 0.86 to 0.99 (Appendix, Tables 6,7).

The point at which the first derivative of the equation for each of the curves was equal to zero (the low point) was the optimum pedal rate. When it was plotted against power output the relationship appeared to be linear. When analyzed by linear regression, there did

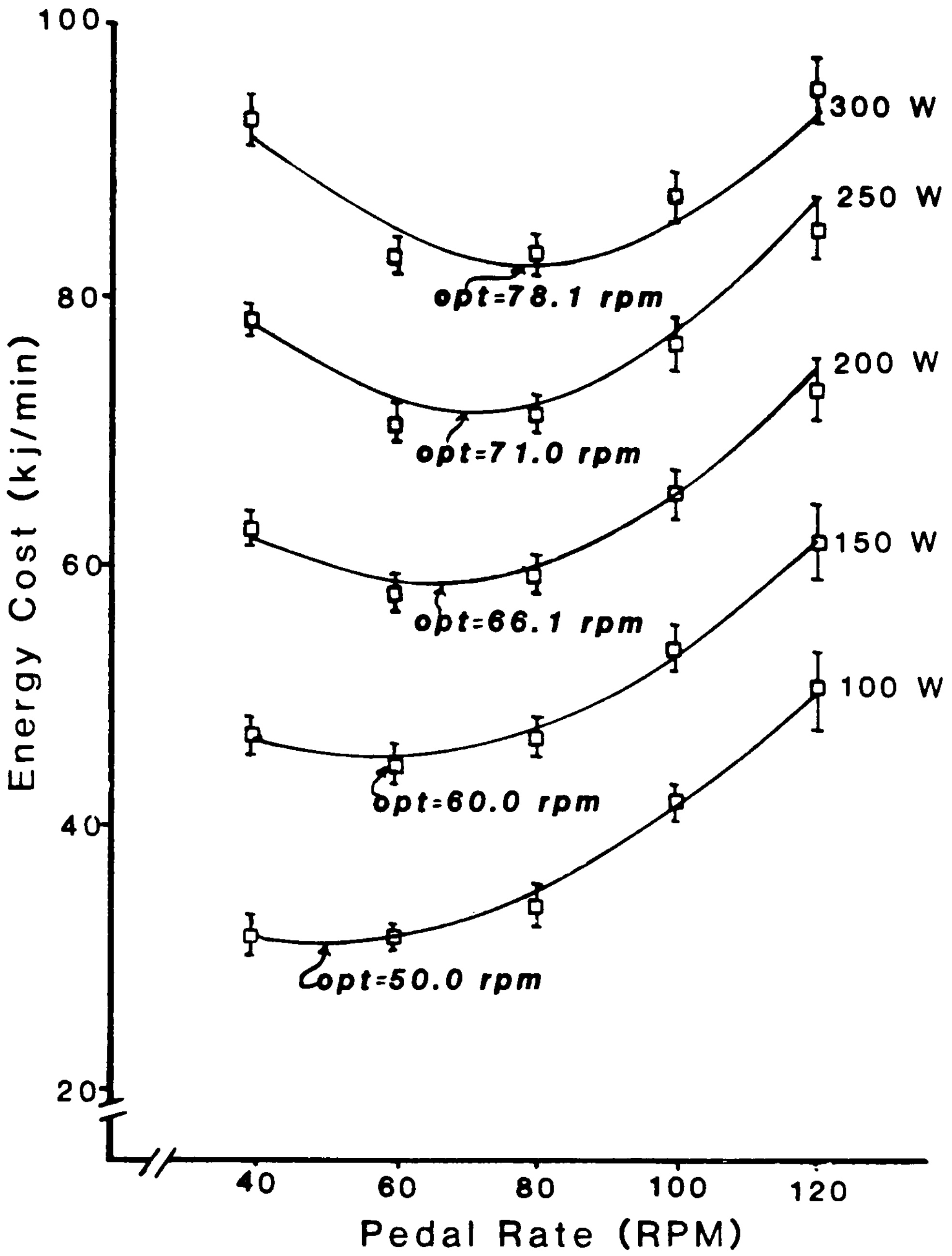

Figure 2: Graph shows energy cost plotted against pedal rate. Each line represents one power output. Points are mean ± S.E. of five values. Energy cost was different between pedal rates at each power output.

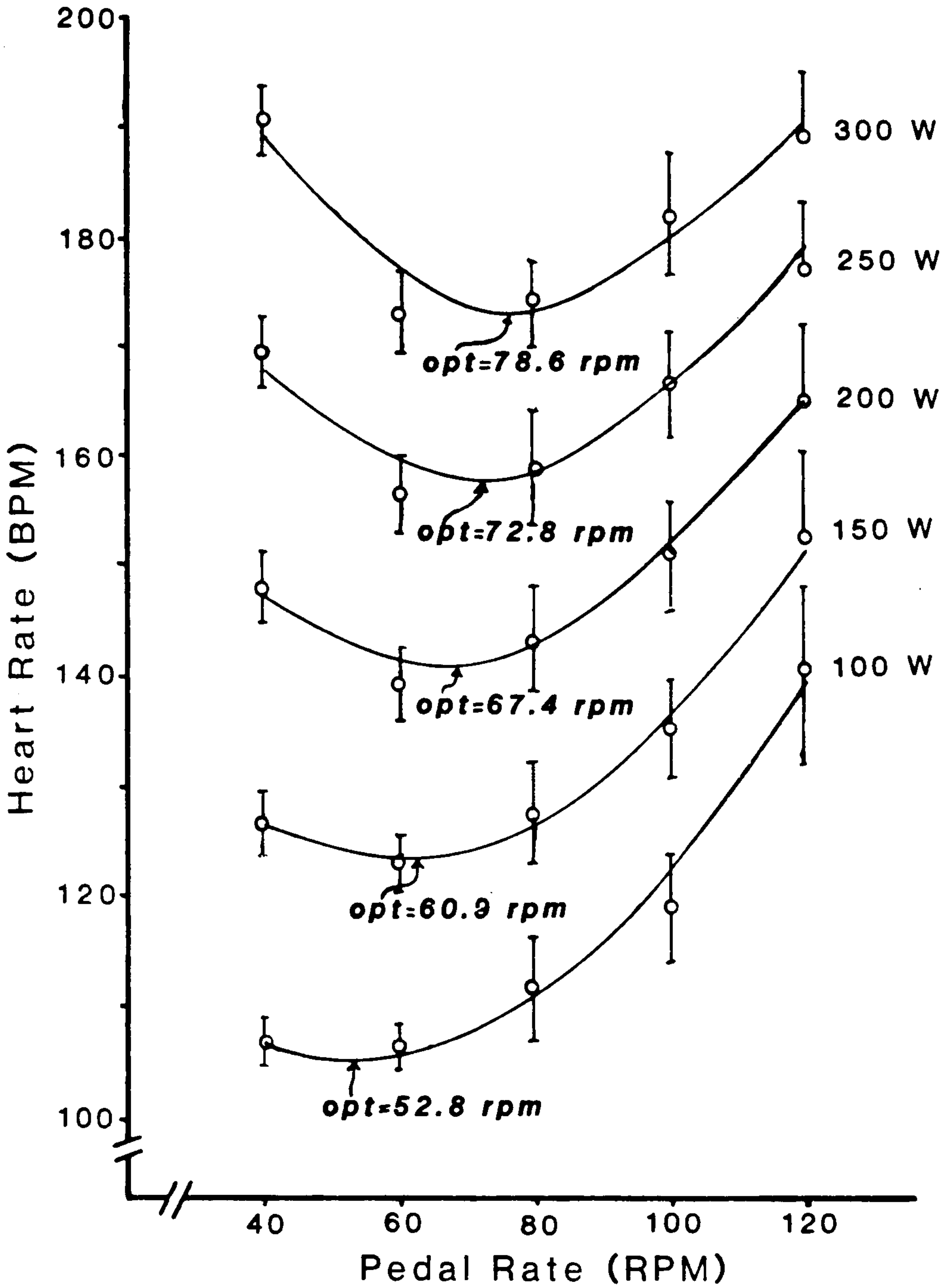

Figure 3: Graph showing heart rate plotted against pedal rate. Each line represents one power output. Each point is a mean ± S.E. of five values. Heart rate was different between pedal rates at each power output.

prove to be a linear relationship in which the optimum pedal rate increased with power output. Correlation coefficients for both lines were 0.99. Analysis of regression coefficients and adjusted means showed the two lines to be not significantly different (Fig. 4, Table 8, Appendix).

When one subject duplicated the tests by riding his bicycle on the treadmill, a high pedal rate of 115 rpm was used instead of 120 RPM due to gearing restrictions of the bicycle. Because of that the ergometer test was repeated at 115 RPM in order to make the tests the same. The energy cost of cycling lines at the various pedal rates were compared visually between riding the bicycle and the ergometer (Fig. 5). This indicates that there is a similarity in the physiological responses to the two types of test in the subject used.

DISCUSSION

As Figures 2 and 3 showed, energy cost and heart rate varied as a function of pedal rate at a given power output. That indicates - by the low point in the curve - that an optimum pedal rate exists for this type of rider. Many investigators have concluded that there are optimum pedal rates (27, 29, 38, 44, 46, 53, 73, 74, 91). Their studies disagree though, on the absolute value of the pedal rate, whether it changes or not with power output and the training state of the rider, and the method of determining optimum pedal rate.

Most of the researchers found optimum pedal frequencies of from 30 to 60 RPM (27, 29, 38, 53, 73, 74). On the other end of the scale, Hagberg and coworkers (44, 46) determined optimal pedal rates in

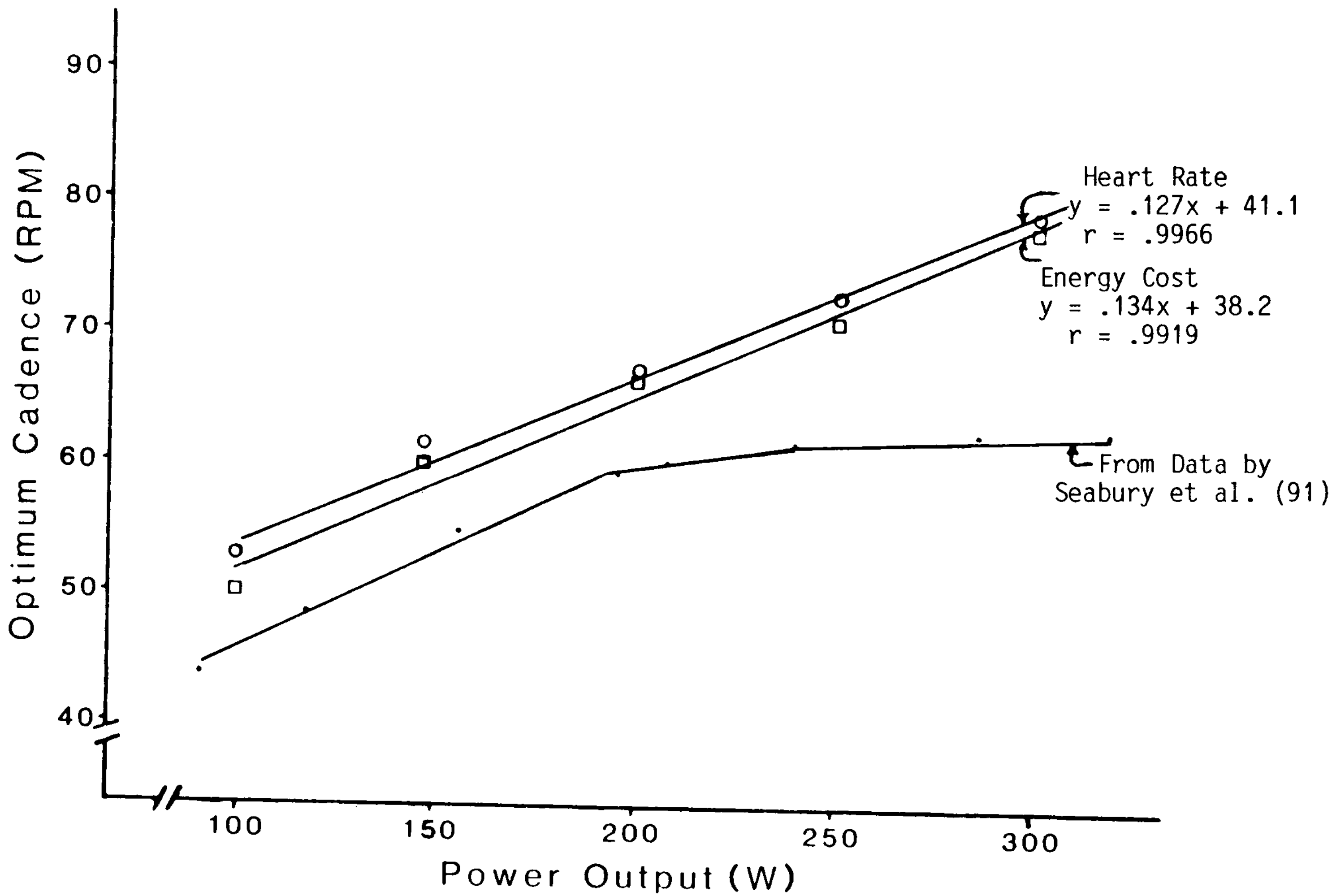

Figure 4: This graph shows the optimum pedal rate as a function of power output. The upper two curves are from data generated in this study. They are not significantly different. The lower line is from data by Seabury et al. (91) and is for comparison only.

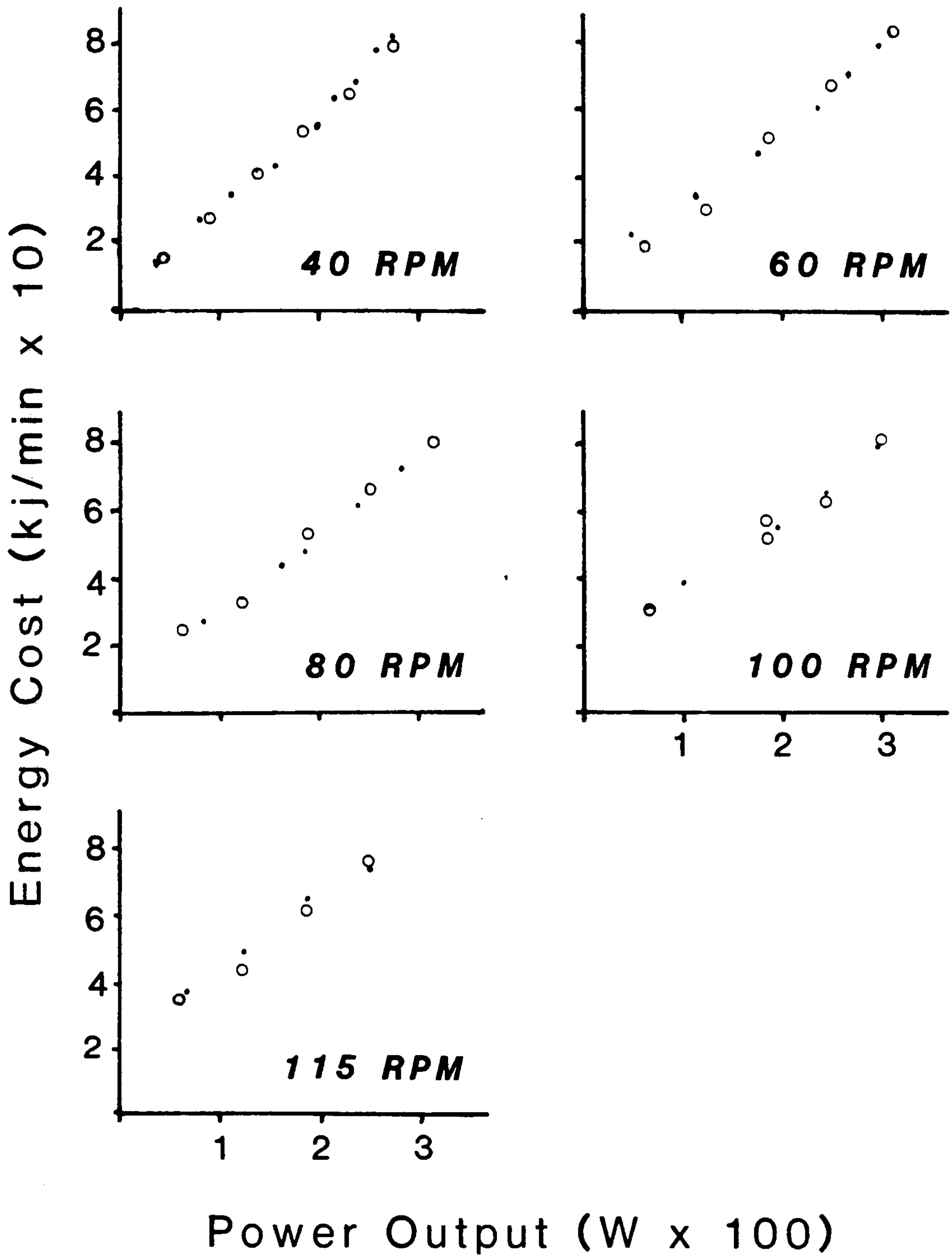

Figure 5: These graphs show the similarity between the cost of cycling lines for riding the ergometer and riding the bicycle on the treadmill. o = bicycle ergometer, • = bicycle on treadmill.

champion cyclists of about 90 RPM.

In general, the studies that found lower pedal rate optima used low power outputs. Dickinson (27) found an optimum pedal frequency of 33 RPM. However the study used only one subject who was also too short for the ergometer. According to my calculations using Dickinson's two papers (27, 28), the power output was not the same for the different pedal rates (from 17.8 to 234W) and the time of work was not identical (from 0.5 to 12.75 min). This invalidates to some extent the comparisons between tests. Hess and Seusing (53) used identical power outputs and time of exercise and estimated an optimum pedal frequency of 45 RPM. These authors used a power output of only 30W, a very low value. Although this ensures a steady state, it is not of much use in work with competitive cyclists, or in tests near $\dot{V}O_2$ max. Eckermann and Millahn (29) also determined a 45 RPM pedal rate optimum. They went as far as to say that the choice of pedal frequency should not be left to the subject becaues he will invariably pick one that is too fast. Their subjects used moderate power outputs of 100 and 150W.

In contrast with the studies cited above, Seabury et al. (91) investigated the effect of power output on optimum pedal rate. They found that the most efficient pedal rate increased from 42 RPM at 40W to 60 RPM at 327W. They were the first to show that. We have seen the same phenomenon in this study and have further shown that optimum pedal rate varies linearly with power output. That is different from the change Seabury observed. Their optimum pedal rate levelled off above a power output of 200W, only increasing by 4 RPM from 196 to 327W (see Figure 4). This may be explained by the fact that our subjects were trained at high pedal rates, and there may be a certain amount of acquired skill needed to be efficient at higher pedal rates.

Increasing pedal rate with power output is a logical phenomenon when the forces needed to perform the work are taken into account. If a rider maintained a steady 50 RPM cadence, the mean force required to push the pedals would rise from 109N at 100W to 328N at 300W. By increasing the pedal rate with power output, the average force required at 100W and 50 RPM was 109N, and at 300W and 79 RPM was 207N. That lessened the force required by the muscles by 120N. That is probably a major influence in the optimization of pedal rate.

None of my optimal rates approached those of the Hagberg group (44, 46). Their power outputs averaged about 330W, and their calculated optimum rate was 91 RPM. If plotted on the graph in Figure 4, that power output would elicit an optimum pedal rate of only 83 RPM. When I combined my data with those of Seabury et al. (91) and Hagberg et al. (44, 46) a feasible conclusion seems to be that in addition to the absolute power output, the skill of the cyclist plays a major role in the magnitude of the optimum pedal rate, i.e. the more highly skilled the cyclist, the higher the optimum pedal frequency. The cyclists used in the Hagberg study were definitely more skilled than those in the study here described.

The mode of testing may also influence the optimum pedal rate. Due to the different set-up of the bicycle on the treadmill - which the Hagberg group used (44-46) - and the ergometer with its massive flywheel, there might be a difference in the energy cost of the two tests. Only one subject in the present study was tested on the treadmill because of the possibility that a person unaccustomed to the set-up might lose balance. Having only one subject presents problems in itself, but I believed that the loss of significance in some tests was outweighed by the risk to extra riders.

When the energy cost of cycling lines for the different pedal rates on the ergometer were compared with those from cycling on the treadmill, no difference was found. These results indicate that there may be little or no inherent difference between the two testing modes, and that the ergometer comes as close to approximating the cycling experience in the laboratory as any method short of using a treadmill with a wind generator to give both the cooling effect and the wind resistance of riding outdoors.

From these experiments it is evident that not only is there an "optimum" pedal rate, but that it varies. There are probably several reasons for this variation. Two of these reasons are the absolute power output at which the riders are working and the skill of the rider. The data, although limited, indicate that on the basis of metabolic cost, riding the ergometer is very similar to riding a bicycle on a treadmill. Because of this, more testing is warranted before challenging the validity of the use of the ergometer for tests on highly trained racers.

CHAPTER IV

STUDY TWO

INTRODUCTION

Tests of efficiency on the bicycle ergometer have been conducted for many years (15, 27, 35, 44, 46). The majority of these tests have shown that the optimum or most efficient pedal rate is somewhere in the range of 40 to 60 RPM (29, 53). Another study (73) showed that from the standpoint of being able to maintain the highest power output over a period of several minutes, 80-100 RPM was the highest. Still another group of researchers (44, 46) found 90-100 RPM to be optimal for racers.

In contrast to these studies, Seabury et al. (91) found that optimum pedal rate varied with power output; higher power outputs elicit higher optimum pedal rates. The previous study supports that contention.

However, these tests have all dealt with relatively short-term exercise. The time at a given power output has been from one to six minutes. While this is an easy type of study to carry out, one cannot assume that it approximates the conditions of an exercise bout in which a cyclist will be competing.

For that reason, this experiment was designed to determine the optimum pedal rate of a group of sub-national class bicycle racers over a prolonged period of time. The cyclists rode for 20-30 minutes, about the time it takes to race ten miles. During the ride, efficiency was estimated using energy cost. As further indications of stress, heart rate, perceived exertion (RPE), blood lactate concentration, plasma catecholamines (CA), and plasma B-endorphin (B-EP) were measured.

The above are all indicators of stress of one kind or another, either metabolic, psychological, or physical. The goal of these measurements was to be able to find optimum pedal rates for prolonged work. Since prolonged tasks are the norm rather than tasks that take 1-5 min to complete, this is a more appropriate test of efficiency than are short tests. These tests should also help to see which factors are most important in the determination of optimum pedal rate. Is efficiency the only determinant of pedal rate, or is there an input dealing with comfort or pain? This type of approach to optimum rate of movement should be applicable to activities other than cycling. Any operation, whether in sports or industry, that involves moving a load for a period of time longer than just a few seconds should benefit from finding the optimum combination of speed of movement and load to get the most work from the least energy. It is also necessary to determine the best mode of testing different types of subjects in a laboratory setting, and these experiments should help in that aspect.

METHODS

For this study five trained bicycle racers were used as subjects. Each subject was informed of the nature of the study and its possible risks and benefits and signed an informed consent form which stated such. The subjects ranged in age from 22 to 31 yrs and in $\dot{V}O_2$ max from 56 to 73 ml/kg.min. Each of the subjects had at least one season of racing experience. All were familiar with the laboratory set-up from participation in other tests. Table 1 lists the physical characteristics of the subjects.

Ergometer

A Monark ergometer was used for all the tests. It had been altered to racing style by the addition of racing style handlebars and seat, each fully adjustable to duplicate the measurements of the subjects' bicyles. It was also equipped with racing pedals with toe clips and straps. All subjects wore cycling shoes with cleats in order to make them more comfortable and allow the application of power to the full pedal stroke. Fans were directed on the subjects from both front and rear.

Pedal cadence was measured by the attachment of a mechanical counter to the ergometer. This was attached to a digital readout which the rider could see and to an ink-writing oscillograph (Narco Biosystems DMP-4B) that the experimenter could monitor. A metronone was also used for those subjects who preferred it.

Test Variables

For each test, the subject reported to the lab at least four hours after eating. An indwelling catheter (Deseret Minicath 19g) was inserted into a vein in the back of the hand or forearm near the wrist. Blood samples of approximately 6-7 ml were drawn prior to the test, at 10, 20, and 30 min of exercise and 5 min after completion of the exercise bout. About 1 ml was placed in a spot plate well coated with sodium fluoride. Duplicate 50 μl samples were taken from this and placed in test tubes containing 2.0 ml of perchloric acid. These were centrifuged and the supernatent frozen for later assay for lactic acid using the method of Gutman and Wahlfield (43) as adapted by previous users in this laboratory (81, 82). Another 2.5 ml was placed in tubes containing 50 µl of a solution of 90 mg/ml EGTA and 60 mg/ml glutathione, centrifuged and the plasma frozen for assay for epinephrine and norepinephrine using the methods of Passon and Peuler (80), using COMT prepared with the method of Axelrod and Tomchick (7). This method was also adapted by others in this laboratory (81, 82). The remainder was placed in heparinized test tubes and centrifuged, and the plasma frozen for assay of B-endorphin using the B-Endorphin Assay Kit (NEN).

Heart rate was measured with a conventional bipolar lead system attached to a cardiotachometer (Narco Biosystems BT 1200). This was recorded as a rate by attachment to the ink-writing oscillograph.

Inspired ventilation was obtained by the use of a Parkinson-Cowan dry gas meter which had been calibrated with a Collins 120-liter spirometer. This was also recorded on the oscillograph.

Oxygen uptake ($\dot{V}O_2$) and carbon dioxide elimination ($\dot{V}CO_2$) were measured by conventional open circuit spirometry using a Koegel low resistance valve and meteorological balloons. The expired O_2 and CO_2 fractions were measured on an Applied Electrochemistry S-3A O_2 analyzer and a Beckman LB-2 CO_2 analyzer, which had been calibrated with known gases standardized by the Scholander technique.

Perceived exertion was taken with the Borg scale with word cues (16). The riders were asked to judge the difficulty of the task by pointing to a number on the scale. The ratings of perceived exertion

(RPE) were taken during exercise at the time of blood sampling.

Analysis of variance for repeated measures was used to detect differences in variables between pedal rates. Least square means analysis was used to determine which pedal rates were different from each other.

Test Protocol

The subjects had all performed several maximal tests before this study was begun. A load designed to elicit 85% of the subjects $\dot{V}O_2$ max was used for this test. This level was chosen to correspond to the highest power output that they could maintain for 30 minutes. Each subject performed one or two tests per week. Since they were already well trained, that was determined to be a sufficient time interval between tests to eliminate effects of previous tests upon subsequent ones.

The tests were performed at five pedal rates: 40, 60, 80, 100, and 120 RPM. Each test started with the insertion of the catheter, followed by a rest period of 10-12 minutes. The first blood sample was taken at the end of the rest period. The subject then mounted the ergometer and started to pedal at the rate chosen for that test. The load was adjusted so that it was at the test level within five minutes; at that time the half-hour test was begun. At 10, 20, and 30 min of exercise - or the end of the test (whichever came first) - blood samples and RPE values were taken as described above. Following the test the subject remained seated on the ergometer for five minutes, at the end of which the final blood sample was taken.

The order of the tests was assigned randomly by the use of a random numbers table.

RESULTS

The results that follow do not include values from the 30 min sampling period of exercise, because only one subject was able to complete all five bouts for the full 30 minutes. The rest of the subjects were able to complete only two or three of the tests. Two of the subjects did not do the 40 RPM test due to the fact that the ergometer could not be set at a high enough load to achieve 85% $\dot{V}O_2$ max for those subjects.

Energy Cost

To equate energy cost between subjects - who performed at different power outputs - we used energy cost per unit of work. This gave units of j/Nm. Since it took out the wide variation in power output, it eliminated some of the variation among subjects that would have been due to power alone.

The result obtained was a shallow "U-shaped" curve with a low point between 60 and 80 RPM (Fig.6). The energy cost was significantly different among pedal rates at both 10 and 20 min (Table 9). Least squares means showed that at 10 min, the energy cost at 120 RPM was different from both 60 and 80 RPM, with no other differences. At 20 min, both 40 and 120 RPM were higher than 60 and 80 RPM.

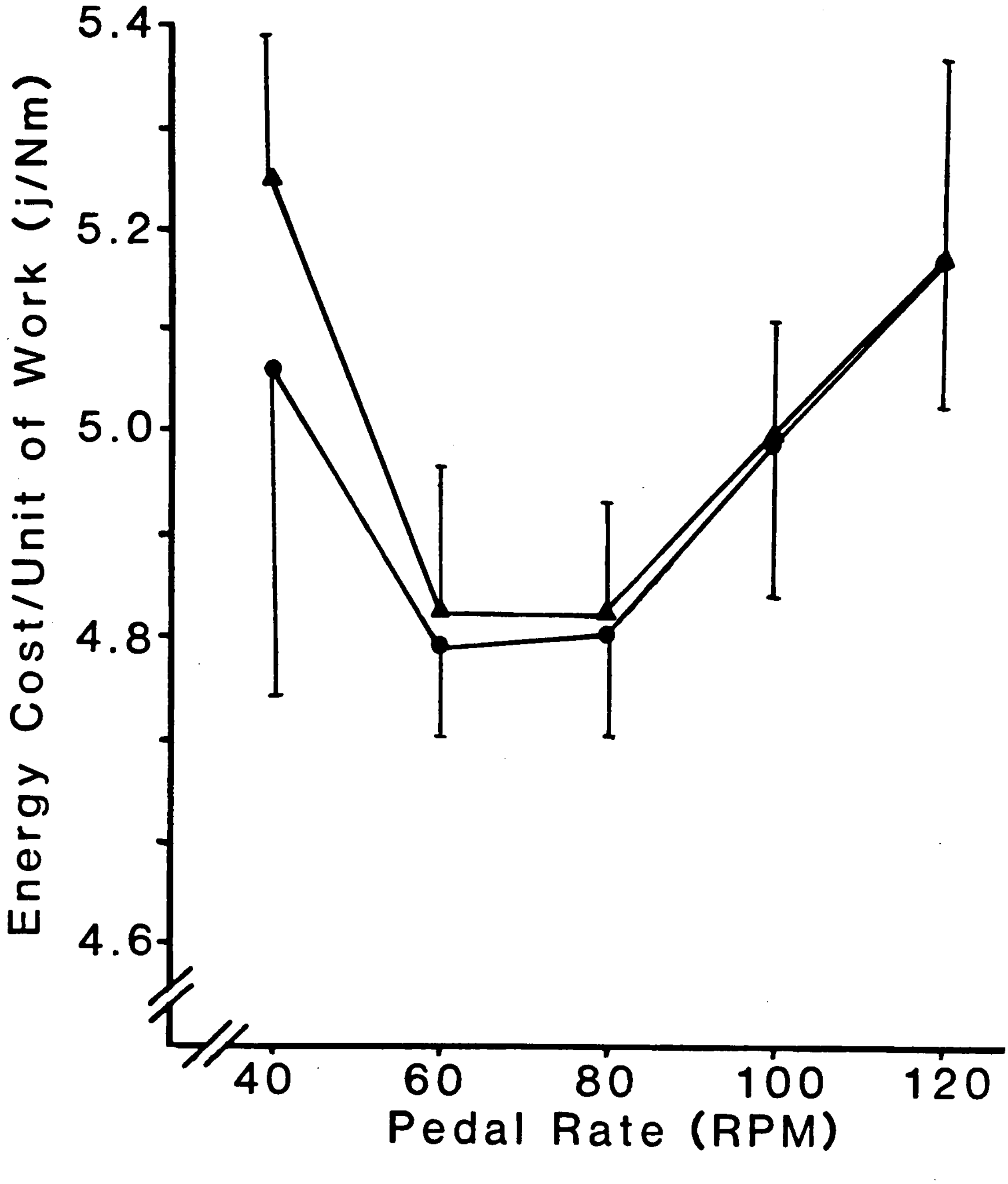

Figure 6: This graph plots the energy cost of cycling against pedal rate in a prolonged test. Values were significantly different at both 10-min and 20-min of exercise. ● = 10-min, ▲ = 20-min values. Points are mean ± S.E.

Heart Rate

As Figure 7 shows, heart rate also varied with pedal rate. The low point was at 80 RPM at both 10 and 20 min. The differences were significant ($p<.05$, Table 10, Appendix). Least squares means shows that at 10 min, the heart rate at 80 RPM was lower than all except 60 RPM. At 20 min, it was only different from 40 RPM, but was approaching a significant difference from 60 and 100 RPM ($p<.1$).

Perceived Exertion

At both 10 and 20 min, RPE also showed a significant variation among pedal rates ($p<.05$, Table 11, Appendix). As Figure 8 shows, the subjects felt 80 RPM to be the least stressful and 40 and 120 RPM to be the most difficult. At 10 min, 120 RPM was different from 60, 80, and 100 RPM and 40 and 80 RPM differed. At 20 min, 80 RPM was lower than all four other pedal rates. 40 RPM was also more difficult than 100 RPM.

Lactic Acid

The differences in the levels of plasma lactate among pedal rates were significant at 10 min ($p<.005$), but not at 20 min ($p>.1$) (Figure 9, Appendix Table 12). At 10 min, the subjects had a higher lactate concentration at 120 RPM than at the other pedal rates ($p<.05$), but no other differences appeared in the use of least square means. At 20 min, 80 RPM lactate was lower than 40 or 60 RPM, but the overall difference was not significant. The values at 5 min recovery were nearly significant ($.05<p<.1$), and least square means analysis showed

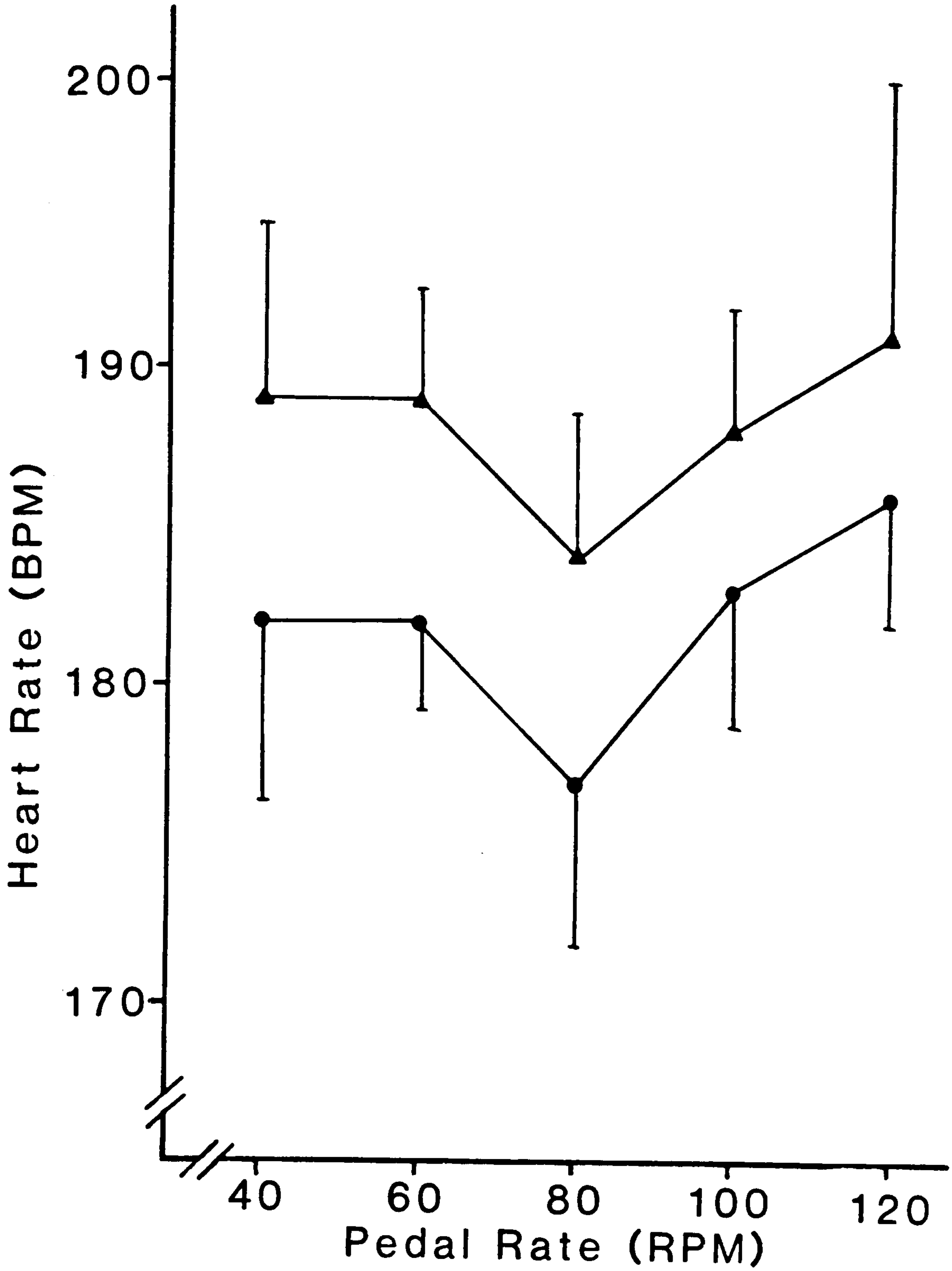

Figure 7: Graph shows the relationship between heart rate and pedal rate in a prolonged test. Differences in heart rate between pedal rates were significant at both 10-min and 20-min of exercise. ● = 10-min, ▲ = 20-min values. Points are mean ± S.E.

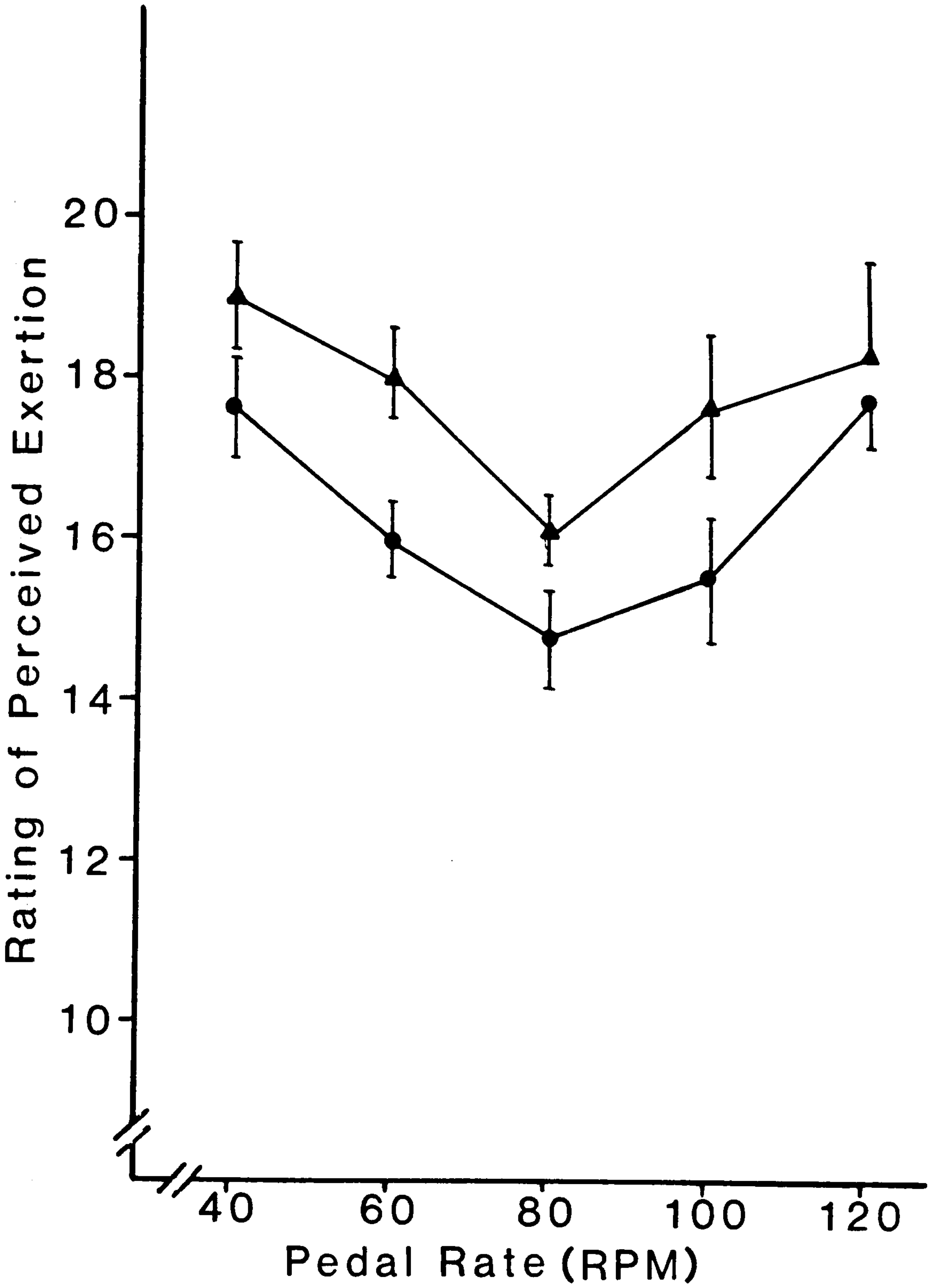

Figure 8: Graph of the relationship between RPE and pedal rate in a prolonged test. Differences were significant between pedal rates at both 10-min and 20-min of exercise. ● =10-min, ▲ = 20-min values. Points are mean ± S.E.

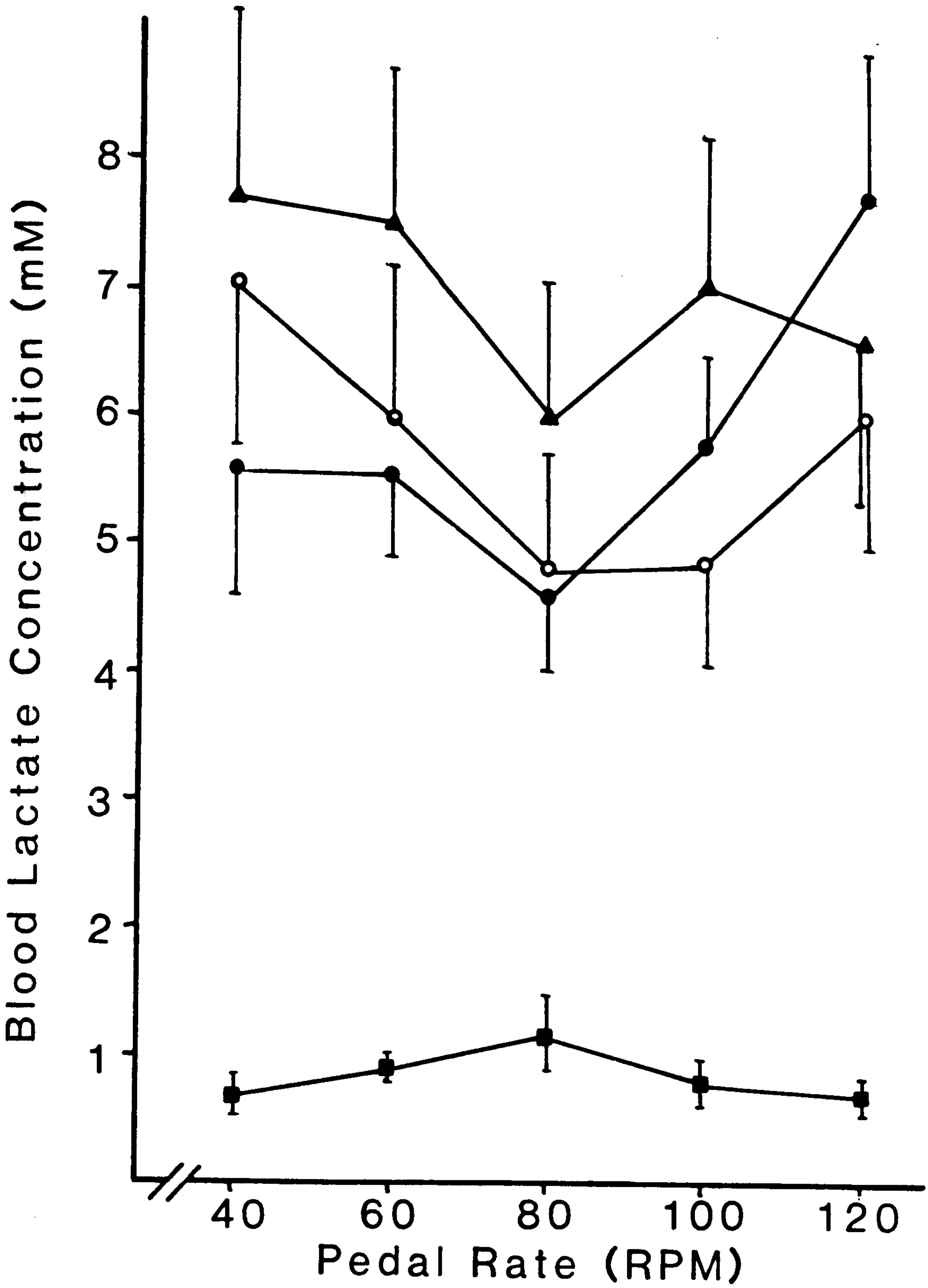

Figure 9: Graph showing the relationship, at various times in a prolonged ergometer test, between blood lactate levels and pedal rate. Significant differences were found only at 10-min of exercise. ■ = rest, ● = 10-min of exercise, ▲ = 20-min of exercise, and o = 5-min of recovery values. Points are mean ± S.E.

that 80 and 100 RPM lactate concentrations were lower than the other values.

Catecholamines

The overall differences in epinephrine and norepinephrine between pedal rates were not significant at either 10 or 20 min of exercise or in recovery. There seemed to be a trend towards differences between pedal rates (Figures 10, 11), but they were not significant (Appendix, Tables 13,14).

B-Endorphin

The results of the B-endorphin assay were inconclusive at best. Plasma concentration of endorphin ranged from 0.5 to 10.4 pg/ml at rest and from 0-15 pg/ml with exercise. Not only was the range as broad as mentioned, but the direction was not always consistent. Some of the tests had the low point at rest and some had a minimum B-endorphin concentration during exercise. This varied from subject to subject and from test to test in the same subject. No further statistics were then done of the results of the endorphin assays.

DISCUSSION

As the results show, several indicators point to a pedal rate of 60-80 RPM as being the most efficient for sustained work in this group of cyclists. Several authors have advocated the existence of an optimum pedalling frequency (27, 38, 44, 46, 91), but none have used work periods of this length with high power outputs. They have also disagreed as to which is the optimal cadence.

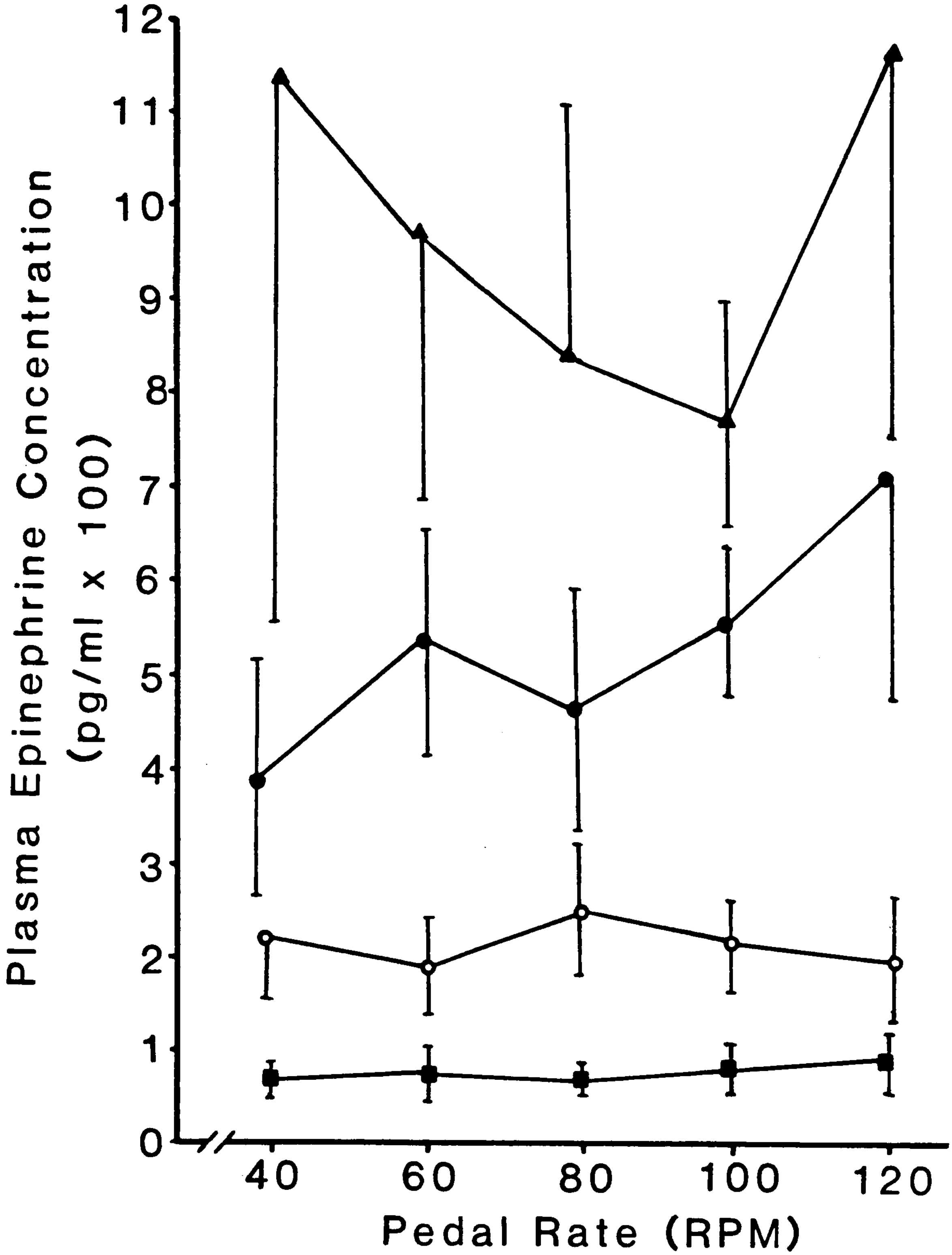

Figure 10: Plot of epinephrine concentration against pedal rate in a prolonged ergometer test. No significant differences were found in any time period. ■ = rest, ● = 10-min exercise, ▲ = 20-min of exercise, and ○ = 5-min recovery values. Points are mean ± S.E.

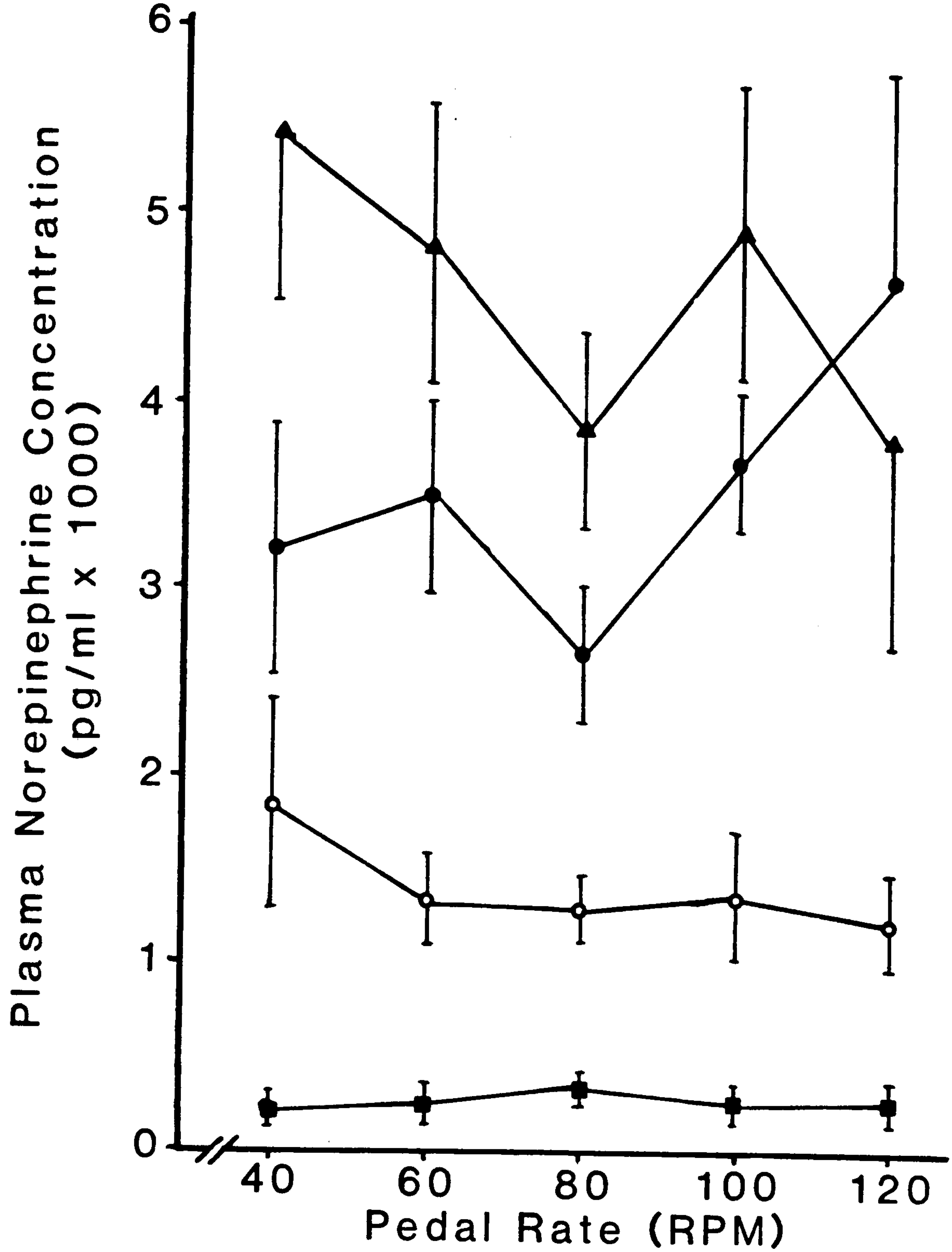

Figure 11: Graph of norepinephrine concentration vs. pedal rate at various times in a prolonged ergometer test. No significant differences were found at any time period. ■ = rest, ● = 10-min exercise, ▲ = 20-min exercise, and ○ = 5-min recovery values. Points are mean ± S.E.

By the use of energy cost (or $\dot{V}O_2$) and/or heart rate, a number of authors have shown that the optimal or most efficient pedal rate is between 30 and 50 RPM (27, 29, 53). In general, these authors used untrained subjects or non-cyclists (27, 29), or the power outputs of the tests were very low - less than 150W (53). Among the authors who used higher power outputs, or a wide range of work rates, the optimal pedal rates tend to be higher. Hagberg et al. (44, 46) used racing cyclists and determined that 91 RPM was optimum. The average power requirement for the tests they did was 330W. Seabury et al. (91) found that the most efficient pedal rate changed with power output, ranging from 42 RPM at 40W to 62 RPM at 327W. A previous study in this laboratory also showed that optimum pedalling rate varied with power output from 50 RPM at 100W to 78 RPM at 300W in trained cyclists. My curve of energy cost vs. pedal rate for this study follows the studies cited above. With the optimal pedal rate at around 70 RPM at work loads that averaged slightly less than 300W, there is a resemblance to the other studies that used high power outputs.

There is also evidence for a most efficient rate of movement in isolated muscle. Kushmerick and Davies (66) found that isolated frog sartorius muscle was most efficient at 2 cm/sec speed of shortening. While it is very difficult to compare isolated frog muscle to intact limbs quantitatively; that study points to the importance of considering the properties of the muscle itself in determining optimum pedal rate in addition to other inputs.

Along with the "U"-shaped curves for the metabolic cost of cycling at different pedalling rates, I found a similar curve for the lactate response across pedal rate. The power output used for these tests was very high, averaging 86% $\dot{V}O_2$ max at the optimum pedal rate. At this fraction of maximum, one would expect to find a rather high lactate concentration in the plasma (62, 63, 86), and indeed that is what was found. In addition, increases above 86% max would be expected to further increase the plasma levels of lactic acid. At the least efficient pedal rate (40 or 120 RPM depending on the subject) the $\dot{V}O_2$ averaged 92% of maximum. This would elicit an even greater lactate response and generally cause lactate to follow energy cost when compared across pedal rates.

Hagberg et al. (46) argue for decreased blood flow to the legs at low pedal rates as being part of the cause for increased lactate build-up. This might limit O_2 availability to the muscle and thus cause more lactate to be produced. It would also slow down the wash-out of lactate from the muscle. This in itself, though, would not cause an increased $\dot{V}O_2$, but the properties discussed by Kushmerick and Davies (66) help to explain the increased energy cost. Hagberg goes on to say that at higher pedal rates blood flow restrictions are not the problem, but that the increased $\dot{V}O_2$ might be caused by the increased work of the muscles that stabilize the trunk during cycling at high pedal rates.

The work of Suzuki (96) shows that in subjects with a higher percent of slow twitch muscle fibers, the delta efficiency decreases with increased pedal rate (100 RPM). He also showed that persons with a high percent of fast twitch fibers had approximately the same efficiency as those with slow twitch at lower pedal rates (60 RPM).

Since racing cyclists lie about in the middle with respect to percent slow twitch fibers (50-57% ST) (18) one might hypothesize that in a prolonged bout of exercise at a high pedal rate, during which mostly ST fibers are working, the $\dot{V}O_2$ would increase with or without the increased work of the supportive muscles of the trunk, solely because of the lesser efficiency of ST fibers at high speeds. The increase in $\dot{V}O_2$ at higher pedal rates might in turn cause an increase in lactate build-up in the blood simply because the subject is working nearer maximum. At lower pedal rates with high force production, FT fibers would be recruited. That could be the cause for increased plasma lactate at the lower frequencies.

In variables designed to measure stress or exertion rather than simply metabolic cost, the curves appeared to be of a similar nature to those just discussed. Perceived exertion was at a minimum at 80 RPM and increased with either higher or lower pedal rate. Stamford and Noble (94), although they did not find metabolic differences between pedal rates, saw different RPE values with changes in frequency. This led them to believe that limb receptors were influencing RPE. Pandolf and Noble (79) hypothesized from their data that sensations in the muscles, joints, and tendons were important in determining perceived exertion. Cafarelli (19) believed that both central and peripheral factors combined in their input to RPE values. Since there were significant differences in heart rate and energy cost among pedal rates in our data, those central inputs could be a major determinant of RPE in our case. However, at power outputs of 300W at 40 RPM, the average force the leg has to generate is 409N. This may well be enough to cause input from the Golgi tendon organs or muscle spindles into an RPE value (another idea that remains to be tested). Although the force required to drive the pedals at 120 RPM is quite low (91N), the proprioceptor inputs at speeds of movement that fast could also affect RPE. This is also a question that needs to be examined in greater detail.

The case for catecholamine changes with different pedal rates is not as clear as with the other metabolic factors. Many investigators have said that norepinephrine is a hormone of physical stress where epinephrine is more of a hormone of emotional stress (65, 104). With no overall differences in the concentrations of epinephrine or norepinephrine between pedal rates one could say that the stresses were not different. However, from visual inspection,the general outcome is that 80 RPM has lower values than 40 and 120 RPM. Howley (57) has shown norepinephrine concentration to be associated with work intensity. Since $\dot{V}O_2$, both absolute and as a percent of maximum, was higher at the extreme pedal rates, this would not be an unusual finding. In fact it may be seen as somewhat unusual that norepinephrine values were not different in light of the fact that the energy cost was different between pedal rates.

Epinephrine on the other hand has been shown to be related to variables including and other than work intensity. Howley (57) showed that epinephrine excretion was not related to the physical intensity of the task. Kindermann et al. (65) showed that epinephrine increases drastically in short term intense work but not long term. Hickson et al. (54) showed that epinephrine is not as affected by long term as short term work. Hartley et al. (49, 50) found that epinephrine was not greatly increased until exhaustion. All tend to indicate that epinephrine is not increased until emotions are excited, as at the end of a test or in an exceptionally strenuous test when the subject may even doubt that he can complete the bout. My results support the previous knowledge. The difference at 20 min between 40 and 80 RPM epinephrine levels may indicate that the subjects felt more stressed at 40 RPM, even to the point of believing that they could not complete the test. This extra stress was also indicated by a higher RPE value.

The results of the endorphin analysis showed little or nothing. In some subjects the resting values were highest and values during exercise were lower; others showed higher values in exercise or recovery. This conflicts with results from other studies (2, 17, 23, 34) that generally found plasma B-endorphin concentration to increase with prolonged work. The tests for this substance still seem to be somewhat erratic in their quantitative results. Appenzeller et al. (2) measured levels of 116 pg/ml before and 200 pg/ml after a run that took four to seven hours to complete. Colt et al. (23) had values that ranged from 8.2-11.8 pg/ml before runs to 17.6 or 28.0 pg/ml after an easy or a hard run respectively. The results of the studies cited above differed by ten-fold in their estimation of endorphin levels. They also used exercise of a longer duration than in the current series of experiments, which could account for our lack of a response. Results of the Colt study (23) indicate that during the runs, less pronounced changes were seen in the well trained than in the less trained runners. This, while contradictory to some studies (2, 17, 34) may help to explain why our well trained cyclists showed no response.

The series of tests performed show that an optimum pedal rate exists for this type of rider. Whether it is strictly a metabolic response which spills over to measures of stress, or a mechanical property of the muscles and joints (i.e. the muscles have to work harder to overcome their own inertia at extreme pedal rates) remains to be shown. An optimum combination of frequency and resistance has been shown to be true in running (22), and optimum speed of contraction has been seen in isolated frog muscle; therefore we should not dismiss this as a phenomenon peculiar to the bicycle or the ergometer, but possibly to many tasks, and even to muscle itself. By picking the wrong combination of speed and load one can either require himself to expend more energy to perform the same amount of work, or decrease the amount of work he can perform. In cycling, the difference may be as much as a 10% energy savings between 80 and 120 RPM. This savings, when applied to increases in power output from 300 to 330W improve the speed of the rider by about 2 mph, or would lower his time for 10 miles by over 2 min. This can truly be an important factor in improving the performance of athletes.

CHAPTER V

CONCLUSIONS

The experiments described in this report examined the changes in various physiological and psychological parameters as they changed with pedalling rate in a group of sub-national class bicycle racers. The first experiment used short (3 min) stages at ever increasing power outputs and measured energy cost and heart rate at each stage for each pedal rate. The second experiment had the cyclists riding for 20-30 minutes at a high power output (about 85% VO_2 max) to test the influence of pedal rate on performance in prolonged work. During that test perceived exertion, plasma lactate, epinephrine, norepinephrine, and B-endorphin were observed as well as heart rate and energy cost.

The following conclusions can be taken from the series of experiments:

1. An optimum pedal rate - one which uses less energy at a given power output - exists in these cyclists. This is evident in both the short stage work bouts and in the prolonged tests. It is reflected in both metabolic rate (energy cost) and heart rate.
2. As seen in the first experiment, the optimal pedal rate changes with power output: higher work rates have higher optimum pedal rates. This was also shown by Seabury et al. (91), but in contrast to their study, I found a linear increase with power output from 100 to 300W rather than a levelling off at the highest work rates.
3. Energy cost of riding the ergometer and riding a bicycle on the treadmill at equivalent power outputs and pedal rates do not seem to be different. Therefore, more studies should be made before

advocating an inherent improvement in the tests by riding on the treadmill over riding on an ergometer.

4. The optimal cadence found in the prolonged tests was similar to those in the short bouts, indicating that the optimal pedal rate does not change over time but remains constant from the beginning to the end of a bout of exercise.
5. Other indices of stress, e.g. blood lactate, RPE, norepinephrine, and epinephrine tend to show the same differences with changing pedal rate as do energy cost and heart rate. Whether these are only a response to change in energy cost, or to an external physical difference in muscle use remains to be explored. B-endorphin showed no consistent changes.

The results of these experiments make it clear that pedal rate is a variable in physiological performance tests that should not be overlooked as has been done in the past in many laboratories. With further experiments on subjects at different fitness levels and from different athletic backgrounds, standards for different tests can be set up to improve the testing of subjects.

This information can also be used by racing cyclists, especially in the individual steady-rate races, to improve performance. There will be individual differences between riders, but picking the most efficient pedal rate should be a relatively easy way to become a better performer.

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APPENDIX

Table 2: Repeated measures analysis of variance table for energy cost vs. pedal rate at varying power outputs in Study 1.

	Source	d.f.	SS	MS	F	p
100W	Pedal Rate	4	69.18	17.30	39.98	<0.001
	Subjects	4	6.40	1.60		
	Error	16	6.91	0.43		
	Total	24	82.49			
150W	Pedal Rate	4	52.30	13.08	36.35	<0.001
	Subjects	4	4.40	1.10		
	Error	16	5.76	0.36		
	Total	24	62.46			
200W	Pedal Rate	4	41.00	10.25	29.10	<0.001
	Subjects	4	3.51	0.88		
	Error	16	5.63	0.35		
	Total	24	50.14			
250W	Pedal Rate	4	35.23	8.81	21.60	<0.001
	Subjects	4	3.76	0.94		
	Error	16	6.52	0.41		
	Total	24	45.51			
300W	Pedal Rate	4	33.43	8.36	13.94	<0.001
	Subjects	4	4.88	1.22		
	Error	16	9.59	0.60		
	Total	24	47.90			

Table 3: Repeated measures analysis of variance table for heart rate vs. pedal rate at varying power outputs for Study 1.

	Source	d.f.	SS	MS	F	p
100W	Pedal Rate	4	4075.31	1018.82	13.71	<0.001
	Subjects	4	1348.37	337.09		
	Error	16	1189.42	74.34		
	Total	24	6613.10			
150W	Pedal Rate	4	2772.11	693.01	12.28	<0.001
	Subjects	4	1496.40	374.10		
	Error	16	903.31	56.46		
	Total	24	5171.82			
200W	Pedal Rate	4	1881.17	470.29	11.10	<0.001
	Subjects	4	1686.99	421.75		
	Error	16	678.01	42.38		
	Total	24	4246.17			
250W	Pedal Rate	4	1392.69	348.17	10.83	<0.001
	Subjects	4	1916.77	479.19		
	Error	16	514.27	32.14		
	Total	24	3823.73			
300W	Pedal Rate	4	1322.18	330.55	12.67	<0.001
	Subjects	4	2179.97	544.19		
	Error	16	417.56	26.10		
	Total	24	3919.71			

Table 4: Results of the Newman-Keuls Multiple-Range a posteriori test for differences among means of energy cost vs. pedal rate at each power output. Values sharing a common line are not significantly different (p<.05).

100W					
Pedal Rate	60 RPM	40 RPM	80 RPM	100 RPM	120 RPM
Energy Cost (kcal/min)	7.37	7.39	7.89	9.63	11.63
150W					
Pedal Rate	60 RPM	80 RPM	40 RPM	100 RPM	120 RPM
Energy Cost (kcal/min)	10.42	10.81	10.97	12.42	14.34
200W					
Pedal Rate	60 RPM	80 RPM	40 RPM	100 RPM	120 RPM
Energy Cost (kcal/min)	13.46	13.74	14.53	15.20	16.95
250W					
Pedal Rate	60 RPM	80 RPM	100 RPM	40 RPM	120 RPM
Energy Cost (kcal/min)	16.49	16.66	17.98	18.10	19.57
300W					
Pedal Rate	60 RPM	80 RPM	100 RPM	40 RPM	120 RPM
Energy Cost (kcal/min)	19.53	19.58	20.76	21.68	22.18

Table 5: Results of the Newman-Keuls Multiple-Range a posteriori test for differences among means of heart rate vs. pedal rate at each power output. Values sharing a common line are not significantly different (p<.05).

100W					
Pedal Rate	40 RPM	60 RPM	80 RPM	100 RPM	120 RPM
Heart Rate (bpm)	105.7	106.2	111.9	119.8	140.5
150W					
Pedal Rate	60 RPM	40 RPM	80 RPM	100 RPM	120 RPM
Heart Rate (bpm)	123.2	127.0	127.7	135.4	152.7
200W					
Pedal Rate	60 RPM	80 RPM	40 RPM	100 RPM	120 RPM
Heart Rate (bpm)	140.1	143.4	148.2	151.1	164.9
250W					
Pedal Rate	60 RPM	80 RPM	100 RPM	40 RPM	120 RPM
Heart Rate (bpm)	157.1	159.1	166.7	169.4	177.1
300W					
Pedal Rate	60 RPM	80 RPM	100 RPM	120 RPM	40 RPM
Heart Rate (bpm)	174.1	174.6	182.4	189.2	190.6

Table 6: Equations and correlation coefficients for curves of energy cost vs. pedal rate at varying power outputs on the bicycle ergometer.

Power Output	Equation of Line	Correlation Coefficient
100W	$y = 9.55 - 0.090x + 0.0009x$	0.9956
150W	$y = 14.41 - 0.132x + 0.0011x$	0.9947
200W	$y = 19.23 - 0.172x + 0.0013x$	0.9898
250W	$y = 24.11 - 0.213x + 0.0015x$	0.9798
300W	$y = 28.85 - 0.250x + 0.0016x$	0.9621

Table 7: Equations and correlation coefficients for curves of heart rate vs. pedal rate at varying power outputs on the bicycle ergometer in Study 1.

Power Output	Equation of Line	Correlation Coefficient
100W	$y = 126.36 - 0.803x + 0.0076x$	0.9890
150W	$y = 153.26 - 0.986x + 0.0081x$	0.9963
200W	$y = 180.76 - 1.186x + 0.0088x$	0.9879
250W	$y = 207.66 - 1.369x + 0.0094x$	0.9431
300W	$y = 234.70 - 1.557x + 0.0099x$	0.8634

Table 8: Table showing the results of the analysis of regression coefficients and analysis of adjusted means of the lines for optimal pedal rate vs. power output using heart rate or energy cost.

Homogeneity of Regression Coefficients

Sample	n	SSx	SP	SSy	b	Regression SS	Regression df	Residual SS	Residual df
1	5	25000	3360	459.03	0.134	451.58	1	7.542	3
2	5	25000	3175	405.96	0.127	403.23	1	2.735	3
Sum						854.81	2	10.277	6
Pooled		50000	6535	864.99	0.131	854.125	1		
Difference						0.681	1		

F = 0.40 p = n.s.

Homogeneity of Adjusted Means

Source	SSx	SP	SSy	df	Residual SS	df	MS
Among	0	0	5.184	1	5.1840	1	5.1840
Within	50000	6535	865.992	8	10.8675	7	1.5525
Total	50000	6535	870.176	9	16.0515	8	

F = 3.34 p = n.s.

Table 9: Analysis of variance table for energy cost vs. pedal rate in prolonged exercise.

Source	df	SS	MS	F	p
At 10-min of exercise					
Pedal Rate	4	2.42	0.61	3.96	0.0236
Subjects	4	5.63	1.41		
Error	14	2.14	0.15		
Total	22	10.37			
At 20-min of exercise					
Pedal Rate	4	2.50	0.63	7.09	0.0036
Subjects	4	3.75	0.94		
Error	12	1.06	0.09		
Total	20	7.27			

Table 10: Repeated measures analysis of variance table for heart rate vs. pedal rate in a prolonged task.

Source	df	SS	MS	F	p
At 10-min of exercise					
Pedal Rate	4	276.75	69.19	3.63	0.0314
Subjects	4	1434.07	358.52		
Error	14	267.00	19.07		
Total	22	1977.82			
At 20-min of exercise					
Pedal Rate	4	183.85	45.96	3.76	0.0332
Subjects	4	1178.22	294.56		
Error	12	146.85	12.20		
Total	20	1435.24			

Table 11: Repeated measures analysis of variance table for perceived exertion vs. pedal rate in a prolonged test.

Source	df	SS	MS	F	p
At 10-min of exercise					
Pedal Rate	4	31.85	7.96	3.43	0.0375
Subjects	4	6.43	1.61		
Error	14	32.53	2.32		
Total	22	69.93			
At 20-min of exercise					
Pedal Rate	4	23.23	5.81	4.74	0.0158
Subjects	4	11.98	2.99		
Error	12	14.69	1.22		
Total	20	46.17			

Table 12: Repeated measures analysis of variance table for lactate concentration vs. pedal rate at various times in a prolonged ergometer test.

Source	df	SS	MS	F	p
At 10-min of exercise					
Pedal Rate	4	23.79	5.94	6.52	0.0035
Subjects	4	47.16	11.79		
Error	14	12.76	0.91		
Total	22	84.01			
At 20-min of exercise					
Pedal Rate	4	9.62	2.41	2.26	0.1230
Subjects	4	60.41	15.10		
Error	12	12.76	1.06		
Total	20	81.52			
At 5-min after exercise					
Pedal Rate	4	16.47	4.12	2.66	0.0766
Subjects	4	42.79	10.70		
Error	14	21.64	1.55		
Total	22	80.24			

Table 13: Repeated measures analysis of variance table for epinephrine concentration vs. pedal rate in a prolonged ergometer test.

Source	df	SS	MS	F	p
At 10-min of exercise					
Pedal Rate	4	177877.87	44469.47	1.40	0.2833
Subjects	4	1277446.77	319361.69		
Error	14	443322.43	31665.89		
Total	22	1898647.07			
At 20-min of exercise					
Pedal Rate	4	975339.94	243834.99	1.88	0.1786
Subjects	4	5251568.98	1312892.22		
Error	12	1555878.76	388969.69		
Total	20	7782787.68			
At 5-min after exercise					
Pedal Rate	4	17781.77	4455.44	2.01	0.1489
Subjects	4	76560.53	19140.13		
Error	14	31021.73	2215.84		
Total	22	125364.03			

Table 14: Analysis of variance table for norepinephrine concentration vs. pedal rate at various times in a prolonged ergometer test.

Source	df	SS	MS	F	p
At 10-min of exercise					
Pedal Rate	4	10263598.42	2565899.61	2.68	0.0751
Subjects	4	12975004.73	3243751.13		
Error	14	13381974.73	955855.34		
Total	22	36620577.88			
At 20-min of exercise					
Pedal Rate	4	5112904.59	1278226.15	1.37	0.3019
Subjects	4	27089841.83	6772460.71		
Error	12	11205513.11	933792.76		
Total	20	43408259.53			
At 5-min after exercise					
Pedal Rate	4	130488.27	32622.07	0.40	0.8052
Subjects	4	1542457.07	385614.27		
Error	14	1140666.93	81476.21		
Total	22	2813612.27			

VITA

J. Richard Coast was born January 15, 1954 in Akron, Ohio to James Otis and Ann (Conlon) Coast. He attended elementary school in Akron and in Phoenix, Arizona, graduating from Palo Verde Elementary in June, 1968. In June, 1972 he graduated from Cortez High School in Phoenix.

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