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Linear increase in optimal pedal rate with increased power output in cycle ergometry

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Summary. This experiment was designed to estimate the optimum pedal rates at various power outputs on the cycle ergometer. Five trained bicycle racers performed five progressive maximal tests on the ergometer. Each rode at pedal rates of 40, 60, 80, 100, and 120 rev · min^{-1}. Oxygen uptake and heart rate were determined from each test and plotted against pedal rate for power outputs of 100, 150, 200, 250, and 300 W. Both $\dot{V}_{O_2}$ and heart rate differed significantly among pedal rates at equivalent power outputs, the variation following a parabolic curve. The low point in the curve was taken as the optimal pedal rate; i.e., the pedal rate which elicited the lowest heart rate or $\dot{V}_{O_2}$ for a given power output. When the optimum was plotted against power output the variation was linear. These results indicate that an optimum pedal rate exists in this group of cyclists. This optimum pedal rate increases with power output, and when our study is compared to studies in which elite racers, or non-racers were used, the optimum seems to increase with the skill of the rider.

Key words: Cycle ergometry – Efficiency – Pedal rate

Introduction

For work on the cycle ergometer in the laboratory, it has been assumed that 50 or 60 rev · min^{-1} was the best pedal rate at which to work (Åstrand and Rodahl 1977; Michielli and Stricevic 1977; Saltin and Åstrand 1967). Several investigators have found optimum pedal frequencies of 30–60 min^{-1} (Dickinson 1928; Eckermann and Millahn 1967; Hess and Seusing 1963) using relatively low power outputs. Others have shown that optimum pedal rates fall in the range of 80 or 90 rev · min^{-1} by using efficiency (Hagberg et al. 1981) or using maximal oxygen uptake (McKay and Banister 1976). Still another group found that optimum pedal rate varied with power output (Seabury et al. 1977). These studies deal with standard cycle ergometry and may differ from those using arm work (Powers et al. 1984).

With estimates of optimum pedal rate as widely varied as these, determining the proper procedure for an ergometer test with regard to pedal rate is an important factor. In addition, the subjects used for this type of study have typically come from groups of diverse ability. Often, either non-cyclists or elite racers were used as subjects. Between those two groups lay quite a large gap. In that gap are the highly trained cyclists who are still somewhat below the elite caliber. This group is one of differing abilities and is hard to characterize, but since the majority of racing cyclists – and subjects of numerous studies – are in this group, it is a very important one to study. One objective of this study was to determine whether an optimum pedal rate (one which uses less energy at a given power output) does indeed exist for this group of cyclists, and if so, if it stays the same through widely varied work rates. Another purpose of the experiment was to discover how the optimum pedal rate of these cyclists compared with that of other types of subjects.

Methods

For the study five male volunteers participated after having been told the nature of the experiment and its possible risks, and after having signed an informed consent statement. All subjects were bicyclists with one or more seasons of racing experience. The characteristics of the individual subjects are shown in Table 1.

The subjects each completed five progressive maximal tests on the cycle ergometer (Monark). Each test was performed at one of

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

Subject	Age	Body mass (kg)	$\dot{V}_{O_{2max}}$ (l · min^{-1}) STPD	$\dot{V}_{O_{2max}}$ (ml · kg^{-1} · min^{-1}) STPD	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

five pedal rates (40, 60, 80, 100, and 120 rev · min^{-1}) with work load being increased every third minute until exhaustion. The maximal values used were those achieved at the last power output for which the subject was able to complete the full 3 min.

The ergometer was modified 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; the subjects used cycling shoes with cleats in order to allow for application of power to the full pedal stroke.

During the 3rd min at each power output, the following variables were measured: heart rate, F_EO_2, F_ECO_2, and $\dot{V}_E$ or $\dot{V}_I$. Heart rate was measured using a conventional bipolar lead system attached to a cardiotachometer (Narco Biosystems BT 1200), and recorded as a rate by attachment to an ink writing oscillograph (Narco Biosystems DMP-4B).

Ventilation was measured with a dry gas meter (Parkinson-Cowan) which had been calibrated with a spirometer (Collins 120-l). Oxygen uptake and carbon dioxide output were measured by conventional open circuit spirometry. An O_2 (Applied Electrochemistry S-3A) and CO_2 (Beckman LB-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. The subjects kept cadence with a metronome, in addition to input from the investigators.

From the $\dot{V}_{O_2}$ and heart rate values obtained as mentioned above, both an oxygen cost of cycling and a heart rate line were calculated for each rider at each pedal rate, where $\dot{V}_{O_2}$ or heart rate were plotted against power output for each test. The $\dot{V}_{O_2}$ and heart rate cost of riding at power outputs of 100, 150, 200, 250, and 300 watts (W) were interpolated from each of the lines. These were the values used for the subsequent calculations.

From the cost of cycling lines, values were obtained 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 values from the five subjects were averaged for the determination of optimum pedal rate.

A curve of best fit was determined for heart rate or $\dot{V}_{O_2}$ vs pedal rate at each power output. The first derivative of the equation was used to determine the point in the curve where the slope was zero (that is, the low point in the curve). These low points were considered the optimum pedal rates for the respective power outputs. Optimum pedal rate was then plotted against power output.

Analysis of variance for repeated measures was used to determine overall differences among costs for each pedal rate. Newman-Keuls Multiple-Range *a posteriori* tests were employed to detect which pedal frequencies 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.

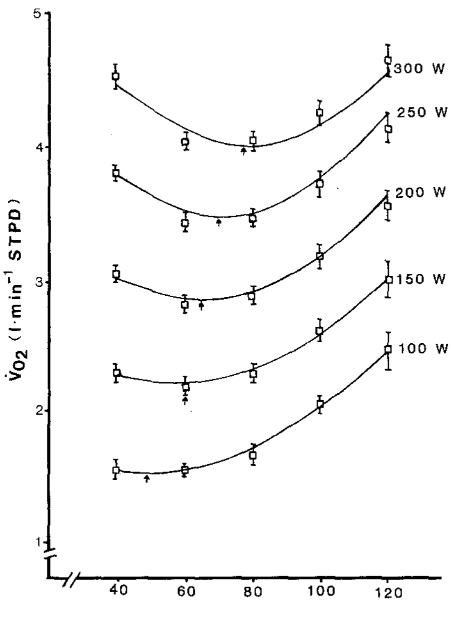

Fig. 1. $\dot{V}_{O_2}$ and pedal rate. Each line represents one power output. Points are mean ± SE of five values. $\dot{V}_{O_2}$ was significantly different between pedal rates at each power output. Arrow indicates optimum pedalling rate at each power output

Results

The results of the progressive tests showed that both heart rate and $\dot{V}_{O_2}$ increased linearly with power output at each pedal rate. The correlation coefficients for either the heart rate or the oxygen cost of cycling lines vs power output were all above 0.95.

Analysis of variance showed that the values for both $\dot{V}_{O_2}$ and heart rate differed significantly among pedal rates at equal power outputs ($P < 0.001$). Although the $\dot{V}_{O_2}$ and heart rate at 60 rev · min^{-1} generally appear lower, there was never a significant difference between those variables at 60 and at 80 rev · min^{-1} pedal rates, as determined by the Newman-Keuls test. The change in the general shape of the curves suggested application of parabolic equations to the graphs rather than trying to decide which of the points was lowest.

When $\dot{V}_{O_2}$ or heart rate was plotted against pedal rate at equal power outputs, each curve could best be described by a parabolic equation (Figs. 1 and 2). Correlation coefficients for the curves varied from 0.86 to 0.99.

When the low (optimum) point of each curve was plotted against power output, the relationship appeared to be linear. When analyzed by linear regression, there did prove to be a linear relationship in which the optimum pedal rate increased with power output. Correlation coefficients for the lines derived by both heart rate and $\dot{V}_{O_2}$ were 0.99. Analysis of regression coefficients and adjusted means showed the two lines not to be significantly different.

$\dot{V}_{O_{2max}}$ and maximum power output both were significantly different among pedal rates, with 80 rev · min^{-1} being highest ($P < 0.05$).

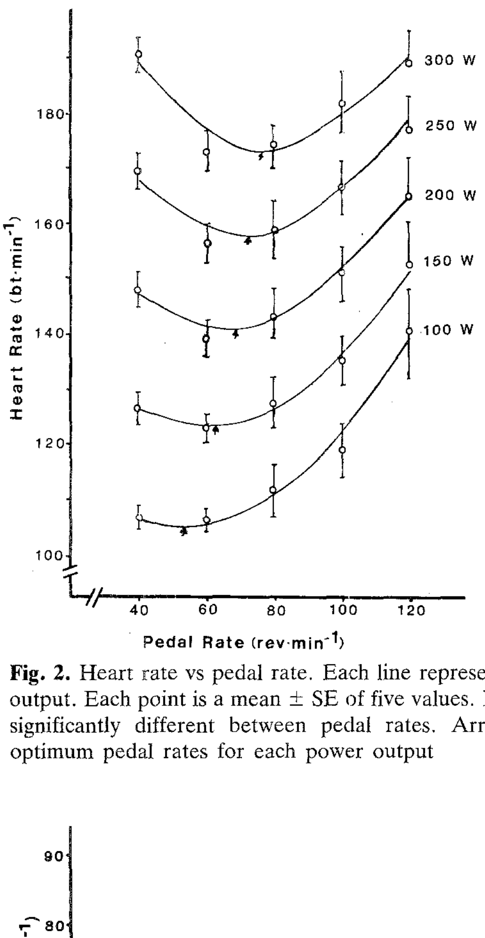

Fig. 2. Heart rate vs pedal rate. Each line represents one power output. Each point is a mean ± SE of five values. Heart rate was significantly different between pedal rates. Arrows designate optimum pedal rates for each power output

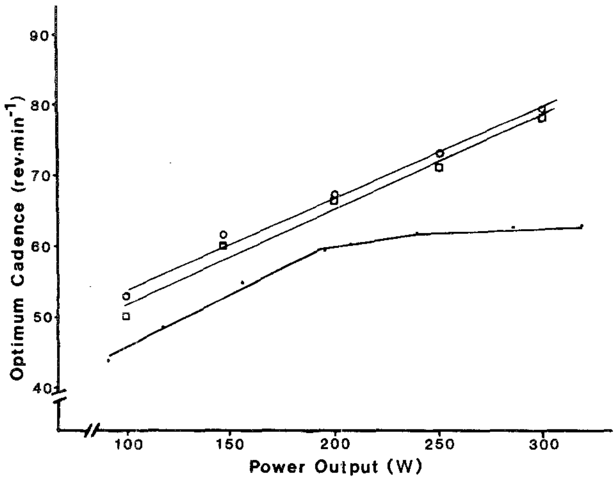

Fig. 3. The optimum pedal rate as a function of power output. ○ are optima from the heart rate curves (Fig. 2). □ are optima calculated from $\dot{V}_{O_2}$ (Fig. 1). The two lines are not significantly different. The lower curve is from data by Seabury et al. (1977)

Discussion

As Figs. 1 and 2 showed, $\dot{V}_{O_2}$ and heart rate varied as a function of pedal rate at a given power output. That showed – by the low point in the curve – that an optimum pedal rate existed for the type of rider evaluated in this study.

Many investigators have concluded that there are optimum pedal rates (Dickinson 1929; Eckermann and Millahn 1967; Garry and Wishart 1931; Hagberg et al. 1981; Hess and Seusing 1963; McKay and Banister 1976; Michielli and Stricevic 1977; and Seabury et al. 1977). Their results disagree, though, on the absolute value of the optimum pedal rate, whether it changes or not with power output and the training state of the subject, and the method of determining optimum pedal rate. Most of the researchers found optimum pedalling frequencies of from 30 to 60 min^{-1} (Dickinson 1929; Eckermann and Millahn 1967; Garry and Wishart 1931; Hess and Seusing 1963; and Michielli and Stricevic 1977). On the other end of the scale, McKay and Banister (1967) showed that the highest $\dot{V}_{O_{2max}}$ was achieved at 80–100 rev · min^{-1}, which we have also seen; and Hagberg and coworkers (1981) determined optimal pedal rates in champion cyclists of about 90 rev · min^{-1}.

In general, the studies that found lower pedal rate optima used lower power outputs. Dickinson (1929) found an optimum pedalling frequency of 33 min^{-1}. However, the study used only one subject who was also too short for the ergometer. According to our calculations using Dickinson's two papers (1928, 1929), the power output was not the same for the different pedal rates (from 17.8 to 234 W) and the time of work was not identical (0.5–12.75 min). That casts doubt on the vailidity of the comparison between tests in her study. Hess and Seusing (1963) used identical power outputs and times of exercise and estimated an optimum pedal frequency of 45 min^{-1}. Those authors used a power output of only 30 W, a very low value. Although this ensured a steady state, it was not of much use in work with competitive cyclists, or in tests near $\dot{V}_{O_{2max}}$ Eckermann and Millahn (1967) also determined a 45 rev · min $^{-1}$ pedal rate optimum. They went so far as to say that the choice of pedalling rate should not be left to the subject because he would invariably pick one that was too fast. Their subjects used moderate power outputs of 100 and 150 W.

In contrast to the studies cited above, Seabury et al. (1977) investigated the effect of power output on optimum pedal rate. They found that the most efficient pedal rate increased from 42 rev · min^{-1} at 40 W to 60 rev · min^{-1} at 327 W. They were first to show this type of result. In the present study we have seen the same phenomenon and have further shown that optimum pedal rate varies linearly with power output. This is different from the change seen in the Seabury study. Their optimum pedal rate levelled off above a power output of 200 W (see Fig. 3). The difference 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 that is necessary for greater efficiency at higher pedal rates.

Increasing pedal rate with power output is a logical phenomenon when the forces required to perform the work are taken into account. If a rider maintained a steady 50 rev · min^{-1} cadence, the mean force needed to push the pedals would rise from 109 N at 100 W to 328 N at 300 W. By increasing the pedal rate with power output, the average force required at 100 W and 50 rev · min^{-1} was 109 N, and at 300 W and 79 rev · min^{-1} was 207 N. That decreased the force required by the muscles by 120 N (see for example Whitt and Wilson 1974). This could be a major influence in the optimization of pedal rate.

The data of Eckermann and Millahn (1967), if plotted on the line in Fig. 3, is near but slightly lower than the optimum we predicted for 100- and 150-W power outputs. Our optimal pedal rates were lower than those of the Hagberg group (1981). Their power outputs averaged about 330 W, and their calculated optimum frequency was 91 min^{-1}. If plotted on the graph in Fig. 3, that power output would elicit an optimum pedal rate of only 83 rev · min^{-1}. When our data are combined with those of the studies mentioned, a feasible conclusion seems to be that in addition to the absolute power output, the skill of the rider plays a 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. A reason for skill playing a role in optimum pedal rate may be, as mentioned earlier, that cyclists routinely train using pedalling rates of 90 rev · min^{-1} and above. This is a common practice for cyclists, and may indeed be an acquired skill that comes about with years of training.

From these experiments it is evident that not only is there an "optimum" pedal rate, but that it varies. This study indicated that a major factor in the determination of optimal pedal rate is the power output at which the cyclist is working, with the skill of the cyclist playing a secondary role. Another suggestion that comes from this study is that there is a real need for making the procedure of a series of tests fit the subjects being used for the tests, not the convenience of the investigators as the rigid 50–60 rev · min^{-1} tests tend to do.

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